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ANALYSIS OF AN INNOVATIVE DISTRIBUTION SYSTEM THROUGH A NOVEL OPTIMAL POWER FLOW ALGORITHM

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Abstract

The main lines of development of the European energy sector are, in short, the transition from a centralized generation architecture to a distributed generation model, using increasing portions of renewable energy and energy storage systems. Finally, new and more efficient equipment for room air conditioning and transport, based on the electric vector, were adopted. So the energy and electrical sectors are evolving very rapidly. In particular, changes are taking place in the electricity market, in renewable generation and in energy efficiency devices.

In this scenario new algorithms are being born, for the study of the network, which take into account the presence of distributed generation, energy storage systems and new directives in the energy field. The SUSI3 algorithm lends itself to taking into consideration all the changes that the energy and electrical sectors are undergoing and for this reason it has been used for the study of an innovative distributed system object of the thesis.

Sommario

Le principali direttrici di sviluppo del settore energetico europeo riguardano, in sintesi, la transizione da una architettura di generazione centralizzata verso un modello di generazione distribuita, utilizzando quote crescenti di energia rinnovabile e di sistemi di accumulo energetico. Infine sono stati adottati nuovi apparati più efficienti per la climatizzazione degli ambienti e il trasporto, basati sul vettore elettrico. Quindi il settore energetico ed elettrico si stanno evolvendo molto rapidamente. In particolare sono in corso dei cambiamenti nel mercato elettrico, nella generazione da fonti rinnovabili e nei dispositivi per l'efficienza energetica.

In questo scenario stanno nascendo nuovi algoritmi, per lo studio della rete, che tengano conto della presenza della generazione distribuita, dei sistemi di accumulo e delle nuove direttive in ambito energetico. L'algoritmo SUSI3 si presta a tenere in considerazione l'insieme dei cambiamenti che il settore energetico ed elettrico sta subendo e per questo motivo è stato utilizzato per lo studio di un innovativo sistema distribuito oggetto della tesi.

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List of Abbreviations

OPF	**O**ptimal **P**ower **F**low
TSO	**T**rasmission **S**ystem **O**perator
DSO	**D**istribution **S**ystem **O**perator
LV	**L**ow **V**oltage
MV	**M**edium **V**oltage
MGs	**M**igro **G**rids
SGs	**S**mart **G**rids
DG	**D**istributed **G**eneration
DERs	**D**istributed **E**nergy **R**esources
RESs	**R**enewable **E**nergy **S**ources
PV	**P**hotovoltaict
E-LAN	**L**ocal **A**rea **E**nergy **N**etwork
IoE	**I**nternet **o**f **E**nergy
ESS	**E**nergy **S**torage **S**ystem
PCC	**P**oint **C**ommon **C**oupling
ICT	**I**nformation **C**omunication **T**echnology
RTP	**R**eal **T**ime **P**ricing
MO	**M**arket **O**perator
EMS	**E**nergy **M**anagement **S**ystem
DSM	**D**emand **S**ide **M**anagement
TOU	**T**ime **O**f **U**se
DR	**D**emand **R**esponse
EED	**E**nergy **E**fficiency **D**irective
EPBD	**E**uropean **P**erformance of **B**uildings **D**irective
ETS	**E**mission **T**rading **S**cheme
LULUCF	**L**and **U**se **L**and **U**se **C**hange and **F**orestry

Dedicated to my family and friends.

Chapter 1

Introduction

At first this chapter deals with the description of the meaning of smart grid. After that the path to reach the smart grid is resumed. Indeed actually there is in progress an evolution of the electrical power grid which tends towards the smart grid.

1.1 Description of the smart grid.

The existing electricity grid is the result of very fast urbanization and infrastructure developments in different and diffuse areas of the world. Moreover, the rapid growth in the cost of fossil fuels, together with the incapacity of utility companies to increase their generation capacity in line with the rising demand for electricity, has accelerated the need to evolve the distribution network by introducing technologies and devices to support with demand-side management. So it's ongoing an development of the current electrical power system towards the smart grids.
The smart grid is a modern electric power grid infrastructure for improved efficiency, reliability, and safety, with smooth integration of renewable and alternative energy sources, through automated control and modern communication technologies. In the smart grid, a real time and reliable information and electrical data becomes the key factor for safe delivery of power from the generators, such as the main centralize generators, the renewable energy sources and energy storage systems, to the end-users. To allows this huge flow of information and energy it has been develop a smart infrastructure system that is the energy, information, and communication infrastructure underlying the smart grid. Furthermore is important a smart management system that provides advanced management and control services and functionalities. The smart management system takes advantage of the smart infrastructure to follow different advanced management objectives. Thus far, most of such objectives are related to energy efficiency improvement, supply and demand balance, emission control, operation cost reduction, and utility maximization. At last is fundamental to consider a very efficient system of protection. The smart protection system is the subsystem in smart grid that provides advanced grid reliability analysis, failure protection, and security and privacy protection services. By taking advantage of the smart infrastructure, the smart grid must not only realize a smarter management system, but also provide a smarter protection system which can more

effectively and efficiently support failure protection mechanisms, address cyber security issues, and preserve privacy.
In particular the smart grids contains a lot of features that are resumed in what follows. The first one is the smart meter that represent the most dependable device in the field of power generations and consumption for data measurement. The smart metering refers to using advanced meters in conjunction with communication systems to allow customers to monitor their energy consumption in real time. After that is important to consider the distributed generation which means generating electricity from small and renewable energy sources. The distributed generation is one of greater and diffuse use in a smart grid as well as challenging for the supplier authorities. With the introduction of the distributed generation is important to face up to the renewable energy integration. Enhancing the capability of the grid the renewable energy integration supports the national network to meet the extended demand of the consumers with potential security. The renewable energy integration has to overcome some different challenges as the environmental impact and the voltage fluctuation. Indeed, for example the solar energy is unavailable during the night and the wind turbines don't generate electric energy in the absence of wind. So is important to consider an energy storage system coupled with the renewable energy sources supplying the grid in those moment. While the voltage fluctuation is link to the unstable wind speed and irregular solar radiation, in case of, respectively, photovoltaic and wind turbines system. After that, as previously anticipated, the communication systems are fundamental to transport information and energy. In particular it is important to enable the bi-directional communication system that makes the smart technology easier to use for both consumers and suppliers. Also the smart grid has to include several automatic technologies and devices for manage in an optimal and safety way the sources and loads into the grid. Subsequently the smart grid technology must be secured and protected from considerable threats or external attacks. As the technology is interconnected throughout the entire system, if a part of the network is attacked, eventually the entire system is exposed to a dangerous threat and it may evolve to total blackout or total system failure. That is why cyber security must be strong enough to make the system run smoothly, efficiently and in a safety way. At least different countries are adopting some new policies which are making the entire system work smarter and safety.
Moreover the smart grids and the smart technologies lead to those advantages. The first one is the increase of the reliability of the system understood as the decrease of the cost of interruptions and power quality disturbances and the decrease of the probability and consequences of diffused blackouts. After that the smart grid contributes to keep downward prices on electricity prices. Moreover the smart grid tends to increase the efficiency of the system understood as the reduction of the cost to produce, deliver, and consume electricity. Furthermore the smart grid leads to reduction of emissions by enabling a larger penetration of renewable and improving efficiency of generation, delivery, and consumption of electrical energy. At last the

smart grid increase the security and safety by reducing the probability and consequences of man-made attacks and natural disasters.
In conclusion the smart grid represents the next step of the evolution of the electrical grid that leads to a new way to generate, control and consume the electrical energy both for producers and consumers of the electrical energy.

1.2 The new European directive.

On 30 November 2016 the European Commission presented a package of measures to keep the European Union competitive as the clean energy transition changes global energy markets. The Clean Energy for All Europeans legislative proposals cover energy efficiency, renewable energy, the design of the electricity market, security of electricity supply and governance rules for the Energy Union. In addition the Commission proposed a new way forward for ecodesign as well as a strategy for connected and automated mobility. The package also includes actions to accelerate clean energy innovation and to renovate Europe's buildings. It provides measures to encourage public and private investment, promote EU industrial competitiveness and mitigate the societal impact of the clean energy transition. We are also exploring ways in which the EU can show further leadership in clean energy technology and services to help non-EU countries achieve their policy goals. Those proposals are resumed in what follows.

1.2.1 The new energy efficiency measures.

The European Commission adopts today proposals for a revision of the Energy Efficiency Directive (EED) and of the European Performance of Buildings Directive (EPBD) to bring them up to date with the 2030 energy and climate goals, to check their effectiveness, to simplify and improve the text, and to facilitate implementation at national level. On the basis of a comprehensive costs and benefits assessment, it also proposes to review the target to be reached by 2030 to a binding 30% EU level, emphasising the European Union's commitment to its international climate and energy goals for 2030 and beyond. Apart from the updates needed to reflect the new 30% target for 2030, one of the main changes introduced is the extension of the energy savings requirement to 2030 (specified in Article 7).
Article 7 is estimated to achieve half of the energy savings required under the whole Directive, and the aim is to reach this amount in a way that drives long term energy efficiency savings, thus also reducing costs for consumers and increasing security of supply. With the new Directive, alternative measures to save energy are put on an equal footing with Energy Efficiency Obligation Schemes, and a streamlined and clearer structure of Article 7 is set out.
A binding 30% EU energy efficiency target for 2030 emphasises EU commitment towards its international climate and energy goals for 2030 and beyond. This also underpins the EU's commitment under the European Energy Union to put energy

efficiency first. A binding policy framework will provide further certainty to investors that it is worth investing in energy efficiency. It will contribute to long-term predictability, and will have a positive impact on technology costs and payback periods of efficiency improvements of products, vehicles, buildings and services.
Meeting the 30% energy efficiency target in 2030 will be ensured by a strong political commitment on all levels, by:

1. extending successful policy areas (e.g. Article 7 of the Energy Efficiency Directive);
2. improving existing policies (e.g. Energy Performance of Buildings Directive);
3. improving the financing conditions of energy efficiency (e.g. through the Smart financing of Smart Buildings initiative);
4. improving the coordination and cooperation between all involved levels, sectors and stakeholders (via the new Governance initiative);
5. enlarging the scope and strengthening of minimum requirements of products, vehicles and buildings (e.g. of Eco-design, Energy Performance of Buildings Directive and vehicle standards); and
6. informing and involving consumers better (e.g. through energy labelling and the Market Design Initiative).

In addition, the Commission adopted today a number of measures that will improve the energy efficiency of products, in particular a new Ecodesign Working Plan for the 2016-2019 period ensuring that this successful policy will continue to contribute to the EU's energy efficiency targets.
Successful energy efficiency policy cannot be achieved without unlocking and mobilizing private investment. This is why the Commission complements these measures with an investment initiative called Smart Finance for Smart Buildings. Building upon the Investment Plan for Europe including the European Fund for Strategic Investments, and the European Structural and Investment Funds, this initiative will encourage a more effective use of public funds, help project developers bring good project ideas to maturity, and make the energy efficiency market more trusted and attractive for all stakeholders.

1.2.2 New energy union governance to deliver common goals.

The goal of the Energy Union with an ambitious climate policy at its core is to give EU consumers - households and businesses - secure, sustainable, competitive and affordable energy. This requires a fundamental transformation of Europe's energy system across five dimensions: energy security; the internal energy market; energy efficiency; de carbonisation; research, innovation and competitiveness. The targets set for 2030 are included in the Energy Union strategy: reducing greenhouse gas

emissions by at least 40%, improving energy efficiency by at least 27% that the Commission proposes today to upgrade to 30% binding at EU level and reaching at least 27% renewable energy in our final energy consumption.
These objectives can only be achieved through a set of coherent and coordinated actions – legislative and non legislative – at EU and national level. Designing and managing such a broad set of diverse actions requires the Energy Union to establish robust Governance. It must ensure policies and measures at each level are efficient, coherent, complementary and sufficiently ambitious. In this way, efforts by the EU and its Member States will come together as a cohesive whole that is sufficient to meet common challenges.
In October 2014, the European Council agreed in the context of the 2030 Climate and Energy Policy Framework that a reliable and transparent Governance system without any unnecessary administrative burden will be developed covering all five dimensions of the Energy Union.
The proposed Regulation provides the legislative foundation for the new Governance of the Energy Union. It will be complemented by non-legislative initiatives, for example, to build where necessary sufficient administrative capacity within Member States and to engage with various stakeholders such as non-state actors, civil society and business.

1.2.3 New electricity market design: a fair deal for consumers.

The new rules will touch upon a variety of principles and technical provisions with real tangible economic effects. These include, amongst others:

1. Short term markets will be made overall more flexible and responsive to the rise in variable renewable generation;

2. Wholesale price caps will be removed, making prices reflect the real value of electricity in time and location (scarcity pricing) in order to drive investments towards the flexible assets most needed for the system, including demand-response and storage. More liquid and interconnected markets will increase trade opportunities;

3. Dispatch rules will be adapted to the new market reality, creating a level-playing field for larger generation capacities. Rules on priority dispatch will however be maintained for small-scale renewable installations and emerging technologies to ensure their development;

4. Grid bottlenecks on the borders will be minimized, among other things by re-investing congestion revenues into the grid;

5. The overall electricity system operation by TSOs will see more coordination on a regional level to ensure most optimal utilisation of the grid and better grid stability; and

6. Better demand participation: remuneration for demand response will be more in line with the flexibility provided by such services, creating a better economic case for distributed resources and for self-generation.

Each consumer in Europe should be put at the centre of the Energy Union and reap the benefits of access to more secure, clean and competitive energy. The new rules for the retail electricity markets will include the following:

1. Consumers will be provided with better information about their energy consumption and their costs through clear electricity bills. Suppliers will have to prominently display basic information on every bill, and report energy costs, network charges and taxes/levies in the same way for clarity;

2. All EU electricity consumers will get free-of-charge access to at least one certified energy comparison tool that meets minimum quality standards in order to provide reliable information about the offers provided to consumers;

3. Switching conditions will be made easier. All switching related charges will be prohibited, except for early termination fees on fixed term contracts. These must be limited in size and contracts containing them must provide consumers with tangible advantages in return;

4. Every consumer will also be entitled to a smart meter equipped with common minimum functionalities. Member States not planning to roll-out smart meters are required to assess the cost-effectiveness of a large-scale smart metering deployment on a regular basis;

5. Consumers and communities will be empowered to actively participate in the electricity market and generate their own electricity, consume it or sell it back to the market while taking into account the costs and benefits for the system as a whole;

6. Every consumer will be able to offer demand response and to receive remuneration, directly or through aggregators. Dynamic electricity price contracts reflecting the changing prices on the spot or day-ahead markets will allow consumers to respond to price signals and actively manage their consumption;

7. This necessitates the removal of retail price regulation while ensuring the full and appropriate protection of vulnerable consumers. Targeted price regulation such as social tariffs will be permitted for a transition period to address the needs of vulnerable consumers until their situation can be addressed by appropriate energy efficiency and social policy measures;

8. With the bulk of renewable electricity connected at distribution level, Member States will have to allow and incentivise Distribution System Operators (DSO) to use flexibility services and energy efficiency measures to improve the efficiency of their operations; and

9. A new EU DSO entity will be created. It will be responsible for putting in place rules on grid management and use and EU-level cooperation with TSOs. It will also work on the integration of renewables, distributed generation, energy storage, demand response and smart metering systems.

With the new energy market rules in place all consumers will be able to generate, store and/or sell their own electricity to the market based on retail market conditions and taking into account the costs and benefits for the system as a whole. Active consumers who decide to generate their own electricity, for example by installing rooftop solar panels, will be able to fully benefit from the market either individually or in cooperatives, like renewable energy communities. The new market rules aim to deliver a better deal for all energy consumers. For vulnerable and energy poor consumers in particular, the objective is to ensure that they are not left behind as most consumers become active market participants. The new energy market rules oblige Member States to measure and monitor energy poverty and report to the Commission every two years. The Commission will facilitate best practice sharing on how to fight energy poverty, through an Energy Poverty Observatory. The new rules will also ensure that all customers in arrears with their energy suppliers are fully made aware of their options to avoid disconnection. Temporary price regulation to protect vulnerable and energy poor consumers, for example through the use of social tariffs, will be further allowed. In the medium term, however, energy efficiency measures proposed under the Energy Efficiency Directive and the Energy Performance of Buildings Directive will ensure that the root causes of energy poverty can be effectively addressed.

1.2.4 The revised renewable energy directive.

The European Commission adopts today a revised Renewable Energy Directive. The provisions are adapting the framework for renewable energy development to the 2030 perspective, provide certainty and predictability to investors and address the potential of renewable energy in a number of sectors.
The proposal identifies six key areas for action:

1. Creating an enabling framework for further deployment of renewables in the Electricity Sector;
2. Mainstreaming renewables in the Heating and Cooling Sector;
3. Decarbonising and diversifying the Transport Sector;
4. Empowering and informing consumers;
5. Strengthening the EU sustainability criteria for bioenergy; and
6. Making sure the EU level binding target is achieved on time and in a cost effective way.

In particular for each area are improved several actions to reach the goal. The preparation of the revised renewable energy Directive has been done in close coordination with, and is complementary to, other related Commission initiatives. First and foremost, this includes the Market Design and Energy Union Governance proposals but also the revision of the Energy Efficiency and Energy Performance of Buildings Directives, the EU ETS and the Effort Sharing Regulation, the LULUCF Regulation and the Bioenergy Sustainability Policy. These other pieces of legislation mutually complement the revised Directive. They will contribute to enable the EU to reach, collectively, a share of at least 27% in the final energy consumption by 2030 in a cost effective way and to deliver on the EU political priority of becoming the world's number one in renewables.
The Market Design initiative will, inter alia, facilitate the development of an electricity market fit for renewable energies, where short term markets are fully developed and integrated and flexibility plays a key role in enhancing the market value of renewables. This enhanced electricity market design, together with the strengthened EU ETS, will be a key foundation of the 2030 framework and will ensure that renewable energy generators can earn a higher fraction of their revenues from the energy markets. The revision of the Renewables Directive will build on this approach and complement it by introducing various measures aimed at attracting the necessary investments cost-efficiently and in a timely manner.
The Energy Union Governance frames the Integrated National Energy and Climate Plans, which set out national contributions to the legally binding EU-level RES target. The Energy Union Governance foresees an iterative process between the Commission and Member States to ensure ambitious and reliable National Plans including in renewable energy and also proposes different options for concrete measures to fill a potential gap either on ambition or delivery of the EU renewables target. At the same time, the Governance Regulation streamlines and integrates the existing planning, reporting and monitoring obligations of the energy acquis including those for renewable energy post 2020.
The Energy Efficiency Directive (EED) and Energy Performance for Buildings Directive (EPBD) aim, respectively, at facilitating the achievement of the energy efficiency target and at enhancing the energy performance of buildings. The provisions in the heating and cooling section are consistent with and complement the measures in both the EED and the EPBD, in particular by tackling existing buildings, tertiary and industry, as well as by including specific requirements on renewables. The EU Emission Trading Scheme (EU ETS) will be reformed for the period after 202012. Existing legislation includes the Market Stability Reserve to address the current surplus of allowances and to improve the ETS resilience to major shocks by adjusting the supply of allowances to be auctioned. The strengthened EU ETS will play an increasing role in providing a stronger investment signal for lower carbon technologies, including renewables, and will ensure that synergies between renewable energy and climate policies are better exploited. Furthermore, the proposed Effort Sharing Regulation13

makes proposals for setting national binding emission reduction targets for greenhouse gases for the sectors outside the EU ETS and on Land Use, Land Use Change and Forestry (LULUCF). The LULUCF Regulation aims at integrating carbon emissions credits and debits form agriculture and forestry into the EU 2030 climate and energy framework. The reinforced EU sustainability criteria will provide further assurance that bioenergy used in the EU continues to contribute to climate change mitigation, while minimizes the risk of unintended biodiversity impacts due to biomass production.

Chapter 2

Description of SUSI3 and Source Locator

At first this chapter deals with the description of the algorithm related at the programs SUSI3 and Source Locator. The program SUSI3, developed by Prof. Tenti and Ph.D. Tommaso Caldognetto of University of Padova, solves the optimal power flow problem, of an input network, with a control function and some boundaries in different cases like islanding operation and demand response. Generally, the power flow algorithms include the Newton-Raphson method in both polar and rectangle forms, the Gauss-Seidel method, the DC power flow method, and all kinds of decoupled power flow methods. In SUSI3 the solution of optimal power flow is obtain with a direct formula. While Source Locator, developed by Prof. Tenti and Ph.D. Tommaso Caldognetto of University of Padova, allows us to verify the consequence of the connection in a new or already existing fully controllable node of a current source, with a given apparent power. At last, in the second part, some results of an analysis are reported, done with SUSI3, of an innovative European network low voltage for a better understanding of the functionality of SUSI3 and Source Locator.

2.1 Description of the algorithms SUSI3 and Source Locator.

The program SUSI3 solves the optimal power flow problem, of an input grid, with a control function and some boundaries in different cases, such as islanding operation and demand response. The input grid could be an actual radial grid or an innovative meshed grid with distributed generations and energy storage systems. An representation of a typical innovative distribution grid is reported into the Fig. 1.1. In that figure the distributed generators, like the current and voltage source, the energy storage systems and photovoltaic sources, are interconnected with the main generators and loads through the distribution network. The generator at slack node is a voltage source because is fundamental that a voltage source gives the voltage reference, in amplitude and in phase, for the rest of generators. While at user node the photovoltaic sources, batteries and loads are reported because the end users decide, independently, to install a distributed generator o energy storage system. At last the distributed network, both radial and meshed, is represented with the node admittance matrix that is explain subsequently. Actually the distribution grid are radial but in the next future, the evolution of the electric system will be with the meshed grid. After defining the network into the program SUSI3, the program solves te optimal power flow of the input grid.

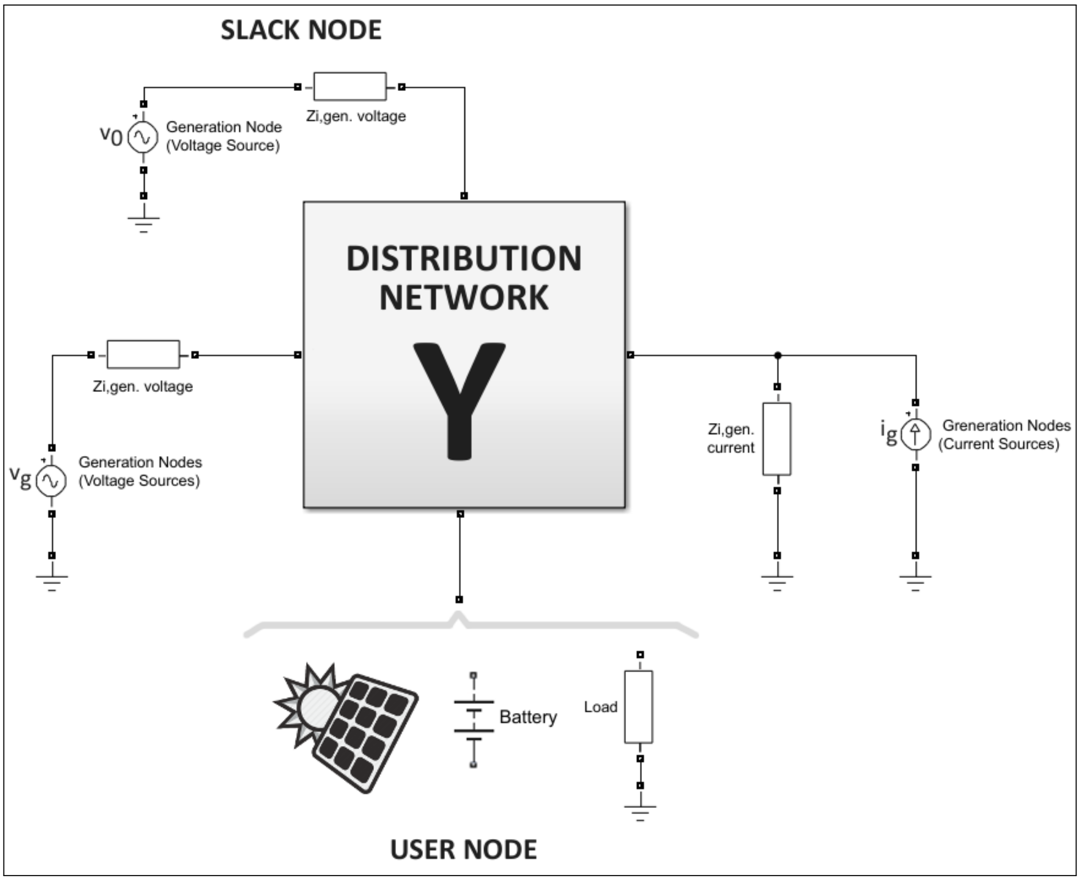

FIGURE 2.1: Typical representation of an innovative distribution network.

The algorithm of SUSI3 is very similar, in the core, at the algorithm of optimal power flow. The power flow analysis is concerned with describing the operating state of an entire power system, by which we mean a network of generators, transmission lines, distributed sources and loads that could represent an area as small as a city or as large as several states. Given certain known quantities, typically, the amount of power generated and absorbed at different nodes, power flow analysis allows us to determine the unknown quantities. The most important of these quantities are the voltages at node throughout the transmission system, which, for alternating current, consist of both a magnitude and a phase angle. Once the voltages are known, the currents flowing through every transmission link can be calculated. However, in the power flow problem, the relationship between voltage and current at each bus is nonlinear, and the same holds for the relationship between the active and reactive power absorbed or generated at a bus with the voltage magnitude at a source bus. Thus power flow calculation involves the solution of nonlinear equations that gives

us the electrical response of the transmission system to a particular set of loads and generator power outputs.
At the beginning, to solve the optimal power flow problem, the program SUSI3 has to create the matrices to define the topology of the grid. The network is associated with an oriented graph, whose edges coincide with the grid branches. The graph is characterized by the complete incidence matrix $\mathbf{A}_c$ which includes L rows and N+1 columns. Each row is null except for the elements identifying the origin node, set to +1, and the end node, set to -1, of the corresponding branch. Now we can define the basic network relations that link the voltage/current of the branch with the voltage/current of the node. The first basic equation explicit the relation between the branch voltage $\mathbf{w}$ with the node voltage $\mathbf{v}_c$ as follows:

$$\mathbf{w} = \mathbf{A}_c \mathbf{v}_c \tag{2.1}$$

The second basic equation explicit the relation between the node current $\mathbf{i}_c$ with the branch current $\mathbf{j}$ as follows:

$$\mathbf{i}_c = \mathbf{A}_c^T \mathbf{j} \tag{2.2}$$

For the follows equation is important to divide the complete incidence matrix $\mathbf{A}_c$ as:

$$\mathbf{A}_c = \begin{Vmatrix} \mathbf{a} & \mathbf{A} \end{Vmatrix} \tag{2.3}$$

where $\mathbf{a}$ is the vector corresponding to the first column of $\mathbf{A}_c$, i.e. to the reference node that correspond at slack node, and $\mathbf{A}$ is the reduced incidence matrix of size LxN, containing all columns corresponding to the other grid nodes from 1 to N. After that we can define the node admittance matrix $\mathbf{Y}$ that is is an NxN matrix, generally it is sparse, describing a power system with N buses. For an admittance diagram with N buses, the admittance between the bus in consideration, k, and another bus, i, connected to k, can be described by this equation:

$$y_{ik} = g_{ik} + jb_{ik} \tag{2.4}$$

where y_{ik} is the admittance between node i and k, g_{ik} is the real part of y_{ik} while b_{ik} is the imaginary part of y_{ik}. The term y_{ik} accounts for the admittance of linear loads connected to bus k as well as the admittance-to-ground at bus k. The general mathematical expression follows:

$$Y_{ij} = \begin{cases} y_i + \sum\limits_{\substack{k=1 \\ k \neq i}}^{n} y_{ik} & if \quad i = j \\ \\ -y_{ij} & if \quad i \neq j \end{cases} \tag{2.5}$$

It is important to note that y_{ij} is non-zero only where a physical connection exists between two buses. Generally the real part of the node admittance to the ground relative at any branch is neglected because its value is very high compared to the other parameters. Now we can write some relevant equations. The first relevant couple of equation, that is fundamental to the analysis of the power flow, explicit the relation between the node currents/voltages and branch currents/voltages as:

$$\mathbf{i} = \mathbf{A}^T\mathbf{j} \quad and \quad \mathbf{w} = \mathbf{A}\mathbf{u} \tag{2.6}$$

The second relevant couple of equation explicit the relation between the node currents/voltages and branch voltages/current as:

$$\mathbf{w} = \mathbf{Z}\mathbf{j} \quad and \quad \mathbf{i} = \mathbf{Y}\mathbf{u} \tag{2.7}$$

where $\mathbf{Z}$ is the diagonal impedance matrix of the network. Now we can define the general input/output equations. In general the input variables for network control are voltages $\mathbf{u}_\mathrm{g}$ impressed at generator nodes and currents $\mathbf{i}_\mathrm{u}$ impressed at user nodes. The output variables are currents $\mathbf{i}_\mathrm{g}$ at generator nodes and voltages $\mathbf{u}_\mathrm{u}$ at user nodes. The input/output relations may be expressed by making reference to hybrid transfer matrix $\mathbf{H}$ as:

$$\left\|\begin{matrix}\mathbf{i}_g\\ \mathbf{u}_u\end{matrix}\right\| = \mathbf{H}\left\|\begin{matrix}\mathbf{u}_g\\ \mathbf{i}_u\end{matrix}\right\| = \left\|\begin{matrix}\mathbf{H}_{gg} & \mathbf{H}_{gu}\\ \mathbf{H}_{ug} & \mathbf{H}_{uu}\end{matrix}\right\| \left\|\begin{matrix}\mathbf{u}_g\\ \mathbf{i}_u\end{matrix}\right\| \rightarrow \begin{cases}\mathbf{i}_g = \mathbf{H}_{gg}\mathbf{u}_g + \mathbf{H}_{gu}\mathbf{i}_u\\ \mathbf{u}_u = \mathbf{H}_{ug}\mathbf{u}_g + \mathbf{H}_{uu}\mathbf{i}_u\end{cases} \tag{2.8}$$

We can re-write the second equation of (2.8) in the partitioned form:

$$\mathbf{i} = \mathbf{Y}\mathbf{u} \rightarrow \left\|\begin{matrix}\mathbf{i}_g\\ \mathbf{i}_u\end{matrix}\right\| = \left\|\begin{matrix}\mathbf{Y}_{gg} & \mathbf{Y}_{gu}\\ \mathbf{Y}_{ug} & \mathbf{Y}_{uu}\end{matrix}\right\| \left\|\begin{matrix}\mathbf{u}_g\\ \mathbf{u}_u\end{matrix}\right\| \rightarrow \begin{cases}\mathbf{i}_g = \mathbf{Y}_{gg}\mathbf{u}_g + \mathbf{Y}_{gu}\mathbf{u}_u\\ \mathbf{i}_u = \mathbf{Y}_{ug}\mathbf{u}_g + \mathbf{Y}_{uu}\mathbf{u}_u\end{cases} \tag{2.9}$$

Begin $\mathbf{Y}$ symmetrical and invertible, the same holds also for square sub-matrices $\mathbf{Y}_\mathrm{gg}$ and $\mathbf{Y}_\mathrm{uu}$. Moreover we have this equation:

$$\mathbf{Y}_{gu} = \mathbf{Y}_{ug}^T \tag{2.10}$$

In conclusion, the transfer matrix $\mathbf{H}$ is:

$$\mathbf{H} = \left\|\begin{matrix}\mathbf{H}_{gg} & \mathbf{H}_{gu}\\ \mathbf{H}_{uu} & \mathbf{H}_{uu}\end{matrix}\right\| = \left\|\begin{matrix}\mathbf{Y}_{gg} - \mathbf{Y}_{gu}\mathbf{Y}_{uu}^{-1}\mathbf{Y}_{ug} & \mathbf{Y}_{gu}\mathbf{Y}_{uu}^{-1}\\ -\mathbf{Y}_{uu}^{-1}\mathbf{Y}_{ug} & \mathbf{Y}_{uu}^{-1}\end{matrix}\right\| \tag{2.11}$$

The symmetry of $\mathbf{Y}$ implies that $\mathbf{H}_\mathrm{gg}$ and $\mathbf{H}_\mathrm{uu}$ are symmetrical too, and is verify this equation:

$$\mathbf{H}_{gu} = -\mathbf{H}_{ug}^T \tag{2.12}$$

Now the program has all the matrices that are helpful for the calculation and now it proceeds to the calculation of the optimal power flow.
The optimal power flow is fundamental in power system operations, and there has

been extensive research on optimal power flow algorithms. In what follow a real-time algorithm is described for time varying optimal power flow problem based on Newton-Raphson method that is, in the core, very similar at the algorithm of the program SUSI3. Generally a power network has a topology represented by a connected undirected graph with N^+ nodes, where $N^+ = 0 \cup N$, N=1,. . . ,n and $E \subseteq N^+ x N^+$. In particular the bus 0 will be the slack bus, and the phase angle of its voltage will be the reference and taken as zero. For each bus $i \in N^+$, let $V_i(t)$ be the complex voltage phasor, and $p_i(t)$, $q_i(t)$ be the net active and reactive power injections, generation minus load, at bus *i* at time *t*. While for slack bus the active and reactive power is the result of a balance of the active and reactive power into the grid, consider the load power and loss power into the feeder. Now we can proceed with the calculation of power flow of the network with the algorithm that is describe in what follows. At first is important to define the equation of the current, active and reactive power for each line *ij*. The complex current phasor through line $(i,j) \in E$ will be denoted by $I_{ij}(t)$. For steady states, we can write the follow pair of equations:

$$\begin{aligned} p_i(t) + jq_i(t) &= \sum_{j \in N^+} V_i(t) V_j^*(t) Y_{ij}^* \\ I_{ij}(t) &= -Y_{ij}(V_i(t) - V_j(t)) \end{aligned} \tag{2.13}$$

For each bus, there are physical constraints on how much power can be injected by the connected devices. We assume that they can be modelled by time-varying constraints

$$(p_i(t), q_i(t)) \in \chi_i(t), \quad i \in N^+ \tag{2.14}$$

where each $\chi_i(t)$ is a compact convex subset of $\mathbb{R}^2$ for every $t \in \tau$. For the slack bus, we assume that $\chi_0(t)$ admits a box constraint given by:

$$\chi_0(t) = [p_{0,min}(t), p_{0,max}(t)] x [q_{0,min}(t), q_{0,max}(t)] \tag{2.15}$$

Information about the capabilities of controllable devices, as well as the changes in loads and renewable generations, can be encoded in these time-dependent regions. The voltages and currents also need to be bounded for operational reasons. We assume that they are given by:

$$\begin{aligned} v_{i,min} \leq |V_i(t)| \leq v_{i,max} \quad & i \in N^+ \\ |I_{ij}| \leq l_{ij,max} \quad & (i,j) \in E \end{aligned} \tag{2.16}$$

For each bus *i*, we assume that a cost $C_i(p_i, q_i; t)$ will be incurred if some power (p_i, q_i) is injected into the network. In particular the cost function minimized by the optimum control is:

$$\phi = \phi_{loss} + \phi_{stress} + \phi_{dev} \tag{2.17}$$

where ϕ_{loss} accounts for the energy loss in distribution grid and power converters;

ϕ_{stress} accounts for the current stress in distribution feeders, power converters and energy sources; ϕ_{dev} accounts for voltage deviation at grid nodes. While the actual control quantities are the controllable direct $\mathbf{u}_{\text{d}}$ and quadrature $\mathbf{u}_{\text{q}}$ components of generator voltages $\mathbf{u}_{\text{g}}$, and the controllable active $\mathbf{i}_{\text{a}}$ and reactive $\mathbf{u}_{\text{r}}$ components of source currents $\mathbf{i}_{\text{s}}$. We can therefore rewrite the above equations as a function of these control quantities. So our goal is to minimize the total cost $\sum_i C_i(p_i(t), q_i(t); t)$ under the physical and operational constraints for each time t by properly operating the controllable devices in the network. As we have mentioned before, traditional optimal power flow algorithms can be used to find the optimal control strategy on a slow timescale, but will not be suitable for real-time applications on future smart grids. For real-time operations, we need an algorithm that can track the time-varying loads and renewable generations on a faster timescale. We require that the real-time operation at time t should be close to an optimal solution provided by a traditional optimal power flow algorithm with the current feasible region given by $\chi_i(t)$, $i \in \mathrm{N}^+$; we refer to them as suboptimal strategies. Although loads and generations change with time, if the time intervals between each real-time updates are sufficiently small, the regions $\chi_i(t)$ will not change too much as we proceed from time t to $t+1$. As a result, in many situations the optimal control at time t is expected to be close to the optimal control at the previous time instant. The goal of the real-time algorithm is then to find a suboptimal strategy for each $t \in \tau$ for the time-varying optimal power flow is the follow:

$$
\begin{aligned}
\min_{\substack{p_i(t), q_i(t) \\ V_i(t)}} \; & \sum_{i \in N^+} C_i(p_i(t), q_i(t); t) \\
s.t. \quad p_i(t) + jq_i(t) &= \sum_{j \in N^+} V_i(t) V_j^*(t) Y_{ij}^* \\
(p_i(t), q_i(t)) &\in \chi_i(t), \quad i \in N^+ \\
v_{i,min} \leq |V_i(t)| &\leq v_{i,max} \quad i \in N^+ \\
|Y_{ij}(V_i(t) - V_j(t))| &\leq l_{ij,max}, \quad (i,j) \in E
\end{aligned}
\tag{2.18}
$$

given the current state of the network and the previous real time operation. This is a generally description of the algorithm for the optimization of the power flow.
While Source Locator calculates the control factor of a new generator that is linked in a new or already existing fully controllable node. The control factor is equal to the ratio of the maximum value of the current that the new generator injects into a specific feeder and the value of current that flows into it. This ratio is related at the worst results of the analysis of SUSI3. In particular Source Locator uses the results of SUSI3 and it gives the results in function of the worst operative condition. Practically the control factor, of a certain feeder, refers at the case in which the value of the current is the highest because, for the feeders, that is the worst operative condition. So the program gives us a suggestion in which fully controllable node is better to install a current source to solve, for example, a current overstress into feeders

and distributed sources. Another practical use is to reset the current into a specific branch to allow the technician to do the maintenance without open the switches of protection. In this way the dispatcher can improve the quality of the grid and increase the power quality and the reliability of the network. So the programs SUSI3 and Source Locator represent a very powerful system to study a system and to bring changes to improve management and performance.

2.2 Study of a simple grid with SUSI3.

In this section an example of the functionally of SUSI3 is reported with a practical analysis. In particular has been studied an example of innovative system based on an European LV benchmark. The innovative part is the introduction, into the grid, of the distributed generations such as the wind turbine, photovoltaic sources and energy storage systems. The batteries cover a very important role for the stability of the innovative network. Actually the batteries aren't use intensely because they have some technical limits, like the small capacity and a short life-time. In the next future, if the technologies and the materials of the batteries evolve, will be possible to improve the power quality and the reliability of a distribution network. For example the energy storage systems will be able to manage, with the support of the main generators and renewable energy sources, the regulation of frequency and voltage. Otherwise the energy storage systems and the renewable energy sources could substitute, in part, the main generators for the load balance during some period of the day. For example when is more economically convenient or during a failure into the grid. For now, in the structure of a typical LV network, there are photovoltaic sources that feed the grid or local loads and the energy storage systems or batteries are rarely used.
Furthermore the physical structure of low voltage distribution networks is typically three phase, radial and originate from an MV/LV transformer, generally 20/0,4 kV line-to-line voltages and the system frequency is 50 Hz. The low voltage distribution network may include one or multiple lines and the consumers are connected anywhere along the lines. The connection of single-phase consumers makes LV distribution networks inherently unbalanced so the effort is made to reduce the unbalance because we want to decrease the omopolar component of the current which causes distortion and additional power losses into the grid. A method, to reduce this unbalance, is to connect the single-phase consumers evenly between the three phases of the system. So for the grid, three single-phase consumer, with similar absorption curve, are equal to a three-phase consumer with no or small unbalance. The condition of the same absorption curve is fundamental, for this solution.
The type of lines, of low voltage network, are both overground cable lines and overhead lines. The first type is mainly encountered in urban area with a high load density. The second one are mainly used in rural areas with a low load density. The overhead lines are mainly constructed with bare conductors made of aluminum or

copper, but it is probable some variations. The cables are usually enclosed in either metallic or galvanized conduit. The grounding of the low voltage network largely depends on regional preferences. Using the classification of IEC 60364, public LV networks are often of the TN type or the TT type. The first letter T means that the neutral of the transformer is connected to ground. While the second letter N means that the frame of the application being supplied is connected to neutral. At last the second letter T implies that the frame of the application being supplied is connected to ground locally. The TN type is common in Anglo-Saxon countries, while the TT is widely used in other countries. The topology of the innovative European benchmark that is study with SUSI3 is shown in Figure 2.2. The example network is divide in three subnetworks. The first is that domestic, the second is that the commercial and the last is that industrial. This is only an ideal division because, in the real grid, this three subnetwork are generally mixed.

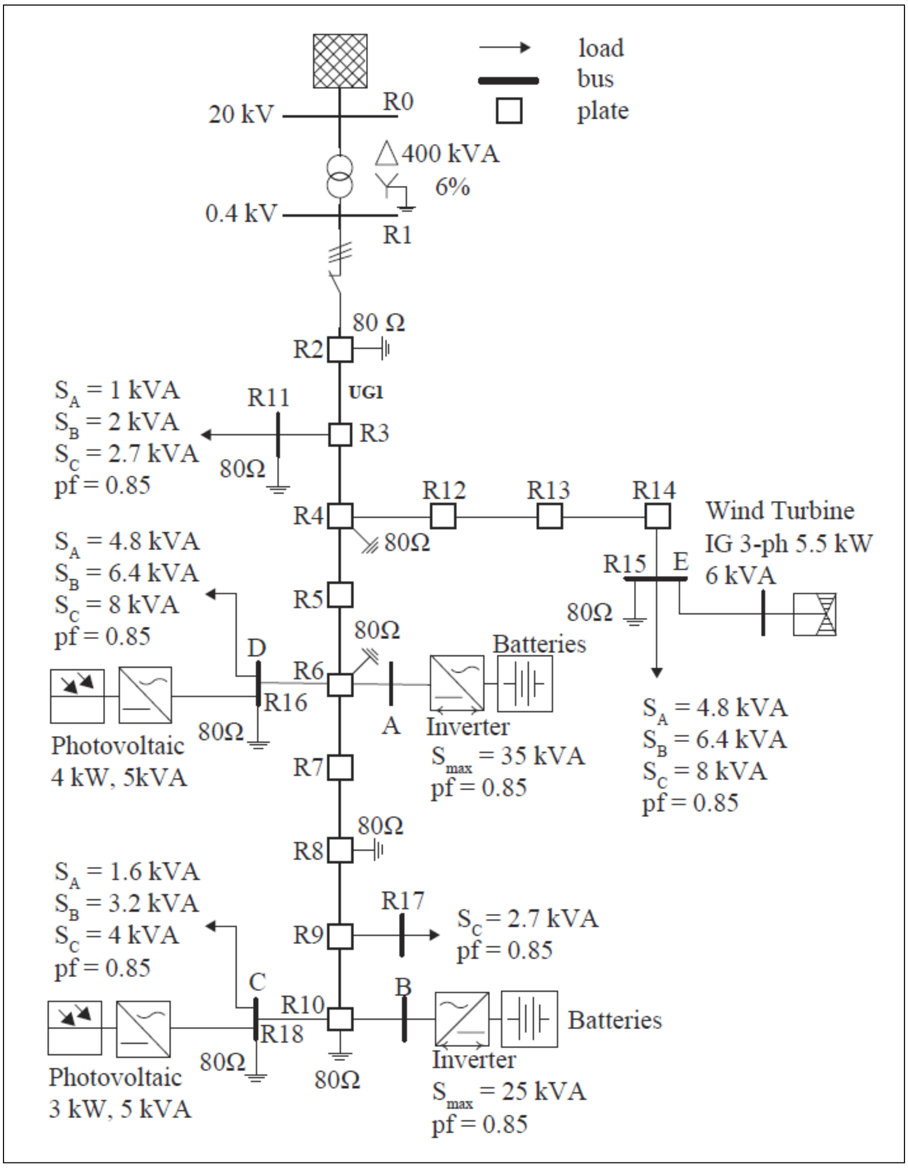

FIGURE 2.2: Topology of an innovative European low voltage distribution benchmark network.

In what follows, the benchmark network data are organized in a number of tables. The first table contains the topology and the data of the feeders related at the industrial subnetwork. While and third tables contain those informations related, respectively, at commercial and domestic subnetwork.

TABLE 2.1: Line parameters of industrial feeder of European LV distribution network benchmark.

Node from	Node to	Cond. ID	R'_{ph} [Ω/km]	X'_{ph} [Ω/km]	R'_0 [Ω/km]	X'_0 [Ω/km]	l [m]
I1	I2	UG2	0.266	0.151	0.733	0.570	200

TABLE 2.2: Line parameters of residential feeder of European LV distribution network benchmark.

Node from	Node to	Cond. ID	R'_{ph} [Ω/km]	X'_{ph} [Ω/km]	R'_0 [Ω/km]	X'_0 [Ω/km]	l [m]
R1	R2	UG1	0.163	0.136	0.490	0.471	35
R2	R3	UG1	0.163	0.136	0.490	0.471	35
R3	R4	UG1	0.163	0.136	0.490	0.471	35
R4	R5	UG1	0.163	0.136	0.490	0.471	35
R5	R6	UG1	0.163	0.136	0.490	0.471	35
R6	R7	UG1	0.163	0.136	0.490	0.471	35
R7	R8	UG1	0.163	0.136	0.490	0.471	35
R8	R9	UG1	0.163	0.136	0.490	0.471	35
R9	R10	UG1	0.163	0.136	0.490	0.471	35
R3	R11	UG4	1.541	0.206	2.334	1.454	30
R4	R12	UG2	0.266	0.151	0.733	0.570	35
R12	R13	UG2	0.266	0.151	0.733	0.570	35
R13	R14	UG2	0.266	0.151	0.733	0.570	35
R14	R15	UG3	0.326	0.158	0.860	0.630	30
R6	R16	UG6	0.569	0.174	1.285	0.865	30
R9	R17	UG4	1.541	0.206	2.334	1.454	30
R10	R18	UG5	1.111	0.195	1.926	1.265	30

The geometric dimensions of the overhead and underground lines are reported in these table.

TABLE 2.3: Geometry dimensions of overground and underground line.

Type of line	Conductor ID.	a [m]	b [m]
overground	OHx	8	0.3
underground	UGy	0.1	

TABLE 2.4: Line parameters of commercial feeder of European LV distribution network benchmark.

Node from	Node to	Cond. ID	R'_{ph} [Ω/km]	X'_{ph} [Ω/km]	R'_0 [Ω/km]	X'_0 [Ω/km]	l [m]
C1	C2	OH1	0.387	0.295	0.619	0.472	30
C2	C3	OH1	0.387	0.295	0.619	0.472	30
C3	C4	OH1	0.387	0.295	0.619	0.472	30
C4	C5	OH1	0.387	0.295	0.619	0.472	30
C5	C6	OH2	0.524	0.307	0.838	0.491	30
C6	C7	OH2	0.524	0.307	0.838	0.491	30
C7	C8	OH2	0.524	0.307	0.838	0.491	30
C8	C9	OH2	0.524	0.307	0.838	0.491	30
C3	C10	OH2	0.524	0.307	0.838	0.491	30
C10	C11	OH2	0.524	0.307	0.838	0.491	30
C11	C12	OH3	1.150	0.332	1.840	0.531	30
C11	C13	OH3	1.150	0.332	1.840	0.531	30
C10	C14	OH3	1.150	0.332	1.840	0.531	30
C5	C15	OH3	1.150	0.332	1.840	0.531	30
C15	C16	OH3	1.150	0.332	1.840	0.531	30
C15	C17	OH3	1.150	0.332	1.840	0.531	30
C16	C18	OH3	1.150	0.332	1.840	0.531	30
C8	C19	OH3	1.150	0.332	1.840	0.531	30
C9	C20	OH3	1.150	0.332	1.840	0.531	30

In the following two tables the data related at geometry dimensions and parameters of overhead lines and underground lines, for European LV distribution benchmark network, are reported. In particular the GMR is the geometric root radius. Subsequently the data of transformers and loads are reported. In particular for each transformer the type of connection and the electrical data, such as the nominal voltage at primary and secondary and the rated apparent power are reported . While, for the loads, the value of maximum demand of each consumer group in terms of apparent power and the power factor of each consumer group are reported. At last the test case, defined for this European LV distribution benchmark network, are reported.

TABLE 2.5: Geometry dimensions and parameters of overhead lines for European LV distribution benchmark network.

Cond. ID	Size [mm^2]	Number of strands	d_c [mm]	R'_{ph} [Ω/km]	GMR [cm]
OH1	50	19	13	0.387	0.345
OH2	35	7	11	0.524	0.287
OH3	16	7	8	1.150	0.192

TABLE 2.6: Geometry dimensions and parameters of underground lines for European LV distribution benchmark network.

Cond. ID	Size [mm^2]	Number of strands	d_c [mm]	R'_{ph} [Ω/km]	GMR [cm]
UG1	240	37	1.75	0.162	0.671
UG2	150	37	1.38	0.265	0.531
UG3	120	37	1.24	0.325	0.475
UG4	25	1	0.564	1.54	0.220
UG5	35	1	0.668	1.11	0.260
UG6	70	1	0.944	0.568	0.368

TABLE 2.7: Transformer parameters of European LV distribution network benchmark.

Node from	Node to	Connection	V_1 [kV]	V_2 [kV]	X^*_{tr} [Ω]	Srated [kVA]
R0	R1	3-ph Δ-Y grounded	20	0.4	0.016	500
I0	I1	3-ph Δ-Y grounded	20	0.4	0.021	150
C0	C1	3-ph Δ-Y grounded	20	0.4	0.032	300

TABLE 2.8: Loads of European LV distribution network benchmark.

Node	Max demand of each consumer group S_{max} [kVA]	Contribution of group to max feeder demand S_c [kVA]	Power factor
R11	15	5.7	0.85
R15	72	57	0.85
R16	55	25	0.85
R17	15	5.7	0.85
R18	47	25	0.85
I2	70	70	0.85
C12	20	11	0.85
C13	8	4.4	0.85
C14	25	13.8	0.85
C17	16	8.8	0.85
C18	8	4.4	0.85
C19	25	13.8	0.85
C20	20	11	0.85

Now we have all the data of the grid, distributed and main sources and loads for the analysis. The next step is to insert this data into SUSI3 following the proceeding describe in the appendix. After that the last thing, before starting the simulation with SUSI3, is to define the test cases and the relative boundaries in the same way as describe into the appendix. The case test that we define for this network are:

1. Test case 0: this test case relates to the reference situation where energy storage systems are off and renewable energy systems generate the active power with the central control inactive. This case refers to the traditional grid where the active and reactive power are generated from the PCC_0 and the renewable energy systems generate the active power. Practically the main generator and the photovoltaic sources participate at load balance;

2. Test case 1: this test case is similar to case 0, however all distributed energy resources, driven by the E-LAN dispatcher, feed reactive power too. This situation doesn't refer to a real situation, because actually all distributed energy resources, like photovoltaic or wind generators, are capable to generate only active power;

3. Test case 2: this test case deals with unbalance and reactive power compensation at node 0, also called PCC_0. In this case the distributed energy resources are driven to make the whole network performing as a balanced load with unit power factor at PCC_0;

4. Test case 3: this test case refers to islanded operation. The power exchange at PCC_0 vanishes, and the dispatcher ensures active power balance by properly driving the energy storage systems. The renewable energy systems feed the active power and react to the reactive power commands issued by the dispatcher;

5. Test case 4: this test case relates to demand response at node PCC_0. The energy storage systems feed active and reactive power to suit the power demand, while renewable energy systems behave as in case test 3; and

6. Test case 5: this test case refers to situation where the current in a selected grid branch is cleared to allow the maintenance. The selected grid branch is the one that connect the transformer to network RN 2. For this purpose, the controller drives to zero that current, thus enabling no-load sectioning of the serviced line without shutting down the entire network.

In the follow tables the results of the simulations, using SUSI3, are reported. These results are only a part of the results that SUSI3 gives. These results resume the main aftermath of the input grid with the previous test cases. From that the dispatcher can understand a lot of things regard the grid and he can take some decisions about it. In particular in the first tables the results related at the efficiency, in percentage, the voltage deviation and the maximum and minimum phase shift are reported. In the second table the results of the main power flow and power loss are resumed. In particular the main power flow refers the total active and reactive power feed by sources, absorbed by loads and feed at node 0. While the power loss are the distribution losses and the transformer plus converter losses.

TABLE 2.9: Main results of the analysis, done with SUSI3, related at efficiency, voltage deviation and maximum and minimum phase shift.

Test case	Efficiency [%]	Voltage deviation [V]	Phase shift (max/mean) [deg]
0	97.19	1.62	0.45 / 0.22
1	97.26	1.33	0.72 / 0.38
2	96.36	0.66	0.40 / 0.30
3	95.01	0.23	0.11 / 0.03
4	96.09	0.49	0.29 / 0.21
5	94.79	0.23	0.11 / 0.03

From the results of the simulation the dispatcher can make some reasonings to understand the power quality and the reliability of the network. After that he can improve the management of the grid adopting some improvements. In particular the efficiency of the system is a very important parameter of the power quality and it is calculated with this equation:

$$\eta = \frac{P_{load}}{P_{gen}} = 1 - \frac{P_{loss}}{P_{gen}} \tag{2.19}$$

The value of the efficiency is quite constant at changing of the test case and it is always very high. Also we observe that the voltage deviation is very low respect at the rated voltage so we can guarantee that at the load bus the voltages in into the range. So this means that with the control function we can reach high value of power quality and we can increase the reliability of the system.

TABLE 2.10: Main results of the analysis with SUSI3 relative at the main power flow and power loss into the network.

Test case	Total P fed by sources [kW]	Total Q fed by sources [kVAR]	Total P absorbed by loads [kW]	Total Q absorbed by loads [kVAR]	P fed at node 0 [kW]	Q fed at node 0 [kVAR]	Distribution losses [kW]	Transformer + converter losses [kW]
0	94.13	58.60	92.95	57.14	69.54	58.60	1.90	0.75
1	94.50	58.07	93.61	57.11	69.54	28.44	1.50	1.06
2	94.73	58.12	94.24	57.80	40.82	0.00	0.85	2.59
3	94.69	58.75	94.26	58.59	0.00	0.00	0.79	4.29
4	94.68	58.23	94.24	58.01	30.00	0.00	0.80	2.91
5	94.63	58.69	94.20	58.54	2.73	2.56	0.79	4.14

The results resumed in the second table give us the value of the total power active and reactive power generate at node 0 and from distributed sources. At last is reported the distribution and transformer plus converter losses for each test case. This last table gives us an idea of the main power flow into the grid, that is fundamental for the study of the grid and to do some improvements to reach high value of power quality and reliability of the system.

Chapter 3

Description of the analyzed system

At first this chapter deals with the description of the original grid that is the base of the radial and meshed network. In particular all the data of the radial and meshed network, that are studied with SUSI3, are reported into the following tables.

3.1 Description of radial and meshed grid.

In this section are reported the data of the radial and meshed grid that are studied with SUSI3. The general data that are in common for the radial and meshed grid are reported into these tables, while the information about the meshed grid are specified in the last table. In particular the data that we have to add for the meshed grid are related at the feeder of new branches. The first table resumes the general data of both grids. In the following figure both grids are represented.

TABLE 3.1: General data of the radial and meshed grid.

Mains data	Nominal rms voltage (line-to-neutral) [V]	234,8
	Frequency [Hz]	50
	Number of phases (1 or 3)	3
Grid data	Rated voltage drop (%)	5,0
	Line resistances (phase wires) / rated value	1,00
	Line reactance (phase wires) / rated value	1,00
	Line resistances (neutral wires) / rated value	2,00
	Line reactance (neutral wires) / rated value	1,00
Cost function parameters	Weight of "distribution loss" term	0,50
	Weight of "conversion loss" term	0,50
	Weight of "current stress of feeders" term	1,00
	Weight of "power stress of sources" term	1,00
	Weight of "current stress of sources" term	1,00
	Weight of "voltage deviation at user nodes" term	1,00
Warning and saturation thresholds	Limit current in feeders / rated current (warning)	105%
	Max active power in sources / rated value (saturation)	110%
	Max current in converters / rated value (saturation)	120%
Tolerance	Line parameters tolerance / estimation inaccuracy	2%

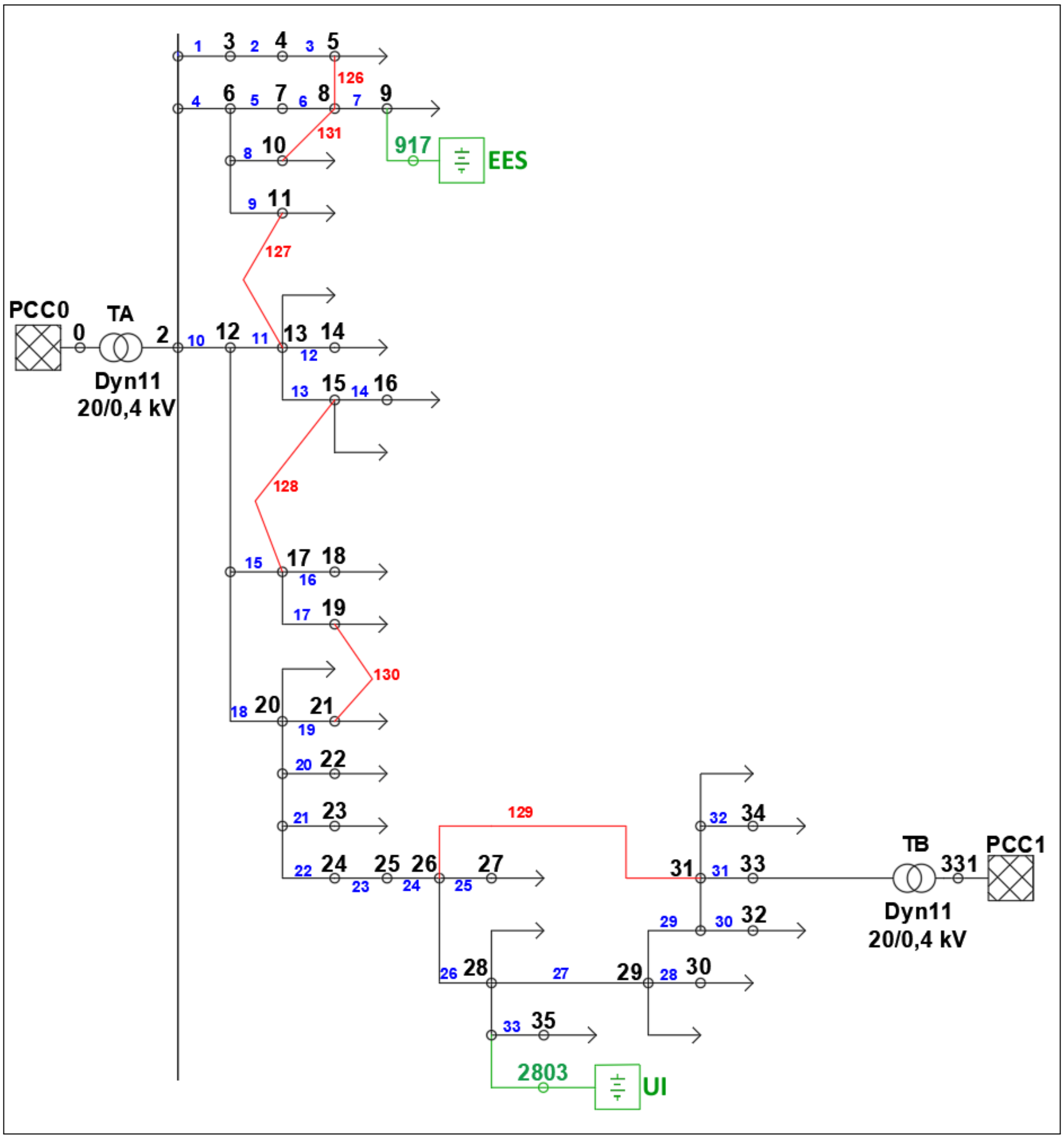

FIGURE 3.1: Representation of the radial and meshed network.

In particular the red lines are related at meshed grid. In this table the typical rated voltage, the frequency and the rated voltage drop, that we have in an radial low voltage grid, are reported. Also the cost function parameters, the warning and saturation thresholds and tolerance are resumed into the same table. The cost function parameters are fundamental for the optimization. In fact the cost function ϕ_{loss}, that takes into account the energy loss in distribution and power converters, depends on the coefficients c_d and c_c that are respectively the weight factors for distribution loss and power converter loss. The cost function ϕ_{loss} is calculated by this formula:

$$\phi_{loss} = c_d\phi_d + c_c\phi_c \tag{3.1}$$

where ϕ_d and ϕ_c are respectively the cost function of distribution loss and power converter loss. The cost function ϕ_{stress}, that takes into account the current stress in distribution feeders, power converters and energy sources, depends on the coefficients c_g, c_p and c_a that are respectively the weight factors for current stress of distribution feeders, the active power stress of energy sources and the apparent power stress of converters interfacing the distributed sources with the grid. The cost function ϕ_{stress} is calculated by this formula:

$$\phi_{stress} = c_g\phi_g + c_p\phi_p + c_a\phi_a \tag{3.2}$$

where ϕ_g, ϕ_p and ϕ_a are respectively the cost function of current stress of distribution feeders, the active power stress of energy sources and the apparent power stress of converters interfacing the distributed sources with the grid. At last the cost function ϕ_{dev}, that accounts for voltage deviation at grid nodes, depends on the coefficient c_u that is the weight factor of the cumulative deviation node voltages respect to the reference node. The cost function ϕ_{dev} is calculated by this formula:

$$\phi_{dev} = c_u\phi_u \tag{3.3}$$

where ϕ_u is the cost function of voltage deviation at grid nodes. In particular every cost function ϕ are function of the current sources $\mathbf{i}_s$, or more precisely of the active $\mathbf{i}_a$ and reactive $\mathbf{i}_r$ components of source currents. While the warning and saturation thresholds are useful for define the upper limit for branches, sources and converters. In particular we admit an over current about 5% respect of the rated current of the feeder. If the current into a feeder exceeds this value the program generates an warning. For the maximum active power sources we admit an over power about 10% respect of the rated value and if the this value is overcome the software generates a saturation advise and it tries again to solve the problem imposing at that generator the maximum power. At last we define an over current in converters about 20% respect of the rated value and if this limit is overtake the program generate a saturation note. While the tolerance is used to define a range in which the program pick randomly the line parameters for simulate an actual operation. Indeed during the normal operation we don't know precisely the value of line parameters and for sure they are different of the line parameters that we have into the tables. The second table report all the data and parameters of the feeders that are present into the grid.

TABLE 3.2: List of feeders, with the related parameters and geometric data, used into the radial and meshed grid.

Name	Type	R_{ph} [Ohm/km]	X_{ph} [Ohm/km]	R_N [Ohm/km]	X_N [Ω/km]	Ampacity [A]	Section [mm^2]
3x150+95N	1	1,27E-01	9,30E-02	1,95E-01	9,50E-02	311	545
4x16_Al	2	1,91E+00	1,91E+00	1,91E+00	1,91E+00	65	64
3x25+16C_Al/Cu	3	1,20E+00	8,00E-02	1,16E+00	8,00E-02	97	91
3x50+25C_Al/Cu	4	6,41E-01	7,00E-02	7,34E-01	9,00E-02	137	175
3x50+25C	5	3,91E-01	7,00E-02	7,34E-01	9,00E-02	166	175
4x16	6	1,16E+00	8,20E-02	1,16E+00	8,20E-02	85	64
3x70+54Al	7	4,43E-01	7,00E-02	6,28E-01	1,50E-01	180	264
4x6	8	3,06E+00	9,50E-02	3,06E+00	9,50E-02	46	24
3x50+25N	9	3,90E-01	1,01E-01	7,34E-01	1,03E-01	166	175
2x16_Al	10	1,91E+00	1,00E-01	1,91E+00	1,00E-01	70	32
3x95+50N	11	1,95E-01	9,70E-02	3,91E-01	9,90E-02	249	335
4x10	12	1,84E+00	8,60E-02	1,84E+00	8,60E-02	55	40
3x95+35C_Al/Cu	13	3,20E-01	7,00E-02	5,29E-01	7,00E-02	239	320
3x50+25	14	3,91E-01	7,80E-02	7,34E-01	7,90E-02	166	175
4x1x16	15	1,14E+00	1,12E-01	1,14E+00	1,12E-01	105	64
4x1x25	16	7,19E-01	1,06E-01	7,19E-01	1,06E-01	140	100
1x6+6C	17	3,06E+00	9,60E-02	3,06E+00	9,60E-02	62	12
3x150+95Al	18	2,06E-01	9,30E-02	3,20E-01	9,50E-02	245	545
1x25+25C	19	7,34E-01	8,00E-02	7,34E-01	8,00E-02	145	50
1x10+6C_Al/Cu	20	3,08E+00	9,00E-02	3,08E+00	9,00E-02	68	16

These feeders are contained into the Enel's library and they are commonly use at low voltage grid. In particular it is possible to note that the ratio between the resistance and reactance, related at the phase and one kilometer, is greater than one. That is an aspect that characterizes the feeders of every low voltage network. This feature is very important for the regulation of the frequency and the voltage in a low voltage grid. While in the follow table is reported the topology of the grid with the length and type of each feeders. In particular the column of feeder type is useful to connect each branch to related feeder that is contained into the table of feeders. Indeed into the previous table we associated each feeder with a number that define the type. In this way every time that we want to define the features of a feeders we can use the type number. While in the tables 3.4, 3.5 and 3.6 all type of load that we have into the grid, divide in domestic, industrial and commercial load, are reported . This split is only an ideal division. For every load we define a type and control boundary. The meaning of these two value will be described into the manual in the end into the appendix. For each load is also define the rated active and reactive power of a source and an energy storage system that is present into the plant of that end-user.

TABLE 3.3: Topology of the radial network.

Feeder type	Length [m]	N° line	Start node	End node
1	30	1	2	3
1	70	2	3	4
2	15	3	4	5
1	70	4	2	6
1	60	5	6	7
3	81	6	7	8
3	33	7	8	9
4	95	8	6	10
4	36	9	6	11
18	170	10	2	12
5	21	11	12	13
6	43	12	13	14
7	48	13	13	15
8	45	14	15	16
9	35	15	12	17
9	14	16	17	18
10	22	17	17	19
11	66	18	12	20
12	37	19	20	21
10	23	20	20	22
12	25	21	20	23
11	78	22	20	24
13	57	23	24	25
14	20	24	25	26
2	20	25	26	27
14	21	26	26	28
15	23	27	28	29
8	22	28	29	30
16	14	29	29	31
17	19	30	31	32
13	40	31	31	33
16	42	32	31	34
7	46	33	28	35
2	5	34	2	36
18	61	35	2	37
10	2	36	9	901
2	2	37	9	902
19	2	38	9	903
10	2	39	9	904
10	2	40	9	905
10	2	41	9	906
10	2	42	9	907
19	2	43	9	908
10	2	44	9	909
10	2	45	9	910
10	2	46	9	911
10	2	47	9	912
10	2	48	9	913
10	2	49	9	914
10	2	50	9	915
10	2	51	9	916
10	2	52	10	1001
10	2	53	10	1002
10	2	54	10	1003
10	2	55	10	1004
10	2	56	10	1005
10	2	57	10	1006
10	2	58	10	1007
19	2	59	10	1008
2	2	60	10	1009
19	2	61	10	1010
10	2	62	12	1101
19	2	63	11	1102
10	2	64	11	1103
10	2	65	11	1104
10	2	66	11	1105
10	2	67	11	1106
20	2	68	11	1107
10	2	69	11	1108
10	2	70	11	1109
10	2	71	11	1110
10	2	72	11	1111
10	2	73	13	1301
10	2	74	13	1302
10	2	75	13	1303
10	2	76	14	1401
10	2	77	14	1402
15	2	78	15	1501
10	2	79	15	1502
10	2	80	15	1503
10	2	81	16	1601
10	2	82	16	1602
10	2	83	16	1603
10	2	84	16	1604
20	2	85	16	1605
10	2	86	16	1606
20	2	87	18	1801
10	2	88	18	1802
10	2	89	18	1803
20	2	90	18	1804
10	2	91	18	1805
10	2	92	18	1806
10	2	93	19	1901
10	2	94	19	1902
2	2	95	20	2001
10	2	96	20	2002
10	2	97	21	2101
10	2	98	21	2102
10	2	99	21	2103
19	2	100	23	2301
10	2	101	23	2302
10	2	102	23	2303
19	2	103	23	2304
3	2	104	28	2801
10	2	105	28	2802
10	2	106	30	3001
10	2	107	30	3002
10	2	108	30	3003
10	2	109	30	3004
10	2	110	30	3005
10	2	111	31	3101
10	2	112	31	3102
10	2	113	31	3103
10	2	114	31	3104
10	2	115	34	3401
10	2	116	34	3402
10	2	117	35	3501
10	2	118	35	3502
19	2	119	35	3503
10	2	120	35	3504
10	2	121	35	3505
10	2	122	35	3506
10	2	123	35	3507
18	2	124	9	917
18	2	125	28	2803

TABLE 3.4: Domestic loads and sources.

Label	Category	Type	Control boundary	Load rated P [kW]	Load rated Q [kVAR]	Source rated P [kW]	Source rated Q [kVAR]
DOM (M) [1F] (0)	13	0	0	3,00	1,45	0	0
DOM (M) + PV (M) [3F] (0)	14	-1	0	6,00	2,91	5,00	2,42
DOM (M) [1F] (3)	15	0	3	3,00	1,45	0	0
DOM (M) + PV (XS) [1F] (3)	16	-1	3	3,00	1,45	3,00	1,45
DOM (L) + PV(S) [1F] (3)	17	-1	3	4,50	2,18	4,70	2,28
DOM (M) + PV (XS) [1F] (0)	18	-1	0	3,00	1,45	3,00	1,45
DOM (M) + PV (XS) + ESS [1F] (1)	19	-1	1	3,00	1,45	6,00	2,91
DOM (M) + PV (M) + ESS [1F] (1)	20	-1	1	3,00	1,45	10,00	4,84
DOM (L) + PV (L) + ESS [3F] (1)	21	-1	1	4,50	2,18	20,00	9,69
DOM (L) + PV (M) + ESS [1F] (3)	22	-1	3	4,50	2,18	10,00	4,84
DOM (L) + PV (M) + ESS [1F] (1)	23	-1	1	4,50	2,18	10,00	4,84
DOM (L) + PV (M) [1F] (1)	24	-1	1	4,50	2,18	5,00	2,42
DOM (M) + PV (M) [1F] (0)	25	-1	0	3,00	1,45	5,00	2,42
DOM (M) + PV (M) [1F] (1)	26	-1	1	3,00	1,45	5,00	2,42
DOM (M) [3F] (3)	27	0	3	6,00	2,91	0	0
DOM (M) + PV (M) + ESS [1F] (1)	28	-1	1	3,00	1,45	10,00	4,84
DOM (XS) [1F] (3)	29	0	3	1,50	0,73	0	0
DOM (M) + PV (S) [1F] (3)	30	-1	3	3,00	1,45	4,70	2,28
DOM (S) + PV (XS) [1F] (1)	31	-1	1	2,00	0,97	3,00	1,45

TABLE 3.5: Industrial loads and sources.

Label	Category	Type	Control boundary	Load rated P [kW]	Load rated Q [kVAR]	Source rated P [kW]	Source rated Q [kVAR]
IND (M) + PV (XL) [3F] (0)	32	-1	0	10,00	4,84	13,80	6,68
IND (L) + PV (L) + ESS [3F] (1)	33	-1	1	22,00	10,66	10,00	4,84
IND (M) + PV (L) [3F] (1)	34	-1	1	10,00	4,84	10,00	4,84
IND (L) + PV (M) [1F] (1)	35	-1	1	6,00	2,91	5,00	2,42
IND (M) + PV (M) [1F] (1)	36	-1	1	3,00	1,45	5,00	2,42

TABLE 3.6: Commercial loads and sources.

Label	Category	Type	Control boundary	Load rated P [kW]	Load rated Q [kVAR]	Source rated P [kW]	Source rated Q [kVAR]
COM + PV (L) + ESS [3F] (1)	37	-1	1	15,00	7,26	10,00	4,84

TABLE 3.7: Main sources.

Label	Category	Type	Control boundary	Source rated P [kW]	Source rated Q [kVAR]	Efficiency [%]
PCC1 (VS)	10	1	3	250	200	99
ESS (CS)	11	-1	0	100	100	95
ESS (VS)	12	1	0	100	100	95

TABLE 3.8: Load percentage for each type of load.

Kind of load	Actual power costant [%]	Actual power random [%]	Power at time 8 am [%]	Power at time 12 am [%]	Power at time 5 pm [%]	Power at time night [%]
Domestic	30	70	100	100	100	30
Industrial 3F	70	30	100	30	40	10
Industrial 1F	50	50	100	20	30	10
Commercial	40	60	50	100	50	10

TABLE 3.9: Source percentage for each type of load.

Kind of source	Actual power costant [%]	Actual power random [%]	Power at time 8 am [%]	Power at time 12 am [%]	Power at time 5 pm [%]	Power at time Night [%]	Efficiency [%]
Domestic	30	70	100	100	100	30	92
Industrial	50	50	100	10	10	10	94
Commercial	40	60	20	100	20	10	93

In the table 3.7 the data of the sources are reported , a part of the generator that is connect at node 0. Like for the load, the meaning of type and control boundary for sources will be define at the appendix. For the sources the rated active and reactive power and the efficiency are defined. While for the previous tables, in particular in the table 3.8 and 3.9, the load and source percentage, for each type of end-user, are resumed. For all load we define the part that is constant and random. This split is helpful when we define four different period in a day and we set the percentage of the load that we have for each period. For make clear the active power, similarly for the reactive power, for a specific period is calculated with this formula:

$$P_{load} = c_{\%,period}(c_{\%,costant} + c_{\%,random})P_{rated} \tag{3.4}$$

In this way we can define an random load for each end-consumer. This system is very important because is not true that during the normal operation all load consumes the rated active and reactive power.

TABLE 3.10: Connection of the end-user at the distribution grid.

Node	Category of load/source	3-phase connection
5	32	40
9		40
901	13	10
902	14	40
903	15	20
904	16	30
905	16	20
906	16	10
907	15	30
908	17	20
909	18	20
910	18	10
911	18	30
912	19	20
913	19	10
914	19	30
915	13	20
916	13	10
10		40
1001	15	20
1002	15	10
1003	15	30
1004	18	20
1005	18	10
1006	20	30
1007	20	20
1008	20	10
1009	21	40
1010	18	30
11		40
1101	15	20
1102	22	10
1103	13	30
1104	15	20
1105	15	10
1106	15	30
1107	21	40
1108	13	20
1109	13	10
1110	13	20
1111	22	30
13		40
1301	13	30
1302	13	30
1303	13	30
14		40
1401	15	20
1402	23	20
15		40
1501	33	40
1502	13	30
1503	24	10
16		40
1601	15	20
1602	25	20
1603	26	10
1604	25	20
1605	34	40
1606	18	20
18		40
1801	35	10
1802	15	20
1803	15	30
1804	27	40
1805	13	30
1806	15	10
19		40
1901	28	20
1902	16	20
20		40
2001	21	40
2002	36	20
21		40
2101	29	20
2102	15	10
2103	21	40
22	13	30
23		40
2301	13	10
2302	15	20
2303	13	30
2304	30	10
27	15	20
28		40
2801	37	40
2802	13	30
29	15	10
30		40
3001	16	10
3002	16	10
3003	13	20
3004	13	20
3005	16	10
31		30
3101	13	30
3102	13	10
3103	16	30
3104	16	10
32	23	20
34		40
3401	20	10
3402	20	10
35		40
3501	19	20
3502	29	20
3503	18	20
3504	31	10
3505	19	20
3506	19	10
3507	19	30
2		40
3		40
4		40
6		40
7		40
8		40
12		40
36		40
37		40
17		40
24		40
25		40
26		40
331	10	40
33		40
917	11	40
2803	12	40

TABLE 3.11: Data of the transformers.

Trafo	Line number	Start node	End node	V_{1N} [kV]	V_{2N} [kV]	S_N [kVA]	X_{ph} [Ω]	X_N [Ω]	vcc [%]
TA	126 (R) 136 (M)	0	2	20	0,4	250	2,46E-2	2,46E-2	4
TB	127 (R) 137 (M)	33	331	20	0,4	300	5,30E-02	5,30E-02	4

TABLE 3.12: Added lines to build the main meshed grid starting from the radial network.

Feeder type	Length [m]	Line number	Start node	End node
18	20	126	5	8
18	30	127	11	13
18	25	128	15	17
18	80	129	26	31
18	20	130	19	21
18	15	131	8	10

In the table 3.10 the topology of the load are reported, more precisely the information, about which load is connect to a determinate node, are specified. Furthermore the informations for each load and node are reported, such as if they are single phase or three phase. In the table 3.11 all the data for each transformer, that are contained into the grid, are reported. The first transformer is connect at the PCC_0, while the second transformer is link at the PCC_1. While into the last table all the data, related the branches that we add to make the meshed grid based on the radial grid, are reported. Obviously we decide arbitrarily these branches for making the meshed grid. The proposed meshed grid, called main meshed grid, is the result of a several simulation, in base on the defined test cases, to reach a good power quality into the grid.

Chapter 4

Executive summary

This chapter deals with the summary of the results that are reported in the following chapter.

4.1 Main results of the first test case.

In this section the tables and the graphs, related at first test case, are reported. In particular all the graphs show the peak values of the electrical quantities that are used for make comparison.
Considering the second case all the results represented into the following graph, except for the maximum current stress of the sources, are in favor at meshed grid. In particular the difference between the maximum current stress into sources, between the radial and meshed grid, is very small, so that difference is neglected.

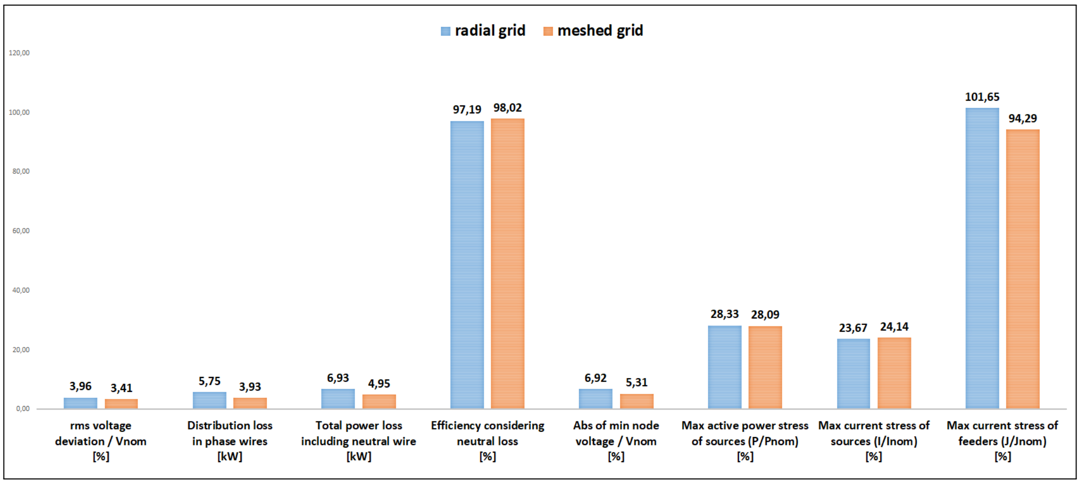

FIGURE 4.1: Comparison between the peak value of the results of the radial and meshed grid, at case 12.

Indeed the voltage deviation relative at the radial grid is greater than that in the meshed grid as the total power loss, the minimum of the minimum node voltage, the maximum active power stress of sources, the maximum current stress into the feeders and the distribution loss in phase wires. Furthermore the efficiency relative at the meshed grid is greater compared to that in the radial grid. Moreover, considering also the results reported in the previous table, we observe that the voltage

deviation, the distribution loss in phase wares, the loss in power sources and the stress into sources, in the meshed grid, are lower compared to those in the radial grid. These results are in favor at the meshed grid and they proof that, for this case, the proposed meshed grid is better compared to the radial grid. The advantage that the meshed grid introduce is that creates new paths for the current flow so, at parity of the sources and loads, there are a better management of the network. Obviously not all meshed version of the radial grid give the same benefits. In particular this meshed grid is obtain at the end of some reasonings and analysis with SUSI3.
Considering the third case, also called case 13, all the results represent into the graph, except for the maximum current and power stress in the sources, are in favor at meshed grid. Indeed the voltage deviation relative at the radial grid is greater than that in the meshed grid as the total power loss, the minimum of the minimum node voltage, the maximum active power stress of sources and the distribution loss in phase wires. Furthermore the efficiency relative at the meshed grid is greater compared to that in the radial grid. In particular the differences between the maximum stress into feeders and sources are very small, so these differences are neglected.

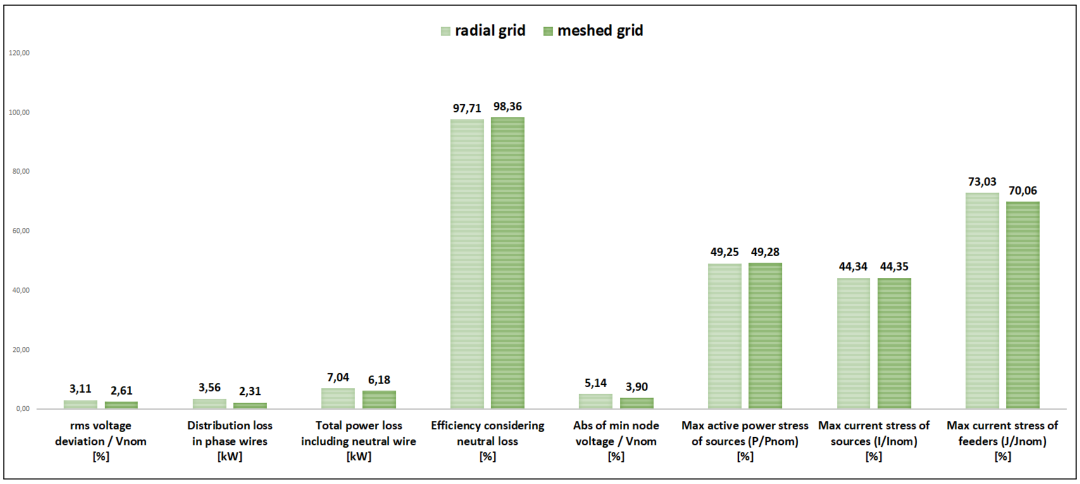

FIGURE 4.2: Comparison between the peak value of the results of the radial and meshed grid, at case 13.

If we consider also the result reported in the following table, is possible to note that the meshed grid gives the best results. Indeed, for each period of the day, the electrical quantities considered are in favor of meshed grid.
These advantages, both for the second and third case, are due to presence of new paths for the flow of current, so there will be a lower concentration of current for each feeder. This fact leads to a reduction of power loss and current stress into feeders. Moreover, only for the third case, the sources, in the meshed grid, are link to a greater number of loads compared to that in the radial grid. So there is a greater number of distributed sources that support each other to load balance. This collaboration between sources leads to a reduction of the power and current stress of sources.
Moreover if we compare the results between the second and third case, we note that the distributed generations gives the best results in terms of management and

power quality. Indeed the voltage deviation, the distributed power loss, the loss in power sources, the efficiency, the absolute value of the minimum voltage and the maximum current stress of feeders, in the third case, are lower compared to that in the second case. While the only two negative aspects, of the third case, are the current and power stress of sources. Indeed the value of these two stress, in the third case, are greater compared to those at second case. Rather than the value of current and power stress of sources in the third case is very small, so they don't represent a problem.
So the meshed grid, with the distributed generation, gives better results in terms of management and power quality.

TABLE 4.1: Results related at the radial grid in the first test case.

Test case	12	12	12	12	13	13	13	13
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	3,96%	3,53%	3,53%	1,04%	2,76%	1,84%	3,11%	1,04%
Distribution loss in phase wires [kW]	5,75	4,57	4,57	0,40	2,89	1,40	3,56	0,40
Loss in power sources & converters [kW]	0,15	0,13	0,12	0,01	1,70	4,58	0,28	0,01
Total power loss including neutral wire [kW]	6,93	5,79	5,77	0,51	5,23	7,04	4,70	0,51
Efficiency considering neutral loss	96,99%	97,19%	97,18%	99,16%	97,71%	96,54%	97,69%	99,16%
Min node voltage vs Vnom (Number of node)	-6,92% (1605)	-5,64% (912)	-5,70% (1606)	-1,69% (912)	-4,62% (1605)	-3,05% (902)	-5,14% (912)	-1,69% (912)
Max node voltage vs Vnom (Number of node)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)
Max active power stress of sources (Number of node)	28,33% (331)	26,29% (331)	25,59% (331)	7,50% (331)	29,52% (3103)	49,25% (1111)	21,72% (331)	7,50% (331)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	23,67% (331)	22,28% (331)	21,51% (331)	6,30% (331)	26,58% (331)	44,34% (1111)	18,85% (331)	6,30% (331)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	101,65% (14)	81,06% (14)	84,00% (14)	24,61% (14)	70,60% (14)	41,72% (14)	73,03% (14)	24,61% (14)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

TABLE 4.2: Results related at the main meshed grid in the first test case.

Test case	12	12	12	12	13	13	13	13
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	3,41%	3,02%	3,00%	0,88%	2,30%	1,48%	2,61%	0,88%
Distribution loss in phase wires [kW]	3,93	3,00	3,02	0,26	1,92	0,91	2,31	0,26
Loss in power sources & converters [kW]	0,15	0,14	0,13	0,01	1,77	4,76	0,28	0,01
Total power loss including neutral wire [kW]	4,95	3,98	3,98	0,35	4,11	6,18	3,25	0,35
Efficiency considering neutral loss	97,79%	98,02%	97,99%	99,40%	98,15%	96,88%	98,36%	99,40%
Min node voltage vs Vnom (Number of node)	-5,31% (1605)	-4,40% (1602)	-4,49% (1602)	-1,32% (1602)	-3,53% (1605)	-2,03% (3004)	-3,90% (1602)	-1,32% (1602)
Max node voltage vs Vnom (Number of node)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)
Max active power stress of sources (Number of node)	28,09% (331)	26,38% (331)	25,44% (331)	7,43% (331)	29,39% (2001)	49,28% (2001)	21,32% (331)	7,43% (331)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	24,14% (331)	23,13% (331)	22,06% (331)	6,43% (331)	26,45% (331)	44,35% (331)	19,25% (331)	6,43% (331)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	94,29% (14)	80,38% (3)	81,59% (3)	24,18% (3)	65,12% (14)	45,88% (14)	70,06% (3)	24,18% (3)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

In particular the previous two tables show the results of the analysis, done with SUSI3, of the radial and meshed grid. Those results prove the statements and the conclusions exposed previously.
Subsequently the results, related at the new version of meshed grid are reported. Furthermore the graph, of the comparison of the results between the new and main meshed network, is reported.
Considering the second case, also called case 12, all the results are in favor of the main meshed grid, except for the maximum power and current stress into the sources. Indeed the voltage deviation, relative at the new version of meshed grid, is greater

than that in the main meshed grid as the total power loss, the minimum of the minimum node voltage, the maximum current stress into the feeders, and the distribution loss in phase wires. Furthermore the efficiency, related at the new meshed grid, is lower compared to at the efficiency in the main meshed grid.

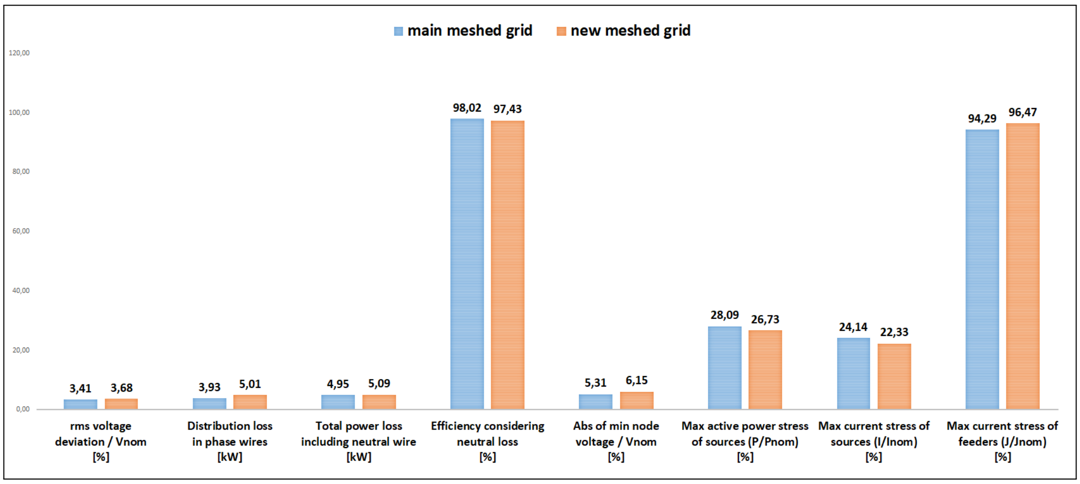

FIGURE 4.3: Comparison of the peak value of the results between the new and main meshed grid, at case 12.

Considering the third case, also called case 13, the situation is different compared to the previous one. Indeed all results are in favor at the main meshed grid.

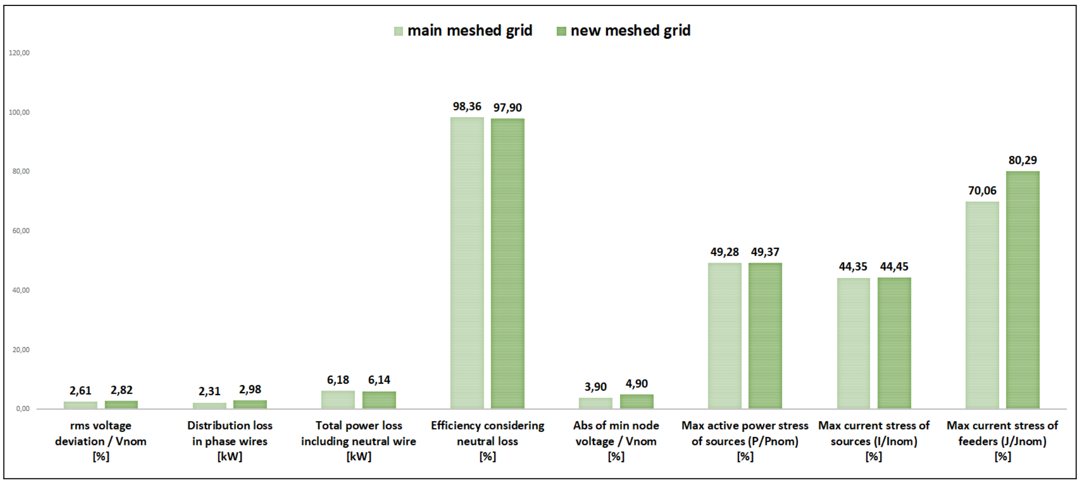

FIGURE 4.4: Comparison of the peak value of the results between the new and main meshed grid, at case 13.

In particular the voltage deviation relative at the new version of meshed grid is greater than that in the main meshed grid as the total power loss, the minimum of the minimum node voltage, the maximum current and power stress of the sources, the maximum current stress into the feeders, and the distribution loss in phase wires. While the efficiency of the main meshed grid is lower compared to that in the new meshed grid. Also in this case there are no current stress into the feeders that overcome the maximum value in the new meshed grid and it is a good point. Rather

then the main meshed grid offers a better management compared to that with the new meshed grid if we take into account the results reported into the previous table and the graph, for the case 13.
So, considering all this reasonings and results, the main meshed grid offers best advantages and a better management compared to the new meshed grid.
In conclusion the best configuration of this network is that meshed with the distributed generations that participate at load balance to support the centralized generators and reduce the distributed power loss.

TABLE 4.3: Results related at the new meshed grid in the first test case.

Test case	12	12	12	12	13	13	13	13
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	3,68%	3,21%	3,24%	0,96%	2,48%	1,51%	2,82%	0,96%
Distribution loss in phase wires [kW]	5,01	3,82	3,91	0,34	2,37	0,97	2,98	0,34
Loss in power sources & converters [kW]	0,13	0,11	0,11	0,01	1,71	4,63	0,26	0,01
Total power loss including neutral wire [kW]	6,28	5,00	5,09	0,45	4,65	6,14	4,08	0,45
Efficiency considering neutral loss	97,19%	97,43%	97,40%	99,22%	97,90%	96,81%	97,90%	99,22%
Min node voltage vs Vnom (Number of node)	-6,15% (1605)	-5,41% (905)	-5,49% (1602)	-1,63% (905)	-4,37% (1605)	-2,46% (915)	-4,90% (905)	-1,63% (905)
Max node voltage vs Vnom (Number of node)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)	0,00% (331)
Max active power stress of sources (Number of node)	26,73% (331)	24,40% (331)	24,08% (331)	7,09% (331)	29,57% (3507)	49,37% (1010)	20,04% (331)	7,09% (331)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	22,33% (331)	20,81% (331)	20,37% (331)	6,00% (331)	26,61% (3507)	44,45% (1010)	17,58% (331)	6,00% (331)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	96,47% (14)	90,67% (14)	91,68% (14)	27,34% (14)	63,34% (14)	42,84% (28)	80,29% (14)	27,34% (14)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

4.2 Main results of the second test case.

In this section the graphs related at second test case are reported. In particular all the graphs show the peak values of the electrical quantities that are used for make comparison.
Considering the radial grid, in the first case, the voltage deviation, the distribution loss in phase wires and the maximum current stress of feeders are greater compared to those at second case. While the rest of the results reported, into the following graph, are in favor of the first case. At first sight is obvious that the first case allows a better management of the radial grid.

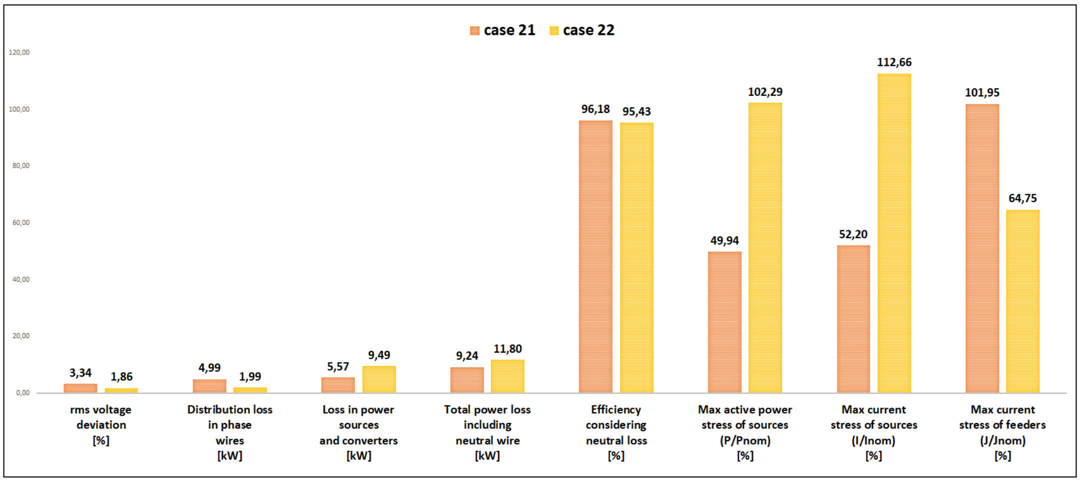

FIGURE 4.5: Comparison between the results of the radial grid at case 21 and 22.

While if we consider also the results of the analysis, done with SUSI3, we note that the optimal control gives more benefits compared to the case without control. Indeed, for each period of the day, the optimal control allows us a better management. Moreover if we consider that the overstress of sources is related a small photovoltaic generator, which is very easy to overstress, therefore the power loss into sources increase from the first case to the second. So if we consider to add a new generator that support the local overstressed sources is possible to delete the stress and to obtain a better management of the grid in the second case. Consequently the active power and current stress, in the distribution sources, will decrease a lot and the power loss, into the distributed generators, decrease too. In conclusion the optimal control gives the best results considering the radial grid.
Considering the meshed grid, in the first case, the voltage deviation, the distribution loss in phase wires and the maximum current stress of feeders are greater compared to those at second case. While the rest of the results reported into the previous graph are in favor of the first case. At first sight is obvious that the first case allows a better management of the meshed grid. So, at the beginning, the optimal control of the active power isn't the best solution for this system. While if we consider that the overstress of sources is related at a small photovoltaic generators, which is very easy

to overstress, we can conclude that this power and current stress of sources aren't an unsolvable problem.

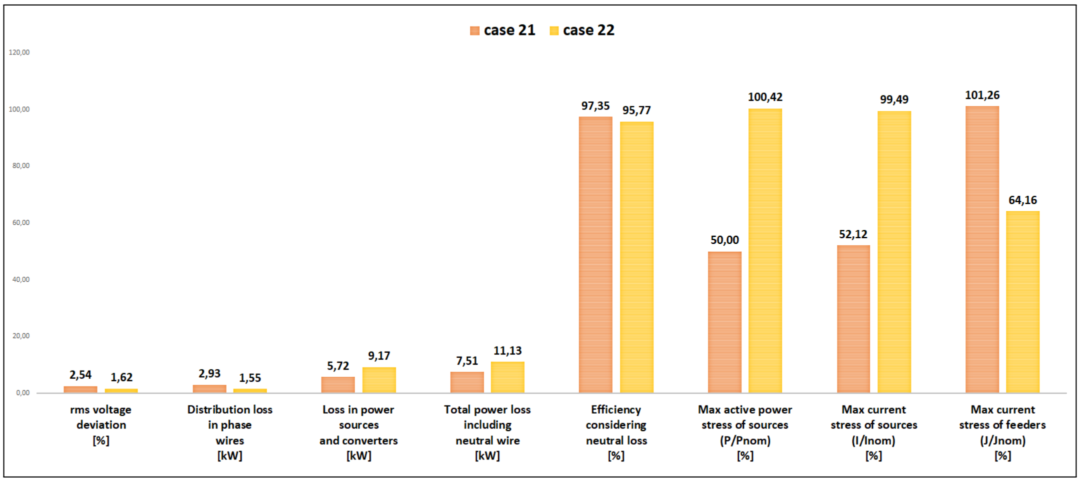

FIGURE 4.6: Comparison between the results of the meshed grid at case 21 and 22.

Indeed if we add a new generator that support the local overstressed sources is possible to delete the stress and to obtain a better management of the grid in the second case. Obviously the introduction of this new generator will lead a different power flow into the grid. In particular it will support the nearby distributed sources at load balance, mostly to the local loads. This will involves to a reduction of the flow of current into the grid, so a decrease of distribution loss in phase wires. Moreover the power and current stress of sources will reduce. In conclusion, if we take into account the results of the analysis, done with SUSI3, the optimal control gives more benefits compared to the system without optimal control.
After that a comparison of the peak values of radial and meshed grid is reported for each case. At first the comparison of the peak values, related at case 21, between the radial and meshed grid is reported in the following graph.

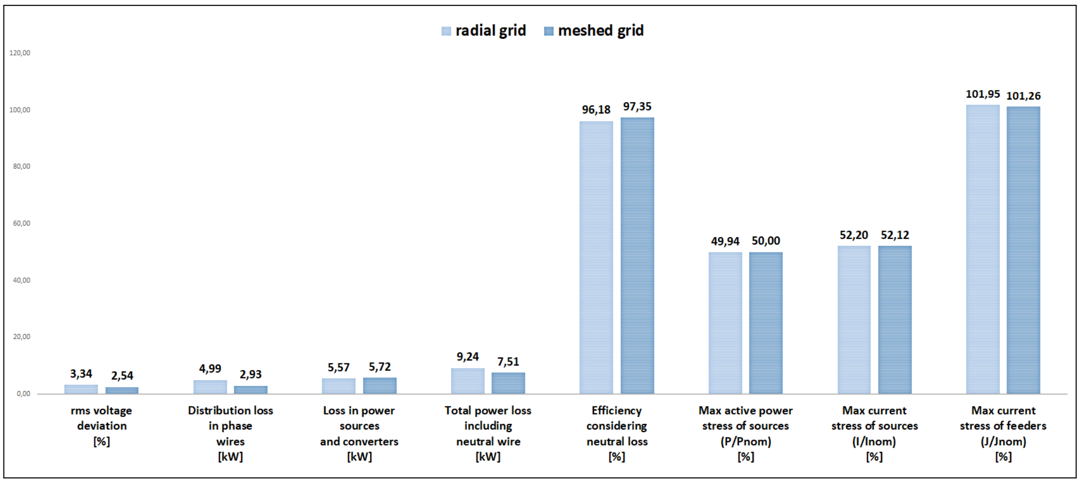

FIGURE 4.7: Comparison between the results of the radial and meshed grid at case 21.

In that case the meshed grid gives the best results in terms of voltage deviation, the distribution loss in phase wires, the total power loss and the efficiency. While for the value of power loss and stress in sources and the current stress of feeders, there are no difference between the radial and meshed grid. Moreover if we consider the results of the analysis for each period of the day, we note that the meshed grid allows us a better management of the system. So the meshed grid is the best configuration of the network in the first case.
While for the second case the comparison, of the peak values, is reported in the following graph in which the meshed grid gives the best results in terms of voltage deviation, distribution loss, total power loss and maximum current stress of feeders. While there are no difference between the peak value of power loss in sources, efficiency, maximum power stress of sources and maximum current stress of feeders.

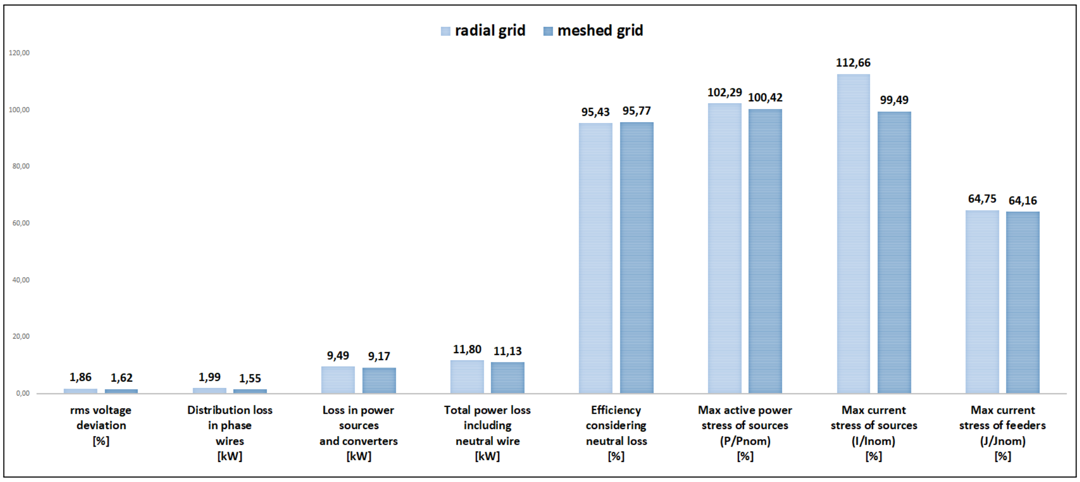

FIGURE 4.8: Comparison between the results of the radial and meshed grid at case 22.

Moreover if we consider the results of the analysis for each period of the day, we note that the meshed grid allows us a better management of the system. So for the second test case the meshed grid gives the best results.
In conclusion, in this test case, the meshed grid, with the optimal control, is the best configuration of this system. In particular the optimal control is of the active power generated by the distributed sources and reactive power from the energy storage systems. So is possible to manage, in an optimal way, the system to reach high value of power quality and reliability of the systems.
Moreover in the following tables the main results, of the analysis done with SUSI3, are reported. In particular the first table resumes the results of the radial grid, while the second table resumes the results of the meshed grid.

TABLE 4.4: Results related at the radial grid relative the second test case.

Test case	21	21	21	21	22	22	22	22
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	3,09%	1,68%	3,34%	1,12%	1,47%	0,61%	1,86%	0,54%
Distribution loss in phase wires [kW]	4,99	2,14	4,86	0,52	1,48	0,49	1,99	0,20
Loss in power sources & converters [kW]	3,40	5,75	1,63	0,13	9,49	8,25	7,71	1,55
Total power loss including neutral wire [kW]	9,24	9,18	7,69	0,78	11,80	9,37	10,66	1,85
Efficiency considering neutral loss	95,93%	95,42%	96,18%	98,66%	94,87%	95,43%	94,82%	97,00%
Min node voltage vs Vnom (Number of node)	-2,83% (1605)	-1,16% (1805)	-3,13% (1601)	-1,12% (1601)	-2,13% (1605)	-0,98% (2303)	-2,40% (912)	-0,67% (1603)
Max node voltage vs Vnom (Number of node)	0,11% (7)	0,30% (1006)	0,03% (33)	0,01% (33)	0,21% (5)	0,37% (5)	0,37% (5)	0,31% (5)
Max active power stress of sources (Number of node)	29,83% (3402)	49,94% (3402)	19,32% (331)	6,71% (331)	102,29% (1604)	99,60% (910)	100,80% (5)	99,98% (902)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	52,20% (917)	44,96% (3402)	45,87% (917)	14,12% (917)	112,66% (1107)	98,40% (2801)	99,32% (1107)	90,01% (902)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	101,95% (7)	71,93% (7)	97,91% (7)	30,99% (7)	64,75% (68)	45,48% (28)	61,80% (28)	23,97% (3)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

TABLE 4.5: Results related at the meshed grid relative the second test case.

Test case	21	21	21	21	22	22	22	22
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	2,19%	0,94%	2,54%	0,88%	1,29%	0,51%	1,62%	0,50%
Distribution loss in phase wires [kW]	2,92	1,11	2,93	0,32	1,15	0,37	1,55	0,17
Loss in power sources & converters [kW]	3,35	5,72	1,52	0,12	9,17	7,83	7,88	1,88
Total power loss including neutral wire [kW]	6,88	7,51	5,49	0,56	11,13	8,63	10,46	2,14
Efficiency considering neutral loss	97,07%	96,34%	97,35%	99,07%	95,24%	95,77%	94,96%	96,52%
Min node voltage vs Vnom (Number of node)	-2,87% (1605)	-0,78% (1601)	-3,21% (1602)	-1,11% (1602)	-1,56% (1605)	-0,83% (3004)	-1,40% (1605)	-0,50% (1605)
Max node voltage vs Vnom (Number of node)	0,01% (2)	0,36% (3402)	0,02% (36)	0,00% (2)	0,04% (1009)	0,30% (1603)	0,02% (33)	0,12% (5)
Max active power stress of sources (Number of node)	29,89% (3402)	50,00% (3402)	21,12% (331)	7,36% (331)	100,42% (5)	99,93% (902)	100,39% (5)	96,92% (902)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	52,12% (917)	45,01% (3402)	42,95% (917)	12,93% (917)	98,96% (2801)	99,49% (2801)	98,99% (2801)	89,10% (2801)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	101,26% (7)	70,44% (7)	95,74% (7)	30,23% (7)	48,57% (28)	48,57% (28)	64,16% (28)	21,61% (28)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

4.3 Main results of the third test case.

In this section the graphs related at second test case are reported. In particular all the graphs show the peak values of the electrical quantities that are used for make comparison.
Considering the radial grid, from the following graph, the optimal control, of the active and reactive power, gives the best results, except for the maximum active power stress into the sources. In particular the maximum value of power stress of sources, in the first case, is much higher compared to those at second case. This is because the optimal control exploited more the distributed sources to reduce the total stress. Moreover the overstressed sources are relative at domestic and industrial end-user, so they are very small and it is very simple to overstress. A solution to reduce the overstressed source is to connect a current source, in a new or already existing fully controllable node close to the overstressed sources, to support the local overstressed sources at load balance and minimization of the total stress. Otherwise we have to increase the rated active and reactive power of the overstressed sources. While the maximum current stress into the feeders remains constant between the first and second case.
So, for the management of the radial network, for this test case, the optimal control of the active power allows us a better management of the system.

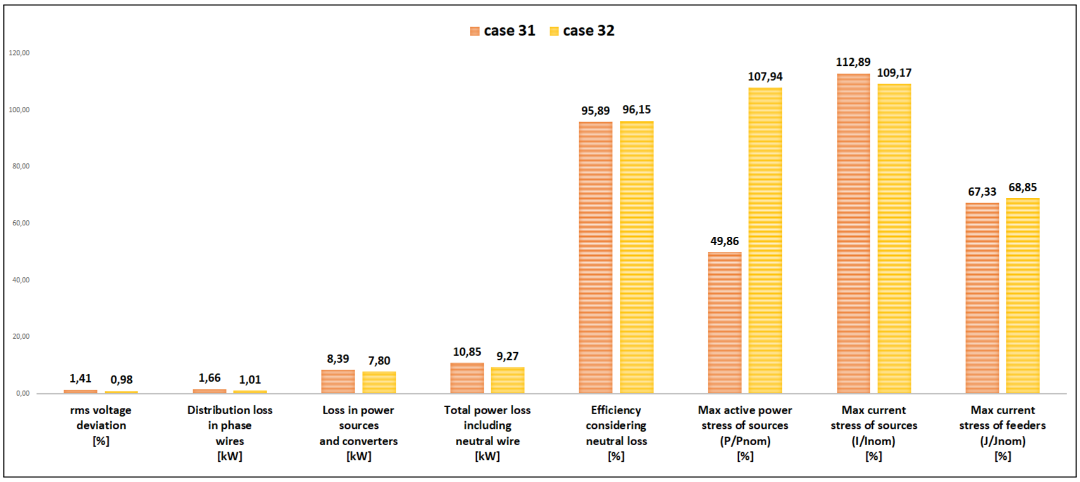

FIGURE 4.9: Comparison between the peak value results of the case 31 and 32, considering the radial grid.

The following graph compares the peak values relative at the results of the meshed grid, between the first and second case. From this graph the grid with the optimal control gives the best results in terms of the voltage deviation, distribution loss into the feeders and the maximum current stress into the feeders and sources. While the value of power loss in sources, total power loss an the efficiency are practically equal. The only negative point is for the maximum power stress into the sources because, with the optimal control, the power stress, into distributed sources, is much greater compared to that without optimal control. Moreover we have to consider that the overstress sources are very small, so it is very simple to reach the upper power limit and overcome that. A solution of the overstressed sources has been proposed previously.

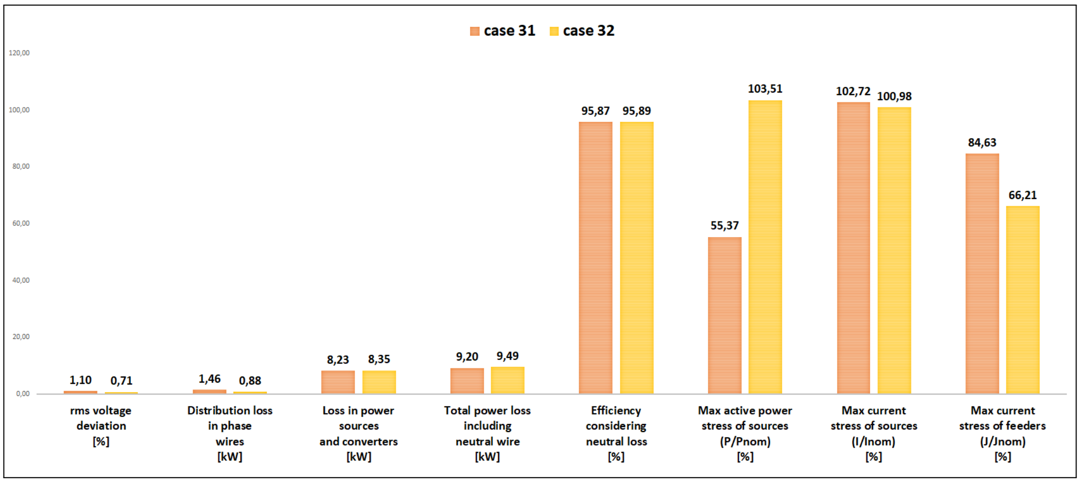

FIGURE 4.10: Comparison between the peak value of the results at case 31 and 32, considering the meshed grid.

So, for the management of this system, the optimal control gives the best results. Considering the first case the graph is the following. In particular the voltage deviation, the distribution loss in phase wires, the total power loss and the maximum current stress of sources are lower compared to that in the radial grid. This is because in the meshed grid the new branches offer new paths in which the current can flow and that bring the advantages described previously. This is a good point for the meshed grid. While the power loss in sources and the efficiency there are no difference between the two cases.

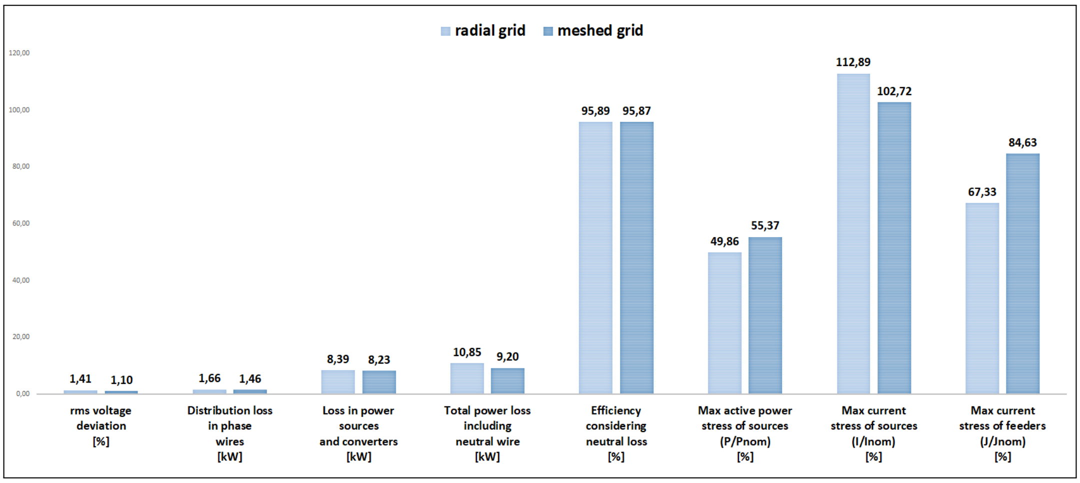

FIGURE 4.11: Comparison between the results of the radial and meshed grid, at case 31.

The two negative aspects of the meshed grid are the maximum power stress into the sources and the maximum current stress into the feeders. This happen because the

new branches, related at radial grid, approaching loads and distributed sources that in the radial grid are distant. So the distributed sources will feed the local loads and the new loads acquired thanks to the new lines. In this way the maximum active power stress of the sources will increase a lot and it will be greater compared to that in the radial grid. Rather than we have to take into account that the overstress is related at distributed sources, such as photovoltaic sources, that are property of domestic of industrial end-user. Moreover these sources are very small and it is very simple to overcome the upper power limit.
So, considering the graph and the results reported in the previous table, the meshed grid allows us a better management of the system in the first case.
Considering the peak value, of the second case in the meshed grid, the voltage deviation, the distribution loss in phase wires, the maximum of the active power and current stress of sources and the current stress into feeders are lower compared to those with the radial grid. This is a good point for the meshed grid. While the efficiency, the power loss in sources and the total power loss are practically equal between the radial and meshed grid, at the case 32. So this shows that the meshed grid with the optimal control of the power generated from all the sources bring the best benefits.

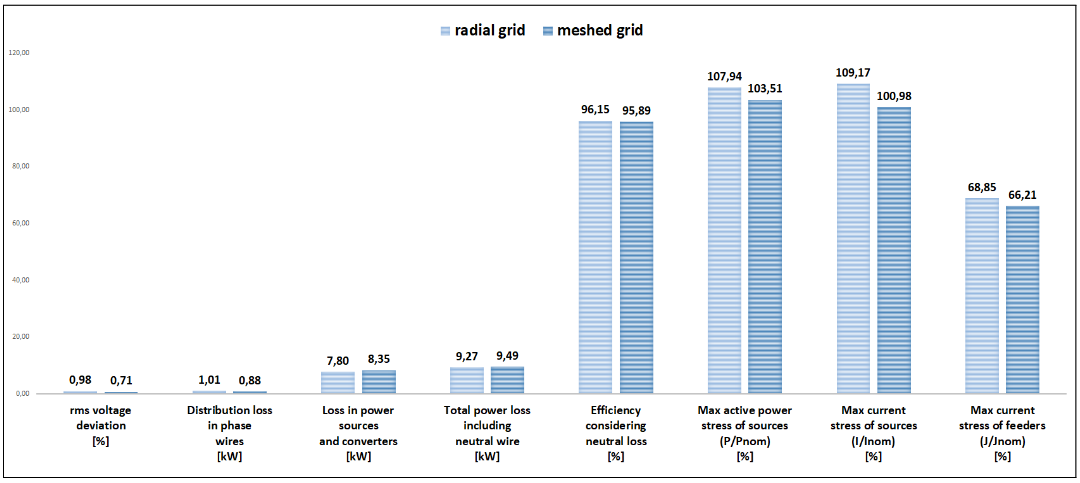

FIGURE 4.12: Comparison between the results of the radial and meshed grid, at case 32.

In conclusion, for this system, the meshed grid, with the optimal control of active and reactive power, gives the best results in terms of management of the grid, considering the graphs and the main results reported in the following tables.
Moreover in the following tables the main results, of the analysis done with SUSI3, are reported. In particular the first table resumes the results of the radial grid, while the second table resumes the results of the meshed grid.

TABLE 4.6: Results related at the radial grid relative the third test case.

Test case	31	31	31	31	32	32	32	32
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	1,19%	0,31%	1,41%	0,46%	0,95%	0,24%	0,98%	0,23%
Distribution loss in phase wires [kW]	1,24	0,40	1,66	0,28	0,88	0,30	1,01	0,14
Loss in power sources & converters [kW]	8,39	7,54	8,03	1,67	7,80	7,13	6,73	1,39
Total power loss including neutral wire [kW]	10,18	8,62	10,85	2,16	9,27	7,91	8,40	1,62
Efficiency considering neutral loss	95,52%	95,89%	94,64%	96,35%	95,96%	96,15%	95,91%	97,30%
Min node voltage vs Vnom (Number of node)	-2,69% (1605)	-0,65% (901)	-3,15% (1606)	-1,14% (1606)	-1,97% (1605)	-0,67% (3003)	-1,53% (1603)	-0,51% (1603)
Max node voltage vs Vnom (Number of node)	0,94% (917)	0,43% (914)	1,51% (917)	0,46% (917)	0,58% (917)	0,40% (3401)	0,68% (917)	0,39% (5)
Max active power stress of sources (Number of node)	30,13% (905)	49,86% (905)	35,72% (917)	12,21% (2803)	100,43% (5)	87,00% (5)	107,94% (3503)	101,71% (5)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	112,89% (2801)	75,55% (1501)	102,45% (1107)	105,24% (5)	100,08% (2001)	83,03% (5)	109,17% (1501)	92,06% (5)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	67,33% (95)	47,16% (28)	60,03% (14)	43,98% (3)	68,85% (95)	47,16% (28)	47,16% (28)	30,81% (3)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

TABLE 4.7: Results related at the meshed grid relative the third test case.

Test case	31	31	31	31	32	32	32	32
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	0,93%	0,29%	1,10%	0,36%	0,69%	0,20%	0,71%	0,21%
Distribution loss in phase wires [kW]	1,13	0,37	1,46	0,18	0,73	0,23	0,88	0,10
Loss in power sources & converters [kW]	7,58	8,23	6,88	1,07	8,35	7,60	8,00	1,31
Total power loss including neutral wire [kW]	9,16	9,11	9,20	1,36	9,49	8,13	9,39	1,47
Efficiency considering neutral loss	95,87%	95,48%	95,33%	97,65%	95,77%	95,89%	95,30%	97,52%
Min node voltage vs Vnom (Number of node)	-2,84% (1605)	-0,95% (1601)	-3,28% (1606)	-1,11% (1606)	-1,32% (1605)	-0,55% (3001)	-1,09% (1605)	-0,40% (1603)
Max node voltage vs Vnom (Number of node)	0,84% (917)	0,46% (914)	1,19% (917)	0,41% (917)	0,74% (917)	0,34% (3401)	0,77% (917)	0,14% (5)
Max active power stress of sources (Number of node)	40,07% (917)	49,90% (1102)	55,37% (917)	19,41% (917)	100,40% (5)	84,05% (5)	103,51% (1604)	100,15% (5)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	102,72% (2001)	89,17% (1107)	99,99% (5)	54,75% (1501)	99,68% (5)	79,34% (5)	100,98% (1107)	91,90% (5)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	71,72% (14)	48,40% (68)	84,63% (14)	29,54% (14)	51,04% (68)	37,83% (95)	66,21% (28)	22,37% (28)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

4.4 Main results of the fourth test case.

In this section the tables and the graphs, related at fourth test case, are reported. In particular all the graphs show the peak values of the electrical quantities that are used for make comparison.
Considering the radial grid, the peak values of the results, of the first and second case, are compared in the following graph.

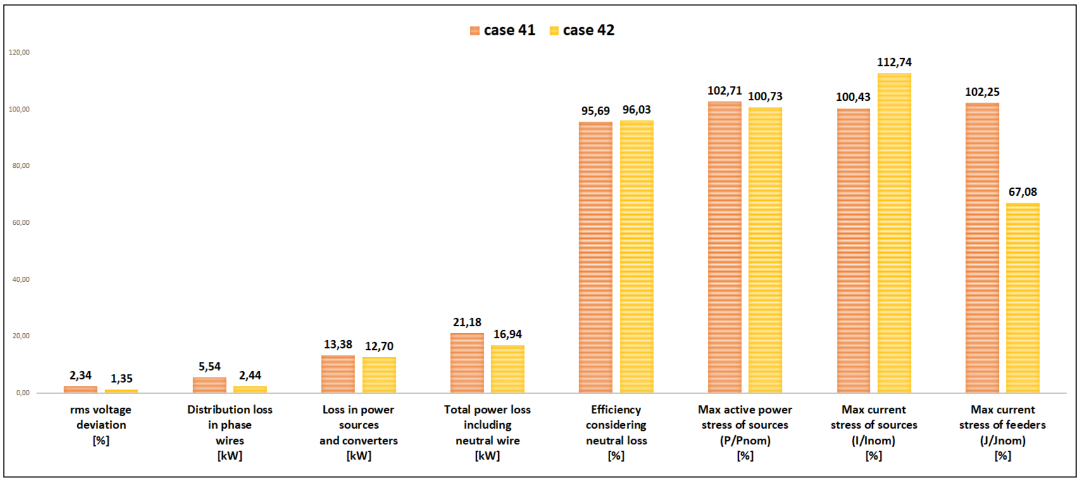

FIGURE 4.13: Comparison between the results of case 41 and 42, relative the radial grid.

From this graph the optimal control gives the best results in terms of voltage deviation, distribution loss into the feeders, loss in power sources, the total power loss, maximum current stress into feeders and maximum power stress into sources. While the efficiency remains constant between the two cases. The only negative aspect is the maximum of the current stress into the sources. Moreover is important to consider that the overstressed sources are very small so is simple to reach the upper limit of active and reactive power and overcome it. To solve this problem a solution is to install a fully controllable generator, close to the overstressed power sources, to support them at load balance and minimization of the total stress. Another solution is to increase the rated active and reactive power of those sources.
So, for this test case in the radial grid, the optimal control gives the best results, considering the graph and the results reported into the following table, in terms of management the system under islanding operation.
Considering the meshed grid, the peak values of the results, of the first and second case, are compared in the following graph. In the previous graph the some result of the simulation, related at meshed grid, are compared. Considering the voltage deviation, the distribution loss in phase wires and the maximum current stress in feeders, the optimal control gives the best results. Furthermore the loss in power sources and the efficiency remain constant between the two cases. While the only two negative aspect of optimal control are maximum active power and current stress into the sources. This is because, with the optimal control, the distributed sources

are more exploited compared to those at first case, in which the optimal control is off.

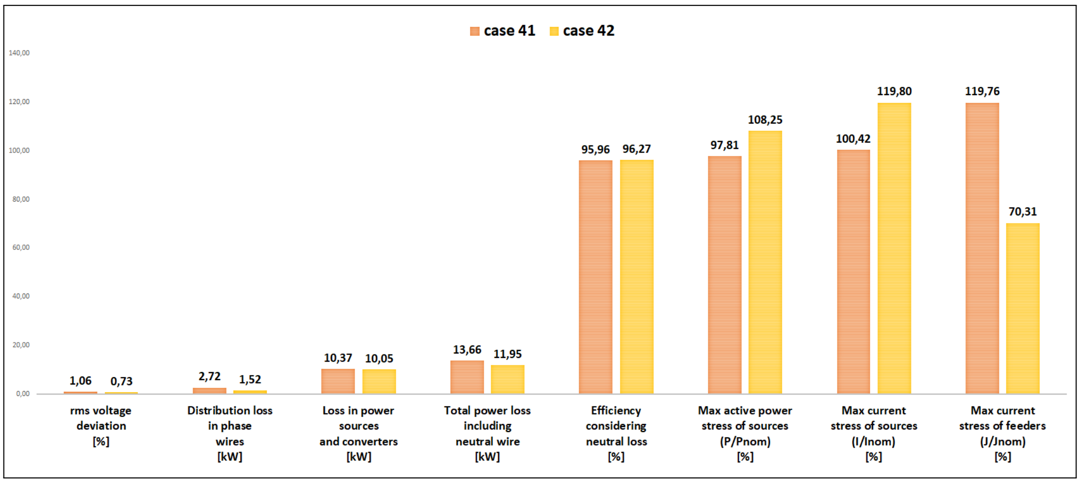

FIGURE 4.14: Comparison between the results of case 41 and 42, relative at meshed grid.

So the optimal control, in this test case considering the meshed grid, gives the best results,taking into account the graph and the results reported into the following table, in terms of management the system.
At last is important to understand which configuration of the distributed grid gives the best results for each case. In the following graph the peak values of the radial and meshed grid, related at case 41, are reported.

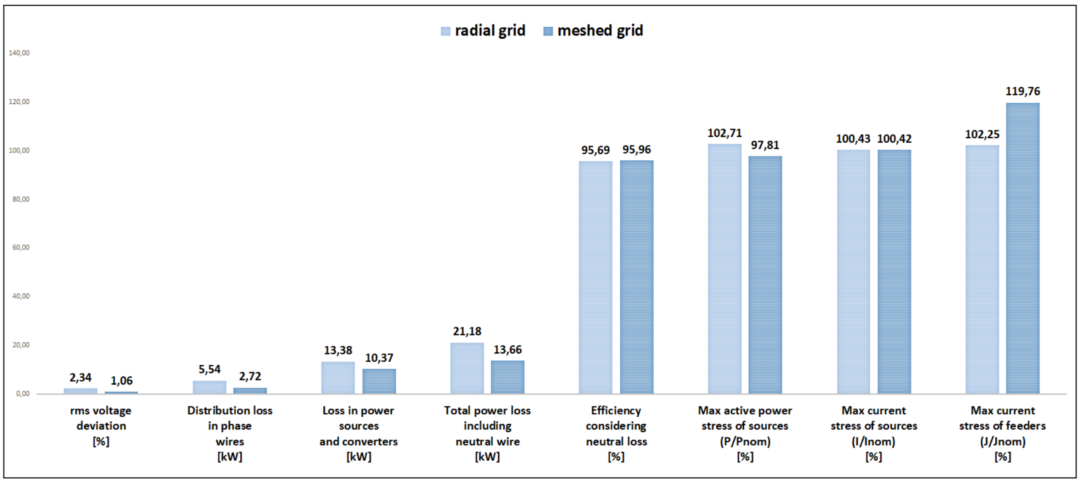

FIGURE 4.15: Comparison between the peak value of the results of the radial and meshed grid at case 41.

From the previous graph, in the meshed grid, the voltage deviation, the distribution loss in phase wires, the loss into sources and the maximum of active power stress in sources, are lower compared to those at radial grid. Furthermore the efficiency and the current stress of sources remain constant between the two cases. The only negative aspect of the meshed grid is the maximum current stress into the feeders.

So, for the case 41, the meshed grid gives the best results, both considering the graph and the results reported in the previous tables, in terms of management the grid and power quality.
While the comparison between the peak value of radial and meshed grid, related at case 42, are reported in the following graph. In the meshed grid the voltage deviation, the distribution loss in phase wires and the loss into sources, are lower compared to those at radial grid. Furthermore the efficiency remain constant between the two configurations of the grid. While the negative aspects, related at meshed grid, are the maximum active power stress and current stress into the sources and the maximum current stress into the feeders. This happen because in the meshed grid the distributed sources are link to a greater number of loads compared to the number of loads in the radial grid. So in the meshed grid the distributed sources have to feed a greater number of loads and it bring to a greater stress of the sources and feeders. Also the distributed sources, that are overstressed, are very small, so it is very simple to reach the upper power limit and overcome it. As previously anticipated to solve these power overstress, of sources, a solution is to connect, in a nearby node, a new current source to support the already existing distributed sources. Rather than the value of the stress into the sources and the feeders are not so different, between the radial and meshed grid related at case 42.
So the meshed grid gives the best results in terms of management and the power quality of the system.

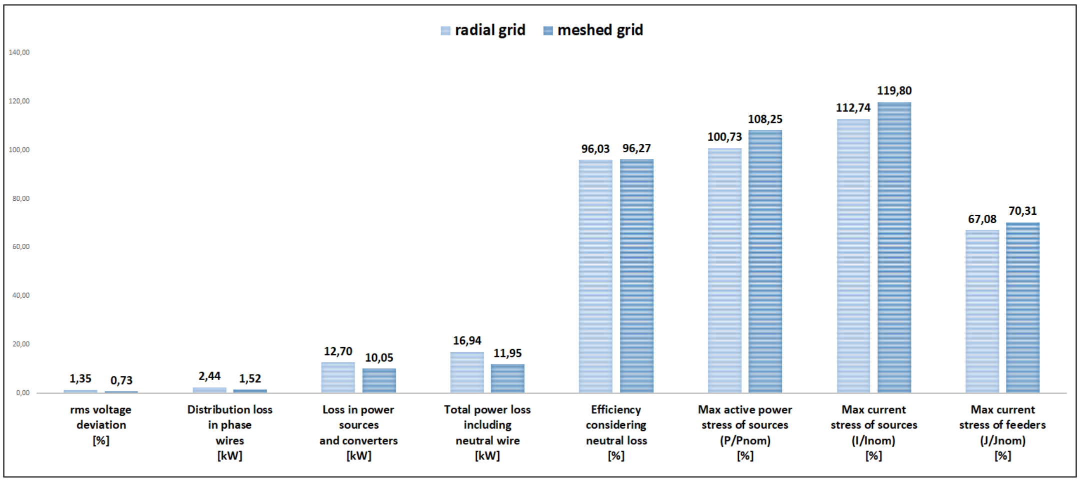

FIGURE 4.16: Comparison between the peak value of the results of the radial and meshed grid at case 42.

In conclusion, considering the results reported in the previous tables and graphs, the meshed grid, with optimal control, allows us a better management of the system.
Moreover in the following tables the main results, of the analysis done with SUSI3, are reported. In particular the first table resumes the results of the radial grid, while the second table resumes the results of the meshed grid.

TABLE 4.8: Results related at the radial grid relative the fourth test case.

Test case	41	41	41	41	42	42	42	42
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	1,96%	0,36%	2,34%	0,83%	1,18%	0,22%	1,35%	0,17%
Distribution loss in phase wires [kW]	3,98	0,41	5,54	0,92	1,74	0,28	2,44	0,16
Loss in power sources & converters [kW]	13,38	7,63	13,34	5,72	9,96	7,30	12,70	1,67
Total power loss including neutral wire [kW]	19,00	8,74	21,18	7,15	13,11	8,06	16,94	1,94
Efficiency considering neutral loss	91,77%	95,69%	89,79%	88,10%	94,28%	96,03%	91,85%	96,75%
Min node voltage vs Vnom (Number of node)	-3,02% (1605)	-0,62% (1805)	-3,33% (1604)	-1,18% (1604)	-1,80% (1605)	-0,58% (1805)	-1,23% (1605)	-0,43% (1603)
Max node voltage vs Vnom (Number of node)	5,03% (917)	1,00% (914)	6,32% (917)	2,17% (917)	3,55% (917)	0,41% (5)	4,18% (917)	0,39% (5)
Max active power stress of sources (Number of node)	80,41% (917)	50,16% (911)	102,71% (917)	34,17% (917)	100,30% (1602)	72,76% (5)	100,73% (1602)	104,62% (5)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	99,92% (3504)	98,15% (1501)	100,43% (3504)	100,32% (5)	99,95% (2801)	73,48% (1501)	112,74% (1503)	94,37% (5)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	79,64% (7)	38,97% (28)	102,25% (7)	49,55% (95)	56,15% (7)	49,79% (95)	67,08% (7)	35,67% (3)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

TABLE 4.9: Results related at the meshed grid relative the fourth test case.

Test case	41	41	41	41	42	42	42	42
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	0,93%	0,19%	1,06%	0,38%	0,68%	0,16%	0,73%	0,17%
Distribution loss in phase wires [kW]	2,06	0,27	2,72	0,38	1,24	0,21	1,52	0,13
Loss in power sources & converters [kW]	10,15	7,31	10,37	2,74	10,05	6,85	9,38	1,85
Total power loss including neutral wire [kW]	12,57	7,94	13,66	3,18	11,95	7,32	11,58	2,04
Efficiency considering neutral loss	94,37%	95,96%	93,08%	94,47%	94,68%	96,27%	94,18%	96,48%
Min node voltage vs Vnom (Number of node)	-1,91% (1605)	-0,57% (3004)	-2,25% (1601)	-0,80% (1601)	-1,20% (1605)	-0,58% (3004)	-1,02% (1605)	-0,39% (1605)
Max node voltage vs Vnom (Number of node)	2,07% (917)	0,42% (1605)	2,65% (917)	0,95% (917)	1,48% (917)	0,42% (1605)	1,71% (917)	0,22% (917)
Max active power stress of sources (Number of node)	76,33% (917)	49,76% (1603)	97,81% (917)	34,60% (917)	108,25% (1604)	72,69% (5)	104,61% (1604)	100,25% (5)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	100,07% (5)	83,01% (1107)	100,42% (2001)	114,36% (5)	119,80% (1107)	69,43% (1501)	99,59% (1107)	96,31% (5)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	91,93% (7)	44,82% (68)	119,76% (7)	44,83% (7)	70,31% (68)	43,40% (28)	67,59% (7)	17,71% (28)
Number of overstressed feeders (current)	0	0	1	0	0	0	0	0

4.5 Main results of the fifth test case.

In this section the tables and the graphs, related at fifth test case, are reported. In particular all the graphs show the peak values of the electrical quantities that are used for make comparison.
At first is important to compare the peak values of the results, relative the radial grid, between the case 51 and 52 to understand if the optimal control, of active power, gives the best results.

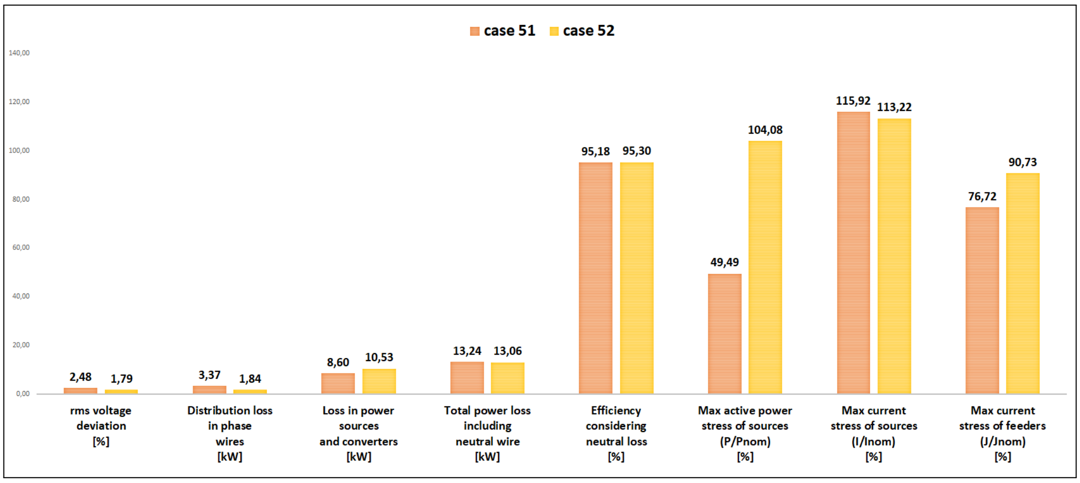

FIGURE 4.17: Comparison between the results of case 51 and 52, considering the radial grid.

From the previous graph the optimal control gives the best results in terms of voltage deviation, distribution loss in phase wires and maximum current stress into sources. Moreover the efficiency and the total power loss remain constant between the first and second case. While for the power loss of sources, the maximum power stress of sources and maximum current stress of feeders the best configuration of the radial grid is without control of the active power. Since the overstressed sources are always a small sources, the current stress into the sources is not a problem because it is easily solved adding a new generator in that node or in a near one. Otherwise, to solve the power overstress of distributed sources, a solution could be to increase the active and reactive power of the overstressed sources.
So, for the radial grid, the optimal control gives the best results, considering the previous graph and the results reported in the following table, and it allows a better management of the system.
After that the comparison of the peak values, between the case 51 and 52, is reported to understand if the optimal control of active power gives the best results, relative the meshed grid. From the following graph the optimal control gives the best results in terms of voltage deviation, distribution loss in phase wires, power loss in phase wires, total power loss and maximum current stress of feeders. While there are no difference of the efficiency and maximum current stress of feeders between the two cases. Moreover the value of active stress into the sources, in the first case, is lower

compared to that in the second case. Since the overstressed sources are always a small sources, the current stress into the sources is not a problem because it is easily solved adding a new generator in that node or in a near one as described above.

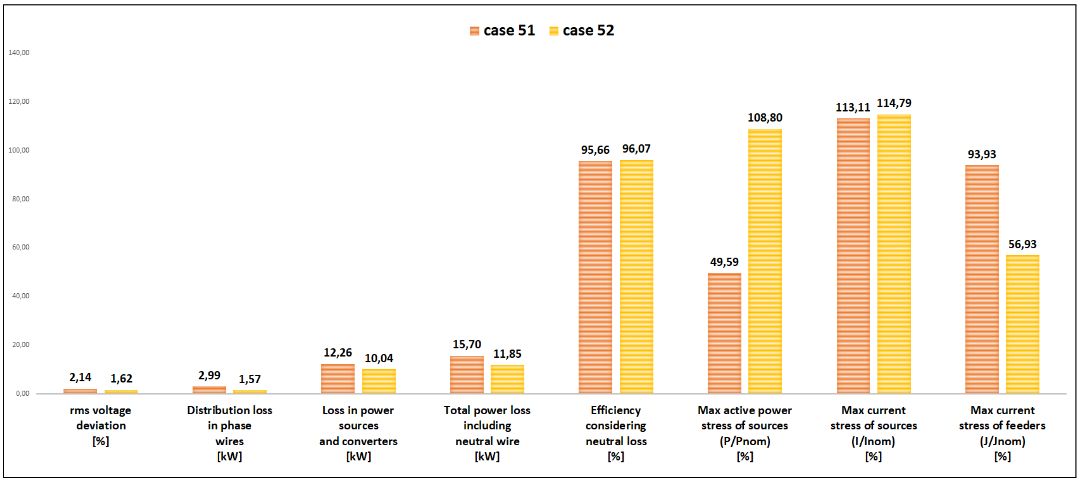

FIGURE 4.18: Comparison between the results of case 51 and 52, considering the meshed grid.

So, for the meshed grid, the optimal control gives the best results, considering the previous graph and the results reported in the following table, and it allows a better management of the system.
At last is important to understand which configuration of the distributed grid gives the best results for each case.
In the following graph the peak values of the radial and meshed grid, related at case 51, are reported.

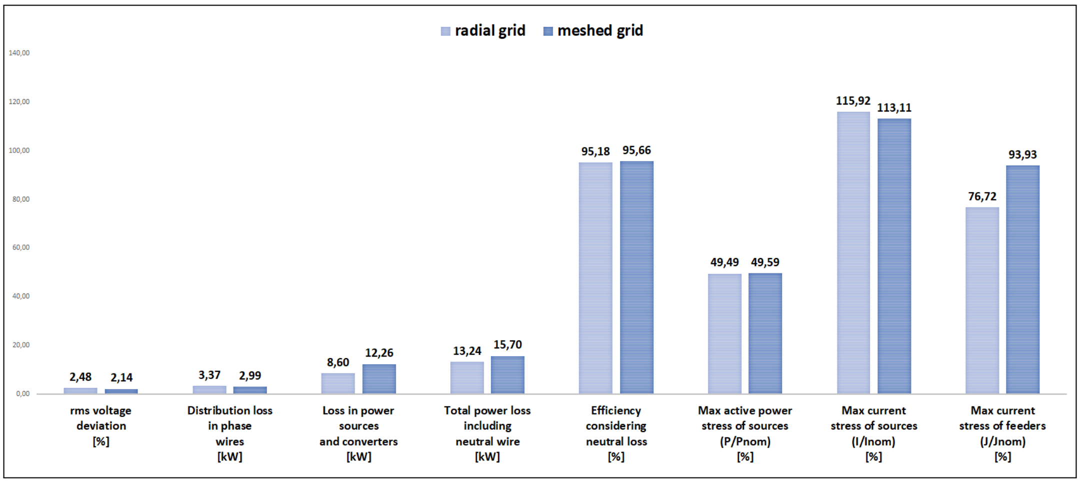

FIGURE 4.19: Comparison between the results of the radial and meshed grid at case 51.

From the previous graph, in the meshed grid, the voltage deviation and the distribution loss in phase wires are lower compared to those at radial grid. Furthermore

the efficiency and the current stress and power stress of sources remain constant between the two cases. The negative aspects, of the meshed grid, are the maximum current stress into the feeders, the power loss into sources and the total power loss. Rather than, as previously described, the overstressed sources are very small, so is very simple to reach the upper limit of active and reactive power and overcome it.
So, for the case 51, the meshed grid gives the best results, both considering the graph and the results reported in the following tables, in terms of management the grid and power quality. While the comparison between the peak value of radial and meshed grid, related at case 52, are reported in the following graph.

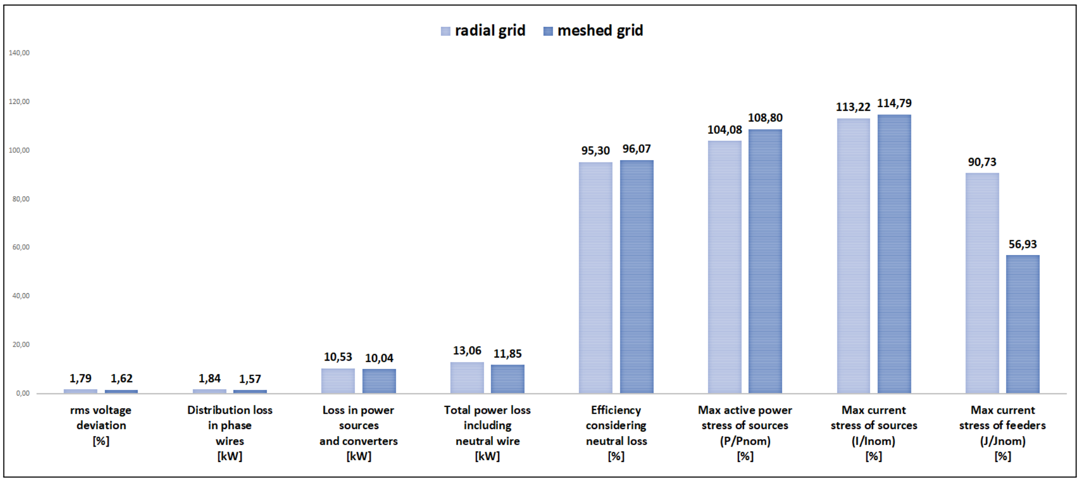

FIGURE 4.20: Comparison between the results of the radial and meshed grid at case 52.

In the meshed grid the voltage deviation, the distribution loss in phase wires, the loss into sources and the total power loss, are lower compared to those at radial grid. Furthermore the efficiency, the active power stress and current stress of sources remain, approximately, constant between the two configurations of the grid. While the maximum current stress of feeders, in the meshed grid, is lower compared to that in the radial grid. This is due to the new paths that, the meshed grid, introduce into the system. Indeed with the addition we create new paths in which the current can flow. So, generally, the concentration of the current will reduce and this lead to a reduction of the current stress of feeders.
So the meshed grid gives the best results, considering the previous graph and the results reported in the following table, in terms of management and the power quality of the system.
Moreover in the following tables the main results, of the analysis done with SUSI3, are reported. In particular the first table resumes the results of the radial grid, while the second table resumes the results of the meshed grid.

TABLE 4.10: Results related at the radial grid relative the fifth test case.

Test case	51	51	51	51	52	52	52	52
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	1,68%	0,62%	2,14%	0,72%	1,24%	0,55	1,62	0,52
Distribution loss in phase wires [kW]	2,21	0,50	2,99	0,50	1,06	0,34	1,57	0,16
Loss in power sources & converters [kW]	12,26	7,72	11,95	3,43	10,04	7,01	9,37	1,38
Total power loss including neutral wire [kW]	14,90	8,77	15,70	4,02	11,85	7,86	11,71	1,64
Efficiency considering neutral loss	93,54%	95,66%	92,37%	93,34%	94,75%	96,07%	94,22%	97,29%
Min node voltage vs Vnom (Number of node)	-2,34% (1605)	-0,80% (3004)	-2,70% (1601)	-0,95% (1601)	-1,92% (3004)	-1,52% (3004)	-2,11% (3004)	-0,79% (3001)
Max node voltage vs Vnom (Number of node)	0,34%	0,37%	0,34%	0,15%	0,19%	0,14%	0,07%	0,11%
Max active power stress of sources (Number of node)	31,50% (1006)	49,59% (902)	19,35% (331)	6,58% (331)	108,80% (1602)	100,14% (5)	105,53% (1602)	100,09% (5)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	113,11% (1503)	99,56% (5)	99,34% (1008)	99,89% (5)	114,79% (1107)	99,62% (5)	109,99% (1009)	92,16% (5)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	78,87% (7)	54,91% (68)	93,93% (7)	49,08% (68)	52,59% (28)	52,59 (28)	56,93% (28)	19,61% (28)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

TABLE 4.11: Results related at the meshed grid relative the fifth test case.

Test case	51	51	51	51	52	52	52	52
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	1,68%	0,62%	2,14%	0,72%	1,24%	0,55%	1,62%	0,52%
Distribution loss in phase wires [kW]	2,21	0,50	2,99	0,50	1,06	0,34	1,57	0,16
Loss in power sources & converters [kW]	12,26	7,72	11,95	3,43	10,04	7,01	9,37	1,38
Total power loss including neutral wire [kW]	14,90	8,77	15,70	4,02	11,85	7,86	11,71	1,64
Efficiency considering neutral loss	93,54%	95,66%	92,37%	93,34%	94,75%	96,07%	94,22%	97,29%
Min node voltage vs Vnom (Number of node)	-2,34% (1605)	-0,80% (3004)	-2,70% (1601)	-0,95% (1601)	-1,92% (3004)	-1,52% (3004)	-2,11% (3004)	-0,79% (3001)
Max node voltage vs Vnom (Number of node)	0,34% (33)	0,37% (3402)	0,34% (2)	0,15% (2)	0,19% (1009)	0,14% (1009)	0,07% (1009)	0,11% (5)
Max active power stress of sources (Number of node)	31,50% (1006)	49,59% (902)	19,35% (331)	6,58% (331)	108,80% (1602)	100,14% (5)	105,53% (1602)	100,09% (5)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	113,11% (1503)	99,56% (5)	99,34% (1008)	99,89% (5)	114,79% (1107)	99,62% (5)	109,99% (1009)	92,16% (5)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	78,87% (7)	54,91% (68)	93,93% (7)	49,08% (68)	52,59% (28)	52,59% (28)	56,93% (28)	19,61% (28)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

4.6 Main results of the sixth test case.

In this section the tables and the graphs, related at fifth test case, are reported. In particular all the graphs show the peak values of the electrical quantities that are used for make comparison.
At first is important to compare the peak values of the results, relative the radial grid, between the case 61 and 62 to understand if the optimal control, of active power, gives the best results.

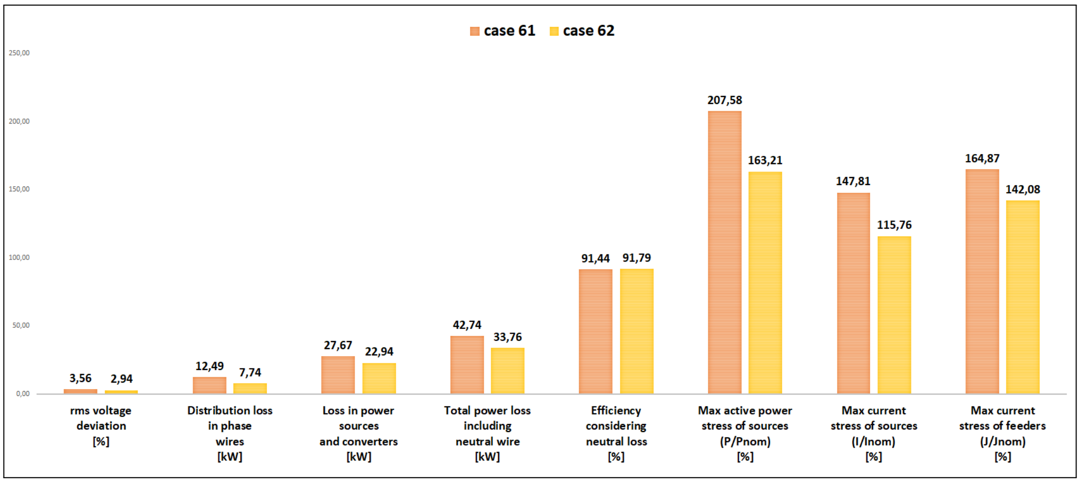

FIGURE 4.21: Comparison between the results of case 61 and 62, considering the radial grid.

From the previous graph the optimal control gives the best results in terms of the voltage deviation and all the rest of the electrical quantities considered in the previous graph. In particular only the efficiency remains constant between the two cases. Moreover the optimal control of the active power brought a reduction of the peak value of the maximum active power stress of source and it is a very good point. Also the optimal control has reduced the peak of maximum current stress of sources and feeders, so it leads a lot of benefits into the system.
So, for the radial grid, the optimal control of the active power gives the best results in terms of management of the system. Those are benefits that characterize the smart grid.
After that is important to compare the peak values of the results, relative the radial grid, between the case 63 and 64 to understand if the optimal control, of active power, gives the best results. From the following graph, in the third case, the value of voltage deviation, distribution loss in phase wires and the maximum current stress of feeders, are lower compared those in fourth case. While, in the third case, the loss in power sources, total power loss and the maximum of active power stress of sources are lower compared to those in the fourth case. At last the efficiency and the maximum current stress of sources remain constant between the two cases. In particular, as previously described, the increase of he active power stress of sources is due to the optimal control. Similarly the reduction of the current stress of feeders.

Moreover we have to consider that the overstressed sources are very small so it is very simple to reach the upper limit and overcome it.

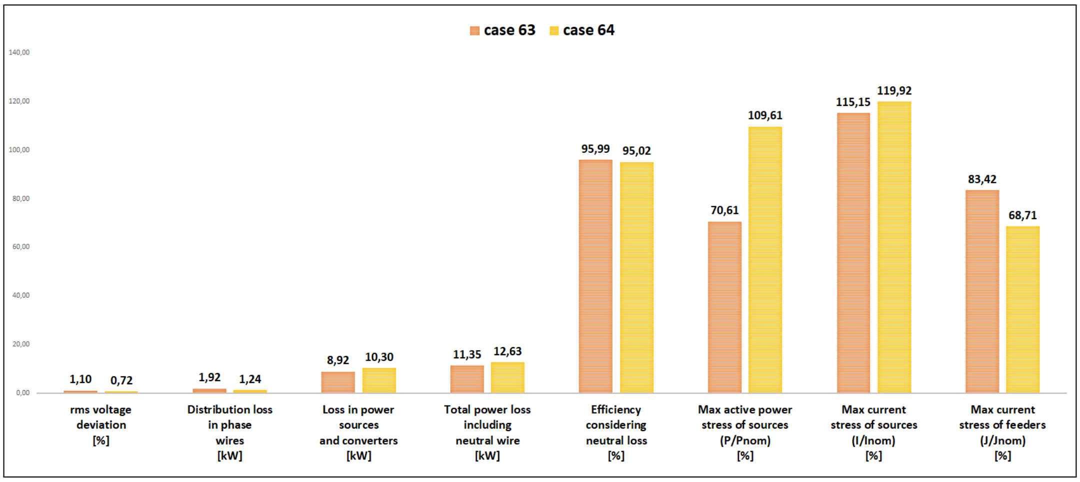

FIGURE 4.22: Comparison of the results between the case 63 and 64, considering the radial grid.

So, for the radial grid, the optimal control, of the active power, gives the best results in terms of management of the system. Those are benefits that characterize the smart grid.
Subsequently is important to compare the peak values of the results, relative the meshed grid, between the case 61 and 62 to understand if the optimal control, of active power, gives the best results.

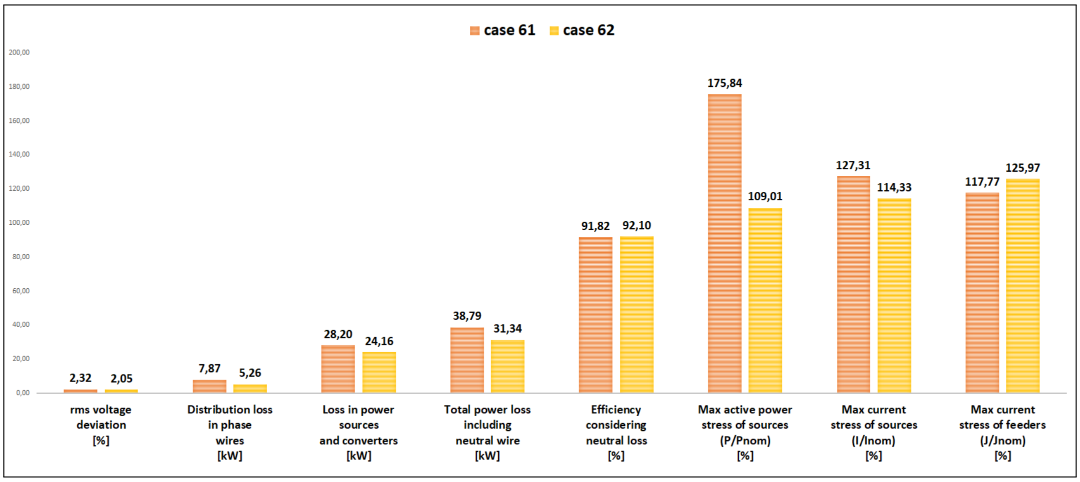

FIGURE 4.23: Comparison of the results between the case 61 and 62, considering the meshed grid.

From the following graph the optimal control gives the best results in terms of voltage deviation, distribution loss in phase wires, loss in power sources, total power loss, maximum active stress and current stress of power sources. In particular the optimal control has reduced the peak value of the maximum active power stress of the sources. That is a very good point that allow us a better management of the

distributed sources. While the efficiency and the maximum current stress of feeders remain constant between the two cases.
So, for the meshed grid, the optimal control, of the active power, gives the best results in terms of management of the system. Those are benefits that characterize the smart grid.
After that is important to compare the peak values of the results, relative the meshed grid, between the case 63 and 64 to understand if the optimal control, of active power, gives the best results.

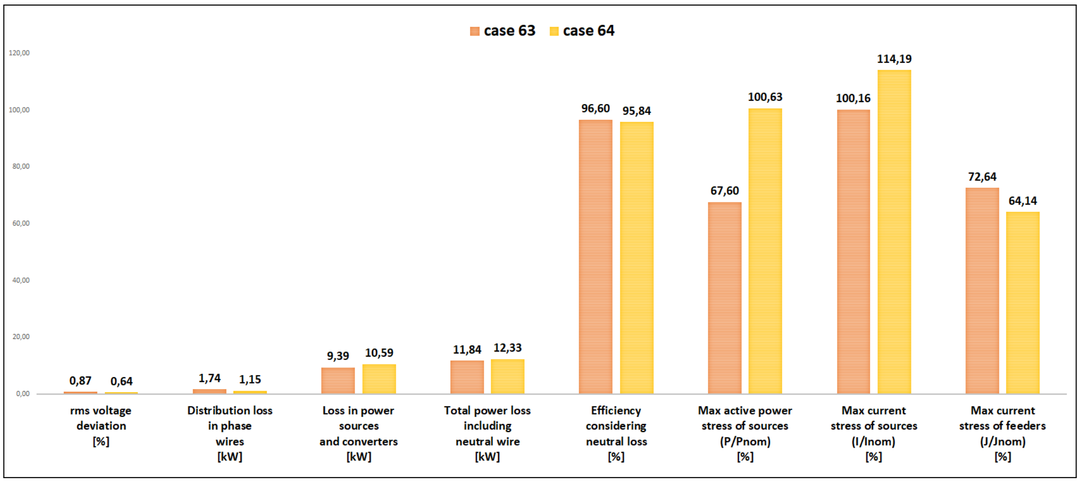

FIGURE 4.24: Comparison of the results between the case 63 and 64, considering the meshed grid.

From the previous graph the optimal control gives the best results in terms of voltage deviation, distribution loss in phase wires and maximum current stress of feeders. While the efficiency and the total power loss remain constant between the two cases. Moreover, in third case, the loss in power sources, the current stress and power stress of sources are lower compared to those at fourth case. This is because the optimal control, of the active power, exploits more the distributed sources to reduce the flow of current into the grid. Consequently the distributed resources are more stressed in reverse of the feeders that will be less stressed. Rather than the distributed sources are very small so it is very simple to reach the upper power limit and overcome it.
So, for the meshed grid, the optimal control, of the active power, gives the best results in terms of management of the system. Those are benefits that characterize the smart grid.
Subsequently a comparison of the peak value of results relative the analysis done with SUSI3, between the radial and meshed grid, for each case, is reported. In the following graph the first case is considered. From the previous graph the meshed grid gives the best results, in terms of voltage deviation, distribution loss, total power loss, current stress and power stress into the sources and current stress of feeders. In particular, in the meshed grid, the current stress decreases because the added lines offer new path in which the current can flow, so th stress of the feeders will decrease. Moreover the added lines approaching a greater number of distributed sources with

the loads, so there will be more support between the distributed sources. While the loss in power sources and the efficiency remain constant between the radial and meshed grid.

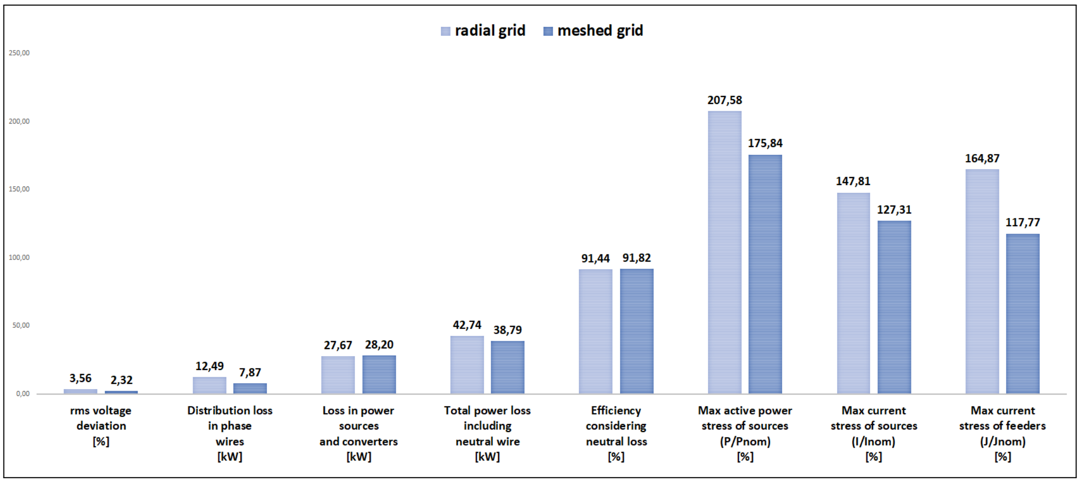

FIGURE 4.25: Comparison of the results between the radial and meshed grid, case 61.

So, in this case, we obtain the best results, considering the previous graph and the results reported in the following table, with the meshed grid because it allows a better management of the system.
In the following graph the second case is considered.

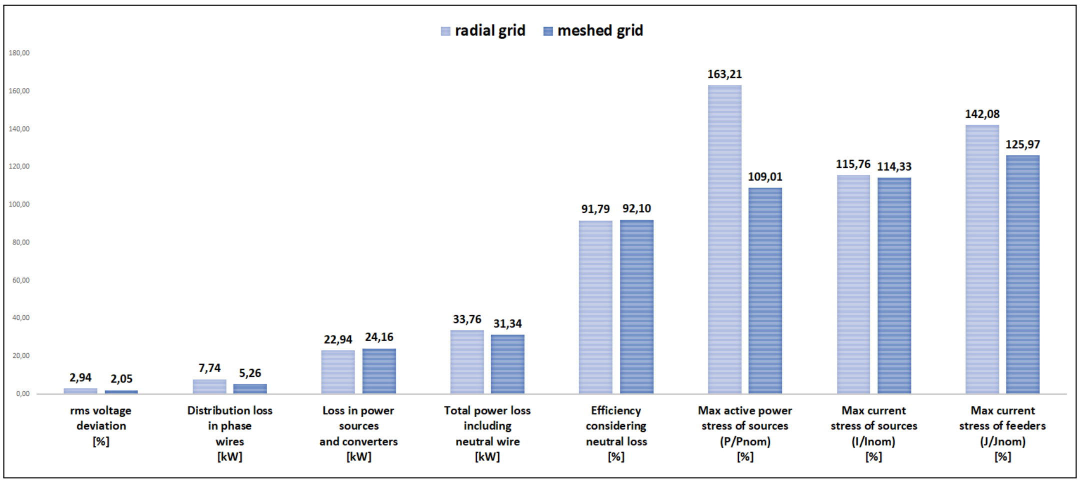

FIGURE 4.26: Comparison of the results between the radial and meshed grid, case 62.

From the previous graph the meshed grid gives the best results, in terms of voltage deviation, distribution loss, total power loss, power stress into the sources and current stress of feeders. In particular, in the meshed grid, the current stress decreases because the added lines offer new path in which the current can flow, so th stress of the feeders will decrease. Moreover the added lines approaching a greater number

of distributed sources with the loads, so there will be more support between the distributed sources. While the loss in power sources, the efficiency and the maximum of current stress of sources remain constant between the radial and meshed grid.
So, in this case, we obtain the best results, considering the previous graph and the results reported in the following table, with the meshed grid because it allows a better management of the system.
In the following graph the third case is considered.

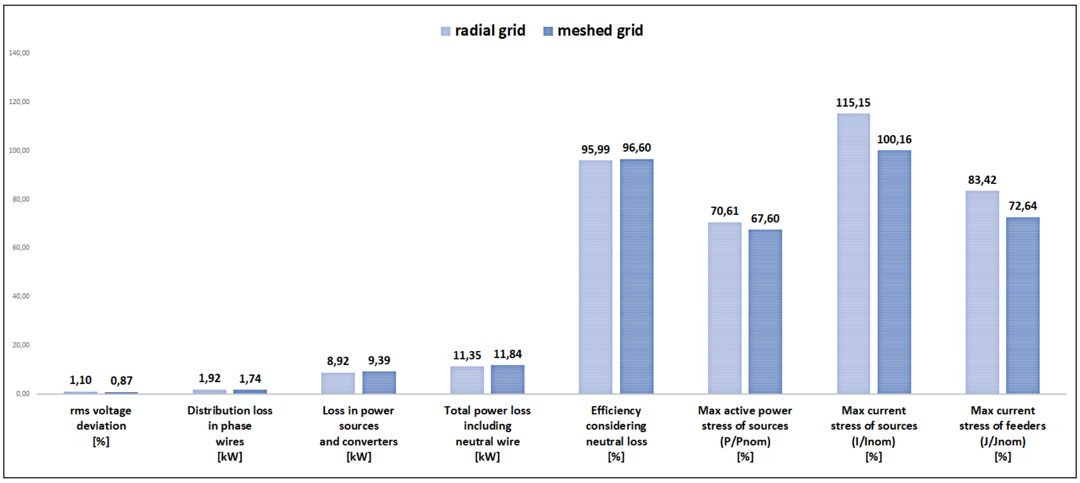

FIGURE 4.27: Comparison of the results between the radial and meshed grid, case 63.

From the previous graph the meshed grid gives the best results, in terms of voltage deviation, distribution loss, current stress and power stress into the sources and current stress of feeders. In particular, in the meshed grid, the current stress decreases because the added lines offer new path in which the current can flow, so th stress of the feeders will decrease. Moreover the added lines approaching a greater number of distributed sources with the loads, so there will be more support between the distributed sources. While the loss in power sources, the total power loss and the efficiency remain constant between the radial and meshed grid.
So, in this case, we obtain the best results, considering the previous graph and the results reported in the following table, with the meshed grid because it allows a better management of the system.
In the following graph the fourth case is considered. From the following graph the meshed grid gives the best results, in terms of voltage deviation, distribution loss in phase wires, current stress and power stress into the sources and current stress of feeders. In particular, in the meshed grid, the current stress decreases because the added lines offer new path in which the current can flow, so th stress of the feeders will decrease. Moreover the added lines approaching a greater number of distributed sources with the loads, so there will be more support between the distributed sources. While the loss in power sources, the total power loss and the efficiency remain constant between the radial and meshed grid. At last the added lines

lead a small reduction of the peak value of the maximum current stress of the feeders. Moreover the added lines will lead a reduction of the current stress for each feeders because these new lines offer new paths in which the current can flow.

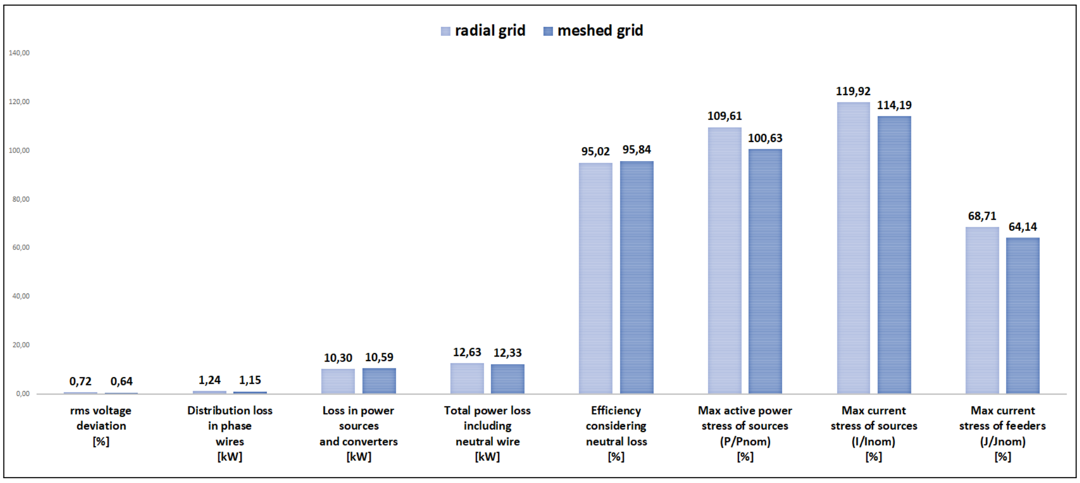

FIGURE 4.28: Comparison of the results between the radial and meshed grid, case 64.

So, in this case, we obtain the best results, considering the previous graph and the results reported in the following table, with the meshed grid because it allows a better management of the system.
In conclusion the best configuration of this grid is that meshed with the optimal control of the active power on, because we obtain a better management of the system.
Moreover in the following tables the main results, of the analysis done with SUSI3, are reported. In particular the first table resumes the results of the radial grid, while the second table resumes the results of the meshed grid.

TABLE 4.12: Results related the radial grid of case 61 and 62.

Test case	61	61	61	61	62	62	62	62
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	3,32%	2,32%	3,56%	2,72%	2,81%	1,99%	2,94%	2,22%
Distribution loss in phase wires [kW]	10,66	4,31	12,49	5,96	6,84	2,90	7,74	3,74
Loss in power sources & converters [kW]	25,98	19,64	27,67	16,11	22,39	18,24	22,94	14,48
Total power loss including neutral wire [kW]	38,84	26,19	42,74	24,09	32,36	23,61	33,76	20,28
Efficiency considering neutral loss	89,31%	91,44%	87,45%	85,09%	90,39%	91,79%	89,21%	85,79%
Min node voltage vs Vnom (Number of node)	-0,17% (1605)	0,00% (0)	-0,26% (1602)	0,00% (0)	0,00% (0)	0,00% (0)	0,00% (0)	0,00% (0)
Max node voltage vs Vnom (Number of node)	5,88% (917)	3,73% (917)	6,60% (917)	4,11% (2803)	5,19% (917)	3,25% (917)	5,39% (917)	3,93% (1602)
Max active power stress of sources (Number of node)	181,77% (2803)	102,07% (2803)	207,58% (2803)	112,04% (2803)	141,23% (2803)	102,52% (3503)	163,21% (3503)	103,11% (3503)
Number of overstressed sources (power)	1	0	1	1	1	0	1	0
Max current stress of sources (Number of node)	130,48% (2803)	106,87% (1107)	147,81% (2803)	103,76% (3501)	103,53% (2801)	101,54% (2002)	115,76% (2803)	118,90% 81801)
Number of overstressed sources (current)	1	0	1	0	0	0	0	0
Max current stress of feeders (Number of branch)	155,16% (27)	114,92% (27)	164,87% (27)	113,12% (27)	134,66% (27)	97,29% (27)	142,08% (27)	95,00% (27)
Number of overstressed feeders (current)	5	1	7	1	1	0	3	0

TABLE 4.13: Results related the meshed grid of case 61 and 62.

Test case	61	61	61	61	62	62	62	62
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	2,32%	1,74%	2,58%	1,86%	1,99%	1,60%	2,05%	1,69%
Distribution loss in phase wires [kW]	6,24	2,63	7,87	3,73	4,53	2,14	5,26	2,75
Loss in power sources & converters [kW]	24,48	18,68	28,20	18,83	23,29	18,53	24,16	16,83
Total power loss including neutral wire [kW]	32,72	22,97	38,79	23,83	29,53	22,10	31,34	21,02
Efficiency considering neutral loss	89,84%	91,82%	87,56%	81,89%	90,49%	92,10%	89,06%	83,74%
Min node voltage vs Vnom (Number of node)	-0,83% (1605)	0,00% (0)	-0,97% (1602)	0,00% (0)	-0,22% (1605)	0,00% (0)	-0,12% (1603)	0,00% (0)
Max node voltage vs Vnom (Number of node)	3,95% (2803)	2,88% (917)	5,29% (2803)	2,96% (917)	4,01% (917)	2,89% (917)	4,15% (917)	2,45% (1602)
Max active power stress of sources (Number of node)	119,88% (2803)	61,00% (2803)	175,84% (2803)	67,81% (917)	102,49% (3503)	103,18% (1604)	109,01% (2803)	102,33% (3503)
Number of overstressed sources (power)	1	0	1	0	0	0	0	0
Max current stress of sources (Number of node)	102,62% (3505)	117,15% (1503)	127,31% (2803)	116,72% (1107)	114,33% (1006)	101,42% (5)	102,33% (3507)	102,20% (3505)
Number of overstressed sources (current)	0	0	1	0	0	0	0	0
Max current stress of feeders (Number of branch)	111,89% (7)	69,47% (7)	117,77% (26)	98,70% (7)	118,35% (7)	68,77% (7)	125,97% (7)	73,15% (30)
Number of overstressed feeders (current)	3	0	2	0	2	0	2	0

TABLE 4.14: Results related the radial grid of case 63 and 64.

Test case	63	63	63	63	64	64	64	64
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	0,97%	0,29%	1,10%	0,37%	0,72%	0,27%	0,70%	0,18%
Distribution loss in phase wires [kW]	1,45	0,41	1,92	0,31	1,07	0,41	1,24	0,17
Loss in power sources & converters [kW]	8,92	7,09	8,49	2,49	10,30	9,32	10,00	1,93
Total power loss including neutral wire [kW]	11,09	8,18	11,35	2,92	12,63	10,57	12,32	2,19
Efficiency considering neutral loss	95,12%	95,99%	94,41%	95,08%	94,58%	95,02%	94,07%	96,39%
Min node voltage vs Vnom (Number of node)	-2,95% (1601)	-0,66% (1601)	-3,40% (1601)	-1,15% 81601)	-2,05% (1605)	-0,64% (1502)	-1,41% (1605)	-0,36% (1605)
Max node voltage vs Vnom (Number of node)	0,70% (917)	0,54% (1006)	0,98% (917)	0,47% (5)	0,54% (917)	1,20% (5)	0,78% (2803)	0,61% (5)
Max active power stress of sources (Number of node)	50,84% (2803)	49,79% (1005)	70,61% (2803)	23,68% (2803)	109,61% (1604)	101,15% (5)	101,18% (1604)	100,51% (5)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	115,15% (2002)	82,86% (1501)	100,46% (2801)	100,41% (5)	106,11% (1107)	119,20% (5)	119,92% (1107)	99,90% (5)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	65,23% (14)	46,72% (95)	83,42% (14)	32,60% (3)	65,17% (68)	68,64% (3)	68,71% (68)	31,05% (3)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

TABLE 4.15: Results related the meshed grid of case 63 and 64.

Test case	63	63	63	63	64	64	64	64
Day time	1	2	3	4	1	2	3	4
rms voltage deviation / Vnom	0,77%	0,23%	0,87%	0,30%	0,64%	0,26%	0,64%	0,19%
Distribution loss in phase wires [kW]	1,29	0,25	1,74	0,22	1,01	0,30	1,15	0,13
Loss in power sources & converters [kW]	9,08	6,56	9,39	1,48	10,20	7,99	10,59	1,68
Total power loss including neutral wire [kW]	10,75	7,05	11,84	1,78	11,72	8,75	12,33	1,88
Efficiency considering neutral loss	95,38%	96,60%	94,27%	97,05%	95,04%	95,84%	94,13%	96,98%
Min node voltage vs Vnom (Number of node)	-2,19% (1605)	-0,55% (3005)	-2,58% (1606)	-0,92% (1606)	-1,53% (1605)	-0,60% (1803)	-1,16% (1605)	-0,35% (1605)
Max node voltage vs Vnom (Number of node)	0,87% (917)	0,26% (32)	1,15% (917)	0,36% (917)	0,93% (917)	0,50% (1603)	0,81% (917)	0,23% (5)
Max active power stress of sources (Number of node)	51,54% (917)	49,64% (2304)	67,60% (917)	23,69% (2803)	100,63% (1010)	100,40% (1010)	100,41% (5)	100,20% (5)
Number of overstressed sources (power)	0	0	0	0	0	0	0	0
Max current stress of sources (Number of node)	100,04% (5)	76,73% (1501)	100,16% (5)	58,43% (1501)	99,72% (5)	100,76% (5)	114,19% (1501)	95,66% (5)
Number of overstressed sources (current)	0	0	0	0	0	0	0	0
Max current stress of feeders (Number of branch)	58,66% (28)	45,68% (28)	72,64% (28)	24,29% (14)	45,72% (95)	47,60% (95)	64,14% (68)	17,40% (95)
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0

Chapter 5

Optimal control inactive

At first this chapter deals with the description of the boundaries related at the first test case defined for the radial and meshed network. This test case is related of a passive grid except for the last part in which the photovolaic distributed sources participate at generation of active power. In particular the optimal control is always off in both grids, so the technical cost function is neglected. Subsequently the results of the simulation are reported into the following tables and they are used for make comparisons. The results come from the analysis, done with SUSI3 and Source Locator. At last a new version of meshed grid is considered to improve the results of the main meshed grid.

5.1 Description of the first test case.

In the first test, the simulated networks work with the control off so the active and reactive power, generated by the PCCs and distributed generators, is the result of the power flow analysis in which the technical cost function is neglected. In particular the technical cost function is the sum of the cost functions relative at the loss, stress and voltage deviation into the grid. The scenario describe above refers at the current way of managing the grid. Currently the main generators are still bound to a balance between supply and demand, or load balance, since the distributed energy storage systems and other related technologies can only store very small quantity of electric energy. While the centralized generation is the pivot of power generation and it leverages economies of scale to minimize the cost of converting energy into electricity. Indeed the designer of the power distribution system, in the context of power distribution planning, has the primary goal to design the distribution system such as to timely meet the demand growth in the most economical, reliable and safe way. The objective of the traditional power distribution planning is the minimization of an economic cost function, like the investment cost to add, reinforce or replace substation and feeders, taking into account the energy loss cost, subject to a set of technical and operational constraints.
So this analysis is very important because it gives an idea of the power flow in a current situation where all distributed generators give no or small contribution at the generation of electric energy. In particular this test case is split in three cases. In the

first one all the distributed generator are off and the PCC_s generate active and reactive power. Furthermore all loads absorb the rated active and reactive power. This last condition isn't similar at real operative condition because all the loads consumption is lower than the rated absorption. So, in this situation, the grid has to suffer an high current and power stress created by the heavy electric power generated by the main generators to balance the rated consumption of the loads.

TABLE 5.1: Boundaries relative at case 11.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P	Source bounded Q
All sources off Rated loads	-1		3	100	100	9		
PCCx slack nodes (reset bounds and power limits)	2	10				-2		

In the second case the boundaries for the generators are the same as those at the first case. While the absorption, of the loads, is lower compared to the rated one and it is random. In particular the program SUSI3 choses the active and reactive power from each load using the constant and random term defined at the beginning. This situation is very close at a current operative condition because the loads absorption is lower than the rated absorption and change during the day following a typical curve. In the following three tables the boundaries are define for each case describe previously.

TABLE 5.2: Boundaries relative at case 12.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources off Actual loads	-1		6	100	100	3		
PCCx slack nodes (reset bounds and power limits)	2	10				-2		

In the last part, also called third case, the photovoltaic distributed generators participate at the generation of active power. In particular the distributed sources are renewable energy resources. While the loads absorption is random as in the previous part. This last operative condition is very similar at a current situation in which the photovoltaic distributed sources participate at the balance of supply and demand with the main generators.

TABLE 5.3: Boundaries relative at case 13.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources feed generated P Actual loads	-1		6	100	100	6	100	
PCCx slack nodes (reset bounds and power limits)	2	10				-2		

5.2 Analysis of the results related at radial grid.

In this section the results of the analysis, made with SUSI3 and Source Locator, are reported in these tables. At first the value of voltage deviation, in percentage, is considered for each case and period of the day. The voltage deviation is a parameter that describes the power quality of a network and its maximum value is set to 5%. If the voltage deviation is greater than the maximum value, the node voltage at end-user node will be out of the range defined by code. In that situation the dispatcher cannot guarantee that the node voltage at end user-node is into the range, so the power quality will decreases. From the results, calculated using SUSI3, the value of voltage deviation is greater than the maximum value in the first period of the day of the first case. While in the rest of the periods, the voltage deviation is very close at upper limit and always lower than the maximum value. In particular during the night the voltage deviation is quite lower compared to the upper limit. In the first case the value of voltage deviation is very high because the loads absorption is very high compared to the consumption, of the loads, in a real operative condition. So the flow of current into the feeders is very intense and it generates an high value of voltage deviation across the feeders. While during the night the most part of the loads are turn off so the load absorption is quite lower than the absorption during the day. So the flow of current is lower and the voltage deviation decreases. In the second case the voltage deviation is always lower than the upper limit because the load absorption is lower compared to the rated consumption. So, in this case, the dispatcher can guarantee that the voltage node at end user node is into the range. This is a very good point for this operative condition that is very close to a real situation. At last the value of voltage deviation at the third case is always lower that the maximum value and always lower compare to the voltage deviation at second case. This is a very interesting result that shows a benefit of the distributed generation. Indeed the only difference between the second and third case is the presence at the third case of the photovoltaic distributed sources that participate at generation of active power. So the photovoltaic systems participate, with the main generators, at the load balance. The photovoltaic distributed generators have a positive benefit for the network because they create locally the active power, so the current flow decreases and the voltage deviation falls.

After that in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power feed by sources and the power throughput grid transportation. Afterwards the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters and it makes an estimation of the power loss into neutral wires. From the analysis the value of the distribution loss into the feeders is always greater than the power loss in sources and converters, except for a period of the day in the third case. Moreover the distribution loss in phase wires at first case is greater compared to that of second and third case. That is the consequence of the difference between the load absorption at first case and the rest of the cases.

TABLE 5.4: Main results related at radial grid, obtained with SUSI3.

Test case	11	11	11	11	11	12	12	12	12	12	13	13	13	13	13
Day time	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ω]	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160
rms voltage deviation / Vnom	5,57%	5,47%	4,96%	4,95%	1,46%	4,03%	3,96%	3,53%	3,53%	1,04%	2,40%	2,76%	1,84%	3,11%	1,04%
P entering grid at node 0 [kW]	221,84	218,58	195,22	195,67	57,81	160,93	158,58	138,97	139,69	41,22	-65,84	90,55	25,59	117,01	41,22
Q entering grid at node 0 [kVAR]	116,08	115,23	100,83	102,11	30,22	85,57	84,65	73,08	73,92	21,79	76,93	82,06	68,76	73,05	21,79
P absorbed by loads [kW]	312,50	305,34	278,31	275,92	83,25	229,70	224,63	201,07	200,00	59,84	231,23	225,10	201,73	200,13	59,84
Q absorbed by loads [kVAR]	140,49	137,54	126,28	125,28	39,54	105,79	102,85	93,73	92,47	28,49	118,65	106,63	99,34	93,59	28,49
P fed by sources [kW]	324,17	316,67	287,57	285,18	84,06	235,63	230,39	205,63	204,57	60,24	322,69	227,99	203,13	203,70	60,24
Q fed by sources [kVAR]	156,72	153,09	139,00	137,84	40,63	114,98	111,67	100,78	99,47	29,18	121,70	111,36	101,02	99,35	29,18
P returned to sources [kW]	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	88,80	0,00	0,00	0,00	0,00
Q returned to sources [kVAR]	0,00	0,00	0,00	0,00	0,00	0,49	0,48	0,44	0,44	0,13	0,00	0,86	0,07	0,75	0,13
P troughput-grid transport [kW]	324,17	316,67	287,57	285,18	84,06	235,63	230,39	205,63	204,57	60,24	176,72	145,48	96,83	172,16	60,24
Q troughput-grid transport [kVAR]	156,72	153,09	139,00	137,84	40,63	114,98	111,67	100,78	99,47	29,18	114,50	111,32	100,35	99,35	29,18
Distribution loss in phase wires [kW]	11,66	11,33	9,26	9,25	0,81	5,93	5,75	4,57	4,57	0,40	2,66	2,89	1,40	3,56	0,40
Loss power in sources & converters [kW]	0,30	0,27	0,25	0,23	0,02	0,16	0,15	0,13	0,12	0,01	18,25	1,70	4,58	0,28	0,01
Total power loss w/o neutral wire [kW]	11,96	11,60	9,51	9,48	0,83	6,09	5,90	4,70	4,69	0,41	20,91	4,59	5,99	3,84	0,41
Efficiency neglecting neutral loss (Total loss/power fed by sources)	96,31%	96,34%	96,69%	96,68%	99,01%	97,42%	97,44%	97,72%	97,71%	99,32%	93,52%	97,99%	97,05%	98,12%	99,32%
Estimated loss in neutral wire [kW]	2,23	2,23	2,22	2,21	0,20	1,03	1,03	1,09	1,07	0,10	3,22	0,63	1,05	0,86	0,10
Total power loss including neutral wire [kW]	14,19	13,83	11,73	11,69	1,03	7,12	6,93	5,79	5,77	0,51	24,13	5,23	7,04	4,70	0,51
Efficiency considering neutral loss	95,62%	95,63%	95,92%	95,90%	98,78%	96,98%	96,99%	97,19%	97,18%	99,16%	92,52%	97,71%	96,54%	97,69%	99,16%
Min node voltage vs Vnom	-10,09%	-10,00%	-8,30%	-8,46%	-2,49%	-6,99%	-6,92%	-5,64%	-5,70%	-1,69%	-2,07%	-4,62%	-3,05%	-5,14%	-1,69%
Node with minimum voltage	1605	1605	1602	1602	1602	1605	1605	912	1606	912	1605	1605	902	912	912
Max node voltage vs Vnom	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,80%	0,00%	0,00%	0,00%	0,00%
Node with maximum voltage	331	331	331	331	331	331	331	331	331	331	1602	331	331	331	331
Max active power stress of sources (P/Pnom)	40,52%	38,85%	36,57%	35,45%	10,39%	29,47%	28,33%	26,29%	25,59%	7,50%	100,34%	29,52%	49,25%	21,72%	7,50%
Node with maximum active power stress	331	331	331	331	331	331	331	331	331	331	1602	3103	1111	331	331
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	34,08%	32,55%	30,94%	29,84%	8,74%	24,78%	23,67%	22,28%	21,51%	6,30%	90,41%	26,58%	44,34%	18,85%	6,30%
Node with maximum current stress	331	331	331	331	331	331	331	331	331	331	1602	3103	1111	331	331
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	148,89%	148,89%	124,89%	128,32%	37,81%	101,65%	101,65%	81,06%	84,00%	24,61%	67,57%	70,60%	41,72%	73,03%	24,61%
Branch with maximum current stress	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
Number of overstressed feeders (current)	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0
Max stress	148,9%	148,9%	124,9%	128,3%	37,8%	101,6%	101,6%	81,1%	84,0%	24,6%	100,3%	70,6%	49,3%	73,0%	24,6%

Indeed, in the first case, the load absorption is equal at rated consumption while in the second and third case it is always lower than the rated one. So, in the first case there will be a greater flow of current into the feeders, of the grid, compared that at second and third case. That causes a greater power loss into the feeders. While in the case 12 the distribution loss in phase wires is always greater compared to that in the case 13. That happen because in the third case the distributed sources participate at load balance, so the flow of current, into the lines, will decrease. Consequently the power loss into the branches will decrease. Moreover during the night the power loss falls because, for each load, the absorption decreases compared to that during the day.

The calculation of the power loss is fundamental for the efficiency. The efficiency of a system is a very important parameter of the power quality. Considering the efficiency during the day it remains quite constant for each case. While during the night the efficiency is always greater compared to that during the day. This is a consequence of the decrease of the load absorption during the night. Furthermore in the first case the efficiency is lower compared to that at second and third case. This happen because the load absorption, in the first case, is greater compared to that at second and third case. So there will be a greater flow of current into the feeders that cause a greater power loss. While the efficiency, in the second case, is lower compared to that in the third case. This is due to at reduction of the flow of current, into the grid, by means of the distributed sources at third case. So the power loss into the feeders will decrease and, consequently, the distribution loss in phase wires will decrease. While, in the third case, the efficiency is greater compared to that at second case, except for the second period of the day. This happen because the distributed sources feed the local loads, so they contribute to the reduction of flow of current into the grid. In this way the power loss into feeders will decrease and, consequently, the efficiency will increase. At last the efficiency is quite high for each case and period of the day, so the dispatcher can guarantee an high value of power quality. That is a very good point for an operative condition.

Subsequently is very important to consider the results of the maximum and minimum voltage and individuate the node with that voltage. This is important because the dispatcher has to guarantee that every node voltages are into the range in every operative condition. The maximum voltage is always equal to the rated value at node PCC_1 because, in that node, there is a generator link at a voltage source that impose the voltage. While the minimum voltage is always lower than the rated value and the relative node is always at end-user node. This is a direct consequence of the fact that the grid is radial without distributed generators, so the minimum voltage must be at end-user node. In particular the value of minimum voltage is lower in the first case compared to that at second and third case. This is due to the greater load consumption, in the first case, compared to that at second and third case. Also during the night, for every case, the minimum voltage is greater than that during the day because the load absorption in greater during the day.

After that the results of current and power stress are reported in the previous table. The number of overstressed power source is always equal to zero, so there aren't overstressed sources into the grid. Rather than, into the table, the maximum value of active power stress is reported for each case and period of the day. The results show that the power stress, into the sources, is always small and during the night decrease compared to that during the day. This is because the load absorption falls. The node with the maximum power stress is always the PCC_1 where is install a generator. Furthermore the maximum power and current stress of sources, in the first case, is greater compared to that at second and third case. This is a direct consequence of the greater load absorption, at first case, compared to that at second and third case. While the power and current stress of sources, in the second case, is lower compared to that in the third case, except for the third period of the day. This happen because the distributed resources are exploited to reduce the flow of current into the feeders, so the total stress will decrease.
For the maximum current stress into the feeders, the results follow the same trend as the power stress into the sources. Indeed at the first case the maximum current stress is greater than that at second and third case. Furthermore, during the night, the maximum current stress decreases because the loads absorption fall. While the current stress of feeders, in the second case, is greater compared to that at third case. This happen because, in the third case, the distributed sources are exploited to reduce the flow of current into the grid. Consequently the current stress and power loss into phase wires will decrease.
Subsequently the number of the branch with the maximum current overstressed is reported into the following table. In particular the branch with the maximum current stress is always the line number 14, in this test case. So the dispatcher has to solve this current stress into the feeder number 14. To solve this current overstress a solution is to link, in a new or already existing fully controllable node, a current source nearby the overstressed branch. For decide in which node connect that generator we have to use the program Source Locator. Before that the results of current overstress are reported in the following table.

TABLE 5.5: Results of current overstress into the feeders.

Test case	**Period of the day**	**Branch number**	**Phase**	**Overstress J/Jnom**
12	1	14	2	1,17

In particular in the previous table the current overstress related at first case are neglected because that case refers of a unreal operative conditions. So, for the analysis with Source Locator, it is better to consider the second and third case that are more close at a real situation. From the analysis with SUSI3 the only feeder in which there is a current stress, that overcome the upper limit defined at beginning, is the branch

14 that starts at node 15 and finishes at node 16. So, to solve the overstress, a solution is to install a current source, with a given apparent power, and make that node fully controllable. Since the overstress is close to node 16 the proposed solution is to install the generator with 50 kVA in the node 16 that become a new fully controllable node. In the following table the results of the calculation, done with Source Locator, are resumed.

TABLE 5.6: Results of the analysis done with Source Locator.

Fully controllable node	Power generate from that node [kVA]	Number of controlled branches	Total control factor J/Jnom	List of control branches (control factor)
917	47,14	10	7,89	24(1.21), 26(1.21), 23(0.84), 125(0.82), 10(0.82), 18(0.81), 22(0.81), 126(0.51), 6(0.43), 7(0.43)
2803	47,14	8	8,32	6(2.07), 7(2.07), 3(1.88), 5(0.65), 4(0.65), 1(0.39), 2(0.39), 126(0.23)
5	5,11	3	0,72	36(0.31), 6(0.20), 7(0.20)
1602	5,55	2	0,85	14(0.51), 84(0.34)
1604	5,55	2	0,85	14(0.51), 86(0.34)
16	6,67	2	1,02	14(0.62), 82(0.41)

With Source Locator is possible to obtain the control factor of a generator install in a fully controllable node to solve a current overstress. It is possible to consider the fully controllable node that are already considered into the grid or add a new fully controllable node. The control factor refers to the current that actually is into that feeder that is calculated from the analysis done with SUSI3. In this case the proposed solution expected to install the generator in a new fully controllable node that is the node 16. So Source Locator calculates the total control factor and the control factor line by line, one by one for all the fully controllable node considering also the new one. From the results the fully controllable node that have the greater number of controlled branches is the node 917, but that node cannot control the line 14, so this solution is neglected. For the same reason the fully controllable node 2803 and 5 are neglected. While the solution to connect a current source, at node 16, gives the control that allows us to solve the current stress in the line number 14. Indeed the current stress is 1,17 and the new generator can control 62% of the current in that line. So, with that solution, is possible to increase or decrease the current in the branch 16 of 62%. Obviously to solve the current stress the generator has to reduce the current. Another solution is to reinforce that line, for example by increasing its section, to support a greater current.

5.3 Analysis of the results related at meshed grid.

In the following table the results of the analysis are reported, done with SUSI3, related at the main meshed grid. While in the last two tables the results of the simulation, done with Source Locator, are resumed.

TABLE 5.7: Main results of the simulation, using SUSI3, of the main meshed grid.

Test case	11	11	11	11	11	12	12	12	12	12	13	13	13	13	13
Day time	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099
rms voltage deviation / Vnom	4,82%	4,73%	4,24%	4,23%	1,25%	3,49%	3,41%	3,02%	3,00%	0,88%	2,21%	2,30%	1,48%	2,61%	0,88%
P entering grid at node 0 [kW]	218,16	214,57	191,19	191,36	56,49	156,40	153,17	134,34	134,19	39,46	-70,34	85,15	20,97	111,51	39,46
Q entering grid at node 0 [kVAR]	107,13	106,95	91,73	93,70	27,76	81,80	81,56	68,99	70,53	20,87	79,16	80,77	67,66	70,27	20,87
P absorbed by loads [kW]	312,76	305,43	277,93	275,48	82,43	226,43	219,86	197,69	195,14	57,89	226,04	219,76	197,50	195,11	57,89
Q absorbed by loads [kVAR]	138,78	135,81	124,47	123,47	38,89	108,90	105,89	96,27	95,00	29,19	120,85	109,39	101,46	96,03	29,19
P fed by sources [kW]	320,51	313,01	283,91	281,51	82,96	230,47	223,78	200,69	198,16	58,15	327,92	221,67	198,40	197,43	58,15
Q fed by sources [kVAR]	154,56	150,95	136,81	135,67	39,98	117,29	113,86	102,62	101,23	29,74	124,10	113,80	102,99	101,20	29,74
P returned to sources [kW]	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	99,78	0,00	0,00	0,00	0,00
Q returned to sources [kVAR]	0,12	0,13	0,09	0,11	0,03	0,07	0,09	0,05	0,07	0,02	0,00	0,85	0,04	0,51	0,02
P troughput-grid transport [kW]	320,51	313,01	283,91	281,51	82,96	230,47	223,78	200,69	198,16	58,15	190,88	140,61	96,92	165,14	58,15
Q troughput-grid transport [kVAR]	154,56	150,95	136,81	135,67	39,98	117,29	113,86	102,62	101,23	29,74	117,22	113,78	102,57	101,20	29,74
Distribution loss in phase wires [kW]	7,75	7,58	5,98	6,03	0,53	4,04	3,93	3,00	3,02	0,26	2,10	1,92	0,91	2,31	0,26
Loss in power sources & converters [kW]	0,31	0,29	0,26	0,24	0,02	0,17	0,15	0,14	0,13	0,01	18,97	1,77	4,76	0,28	0,01
Total power loss w/o neutral wire [kW]	8,06	7,86	6,24	6,28	0,55	4,21	4,08	3,14	3,14	0,27	21,07	3,68	5,67	2,60	0,27
Efficiency neglecting neutral loss (Total loss/power fed by sources)	97,48%	97,49%	97,80%	97,77%	99,34%	98,17%	98,18%	98,44%	98,41%	99,53%	93,58%	98,34%	97,14%	98,68%	99,53%
Estimated loss in neutral wire [kW]	1,74	1,74	1,71	1,71	0,15	0,87	0,87	0,84	0,84	0,08	1,63	0,43	0,52	0,65	0,08
Total power loss including neutral wire [kW]	9,80	9,60	7,95	7,99	0,70	5,08	4,95	3,98	3,98	0,35	22,69	4,11	6,18	3,25	0,35
Efficiency considering neutral loss	96,94%	96,93%	97,20%	97,16%	99,15%	97,80%	97,79%	98,02%	97,99%	99,40%	93,08%	98,15%	96,88%	98,36%	99,40%
Min node voltage vs Vnom	-7,77%	-7,72%	-6,51%	-6,64%	-1,96%	-5,35%	-5,31%	-4,40%	-4,49%	-1,32%	-1,83%	-3,53%	-2,03%	-3,90%	-1,32%
Node with minimum voltage	1605	1605	1604	1604	1604	1605	1605	1602	1602	1602	3004	1605	3004	1602	1602
Max node voltage vs Vnom	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,70%	0,00%	0,00%	0,00%	0,00%
Node with maximum voltage	331	331	331	331	331	331	331	331	331	331	1604	331	331	331	331
Max active power stress of sources (P/Pnom)	40,71%	39,16%	36,87%	35,85%	10,53%	29,46%	28,09%	26,38%	25,44%	7,43%	99,04%	29,39%	49,28%	21,32%	7,43%
Node with maximum active power stress	331	331	331	331	331	331	331	331	331	331	910	2001	2001	331	331
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	35,07%	33,52%	32,05%	30,91%	9,06%	25,53%	24,14%	23,13%	22,06%	6,43%	89,20%	26,45%	44,35%	19,25%	6,43%
Node with maximum current stress	331	331	331	331	331	331	331	331	331	331	910	2001	2001	331	331
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	142,39%	142,39%	118,40%	121,83%	35,86%	94,29%	94,29%	80,38%	81,59%	24,18%	80,20%	65,12%	45,88%	70,06%	24,18%
Branch with maximum current stress	14	14	14	14	14	14	14	3	3	3	14	14	14	3	3
Number of overstressed feeders (current)	4	4	2	2	0	0	0	0	0	0	0	0	0	0	0
Max stress	142,4%	142,4%	118,4%	121,8%	35,9%	94,3%	94,3%	80,4%	81,6%	24,2%	99,0%	65,1%	49,3%	70,1%	24,2%

At first the value of voltage deviation is considered. Its value is always lower than the maximum value and it is a good point. It is lower that the upper limit, also in the first case in which the flow of current into the grid is very intense, since the load absorption is very high. Moreover in the second and third case, that are more close at a real operative condition, the voltage deviation is very small. That is a benefit given from the making the grid meshed. Also the trend of the voltage deviation, at changing the case and period of the day, is the same as the trend in the radial grid.
Subsequently is important to value the power loss, in particular the distribution loss in phase wires and the loss in power sources and converters. In particular the distribution loss in phase wires, in the first case, is greater than that in the second and third case. Similarly the power loss into feeders, in the second case, is greater compared to that at third case. This happen because, in the first case, the flow of current into the grid is very intense because the loads absorption is the same as the rated one. Furthermore, in the third case, the distributed generation contribute to the load balance, so there will be a reduction of flow of current and, consequently, a decrease of power loss into feeders. While the loss in power sources, in the third case, is greater compared to that in the first and second case. This happen because, in the third case, the distributed generation participate at load balance,so there will be an increase of the power loss in sources. While the loss in power sources, in the first case, is greater compared to that in the second case because, in the first case, the load absorption is very intense so there will be a greater exploitation that cause an increase of power loss in sources.
Subsequently the efficiency is considered, because it is an important parameter of power quality. The efficiency is quite constant for each case and it is greater during the night compared to that during the day. Also the efficiency follows the same trend as that for the radial grid. In particular the value of the efficiency is very high and it is a good point for this configuration of the grid.
As the radial grid the minimum voltage is at end user-node. While the maximum voltage node is equal at rated value at the PCC_1 in which there is a generator that works as voltage source.
For the current and power stress into the sources the results follow the same trend as those in the radial grid. In particular the value of the current and power stress is quite constant at change the case and period of the day, except for the third case. Moreover the power and current stress into the sources, in the case 11, is greater compared to that in the case 12 and 13. This is because the load absorption, in the first case, is very intense so the sources will be more stressed. Furthermore the current and power stress is greater during the day compared to that at the night. This is a direct consequence of the higher absorption, from the loads, during the day compared to that during the night. As in the radial grid there are no sources in which there is a power overstress that overcome the maxim value. This is another benefit in favor of meshed grid.
Subsequently the current stress into the feeders are reported into the previous table.

The current stress into the feeders follows the same trend as those in the radial grid. Indeed the current stress of feeders, in the first case, is greater compared to that in the second and third case. Moreover, in the second case, it is greater compared to that in the third case. These facts are due to a greater load absorption in the first case that cause an increase of current stress in feeders. Moreover the current stress of feeders, in the third case, decreases because the distributed sources feed the local loads, so the flow of current, into the feeders, will decrease. In particular it is greater during the day compared to that during the night. This is because during the day the load consumption is greater than that during the night.
After that, the current stress, that overcome the maximum value, is reported in the following table. In particular the branch, in which there is a current overstress, is the line 14, as in the radial grid. Indeed in the radial grid there was only a feeder in the first period of the day with a current overstress.

TABLE 5.8: Results of current stress into the feeders considering the meshed grid.

Test case	**Period of the day**	**Branch number**	**Phase**	**Overstress J/Jnom**
12	1	14	2	1,25
12	3	14	2	1,07

While with the meshed grid the over stressed feeder is the same, but the over stress occurs in two periods of the day, more precisely in the first and third period. Moreover, with the meshed grid, the current overstress is greater compared to that in the radial grid. These facts happen because, in the meshed grid, the new branches allow the current to follow new paths and it is possible that the current flow is focus in a line. To solve the current stress is possible to do the analysis with Source Locator. In particular the proposed solution is the same as that with the radial grid, so we consider the solution which provides the connection of a current source, with a given apparent power equal to 50 kVA, in a fully controllable node close to the line over stressed. From the results of the analysis, done with Source Locator, the generator, link at fully controllable node 16, is capable to control all the current in the line 14. So, with that solution is possible to reset the current into the branch 14 since the control factor is 1,54. In this way is possible to reduce the current over stress in that line acting on the new current stress link at the fully controllable node 16. This generator contribute to the reduction of the current stress into the feeder and support the nearby generator at load balance, so it contributes to the reduction of power loss in sources and in phase wires. So there are a lot benefits that this new current sources leads. This is very helpful, also, when there is a failure in a line, for example the line 14, and instead of open the switches in the failure line, a solution is to control that generator to reset the current in that line. In this way the technicians can make the maintenance to repair the failure. Otherwise, if we don't want to install a new generator, is possible to reinforce, for example by increasing the section of the line 14, to reduce the current overstress.

TABLE 5.9: Results of the analysis made with Source Locator considering the meshed grid.

Fully controllable node	Power generate from that node [kVA]	Number of controlled branches	Total control factor J/Jnom	List of control branches (control factor)
917	47,14	17	10,06	24(1.21), 26(1.05), 23(0.84), 125(0.82),22(0.81), 18(0.72), 9(0.70), 7(0.56), 132(0.49), 11(0.44), 10(0.43), 19(0.41), 3(0.40), 127(0.39), 17(0.32), 27(0.26), 4(0.22)
2803	47,14	6	3,95	7(2.07), 126(0.60), 3(0.57), 8(0.25), 132(0.25), 6(0.21)
16	16,67	5	3,31	14(1.54), 82(1.01), 7(0.27), 9(0.27), 15(0.20)
1602	5,55	2	0,85	14(0.51), 84(0.34)
1604	5,55	2	0,85	14(0.51), 86(0.34)

So the optimal control allows us a better management of the system.

5.4 Comparison between the radial and meshed grid.

Subsequently is important to compare the results of the analysis, done with SUSI3 and Source Locator, between the radial and meshed grid to understand which configuration gives the best results. Indeed isn't obvious that the meshed grid is always better compared to the radial grid. In particular the graph show the comparison of the peak value between the second and third case because they are more close at a real operative condition rather than first case. Considering the second case all the results represented into the graph, except for the maximum current stress of the sources, are in favor at meshed grid. In particular the difference between the maximum current stress into sources betweeen the radial and meshed grid, is very small, so that difference is neglected.

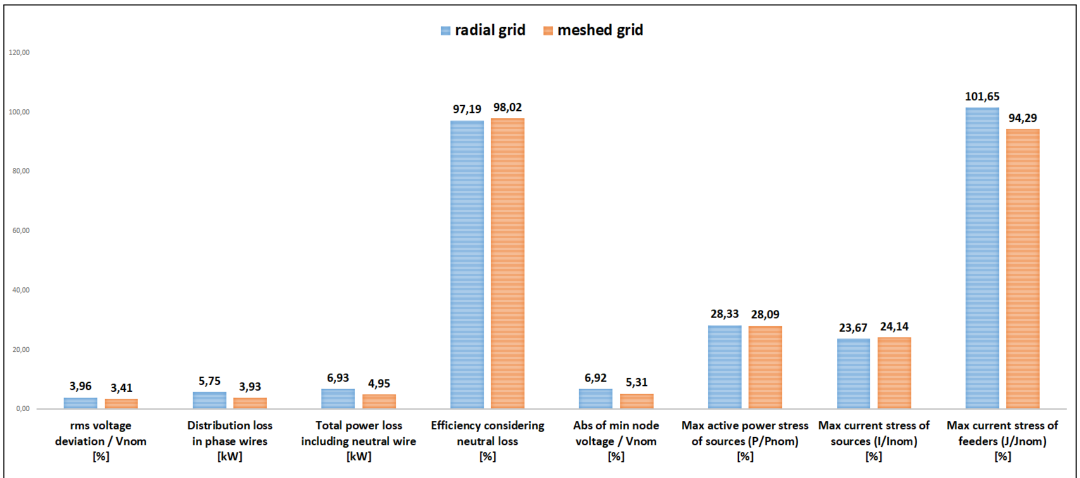

FIGURE 5.1: Comparison between the results of the radial and meshed grid, at case 12.

Indeed the voltage deviation relative at the radial grid is greater than that in the meshed grid as the total power loss, the minimum of the minimum node voltage, the maximum active power stress of sources, the maximum current stress into the feeders and the distribution loss in phase wires. Furthermore the efficiency relative at the meshed grid is greater compared to that in the radial grid. Moreover, considering also the results reported in the previous table, we observe that the voltage deviation, the distribution loss in phase wares, the loss in power sources and the stress into sources, in the meshed grid, are lower compared to those in the radial grid. These results are in favor at the meshed grid and they proof that, for this case, the proposed meshed grid is better compared to the radial grid. The advantage that the meshed grid introduce is that creates new paths for the current flow so, at parity of the sources and loads, there are a better management of the network. Obviously not all meshed version of the radial grid give the same benefits. In particular this meshed grid is obtain at the end of some reasonings and analysis with SUSI3.
Considering the third case, also called case 13, all the results represent into the graph, except for the maximum current and power stress in the sources, are in favor at meshed grid. Indeed the voltage deviation relative at the radial grid is greater than that in the meshed grid as the total power loss, the minimum of the minimum node voltage, the maximum active power stress of sources and the distribution loss in phase wires. Furthermore the efficiency relative at the meshed grid is greater compared to that in the radial grid. In particular the differences between the maximum stress into feeders and sources are very small, so these differences are neglected.

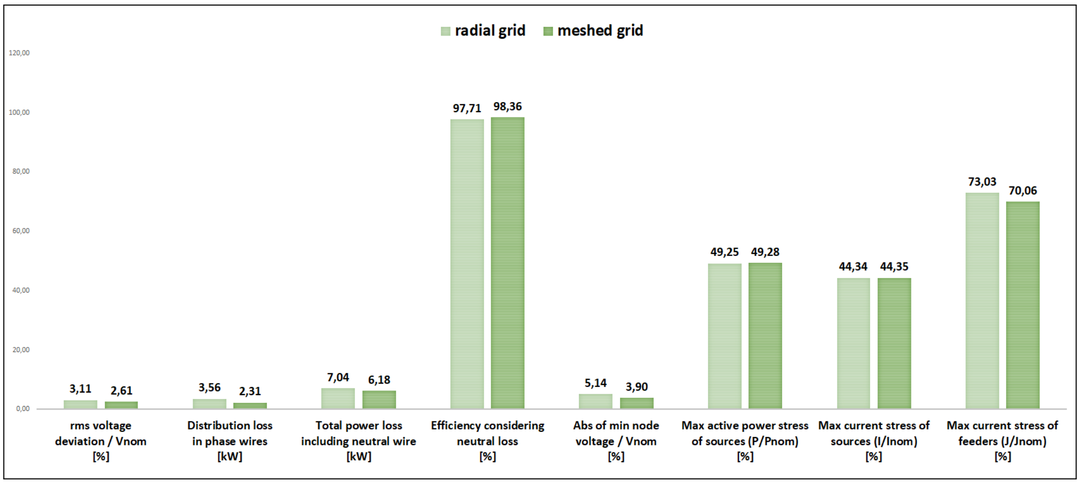

FIGURE 5.2: Comparison between the results of the radial and meshed grid, at case 13.

If we consider also the result reported in the previous table, is possible to note that the meshed grid gives the best results. Indeed, for each period of the day, the electrical quantities considered are in favor of meshed grid.
These advantages, both for case 12 and 13, are due to presence of new paths for the flow of current, so there will be a lower concentration of current for each feeder.

This fact leads to a reduction of power loss and current stress into feeders. Moreover, only for case 13, the sources, in the meshed grid, are link to a greater number of loads compared to that in the radial grid. So there is a greater number of distributed sources that support each other to load balance.This collaboration between sources leads to a reduction of the power and current stress of sources.
These facts are in favor at the meshed grid and they proof that, for this test case, the proposed meshed grid is better compared to the radial grid. So, in this case, the meshed grid offers a better management compared to the radial grid.
Moreover, based on the results obtained, the distributed generation gives better results in terms of management and power quality of the the network studied, both radial and meshed.

5.5 Comparison between the main and new meshed grid.

In this section a new version of meshed grid is proposed for have an alternative at the main meshed grid describe previously. The new version of meshed grid is obtained from some reasonings and analysis with SUSI3 and Source Locator, through a series of attempts that led to the creation of the new meshed network. In this table the data relatives at the new branches are reported.

TABLE 5.10: Add branches at new verion of meshed grid.

Feeder type	**Length [m]**	**Line number**	**Start node**	**End node**
13	15	126	11	13
13	80	127	26	31
13	55	128	9	16
13	15	129	19	21

In the following table the results of the simulation, done with SUSI3 and Source Locator, are resumed. In particular the results that come from the analysis with SUSI3 can be explained in the same way as before. In particular the results of the first case are have been neglected, in the comparison, because they don't refer at real operative condition. Similarly, the results of the period 0 have been neglected in the comparison. Furthermore all the results follow the same trend of the results relative at the main meshed grid reported before. Now it is interesting to make an comparison between the results of the main meshed grid and those related at the new version of meshed grid. The intent to propose a new version of the meshed grid is to obtain a better management of the main meshed grid and radial grid. Sometimes it is difficult to obtain this intent because we get better is a side and getting worse to another side.
Considering the second case, also called case 12, all the results are in favor of the main meshed grid, except for the maximum power and current stress into the sources.

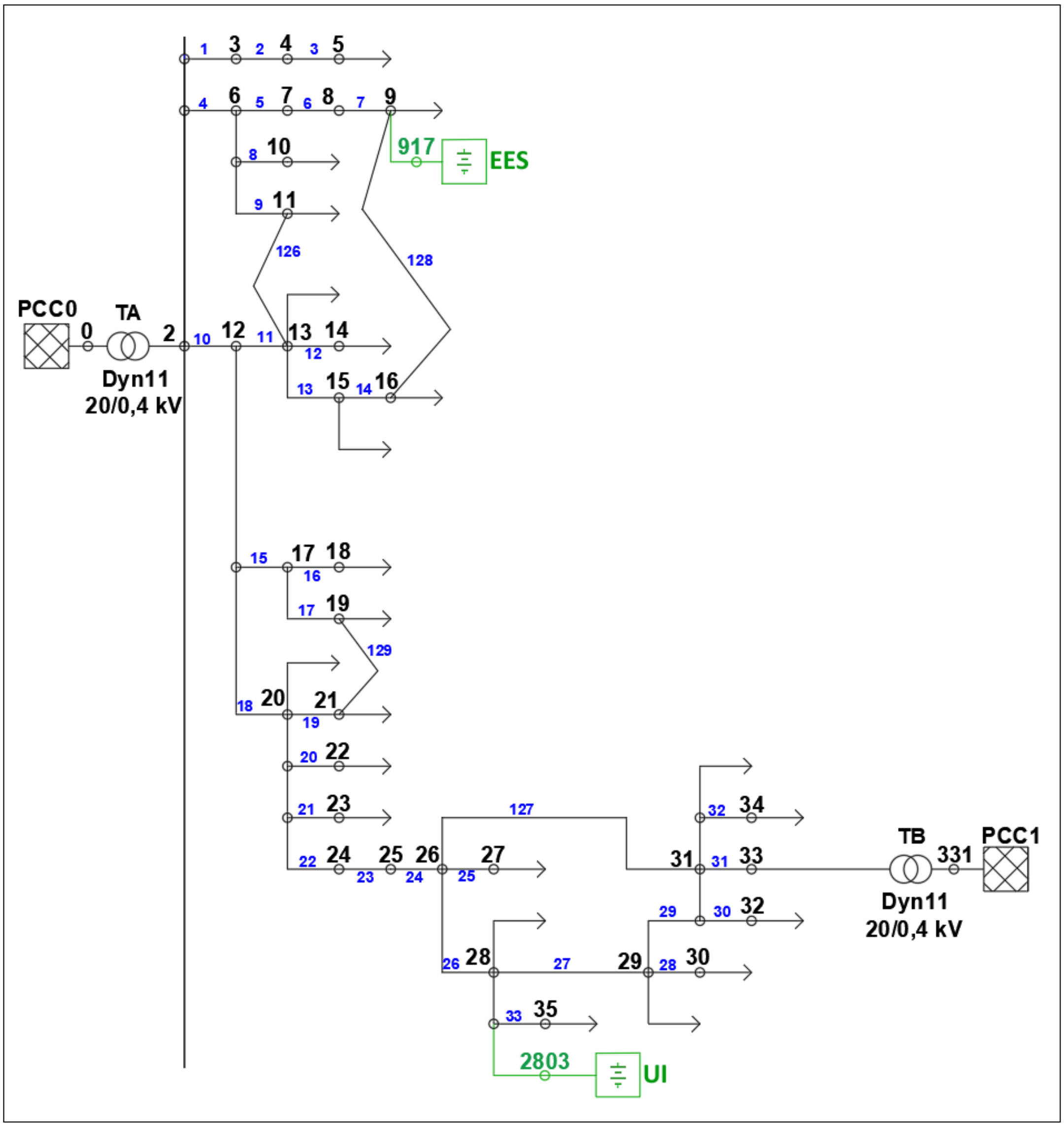

FIGURE 5.3: New meshed grid.

TABLE 5.11: Main results of the simulation, done with SUSI3, related at the new meshed grid.

Test case	11	11	11	11	11	12	12	12	12	12	13	13	13	13	13
Day time	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,103	0,103	0,103	0,103	0,103	0,103	0,103	0,103	0,103	0,103	0,103	0,103	0,103	0,103	0,103
rms voltage deviation / Vnom	5,35%	5,27%	4,76%	4,76%	1,41%	3,72%	3,68%	3,21%	3,24%	0,96%	2,15%	2,48%	1,51%	2,82%	0,96%
P entering grid at node 0 [kW]	225,32	221,80	197,45	197,82	58,41	158,44	156,69	133,84	135,52	39,96	-67,18	89,00	21,03	112,96	39,96
Q entering grid at node 0 [kVAR]	111,30	110,88	94,56	96,48	28,54	78,50	78,14	65,30	66,78	19,71	72,90	76,45	62,49	66,22	19,71
P absorbed by loads [kW]	319,06	311,78	284,52	282,07	84,93	221,38	217,85	190,48	191,26	57,19	222,86	218,30	191,13	191,40	57,19
Q absorbed by loads [kVAR]	138,35	135,38	124,05	123,05	38,90	98,07	96,14	86,42	86,11	26,58	109,85	99,62	91,50	87,13	26,58
P fed by sources [kW]	330,56	323,05	293,84	291,44	85,93	227,12	223,51	194,85	195,73	57,70	324,70	221,13	192,32	194,88	57,70
Q fed by sources [kVAR]	154,67	151,04	136,94	135,78	40,00	105,90	103,74	92,21	91,96	27,09	113,03	103,73	92,89	91,95	27,09
P returned to sources [kW]	0,92	0,91	0,80	0,81	0,24	0,65	0,65	0,55	0,56	0,17	99,60	0,45	0,22	0,50	0,17
Q returned to sources [kVAR]	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,38	0,76	0,16	0,44	0,00
P troughput-grid transport [kW]	330,56	323,05	293,84	291,44	85,93	227,12	223,51	194,85	195,73	57,70	197,79	144,31	100,53	163,06	57,70
Q troughput-grid transport [kVAR]	154,67	151,04	136,94	135,78	40,00	105,90	103,74	92,21	91,96	27,09	106,27	103,73	92,34	91,95	27,09
Distribution loss in phase wires [kW]	10,58	10,36	8,52	8,56	0,75	5,08	5,01	3,82	3,91	0,34	2,25	2,37	0,97	2,98	0,34
Loss in power sources & converters [kW]	0,32	0,30	0,28	0,26	0,02	0,14	0,13	0,11	0,11	0,01	18,47	1,71	4,63	0,26	0,01
Total power loss w/o neutral wire [kW]	10,91	10,66	8,80	8,82	0,77	5,22	5,14	3,93	4,02	0,35	20,72	4,08	5,60	3,25	0,35
Efficiency neglecting neutral loss (Total loss/power fed by sources)	96,70%	96,70%	97,01%	96,97%	99,10%	97,70%	97,70%	97,98%	97,95%	99,39%	93,62%	98,15%	97,09%	98,33%	99,39%
Estimated loss in neutral wire [kW]	2,39	2,39	2,35	2,35	0,21	1,14	1,14	1,07	1,07	0,10	1,45	0,57	0,54	0,84	0,10
Total power loss including neutral wire [kW]	13,30	13,05	11,15	11,17	0,99	6,36	6,28	5,00	5,09	0,45	22,17	4,65	6,14	4,08	0,45
Efficiency considering neutral loss	95,98%	95,96%	96,21%	96,17%	98,85%	97,20%	97,19%	97,43%	97,40%	99,22%	93,17%	97,90%	96,81%	97,90%	99,22%
Min node voltage vs Vnom	-8,87%	-8,84%	-8,02%	-8,11%	-2,41%	-6,17%	-6,15%	-5,41%	-5,49%	-1,63%	-1,60%	-4,37%	-2,46%	-4,90%	-1,63%
Node with minimum voltage	1605	1605	915	915	915	1605	1605	905	1602	905	3003	1605	915	905	905
Max node voltage vs Vnom	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,52%	0,00%	0,00%	0,00%	0,00%
Node with maximum voltage	331	331	331	331	331	331	331	331	331	331	1006	331	331	331	331
Max active power stress of sources (P/Pnom)	42,10%	40,50%	38,55%	37,45%	11,01%	27,47%	26,73%	24,40%	24,08%	7,09%	99,97%	29,57%	49,37%	20,04%	7,09%
Node with maximum active power stress	331	331	331	331	331	331	331	331	331	331	1010	3507	1010	331	331
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	35,52%	33,99%	32,86%	31,69%	9,30%	23,07%	22,33%	20,81%	20,37%	6,00%	90,02%	26,61%	44,45%	17,58%	6,00%
Node with maximum current stress	331	331	331	331	331	331	331	331	331	331	1010	3507	1010	331	331
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	148,46%	148,84%	142,39%	143,64%	42,93%	96,27%	96,47%	90,67%	91,68%	27,34%	51,13%	63,34%	42,84%	80,29%	27,34%
Branch with maximum current stress	14	14	14	14	14	14	14	14	14	14	116	14	28	14	14
Number of overstressed feeders (current)	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0
Max stress	148,5%	148,8%	142,4%	143,6%	42,9%	96,3%	96,5%	90,7%	91,7%	27,3%	100,0%	63,3%	49,4%	80,3%	27,3%

Indeed the voltage deviation, relative at the new version of meshed grid, is greater than that in the main meshed grid as the total power loss, the minimum of the minimum node voltage, the maximum current stress into the feeders, and the distribution loss in phase wires. Furthermore the efficiency, related at the new meshed grid, is lower compared to at the efficiency in the main meshed grid. While the power and current stress, in the new meshed grid, is lower compared to that into the main meshed grid. Also in the new version of meshed grid there are no feeders in which there is a current overstress and it is a good point. The direct consequence to not have an overcome of the maximum current stress is to not install a generator in a new fully controllable node for control the current in that feeder. So, for the second case, the main meshed grid offers a better management compared to the new version of the meshed grid. Rather than the new version of meshed grid has some benefit, such as no current over stress into the feeders and a lower value of current and power overstress into the sources. If we take into account the results reported into the previous table and the graph, for the case 12, the main meshed grid offers a best management.

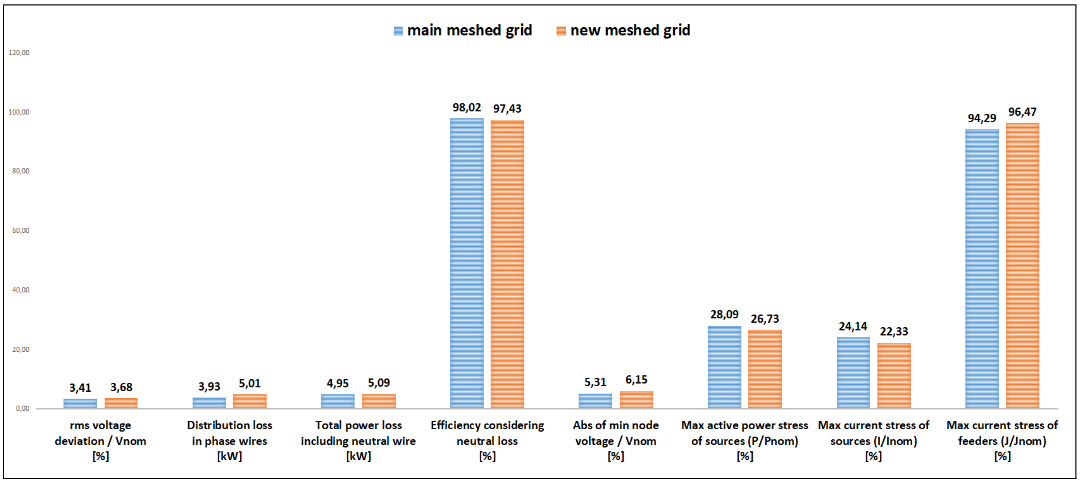

FIGURE 5.4: Comparison the peak value of the results between the new and main meshed grid, at case 12.

Considering the third case, also called case 13, the situation is different compared to the previous one. Indeed all results are in favor at the main meshed grid. In particular the voltage deviation relative at the new version of meshed grid is greater than that in the main meshed grid as the total power loss, the minimum of the minimum node voltage, the maximum current and power stress of the sources, the maximum current stress into the feeders, and the distribution loss in phase wires. While the efficiency of the main meshed grid is lower compared to that in the new meshed grid. Also in this case there are no current stress into the feeders that overcome the maximum value in the new meshed grid and it is a good point. Rather then the main meshed grid offers a better management compared to that with the new meshed grid if we take into account the results reported into the previous table and the graph, for the case 13.previous table and the graph, for the case 13, also called third case.

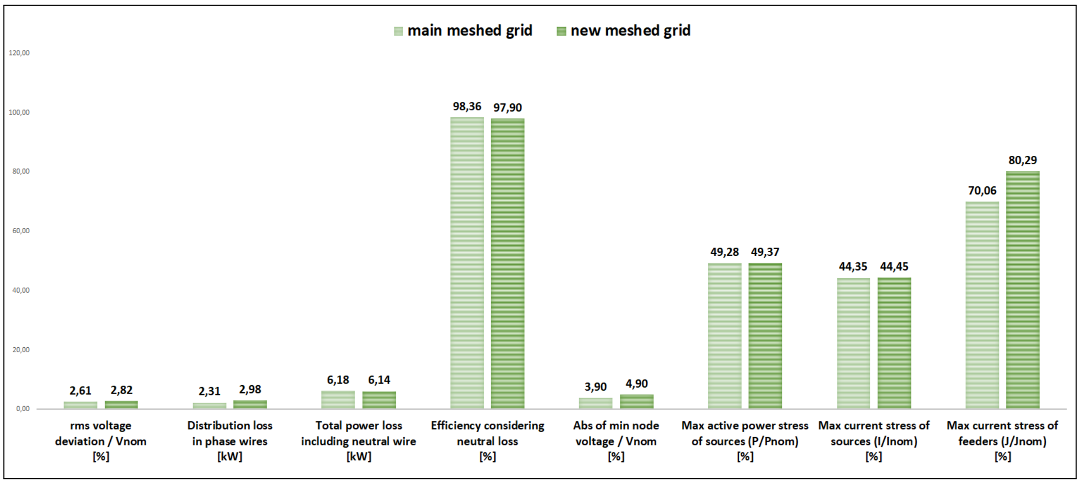

FIGURE 5.5: Comparison the peak value of the results between the new and main meshed grid, at case 13.

So, considering all this reasonings and results, the main meshed grid offers best advantages and a better management compared to the new meshed grid.
In conclusion the best configuration of this network is that meshed with the distributed generations that participate at load balance to support the centralized generators and reduce the distributed power loss.

Chapter 6

Optimal control of reactive power

At first this chapter deals with the description of the boundaries related of the test case defined for the radial and meshed network. This test case is related at an active grid in which the distributed generators, such as photovoltaic sources and energy storage systems, control the active and reactive power flow. While the active and reactive power of the loads are calculated randomly, using the percentage and formula defined at the beginning. Subsequently the results of the simulation are reported into the tables and they are used for make comparisons. The results come from the analysis done with SUSI3 and Source Locator.

6.1 Description of the second test case.

In this test case both networks are active and the distributed generators, such as photovoltaic sources and energy storage systems, control the reactive power flow and participate at generation of the active power. Consequently the reactive power of the PCCs is equal to zero. So the energy storage systems cover a very important role in this scenario. Indeed the presence of the energy storage systems or batteries, in the next future, will be very widespread. In particular, for this test case, the energy storage systems control the reactive power for minimize the total stress into the system. Indeed if the flow of the reactive power into the grid is controlled, it will be possible to reduce the stress and the power loss into the system. These are two benefits of this control. Alternatively the energy storage systems can participate at the regulation of the frequency and the voltage locally. These last two implementations are very important for the management of the network because instead of using a distant and centralize generator to re-establish the frequency and the voltage, is possible to use the local energy storage systems and batteries. This leads to an reduction of active and reactive power flow into the grid, so a better management of the grid. This is a smart management of the network that characterizes the smart grid.
So, for these reasons, is very important to study the grid, both radial and meshed, under this operative conditions. In the first case, also called case 21, all sources feed generated active power and the reactive power is equal to zero at the PCCs. While the energy storage systems generate and control the reactive power. While the loads

are random, so the active and reactive power for each load is the result of the formula defined at beginning.

TABLE 6.1: Boundary of the case 21.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources feed generated P (Q=0) Actual loads	-1		6	100	100	6	100	
Q=0 at,PCCx	2	10				8		
Q=0 at PCC0	1	0				8		
UI control Q (P=0)	2	12				7		
ES control Q (P=0)	2	11				7		

While in the second case, also called case 22, all sources feed generated and control active power and the reactive power is equal to zero at the PCCs. While the energy storage systems generate and control the reactive power. While the loads are random, so the active and reactive power for each load is the result of the formula defined at beginning.

TABLE 6.2: Boundary of the case 22.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources feed control P and Q Actual loads	-1		6	100	100			
Q=0 at,PCCx	2	10				8		
Q=0 at PCC0	1	0				8		
UI control Q (P=0)	2	12				7		
ES control Q (P=0)	2	11				7		

6.2 Analysis of the results relative at radial grid.

In this section the results of the analysis, done with SUSI3 and Source Locator, are reported in these tables. At first the results of the voltage deviation are always lower compared to the maximum value. This is a very good point, for the radial grid, because it confirms the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed generators, like the photovoltaic sources and the energy storage systems, can feed the local load so there will be a lower flow of current into the grid. It will bring to a reduction of the total power loss into the feeders and it is another benefit. In particular the voltage deviation is quite constant for each case during the day and it falls during the night. This is because during the night the load consumption decreases compared to that during the day. Moreover the voltage deviation at the first case is greater compared to that at the second case. This is because in the second case all sources can control the generated active power. In this way all the sources generate the active power obtained from an optimal solution. That is a smart management of the sources that characterizes the smart grid.

TABLE 6.3: Main results related at radial grid, obtained with SUSI3.

Test case	21	21	21	21	21	22	22	22	22	22
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160
rms voltage deviation / Vnom	2,16%	3,09%	1,68%	3,34%	1,12%	0,86%	1,47%	0,61%	1,86%	0,54%
P entering grid at node 0 [kW]	-73,03	89,92	22,82	115,88	40,92	-21,39	61,54	15,01	80,53	17,46
Q entering grid at node 0 [kVAR]	-0,18	0,51	0,17	0,59	0,20	-0,07	0,05	0,00	0,09	0,02
P absorbed by loads [kW]	221,27	222,26	198,26	196,30	57,68	232,58	225,41	203,29	200,58	59,25
Q absorbed by loads [kVAR]	117,13	103,98	94,44	90,31	27,84	109,77	103,33	93,12	90,69	27,65
P fed by sources [kW]	326,84	227,25	200,41	201,16	58,20	290,39	229,85	204,82	205,55	61,43
Q fed by sources [kVAR]	120,65	108,55	96,10	95,12	28,40	119,16	108,98	93,66	99,70	29,40
P returned to sources [kW]	101,46	0,00	0,00	0,00	0,00	56,74	2,97	1,03	2,98	1,98
Q returned to sources [kVAR]	1,53	2,04	1,15	1,07	0,11	8,83	4,27	0,28	6,72	1,55
P troughput-grid transport [kW]	192,17	143,84	97,68	169,28	58,20	176,54	134,70	108,06	151,77	53,76
Q troughput-grid transport [kVAR]	115,73	108,54	95,92	95,12	28,40	60,18	71,50	56,28	77,54	22,68
Distribution loss in phase wires [kW]	4,10	4,99	2,14	4,86	0,52	1,06	1,48	0,49	1,99	0,20
Loss in power sources & converters [kW]	19,73	3,40	5,75	1,63	0,13	19,98	9,49	8,25	7,71	1,55
Total power loss w/o neutral wire [kW]	23,84	8,39	7,89	6,49	0,65	21,04	10,97	8,74	9,70	1,75
Efficiency neglecting neutral loss (Total loss/power fed by sources)	92,71%	96,31%	96,06%	96,77%	98,88%	92,75%	95,23%	95,73%	95,28%	97,15%
Estimated loss in neutral wire [kW]	2,71	0,85	1,29	1,20	0,13	2,07	0,83	0,63	0,95	0,10
Total power loss including neutral wire [kW]	26,54	9,24	9,18	7,69	0,78	23,11	11,80	9,37	10,66	1,85
Efficiency considering neutral loss	91,88%	95,93%	95,42%	96,18%	98,66%	92,04%	94,87%	95,43%	94,82%	97,00%
Min node voltage vs Vnom	-0,94%	-2,83%	-1,16%	-3,13%	-1,12%	-0,91%	-2,13%	-0,98%	-2,40%	-0,67%
Node with minimum voltage	1502	1605	1805	1601	1601	1502	1605	2303	912	1603
Max node voltage vs Vnom	1,93%	0,11%	0,30%	0,03%	0,01%	1,44%	0,21%	0,37%	0,37%	0,31%
Node with maximum voltage	1009	7	1006	33	33	1901	5	5	5	5
Max active power stress of sources (P/Pnom)	100,90%	29,83%	49,94%	19,32%	6,71%	100,73%	102,29%	99,60%	100,80%	99,98%
Node with maximum active power stress	1005	3402	3402	331	331	1010	1604	910	5	902
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	90,87%	52,20%	44,96%	45,87%	14,12%	100,23%	112,66%	98,40%	99,32%	90,01%
Node with maximum current stress	1005	917	3402	917	917	2001	1107	2801	1107	902
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	80,60%	101,95%	71,93%	97,91%	30,99%	48,46%	64,75%	45,48%	61,80%	23,97%
Branch with maximum current stress	6	7	7	7	7	17	68	28	28	3
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0	0	0
Max stress	100,9%	102,0%	71,9%	97,9%	31,0%	100,7%	112,7%	99,6%	100,8%	100,0%

After in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power feed by sources and the power throughput grid transportation. Subsequently the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters. Also it makes an estimation of the power loss into neutral wires. In the first case the values of power loss into the sources are very close to the values of power loss into phase wires. While in the second case the power loss into the distributed sources is always greater than the power loss into the feeders, considering at the same period. This happen because the flow of current into the grid is very small for the same reason explain before for the little value of voltage deviation. Moreover the distribution loss in phase wires, in the first case, is always greater compared to that at second case. While for the power loss into the distributed sources happen the exact opposite. Indeed the loss in power sources, at first case, is always lower compared to that at second case. This happen because the flow of active power is controlled in the second case. So there will be a reduction of power loss in phase wires. While the distributed sources will be more exploited and this over exploitation leads to an increase of loss in power sources.
Furthermore the calculation of the power loss is fundamental for the efficiency. The efficiency of a system is a very important parameter of the power quality that gives an idea of the management of the network. The value of the efficiency is quite high for each case and it is a good point for the management of the grid. Also the value of the efficiency, at first case, is very close to the efficiency in the second case. Furthermore the value of the efficiency of this test case are lower compared to that at the first test case. This is because at the first test case the distributed sources didn't participate at generation so the stress into the sources was very small and it was lower compared to the power loss into the feeders. In this test case the sources are very stressed so there will be an increase of loss in power sources and a reduction of the power loss into the feeders because the current flow into the grid decreases. So the increase of the power loss into the sources is greater compared to the reduction of the power loss into the feeders, between the first test case and the second one. This situation involves in a reduction of the efficiency.
Subsequently is important to understand where the sources overstress come from. In the first case the current stress of sources is greater compared to the power stress, except in the second period of the day. While, in the second case, the value of current stress, into the sources, is very close to the value of power stress, for the same period of the day. Moreover the power and current stress of sources, in the first case, is lower compared to those in the second case. This happen because, in the second case, the optimal control exploited more the distributed sources to reduce the total stress. Despite the increase of the power and current stress into the sources, the total stress of the system will decrease. So, in this test case, the limitation of the sources is

the value of current and active power that can generate. To solve this current overstress of the distribution sources sources, a solution is to increase the rated active power of the overstressed sources. In the following tables the overstressed sources with its value of overstress and upper limit of active and reactive power, for each case, are reported. In this test case, the second case gives the overstressed sources, while in the first case there are no overstressed sources. This happen because, in the first case, the distributed sources are less exploited compared to those in the first case. From the results is possible to note that there are a lot of overstressed sources for different period of the day. Furthermore the value of the overstress is very high in some period of the day.

TABLE 6.4: Over stressed sources at case 21, considering the radial grid.

Day time	Node	Overstressed	Apply limit
1 3	5	P/Pnom =2.14 A/Anom =1.40; P/Pnom =1.74 A/Anom =1.71	Psat=13.80kW Qsat =6.21kVAR; Psat=13.80kW Qsat =5.68kVAR
1 2 3 4	902	P/Pnom =3.29; P/Pnom =2.47; P/Pnom =4.15; P/Pnom =1.37	Psat=5.00kW; Psat=5.00kW; Psat=5.00kW; Psat=5.00kW
1	1501	A/Anom =1.21	Qsat =10.86kVAR
1 3	3503	P/Pnom =1.47; P/Pnom =1.94	Psat=-3.00kW; Psat=-3.00kW
1 2 3	909	P/Pnom =2.78; P/Pnom =1.99; P/Pnom =1.35	Psat=3.00kW; Psat=3.00kW; Psat=3.00kW
1 2 3	910	P/Pnom =2.04; P/Pnom =1.40; P/Pnom =2.72	Psat=3.00kW; Psat=3.00kW; Psat=3.00kW
1 3	911	P/Pnom =1.51; P/Pnom =2.26	Psat=3.00kW; Psat=3.00kW
1 3	1005	P/Pnom =1.33; P/Pnom =1.76	Psat=3.00kW; Psat=3.00kW
1 3	1010	P/Pnom =1.43; P/Pnom =1.67	Psat=3.00kW; Psat=3.00kW
1 3	1004	P/Pnom =2.32; P/Pnom =1.64	Psat=3.00kW; Psat=3.00kW
3	2801	A/Anom =1.74	Qsat =11.05kVAR
3	1107	A/Anom=1.47	Qsat =22.09kVAR

Rather than we have to consider that the overstressed sources are always very small so it takes little to reach the overstress. Indeed the overstressed sources are those property of end-user node and they are often small. So is possible to use this results for make a first sizing of the distributed generator in this operative condition. Also is possible to note that the greater part of the overstressed sources are very close each other, indeed the node 5, 9, 10, 11 and 15 are very close each other. So, to solve this overstress of sources, is possible to install a new generator in a new or already existing fully controllable node that can support those overstressed sources at load balance and for reduction of the total stress.
Subsequently the stress into the feeders are considered. In particular the current stress, in the first case, is always greater compared to that in the second case, considering the same period of the day. This is due to the optimal control that acts on the distributed sources to feed the local loads. In this way the flow of current into the branches will decrease and, consequently, the stress into feeders will reduce.
At last the comparison, of the peak values between the case 21 and 22, is reported in the following graph. In particular, in the first case, the voltage deviation, the distribution loss in phase wires and the maximum current stress of feeders are greater compared to those at second case. While the rest of the results reported, into the previous graph, are in favor of the first case. At first sight is obvious that the first case allows a better management of the radial grid.

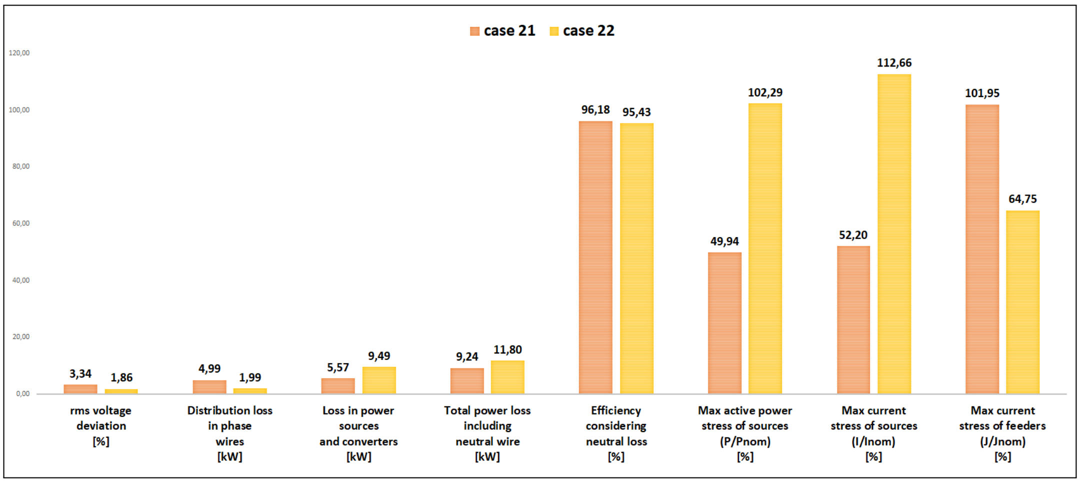

FIGURE 6.1: Comparison between the results of case 21 and 22.

While if we consider also the results of the analysis, done with SUSI3, we note that the optimal control gives more benefits compared to the case without control. Indeed, for each period of the day, the optimal control allows us a better management. Moreover if we consider that the overstress of sources is related a small photovoltaic generator, which is very easy to overstress, therefore the power loss into sources increase from the first case to the second. So if we consider to add a new generator that support the local overstressed sources is possible to delete the stress and to obtain a better management of the grid in the second case. Consequently the active power

and current stress, in the distribution sources, will decrease a lot and the power loss, into the distributed generators, decrease too.
In conclusion the optimal control gives the best results of the radial grid.

6.3 Analysis of the results relative at meshed grid.

In this section the results of the analysis, done with SUSI3 and Source Locator, are reported in these tables. At first the results of the voltage deviation, in percentage, are always lower compared to the maximum value. This is a very good point, for the meshed grid, because it confirms the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed generators, like the photovoltaic sources and the energy storage systems, can feed the local loads so there will be a lower flow of current into the grid. It will bring to a reduction of the total power loss into the feeders and it is another benefit. In particular the voltage deviation is quite constant for each case during the day and it falls during the night. This is because during the night the load consumption decreases compared to that during the day. Moreover the voltage deviation, at the first case, is greater compared to that at the second case. This is because in the second case all sources can control the generated active power. In this way all the sources generate the active power obtained from an optimal solution. That is a smart management of the sources that characterizes the smart grid.
After in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power feed by sources and the power throughput grid transportation. Subsequently the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters. Also it makes an estimation of the power loss into neutral wires. In the first case the power loss in sources is very close to the power loss into the feeders. While, in the second case, the power loss into the sources is always greater than the power loss into the feeders. This happen because the flow of current into the grid is very small for the same reason explain before for the little value of voltage deviation. Moreover the power loss into the sources, in the first case, is always lower compared to that at the second case. While the distribution loss in phase wires, in the first case, is always greater compared to that at second case, considering the same period of the day. This is a direct consequence of the control of the active power generated, from all generators. Indeed in the second case the active power generate, for each sources, is the results of an minimization of the stress that bring to a major exploitation of the distributed sources, so a greater power loss into the sources. This is a benefit that the photovoltaic sources and energy storage system, with an appropriate algorithm, can bring into the grid. That is a smart management of the sources that characterizes the smart grid.
Furthermore the calculation of the power loss is fundamental for the efficiency.

TABLE 6.5: Main results related at meshed grid, obtained with SUSI3.

Test case	21	21	21	21	21	22	22	22	22	22
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099
rms voltage deviation / Vnom	1,47%	2,19%	0,94%	2,54%	0,88%	0,70%	1,29%	0,51%	1,62%	0,50%
P entering grid at node 0 [kW]	-57,63	96,45	27,85	118,97	41,67	-22,44	63,91	18,11	80,04	19,68
Q entering grid at node 0 [kVAR]	0,01	0,08	0,05	0,09	0,03	0,04	-0,19	-0,05	-0,24	-0,04
P absorbed by loads [kW]	235,83	231,89	203,96	204,50	60,31	233,86	229,65	202,92	203,03	59,84
Q absorbed by loads [kVAR]	114,40	103,14	94,58	89,39	27,27	115,02	107,07	98,66	94,77	28,59
P fed by sources [kW]	323,94	234,80	205,07	207,43	60,63	283,70	233,87	204,03	207,63	61,56
Q fed by sources [kVAR]	116,31	107,42	95,96	93,98	27,74	118,73	117,13	101,24	109,11	30,57
P returned to sources [kW]	85,72	0,00	0,00	0,00	0,00	49,20	3,06	0,74	3,05	1,55
Q returned to sources [kVAR]	0,42	1,69	0,93	0,71	0,00	3,26	8,84	2,38	12,31	1,80
P troughput-grid transport [kW]	183,70	156,96	104,80	175,62	60,63	166,06	143,62	108,29	157,88	55,54
Q troughput-grid transport [kVAR]	112,36	107,42	95,84	93,98	27,74	61,56	69,24	56,29	77,32	23,54
Distribution loss in phase wires [kW]	2,38	2,92	1,11	2,93	0,32	0,64	1,15	0,37	1,55	0,17
Loss in power sources & converters [kW]	19,75	3,35	5,72	1,52	0,12	19,06	9,17	7,83	7,88	1,88
Total power loss w/o neutral wire [kW]	22,13	6,26	6,83	4,45	0,44	19,70	10,32	8,20	9,44	2,04
Efficiency neglecting neutral loss (Total loss/power fed by sources)	93,17%	97,33%	96,67%	97,85%	99,27%	93,06%	95,59%	95,98%	95,46%	96,68%
Estimated loss in neutral wire [kW]	1,76	0,62	0,68	1,04	0,12	1,01	0,81	0,43	1,02	0,10
Total power loss including neutral wire [kW]	23,88	6,88	7,51	5,49	0,56	20,71	11,13	8,63	10,46	2,14
Efficiency considering neutral loss	92,63%	97,07%	96,34%	97,35%	99,07%	92,70%	95,24%	95,77%	94,96%	96,52%
Min node voltage vs Vnom	-0,56%	-2,87%	-0,78%	-3,21%	-1,11%	-0,54%	-1,56%	-0,83%	-1,40%	-0,50%
Node with minimum voltage	1605	1605	1601	1602	1602	3004	1605	3004	1605	1605
Max node voltage vs Vnom	1,25%	0,01%	0,36%	0,02%	0,00%	1,20%	0,04%	0,30%	0,02%	0,12%
Node with maximum voltage	1604	2	3402	36	2	1603	1009	1603	33	5
Max active power stress of sources (P/Pnom)	100,85%	29,89%	50,00%	21,12%	7,36%	99,55%	100,42%	99,93%	100,39%	96,92%
Node with maximum active power stress	3402	3402	3402	331	331	3505	5	902	5	902
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	90,80%	52,12%	45,01%	42,95%	12,93%	103,63%	98,96%	99,49%	98,99%	89,10%
Node with maximum current stress	3402	917	3402	917	917	1605	2801	2801	2801	2801
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	90,02%	101,26%	70,44%	95,74%	30,23%	48,57%	48,57%	48,57%	64,16%	21,61%
Branch with maximum current stress	7	7	7	7	7	28	28	28	28	28
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0	0	0
Max stress	100,9%	101,3%	70,4%	95,7%	30,2%	103,6%	100,4%	99,9%	100,4%	96,9%

The efficiency of a system is a very important parameter of the power quality and it is quite high for each case. Also the value of the efficiency at first case is very close at the efficiency in the second case. Furthermore the value of the efficiency of this test case are lower compared to that at the first test case. This is because at the first test case the distributed sources didn't participate at generation so the stress into the sources was very small and it was lower compared to the power loss into the feeders. In this test case the distributed sources are really exploited, so there will be an increase of power loss into the sources and a reduction of the power loss into the feeders because the current flow into the grid will decrease. So the increase of the power loss into the sources is greater compared to the reduction of the power loss into the feeders, between the first test case and the third one. This situation involves in a reduction of the efficiency.
Subsequently is important to understand where the sources overstress come from.

TABLE 6.6: Over stressed sources at case 22, considering the meshed grid.

Day time	**Node**	**Overstressed**	**Apply limit**
1 3	5	P/Pnom =2.96 A/Anom =1.85; P/Pnom=2.79 A/Anom =2.42	Psat=13.80kW Qsat =6.07kVAR; Psat=13.80kW Qsat =5.55kVAR
1 2 3	902	P/Pnom =1.92; P/Pnom =1.71; P/Pnom =2.90	Psat=5.00kW; Psat=5.00kW; Psat=5.00kW
1 2 3	2801	A/Anom =2.12; A/Anom =1.41; A/Anom =2.67	Qsat =10.83kVAR; Qsat =11.03kVAR; Qsat =10.48kVAR
1 3	3503	P/Pnom =1.10; P/Pnom =1.44	Psat=-3.00kW; Psat=-3.00kW
1 3	909	P/Pnom =1.69; P/Pnom =2.38	Psat=3.00kW; Psat=3.00kW
1 3	910	P/Pnom =1.73; P/Pnom =2.21	Psat=3.00kW; Psat=3.00kW
1 3	911	P/Pnom =1.60; P/Pnom =2.07	Psat=3.00kW; Psat=3.00kW
1 3	1005	P/Pnom =1.61; P/Pnom =1.44	Psat=3.00kW; Psat=3.00kW
1 3	1010	P/Pnom =2.21; P/Pnom =2.34	Psat=3.00kW; Psat=3.00kW
1 3	1004	P/Pnom =1.56; P/Pnom =1.27	Psat=3.00kW; Psat=3.00kW

From the results of the simulation, into the sources, the value of the current stress is very close to the value of power stress, for the same period of the day. So, in this test case, the limitation of the sources is the value of current and active power that can generate. To solve this current overstress of the sources, a solution is to increase the rated active power of the overstressed sources. In the following tables the overstressed sources with its value of overstress and upper limit of active and reactive power for each case are reported. In this test case, the case 22 gives the overstressed sources, while in the first case there are no overstressed sources. This happen because, in the first case, the distributed sources are less exploited compared to those in the first case. From the results of the following table is possible to note that there are a lot of overstressed sources for different period of the day. Furthermore the value of the overstress is very high in some period of the day. Rather than we have to consider that the overstressed sources are always very small so it takes little to reach the overstress. So is possible to use this results for make a first sizing of the distributed generator in this operative condition, such as in the radial grid. Also is possible to note that the greater part of the overstressed sources are very close each other, indeed the node 5, 9, 10, 11 and 15 are very close each other. So to solve this overstress of sources is possible to install a new generator in a new or already existing fully controllable node that can support those overstressed sources at load balance and for reduction of the total stress.
After that is important to consider the current stress of feeders. In the first case the stress of feeders is greater compared to that at second case. This is due to greater exploitation of the distributed sources in the second case, due to the optimal control, that lead to a reduction of the flow of current into the branches. This leads to a reduction of the current stress of the feeders in the second case.
At last the comparison of the peak values between the case 21 and 22 are reported in the following graph.

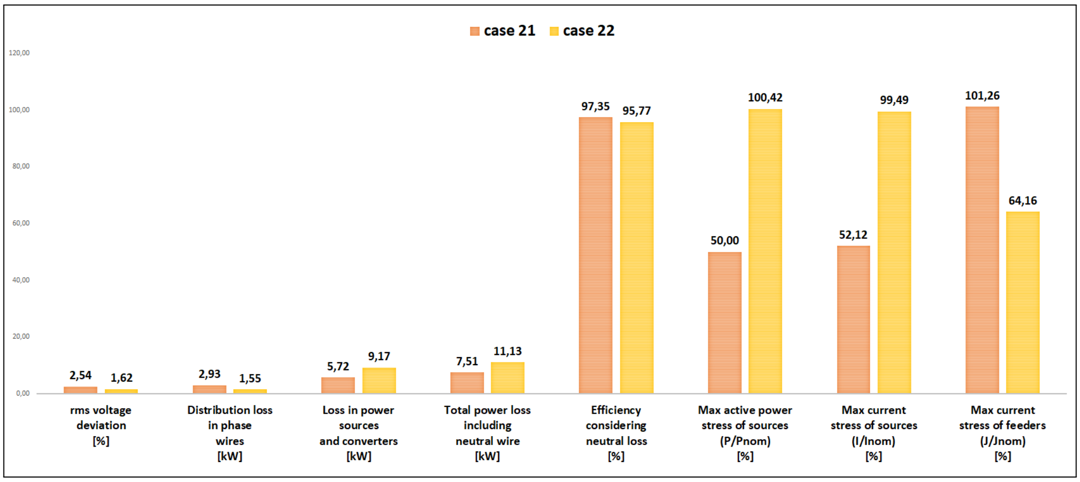

FIGURE 6.2: Comparison between the results of the meshed grid at case 21 and 22.

In particular, in the first case, the voltage deviation, the distribution loss in phase

wires and the maximum current stress of feeders are greater compared to those at second case. While the rest of the results reported into the previous graph are in favor of the first case. At first sight is obvious that the first case allows a better management of the meshed grid. So, at the beginning, the optimal control of the active power isn't the best solution for this system. While if we consider that the overstress of sources is related at a small photovoltaic generators, which is very easy to overstress, we can conclude that this power and current stress of sources aren't an unsolvable problem. Indeed if we add a new generator that support the local overstressed sources is possible to delete the stress and to obtain a better management of the grid in the second case. Obviously the introduction of this new generator will lead a different power flow into the grid. In particular it will support the nearby distributed sources at load balance, mostly to the local loads. This will involves to a reduction of the flow of current into the grid, so a decrease of distribution loss in phase wires. Moreover the power and current stress of sources will reduce.
In conclusion, if we take into account the results of the analysis, done with SUSI3, the optimal control gives more benefits compared to the system without optimal control.

6.4 Comparison between the radial and meshed grid.

In this section a comparison between the results of the radial and meshed grid for each case is reported. Indeed is important to understand which configuration, of the network, is the best for each case.
At first the comparison of the peak values, related at case 21, between the radial and meshed grid is reported in the following graph.

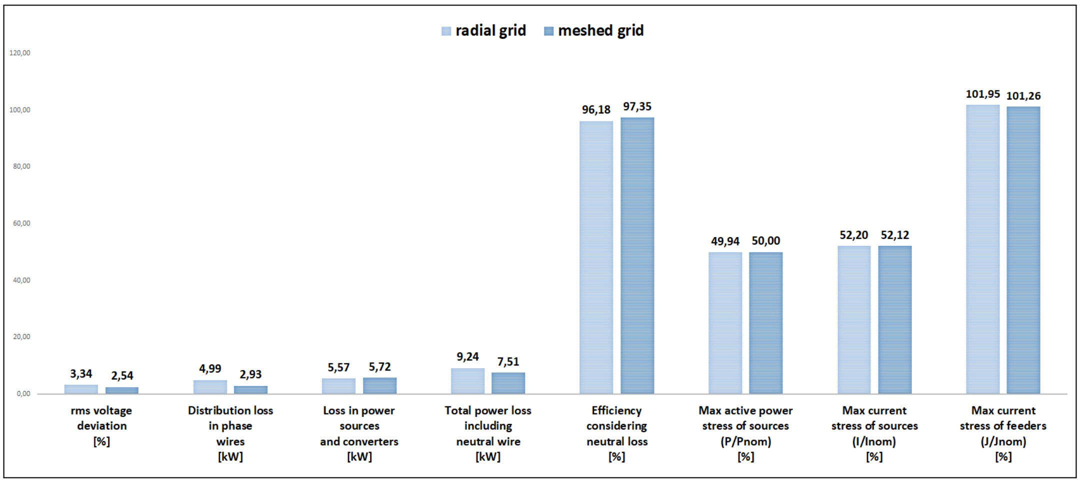

FIGURE 6.3: Comparison between the results of the radial and meshed grid at case 21.

In that case the meshed grid gives the best results in terms of voltage deviation, the distribution loss in phase wires, the total power loss and the efficiency. While for the value of power loss and stress in sources and the current stress of feeders, there

are no difference between the radial and meshed grid. Moreover if we consider the results of the analysis for each period of the day, we note that the meshed grid allows us a better management of the system. So the meshed grid is the best configuration of the network in the first case.
While for the second case the comparison, of the peak values, is reported in the following graph. In particular the meshed grid gives the best results in terms of voltage deviation, distribution loss, total power loss and maximum current stress of feeders. While there are no difference between the peak value of power loss in sources, efficiency, maximum power stress of sources and maximum current stress of feeders. Moreover if we consider the results of the analysis for each period of the day, we note that the meshed grid allows us a better management of the system. So for the second test case the meshed grid gives the best results.

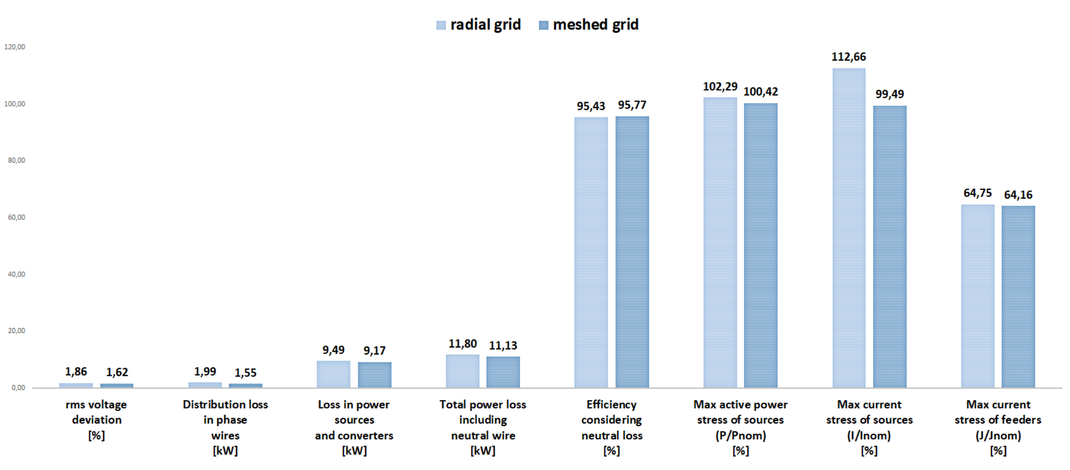

FIGURE 6.4: Comparison between the results of the radial and meshed grid at case 22.

In conclusion, in this test case, the meshed grid, with the optimal control, is the best configuration of this system. In particular the optimal control is of the active power generated by the distributed sources and reactive power from the energy storage systems. So is possible to manage, in an optimal way, the system to reach high value of power quality and reliability of the system.

Chapter 7

Optimal control of active and reactive power

At first this chapter deals with the description of the boundaries related at the test case defined for the radial and meshed network. This test case is related of an active grid in which the distributed generators, like photovoltaic sources and energy storage systems, controls the active and reactive power flow into the network. While the active and reactive power of the loads are calculated randomly, using the percentage and formula defined at the beginning. The results come from the analysis, done with SUSI3 and Source Locator, are used to make comparison.

7.1 Description of the third test case.

In this test case both networks are active and the distributed generators, like photovoltaic sources and energy storage systems, control the active and reactive power flow. Consequently the reactive power at the PCCs is equal to zero. Indeed a large diffusion of energy storage systems is expected to take place in the next future on both MV and LV networks. The energy storage utilization at the end-user level, in coexistence with distributed energy systems, is encouraged by a several of different advantages and opportunities, such as:

1. The expected decreasing cost of storage systems, due to its near future diffusion involving increased production capacity.

2. Economic advantages for active end-users, favoring an optimal local self consumption, replacing, in part, the centralized one.

3. Leveling the distributed generation power production, both in terms of daily peak shaving function.

4. Opportunities in the participation of end users to ancillary services markets.

5. Contribution in supplying the load peak power, reducing the contractual value of admitted power absorption and consequently a consistent portion of the end-user bill since network operation costs, evaluated on the rated power of the connection, are expect to increase in the next years.

In particular it is interesting the combination of the renewable energy sources and energy storage systems. Generally this combination, considering also the loads, is called microgrids. Typically a microgrid is a grid formed by microsources, storage systems, power converters and loads. In this context the renewable energy sources are becoming more obtainable and affordable due to the development of technology and the adoption of government policies. Indeed the residential photovoltaic system has a great potential of being a significant part of the electric market. As renewable energy covers an important role amongst the resources supplying energy to these networks, issues begin arising due to the discontinuous nature of these renewable resources. The output from solar power aligns reasonably well daytime consumption on the electricity grid, reducing the need for new coal power stations. However, high penetration photovoltaic, can lead to voltage instability due to intermittencies related to cloud cover. If the photovoltaic source power is injected into a power system directly on a large scale, it may produce issues related to dispatchability, reliability and stability. In this scenario the energy storage system covers an important role because they can, with some algorithms, mitigate the discontinuous power generation and reduce the voltage volatility. The energy storage systems can perform a lot of different functions on both electrical transmission and distribution systems. In particular the distributed energy storage systems have advanced the voltage control capability in distribution grids further by providing a better solution in terms of both controllability and efficiency. This is because voltage regulation via active power control is much more effective than reactive power control due to the resistive nature of distribution grids. Furthermore due to the sensitivity of the microgrid to load and generation changes, it should have a storage system with both high energy and power densities. However, none of the currently available energy storage technologies satisfies these two features. For that reason, it is necessary to combine two or more energy storage systems creating a hybrid energy storage system. The hybrid energy storage system is usually formed by two complementary storage devices, one of high energy density and the other of high power density. The use of a unique energy storage, usually of high energy density but low power density, creates power control problems as the response of these types of energy storage system is slow. Furthermore, a high power demand usually affects negatively the life cycle of the storage system, reducing it. Adding a short-storage system the operating conditions of the main storage system are alleviated, prolonging its life cycle and simultaneously permitting to satisfy the power requirements. In addition, the use of a short storage system in parallel to a long-storage one reduces the size and the power losses of the main storage system as it has been proved in. So the presence into the grid of the energy storage system combined with the renewable energy sources will play a very important role in the next future. This is way it is fundamental to study these networks into this configurations. For this purpose, into the follow tables, the boundary, related at this test case, are defined. In particular this test case is split into two different cases described in what follows.

In the first case, also called case 31, all sources feeded generated active power and can control generated reactive power and the PCC_1 is the slack node. While the active and reactive power of the loads are calculated randomly, using the formula described in the Chapter 2. This operative condition is far from a real situation because the energy storage systems are rarely used. While, in the next future, when the technology of the batteries and energy storage will improve, this operative condition will be widespread in the low voltage grid or microgrid.

TABLE 7.1: Boundary of case 31.

Case description	**Boundary type**	**Number of bounded entity**	**Load bound code**	**Load bounded P [%]**	**Load bounded Q [%]**	**Source bound code**	**Source bounded P [%]**	**Source bounded Q [%]**
All sources feed generated P All sources feed control Q Actual loads	-1		6	100	100	4	100	
PCCx slack nodes	2	10				-2		
Q=0 and P balanced at line 10 (PCC0)	0	126 (R) 132 (M)	8			1		
Q=0 and P balanced at line 40 (PCC1)	0	127 (R) 133 (M)	8			1		
UI slack nodes (reset bounds and power limits)	2	11				-2		
ES unbounded	2	12				-1		

While in the second case, also called case 32, all sources can control the active and reactive power so the PCC_1 will not be the slack nodes. While the active and reactive power of the loads are calculated randomly. Also this operative condition is far from a real situation because the energy storage system are rarely used, such as in the previous case. As the previous case the path, that the evolution of the network is traveling, bring to a grid in which the renewable energy sources and energy storage systems are able to manage the power flow of a microgrid or smart grid and can do other functions described above.

TABLE 7.2: Boundary of case 32.

Case description	**Boundary type**	**Number of bounded entity**	**Load bound code**	**Load bounded P [%]**	**Load bounded Q [%]**	**Source bound code**	**Source bounded P [%]**	**Source bounded Q [%]**
All sources control P and Q Actual loads	-1		6	100	100			
Q=0 and P balanced at line 10 (PCC node 0)	0	126 (R) 132 (M)	2			1		
Q=0 and P balanced at line 40 (PCC node 1)	0	127 (R) 133 (M)	2			1		
UI slack nodes (reset bounds and power limits)	2	11				-2		
ES unbounded	2	12				-1		

7.2 Analysis of the results relative at radial grid.

In this section the results of the analysis, done with SUSI3 and Source Locator, are reported in these tables.

TABLE 7.3: Main results of the simulation, using SUSI3, of the radial grid.

Test case	31	31	31	31	31	32	32	32	32	32
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160
rms voltage deviation / Vnom	1,25%	1,19%	0,31%	1,41%	0,46%	0,49%	0,95%	0,24%	0,98%	0,23%
P entering grid at node 0 [kW]	-56,05	59,70	3,33	73,08	25,52	-1,89	40,62	3,87	46,60	4,44
Q entering grid at node 0 [kVAR]	0,13	-0,13	-0,01	-0,17	-0,06	-0,02	-0,08	-0,01	-0,09	0,00
P absorbed by loads [kW]	234,50	226,05	204,57	200,84	58,93	234,31	226,28	204,55	201,09	58,96
Q absorbed by loads [kVAR]	106,49	99,83	89,64	87,41	26,33	104,26	100,43	89,37	88,25	26,47
P fed by sources [kW]	342,20	227,29	209,42	202,50	59,23	290,65	229,19	205,38	205,33	60,07
Q fed by sources [kVAR]	140,32	121,48	97,24	106,38	33,87	110,42	107,13	89,46	95,66	27,47
P returned to sources [kW]	105,44	0,00	4,45	0,00	0,01	55,04	2,03	0,53	3,24	0,96
Q returned to sources [kVAR]	32,55	20,79	7,51	17,69	7,37	5,80	6,18	0,02	6,79	0,92
P troughput-grid transport [kW]	207,43	148,99	112,41	169,57	59,04	182,38	144,40	117,24	162,51	55,75
Q troughput-grid transport [kVAR]	106,87	91,79	75,69	90,04	30,01	56,72	64,43	50,16	72,91	20,53
Distribution loss in phase wires [kW]	2,26	1,24	0,40	1,66	0,28	1,30	0,88	0,30	1,01	0,14
Loss in power sources & converters [kW]	27,60	8,39	7,54	8,03	1,67	23,70	7,80	7,13	6,73	1,39
Total power loss w/o neutral wire [kW]	29,86	9,63	7,94	9,69	1,96	25,00	8,68	7,42	7,74	1,54
Efficiency neglecting neutral loss (Total loss/power fed by sources)	91,28%	95,76%	96,21%	95,22%	96,70%	91,40%	96,21%	96,38%	96,23%	97,44%
Estimated loss in neutral wire [kW]	3,70	0,55	0,67	1,17	0,21	2,26	0,59	0,49	0,67	0,09
Total power loss including neutral wire [kW]	33,55	10,18	8,62	10,85	2,16	27,26	9,27	7,91	8,40	1,62
Efficiency considering neutral loss	90,19%	95,52%	95,89%	94,64%	96,35%	90,62%	95,96%	96,15%	95,91%	97,30%
Min node voltage vs Vnom	-1,19%	-2,69%	-0,65%	-3,15%	-1,14%	-0,92%	-1,97%	-0,67%	-1,53%	-0,51%
Node with minimum voltage	915	1605	901	1606	1606	2803	1605	3003	1603	1603
Max node voltage vs Vnom	2,57%	0,94%	0,43%	1,51%	0,46%	1,17%	0,58%	0,40%	0,68%	0,39%
Node with maximum voltage	1604	917	914	917	917	2103	917	3401	917	5
Max active power stress of sources (P/Pnom)	100,67%	30,13%	49,86%	35,72%	12,21%	107,72%	100,43%	87,00%	107,94%	101,71%
Node with maximum active power stress	1604	905	905	917	2803	5	5	5	3503	5
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	107,36%	112,89%	75,55%	102,45%	105,24%	107,93%	100,08%	83,03%	109,17%	92,06%
Node with maximum current stress	1501	2801	1501	1107	5	2001	2001	5	1501	5
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	65,65%	67,33%	47,16%	60,03%	43,98%	97,62%	68,85%	47,16%	47,16%	30,81%
Branch with maximum current stress	30	95	28	14	3	95	95	28	28	3
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0	0	0
Max stress	107,4%	112,9%	75,5%	102,5%	105,2%	107,9%	100,4%	87,0%	109,2%	101,7%

At first the results of the voltage deviation, in percentage, are always much lower compared to the maximum value. This is a very good point, for the radial grid, because it confirms the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed generators, such as the photovoltaic sources and the energy storage systems, can feed the local loads. This leads to the reduction of flow of current into the grid. It will bring to a reduction of the total power loss into the feeders. In this configuration the dispatcher can guarantee that the voltage node at end user will be into the range define by code and an high value of power quality and reliability of the system. In particular the voltage deviation is quite constant for each case during the day and it falls during the night. This is because during the night the load consumption decreases compared to that during the day. Furthermore the voltage deviation at the first case is greater compared to that at the second case. This is because in the second case all sources can control the generated active power. In this way all the sources generate the active power obtained from an optimal solution that minimize the stress into the network. That is a smart management of the sources that characterizes the smart grid.
After in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power feed by sources and the power throughput grid transportation. Subsequently the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters. Also it makes an estimation of the power loss into neutral wires. In this test case the power loss into the sources is always greater than the power loss into the feeders. This happen because the flow of current into the grid is very small for the same reason explain before for the little value of voltage deviation. Furthermore, from the results of the simulation, a lot of distributed sources are overstressed, so there will be a certain power loss. In particular the power loss into the sources, at first case, is always greater compared to that at the second case. This is a direct consequence of the control of the active power generate, from all generators. Indeed in the second case the active power generate, for each sources, is the results of an minimization of the stress. This will lead to a reduction of active power that flows into the feeders and an increase of the exploit of the distributed sources. Moreover the values of distribution loss in phase wires, in the first case, is greater compared to that at second case. This is a direct consequence of the optimal control as described previously. Indeed the optimal control will reduce the flow of active power, so there will be a decrease of the power loss into feeders. This is a benefit that the photovoltaic sources and energy storage system, with an appropriate algorithm, can bring into the grid. That is a smart management of the sources that characterizes the smart grid.
Furthermore the calculation of the power loss is fundamental for the efficiency. The efficiency of a grid is a very important parameter of the power quality that gives an idea of the management of the network. The value of the efficiency is quite high for

each case and it is a good point for the management of the grid. Also the value of the efficiency, at first case, is very close to the value of efficiency in the second case. This happen because, in the second case, the exploit of distributed sources leads to an increase of active power loss into the sources and a reduction of power loss in phase wires compared to the first case. So the total power loss will remain approximately constant. Consequently the efficiency, of the system, doesn't change. Furthermore the value of the efficiency of this test case are lower compared to that at the first test case. This is because at the first test case the distributed sources didn't participate at generation so the stress into the sources was very small and it was lower compared to the power loss into the feeders. In this test case the sources are very stressed so there will be an increase of power loss into the sources and a reduction of the power loss into the feeders because the current flow into the grid decreases. So the increase of the power loss into the sources is greater compared to the reduction of the power loss into the feeders, compared the first test case and the third one, and this situation involves in a reduction of the efficiency.
After that is important to understand where the sources overstress come from.

TABLE 7.4: Overstressed power source at test case 31, using the radial grid.

Day time	Node	Overstressed A/Anom	Qsat [kVAR]
1	5	2.68	14.76
1	1501	1.86	10.69
3	5	3.02	15.18
3	1501	1.37	11.05

TABLE 7.5: Overstressed power source at test case 32, using the radial grid.

Day time	Node	Overstressed	Apply limit
1	5	P/Pnom =3.00 A/Anom =1.75	Psat=13.80 kW Qsat =6.07 kVAR
1	1501	A/Anom =1.49	Qsat =10.72 kVAR
1	1004	P/Pnom =1.22	Psat=3.00kW
1	1005	P/Pnom =1.32	Psat=3.00kW
1	1010	P/Pnom =1.92	Psat=3.00kW
3	5	P/Pnom =3.01 A/Anom =2.07	Psat=13.80kW Qsat =5.70kVAR
3	1004	P/Pnom=1.79	Psat=3.00kW
3	1005	P/Pnom =1.75	Psat=3.00kW
3	1010	P/Pnom =1.88	Psat=3.00kW

From the results of the simulation the value of the current stress, into the sources, is always greater compared to the value of power stress. So, in this test case, the limitation of the sources is the value of current that can generate. To solve this current overstress of the sources, a solution is to increase the rated active power of the overstressed sources. In the following tables the overstressed sources with its value of overstress and upper limit of active and reactive power for each case are reported. The results of these two tables point out that the second case, in which there is an optimal control of the active power generated from all sources, there are more overstressed sources compared to that at first case. This happen because the distributed sources can feed the local loads, so the flow of current into the grid will decrease. Consequently the overstress of the distributed sources will increase. At a certain point will be reach a point of equilibrium in which the stress is the minimum possible. In particular these overstressed sources are very small because they belong to a domestic and industrial end-user. A solution to solve these overstress is to install , in a nearby node, a current source that support the overstressed sources at load balance. Since the sources link at node 5, 10 and 15 are overstressed and close each other, a solution could be to connect a generator in the node 6 that becomes a new fully controllable node. Another solution could be to increase the rated active and reactive power of these overstressed sources.
The following graph compares the peak values of the first and second case to understand if it is a good solution the optimal control of the active power generates from all the sources.

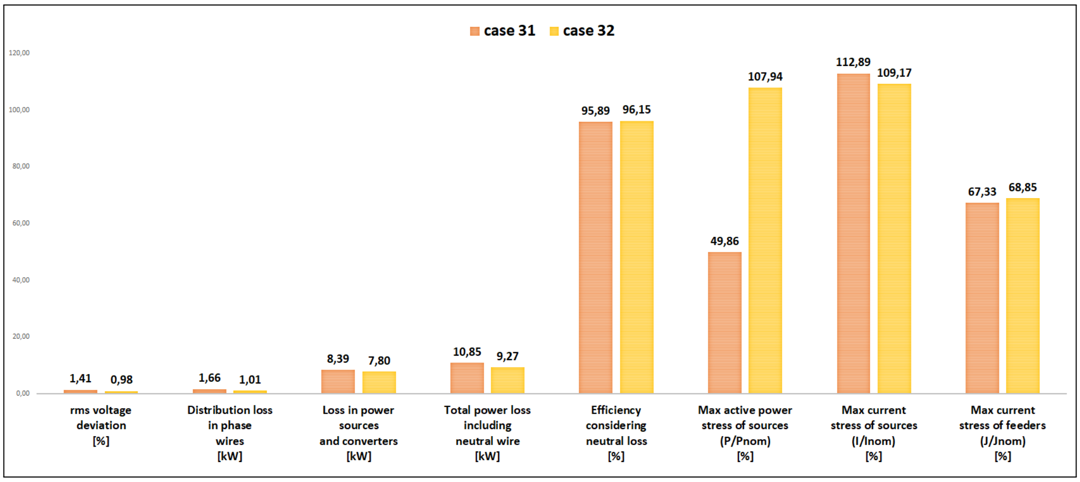

FIGURE 7.1: Comparison between the results of case 31 and 32, considering the radial grid.

From this graph the optimal control of the active power generated from all sources gives the best results, except for the maximum active power stress into the sources. In particular the maximum value of power stress of sources, in the first case, is much higher compared to those at second case. This is because the optimal control exploited more the distributed sources to reduce the total stress. Moreover the overstressed sources are relative at domestic and industrial end-user, so they are very

small and it is very simple to overstress. While the maximum current stress into the feeders remains constant between the first and second case.
So, for the management of the radial network, for this test case, the optimal control of the active power allows us a better management of the system.

7.3 Analysis of the results relative at meshed grid.

In the following table the results of the analysis with the main meshed grid are reported. At first the results of the voltage deviation are always much lower compared to the maximum value. This is a very good point, for this configuration of the meshed grid, because it confirms, another time, the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed generators, such as the photovoltaic sources and the energy storage systems, can feed the local load, so there will be a lower flow of current into the grid. Furthermore the value of the voltage deviation is greater in the first case compared to that at second case. This happen because the optimal control uses the distributed sources to feed the local loads, so the flow of current, into the grid, will decrease. In this way the voltage deviation, across the feeders, will reduce. That is a smart management of the sources that characterizes the smart grid. In particular the voltage deviation is quite constant for each case during the day and it falls during the night. This is because during the night the load consumption decreases compared to that during the day.
Subsequently is important to analyze the results of power loss and the efficiency. The value of power loss, in the distributed sources, is always greater compared to the value of power loss in phase wires. Furthermore the values of distribution loss in phase wires, in the first case, is always greater than that in the second case. Moreover the power loss into the sources, in the second case, is greater than that in the first case, except for the second period of the day. These facts happen because the distributed generators contribute to a decrease of flow of current into the grid. So there will be, in the second case, a greater exploit of distributed sources compared to that at first case. This fact causes an increase of power loss into the sources and a reduction of power loss into feeders.
The calculation of the power loss is fundamental for the calculation of the efficiency. The value of the efficiency is quite constant for each case and period and its value is very high. In particular the value of efficiency remains constant between the first and second case, considering the same period of the day. These facts are a good points for this configuration because the dispatcher can guarantee high value of power quality and reliability of the network.
After that the stress into sources and feeders are considered. From the analysis, in the first case, the value of active power stress into the sources is always lower compared to the value of current stress of sources, considering the same period of the day.

TABLE 7.6: Main results of the simulation, using SUSI3, of the main meshed grid.

Test case	31	31	31	31	31	32	32	32	32	32
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099
rms voltage deviation / Vnom	0,82%	0,93%	0,29%	1,10%	0,36%	0,34%	0,69%	0,20%	0,71%	0,21%
P entering grid at node 0 [kW]	-31,60	44,04	5,49	52,22	17,88	-9,20	32,44	5,98	35,41	8,88
Q entering grid at node 0 [kVAR]	-0,10	0,17	0,03	0,21	0,08	-0,09	0,13	0,02	0,16	0,05
P absorbed by loads [kW]	225,13	220,53	196,02	195,60	57,62	225,38	220,73	196,18	195,74	57,62
Q absorbed by loads [kVAR]	109,75	103,50	93,80	91,12	27,15	108,48	104,01	93,55	91,86	27,23
P fed by sources [kW]	328,60	221,66	201,66	197,06	57,81	293,22	224,45	197,73	199,61	59,41
Q fed by sources [kVAR]	152,85	114,12	106,05	106,34	35,50	118,63	110,11	93,61	100,82	29,46
P returned to sources [kW]	102,14	0,00	5,27	0,00	0,01	67,08	2,99	1,33	2,99	1,68
Q returned to sources [kVAR]	42,63	10,03	12,17	14,40	8,26	10,10	5,74	0,01	8,54	2,19
P troughput-grid transport [kW]	194,37	142,23	104,99	163,56	57,70	180,04	140,66	110,72	157,59	55,38
Q troughput-grid transport [kVAR]	120,48	82,18	86,70	82,24	30,44	65,26	65,51	53,47	77,31	23,31
Distribution loss in phase wires [kW]	1,33	1,13	0,37	1,46	0,18	0,75	0,73	0,23	0,88	0,10
Loss in power sources & converters [kW]	26,67	7,58	8,23	6,88	1,07	21,39	8,35	7,60	8,00	1,31
Total power loss w/o neutral wire [kW]	28,00	8,71	8,59	8,34	1,25	22,14	9,08	7,83	8,88	1,41
Efficiency neglecting neutral loss (Total loss/power fed by sources)	91,48%	96,07%	95,74%	95,77%	97,83%	92,45%	95,95%	96,04%	95,55%	97,62%
Estimated loss in neutral wire [kW]	1,94	0,45	0,51	0,86	0,11	1,26	0,41	0,30	0,50	0,06
Total power loss including neutral wire [kW]	29,93	9,16	9,11	9,20	1,36	23,40	9,49	8,13	9,39	1,47
Efficiency considering neutral loss	90,89%	95,87%	95,48%	95,33%	97,65%	92,02%	95,77%	95,89%	95,30%	97,52%
Min node voltage vs Vnom	-0,95%	-2,84%	-0,95%	-3,28%	-1,11%	-0,49%	-1,32%	-0,55%	-1,09%	-0,40%
Node with minimum voltage	915	1605	1601	1606	1606	910	1605	3001	1605	1603
Max node voltage vs Vnom	1,17%	0,84%	0,46%	1,19%	0,41%	1,09%	0,74%	0,34%	0,77%	0,14%
Node with maximum voltage	1603	917	914	917	917	1603	917	3401	917	5
Max active power stress of sources (P/Pnom)	100,18%	40,07%	49,90%	55,37%	19,41%	100,03%	100,40%	84,05%	103,51%	100,15%
Node with maximum active power stress	1102	917	1102	917	917	1102	5	5	1604	5
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	118,93%	102,72%	89,17%	99,99%	54,75%	103,69%	99,68%	79,34%	100,98%	91,90%
Node with maximum current stress	1107	2001	1107	5	1501	3506	5	5	1107	5
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	92,58%	71,72%	48,40%	84,63%	29,54%	55,17%	51,04%	37,83%	66,21%	22,37%
Branch with maximum current stress	95	14	68	14	14	30	68	95	28	28
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0	0	0
Max stress	118,9%	102,7%	89,2%	100,0%	54,8%	103,7%	100,4%	84,1%	103,5%	100,2%

While in the second case the value of current stress and active power stress, of sources, are very close each other. Moreover the value of active power stress of sources, in the first case, is always lower compared to that in the second case. This happen because the optimal control exploit more the distributed sources to reduce the power loss, the stress into the feeders and the total stress of the system. While the value of current stress of sources remains quite constant for the same period of the day, between the first and second case.
In the following table the overstressed sources, with the relative power limit, are reported. In particular there are a lot of overstressed sources. Moreover these sources are related to an industrial and commercial end-user. So these sources are very small and it is very simple to reach the upper power limit and overcome it. To solve these overstress, a solution could be to link, in a nearby node, a current source to support the already existing generators at load balance and minimization of the total stress. Indeed the overstressed sources are very close each other, so with a new current source, placed in a convenient node, is possible to reduce the stress of distributed sources and support them. Another solution is to increase the rated active and reactive power of the overstressed sources.

TABLE 7.7: Overstressed power sources at test case 31, using the meshed grid.

Day time	**Node**	**Overstressed A/Anom**	**Qsat [kVAR]**
1	5	1.38	14.83
1	1107	1.27	21.52
1	1501	1.86	10.80
3	5	1.37	15.26
3	1107	1.21	22.13
3	1501	1.67	11.06

From the comparison of the results of overstressed sources between the two cases is possible to observe, at the beginning, that the number of overstressed sources, at the first case, is lower compared to that at second case. Furthermore the value of the overstress, in the first case, is often lower than that at second case. This is because the optimal control acts to balance the load with the distributed generation and minimize the stress. So, in this case, the algorithm exploits the distributed sources, such as photovoltaic sources and energy storage systems, for the generation of active and reactive power. This leads to a lower current flow into the grid, but it takes to an high value of overstress for the sources. As previously anticipated a solution could be to connect a new current source or increase the rated active and reactive power of the overstressed sources. Obviously these solutions will lead to a higher cost but it will be possible to reduce the overstress into the sources. Another solution is to install, for each kind of load, a renewable source and energy storage system to allow the self-consumption locally and to reduce the power stress of the nearby generators.

TABLE 7.8: Overstressed power sources at test case 32, using the meshed grid.

Day time	Node	Overstressed	Apply limit
1	5	P/Pnom =4.03 A/Anom =1.24	Psat=13.80kW Qsat =6.50kVAR
1	1501	A/Anom =1.24	Qsat =10.83kVAR
1	1602	P/Pnom =1.12	Psat=5.00kW
1	1604	P/Pnom =1.12	Psat=5.00kW
1	3503	P/Pnom =1.26	Psat=-3.00kW
1	1005	P/Pnom=1.31	Psat=3.00kW
1	1010	P/Pnom =2.27	Psat=3.00kW
3	5	P/Pnom=4.52 A/Anom =1.33	Psat=13.80kW Qsat =6.46kVAR
3	3503	P/Pnom =1.56	Psat=-3.00kW
3	1004	P/Pnom=1.40	Psat=3.00kW
3	1005	P/Pnom =1.36	Psat=3.00kW
3	1010	P/Pnom =2.41	Psat=3.00kW
4	5	P/Pnom =1.58	Psat=13.80kW

The following graph compares the peak values, between the first and second case, to understand if it is a good solution the optimal control of the active power generated from all sources.

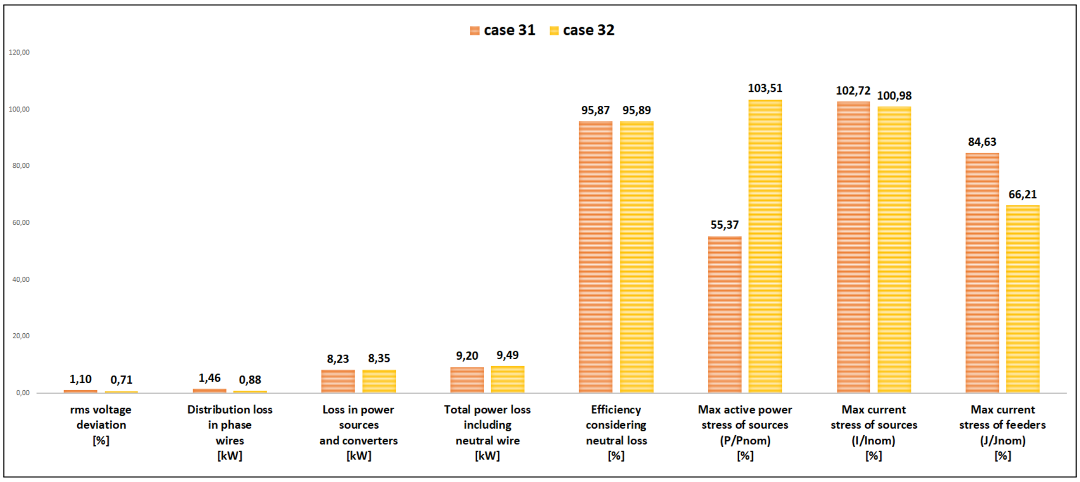

FIGURE 7.2: Comparison between the results of the meshed grid at case 31 and 32.

From this graph the grid with the optimal control gives the best results in terms of the voltage deviation, distribution loss into the feeders and the maximum current stress into the feeders and sources. While the value of power loss in sources, total

power loss an the efficiency are practically equal. The only negative point is for the maximum power stress into the sources because, with the optimal control, the power stress, into distributed sources, is much greater compared to that without optimal control. Moreover we have to consider that the overstress sources are very small, so it is very simple to reach the upper power limit and overcome that.
So, for e management of this system, the optimal control gives the best results.

7.4 Comparison between the radial and meshed grid.

After that is important to compare the results of the radial and meshed grid to understand which configuration gives the best results. In the following graphs are compared the values of the radial and meshed grid.
Considering the first case the voltage deviation, the distribution loss in phase wires, the total power loss and the maximum current stress of sources are lower compared to that in the radial grid. This is because in the meshed grid the new branches offer new paths in which the current can flow and that bring the advantages described previously. This is a good point for the meshed grid. While the power loss in sources and the efficiency there are no difference between the two cases. The two negative aspects of the meshed grid are the maximum power stress into the sources and the maximum current stress into the feeders. This happen because the new branches, related at radial grid, approaching loads and distributed sources that in the radial grid are distant. So the distributed sources will feed the local loads and the new loads acquired thanks to the new lines. In this way the maximum active power stress of the sources will increase a lot and it will be greater compared to that in the radial grid. Rather than we have to take into account that the overstress is related at distributed sources, such as photovoltaic sources, that are property of domestic of industrial end-user.

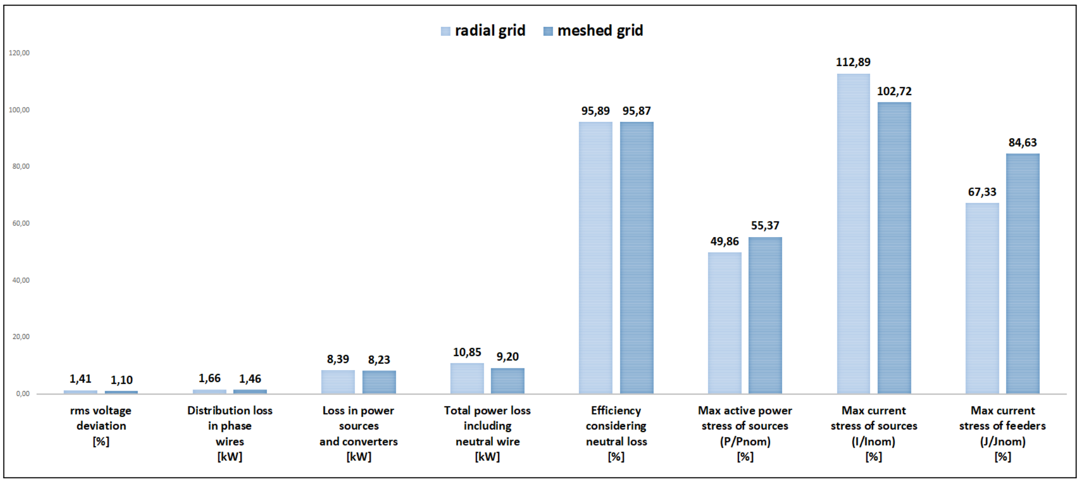

FIGURE 7.3: Comparison between the results of the radial and meshed grid, at case 31.

Moreover these sources are very small and it is very simple to overcome the upper power limit.
So, considering the graph and the results reported in the previous table, the meshed grid allows us a better management of the system in the first case.
Considering the peak value, of the second case in the meshed grid, the voltage deviation, the distribution loss in phase wires, the maximum of the active power and current stress of sources and the current stress into feeders are lower compared to those with the radial grid. This is a good point for the meshed grid. While the efficiency, the power loss in sources and the total power loss are practically equal between the radial and meshed grid, at the case 32. So this shows that the meshed grid with the optimal control of the power generated from all the sources bring the best benefits.

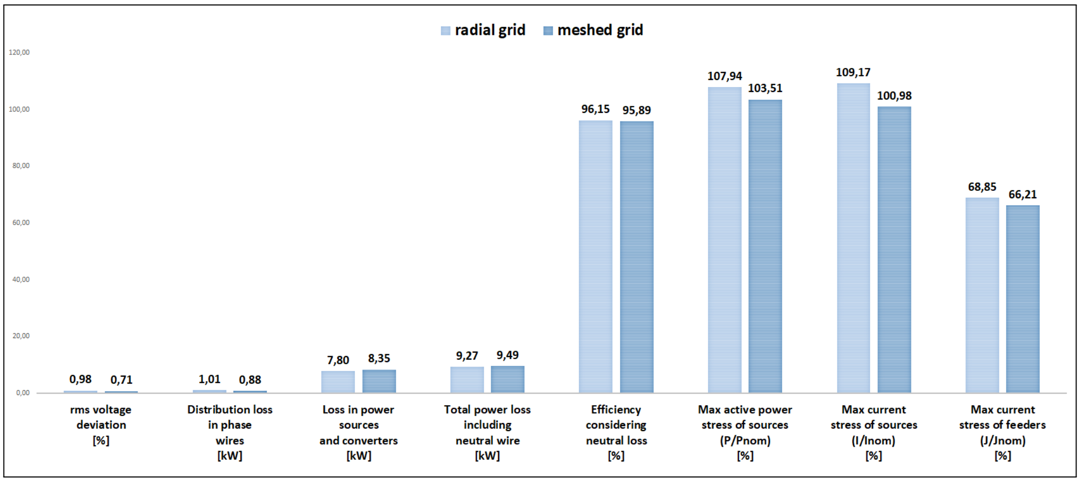

FIGURE 7.4: Comparison between the results of the radial and meshed grid, at case 32.

In conclusion, for this system, the meshed grid, with the optimal control of active and reactive power, gives the best results in terms of management of the grid, considering the graphs and the main results reported in the previous tables.

Chapter 8

Island operation

At first this chapter deals with the description of the boundaries related at the test case defined for the radial and meshed network. This test case is related at an active grid in which the PCCs don't generate active and reactive power. This operative condition is link at the island operation. Subsequently the results of the simulation are reported into the tables and they are used for make comparisons. The results come from the analysis done with SUSI3 and Source Locator.

8.1 Description of the fourth test case.

In this test case the PCCs don't participate at the load balance with the distributed generators, so the active and reactive power generated from the PCCs is equal to zero. While the distributed sources, like the renewable sources and energy storage systems, generate the active and reactive power to balance the load and to minimize the stress into the network. In particular the system formed by distributed generators, like renewable sources and energy storage systems, and loads with active and passive controls is called microgrids. In this scenario the rapidly increasing demand for electricity, clubbed with the need for environment friendly resources, is accelerating the entry of more and more distributed generation into the power system network. However the complexity and security constraints introduced in the conventional utility network by the addition of dispersed generation is significant. Islanding is one among them which requires considerable attention. An island represents a portion of power system, electrically separated from the interconnected network, providing power to the local loads. A typical scheme of islanding is represents into the follow figure. Current protection practices mandate the disconnection of the distributed generation systems as soon the islanding is detected. But tripping the distributed generation during a mains failure has limited the benefits offered by distributed generation, particularly when it is capable of supplying the local load within the statutory voltage, frequency and power quality limits. Current utility practices do not permit autonomous operation and, except in special cases, require that all down stream distributed generation units be disconnected after both planned or unplanned switching events. An unplanned islanding and micro-grid formation is due to either a fault and its subsequent switching incidents or some other unexpected switching process. This requirement is imposed to address safety concerns and to comply with the existing control and protection constraints of distribution systems. However, to realize the full benefit of high distributed generation penetration depth, the autonomous operation of micro-grids needs to be considered.

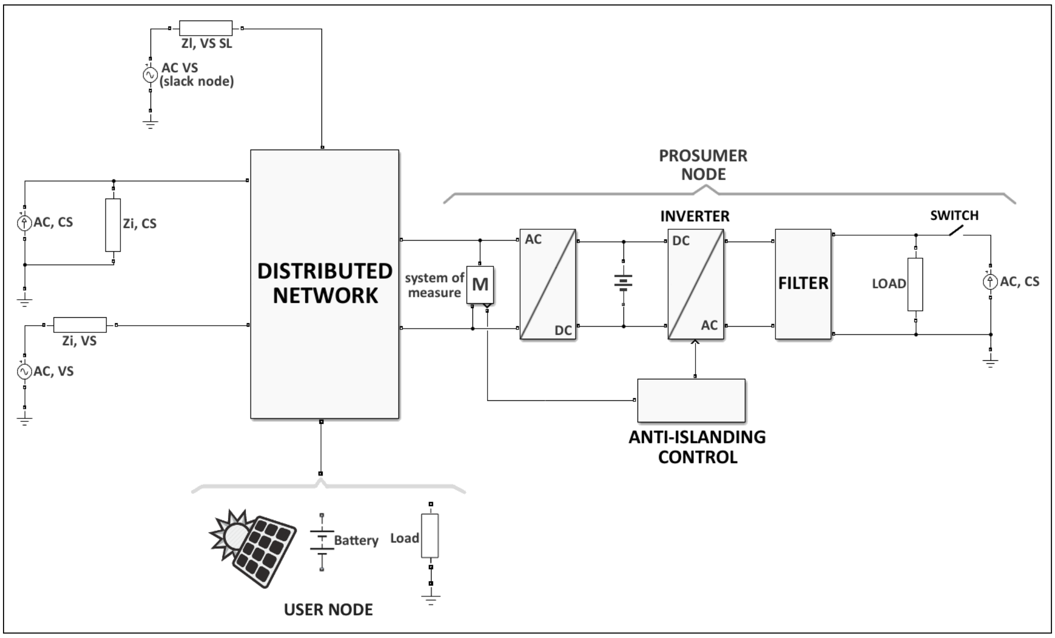

FIGURE 8.1: Islanding scheme.

Prior to islanding, the operating conditions of micro-grid could be widely varied, for example the distributed generation units can share load in various manners and the entire micro-grid portion of the network may be delivering or importing power from the main grid. Furthermore, the disturbance can be initiated by any type of fault and line tripping may be followed up with single or even multiple reclosure actions. After islanding, reconnection of the micro-grid to the utility grid is permitted only once restoration of the main system and the micro-grid is achieved. Grid restoration is identified when system voltages and frequencies have returned to, and been maintained in, a normal range for a reasonable period of time. This reconnection must be carried out through proper synchronization of the micro-grid to the utility at the point of common coupling. Limits have been proposed for acceptable voltage magnitude error, frequency error and phase-angle error between the micro-grid and the main grid. Under the present regulations governing distribution system operation, an islanding scenario is only permitted for loads with dedicated generation units. As a result, distributed generation units must be equipped with specific islanding detection and prevention schemes to disconnect the unit within two seconds of an islanding event. Several active and passive techniques have been introduced to detect an islanding condition, using local power system measurements. In the case of future micro-grid applications, with the potential of autonomous operation, a fast

and reliable detection algorithm is required to effectively distinguish between an islanding condition and other types of disturbances.
So is very important to study the behavior of the radial and meshed grid under this operative conditions. In particular we consider the grid, without considering the generators at PCCs, as a micro-grid. Following the boundaries related at this test case are reported into the tables. In the first case, called case 41, all sources generate active power and control the reactive power, except for the PCCs. So for the reactive power there is a control that impose, for each sources, to generate the optimal reactive power to minimize the stress in the grid. While for the active power this control is turn off, so the active power generated from the distributed sources is the results of load balance or balance between supply and demand. While the load are random, so the active and reactive power of each load is the results of the calculation using the formula described previously. This scenario is not close at a real situation because nowadays the switches intervene promptly to disconnect the end user to the rest of the network. Rather than this could be a real situation in the next future in which the islanding operation will be allow by code.

TABLE 8.1: Boundary of the case 41.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources feed generated P All sources control Q Actual loads	-1		6	100	100	4	100	
PCC0 bounded to zero power	1	0				9		
PCCx bounded to zero power	2	10				9		
UI slack nodes (reset bounds and power limits)	2	12				-2		
ES unbounded	2	11				-1		

In the second case, called case 42, all sources control active power and the reactive power, except for the PCCs. So for the active and reactive power there is a control that impose, for each sources, to generate the optimal active and reactive power to minimize the stress in the grid and to balance the load. While the load are random, so the active and reactive power of each load is the results of the calculation using the formula describe previously. This scenario is not close at a real situation because nowadays the switches intervene promptly to disconnect the end user to the rest of the network. Rather than this could be a real situation in the next future in which the islanding operation will be allow by code. Furthermore the control of active power generated by the distributed sources, like the renewable generator and energy storage system, plays a very important role into a smart or micro grids. Indeed, from the results, we expect that the management of the grid it will be better compared to that at the first case. This is because the active power, of each distributed sources, related at the first case, is the result of the load balance. While in the second case the active power, of each distributed sources, related at the second case, is the result of the optimal control to minimize the stress with the boundary of load balance.

TABLE 8.2: Boundary of the case 42.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources control P and Q Actual loads	-1		6	100	100			
PCC0 bounded to zero power	1	0				9		
PCCx bounded to zero power	2	10				9		
UI slack nodes (reset bounds and power limits)	2	12				-2		
ES unbounded	2	11				-1		

8.2 Analysis of the results relative at radial grid.

In this section the results of the analysis, made with SUSI3 and Source Locator, are reported in these tables. The first table resumes the main results of the analysis of the radial grid. At first the results of the voltage deviation, in percentage, are always much lower compared to the maximum value. This is a very good point, for this configuration of the radial grid, because it confirms the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed generator, like the photovoltaic sources and the energy storage systems, can feed the local loads so there will be a lower flow of current into the grid. It will bring to a reduction of the total power loss into the feeders and it is another benefit. In this configuration the dispatcher can guarantee that the voltage node at end user will be into the range define by code and an high value of power quality and reliability of the grid. In particular the voltage deviation, during the day, is greater compared to that during the night. This is because during the night the load consuming decreases compared to that during the day. Moreover the voltage deviation, in the first case, is greater compared to that in the second case. This is because all distributed sources, in the second case, can control the generated active power. In this way all the distributed sources generate the active power obtained from an optimal solution. That is a smart management of the distributed sources that characterizes the smart grid.
After in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power fed by sources and the power through grid transportation. Subsequently the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters. Also it makes an estimation of the power loss into neutral wires. In this test case the power loss into the sources is always greater than the power loss into the feeders. This happen because the flow of current into the grid is is reduced for the same reason explain before for the little value of voltage deviation.

TABLE 8.3: Main results of the simulation, using SUSI3, of the radial grid.

Test case	41	41	41	41	41	42	42	42	42	42
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160
rms voltage deviation / Vnom	1,87%	1,96%	0,36%	2,34%	0,83%	0,55%	1,18%	0,22%	1,35%	0,17%
P entering grid at node 0 [kW]	0,00	-0,16	-0,04	-0,13	-0,06	-0,02	-0,10	-0,02	-0,09	-0,02
Q entering grid at node 0 [kVAR]	-0,04	-0,01	-0,01	0,01	0,00	-0,05	-0,01	-0,02	0,01	0,00
P absorbed by loads [kW]	231,08	226,62	202,44	201,71	59,04	232,08	226,41	202,44	201,25	58,93
Q absorbed by loads [kVAR]	115,92	114,93	102,73	103,26	30,37	116,63	114,74	102,73	102,97	30,24
P fed by sources [kW]	323,55	230,83	202,89	207,48	60,09	288,88	229,10	203,02	207,86	59,68
Q fed by sources [kVAR]	151,28	179,45	108,70	167,18	85,69	129,72	136,11	102,83	157,34	31,53
P returned to sources [kW]	88,03	0,22	0,04	0,23	0,12	55,48	0,96	0,30	4,17	0,59
Q returned to sources [kVAR]	34,77	63,86	5,89	63,10	55,12	12,80	21,06	0,03	53,95	1,23
P troughput-grid transport [kW]	185,86	150,73	106,44	174,33	59,72	174,73	142,12	115,42	163,81	54,87
Q troughput-grid transport [kVAR]	118,87	139,61	82,24	139,88	78,48	71,33	89,17	56,91	127,12	23,99
Distribution loss in phase wires [kW]	4,43	3,98	0,41	5,54	0,92	1,32	1,74	0,28	2,44	0,16
Loss in power sources & converters [kW]	25,09	13,38	7,63	13,34	5,72	22,29	9,96	7,30	12,70	1,67
Total power loss w/o neutral wire [kW]	29,52	17,36	8,04	18,88	6,64	23,61	11,70	7,58	15,13	1,83
Efficiency neglecting neutral loss (Total loss/power fed by sources)	90,88%	92,48%	96,04%	90,90%	88,95%	91,83%	94,89%	96,27%	92,72%	96,93%
Estimated loss in neutral wire [kW]	2,99	1,64	0,70	2,30	0,51	1,85	1,41	0,48	1,81	0,11
Total power loss including neutral wire [kW]	32,51	19,00	8,74	21,18	7,15	25,46	13,11	8,06	16,94	1,94
Efficiency considering neutral loss	89,95%	91,77%	95,69%	89,79%	88,10%	91,19%	94,28%	96,03%	91,85%	96,75%
Min node voltage vs Vnom	-5,35%	-3,02%	-0,62%	-3,33%	-1,18%	-1,05%	-1,80%	-0,58%	-1,23%	-0,43%
Node with minimum voltage	915	1605	1805	1604	1604	916	1605	1805	1605	1603
Max node voltage vs Vnom	1,58%	5,03%	1,00%	6,32%	2,17%	1,25%	3,55%	0,41%	4,18%	0,39%
Node with maximum voltage	1602	917	914	917	917	1901	917	5	917	5
Max active power stress of sources (P/Pnom)	99,27%	80,41%	50,16%	102,71%	34,17%	100,77%	100,30%	72,76%	100,73%	104,62%
Node with maximum active power stress	3002	917	911	917	917	1005	1602	5	1602	5
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	117,66%	99,92%	98,15%	100,43%	100,32%	118,43%	99,95%	73,48%	112,74%	94,37%
Node with maximum current stress	3506	3504	1501	3504	5	2001	2801	1501	1503	5
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	86,92%	79,64%	38,97%	102,25%	49,55%	70,66%	56,15%	49,79%	67,08%	35,67%
Branch with maximum current stress	7	7	28	7	95	95	7	95	7	3
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0	0	0
Max stress	117,7%	99,9%	98,2%	102,7%	100,3%	118,4%	100,3%	73,5%	112,7%	104,6%

Furthermore, from the results of the simulation the optimal control exploit more the distributed sources so the power loss into them will increase. In particular the power loss into the sources at first case is always greater compared to that at the second case. Moreover the value of distribution power loss in phase wires, in the first case, is always greater compared to that in the second case. These two facts are a direct consequence of the control of the active power generated, from all distributed sources. Indeed in the second case the active power generate, for each sources, is the results of an minimization of the stress. So SUSI3 calculates an optimal point in which there is a balance between the supply and demand and the total stress is minimized. This is a benefit that the photovoltaic sources and energy storage systems, with an appropriate algorithm, can lead into the grid, also in a islanding operative condition. That is a smart management of the sources that characterizes the smart grid.
Furthermore the calculation of the power loss is fundamental for the efficiency. The efficiency of a grid is a very important parameter of the power quality that gives an idea of the management of the system. The value of the efficiency is not so high for each case and it isn't a good point for the management of the grid in this configuration. Furthermore the value of the efficiency at first case is always lower than that at the second case. This is because in the second case the active power generated from the distributed sources, like renewable sources and energy storage systems, is the results of an optimization. Furthermore the value of the efficiency of this test case are lower compared to that at the first test case. This is because at the first test case the distributed sources didn't participate at generation so the stress into the sources was very small. So the power loss, into the sources at first test case, is lower compared to that at this test case. In this test case the sources are very stressed so there will be an increase of power loss into the sources and a reduction of the power loss into the feeders because the current flow into the grid decreases. So the increase of the power loss into the sources is greater compared to the reduction of the power loss into the feeders, compared the first test case and this test case, and this situation involves in a reduction of the efficiency.
After that is important to understand where the sources overstress comes from. From the results of the simulation, into the sources, the value of the current stress is, for the most part, greater compared to the value of power stress. So, in this test case, the limitation of the sources is the value of current and active power that can generate. To solve this current and power overstress of the sources, a solution is to increase the rated active power of the overstressed sources. Another solution is to install a fully controllable generator, in a nearby node of the overstressed sources, to support the already existing sources at load balance and minimization of the total stress. In the following tables the overstressed sources, with its value of overstress and upper limit of active and reactive power for each case, are reported. The results of these two tables point out that the first and second case have very similar power overstress of the sources. This is because the main generator, link at PCCs,

don't participate, in both cases, at load balance so the distributed generator are really exploited and stressed with or without active control. In particular at first case the number of power overstressed sources is lower compared to that at second case. This happen because the distributed sources, at second case, are more exploited compared to those at first case. In particular at the first case the power overstress into the sources is related only at reactive power, while in the second case, both active and reactive power. The following graph compares the results of the first and second case to understand if it is a good solution the optimal control of the active power generates from all the distributed sources, using the radial grid.

TABLE 8.4: Overstressed power source at test case 41, using the radial grid.

Day time	Node	Overstressed A/Anom	Qsat [kVAR]
1	5	3.22	14.80
3		3.79	15.20
4		1.35	15.33
1	1501	4.44	10.70
3		4.48	11.04
4		1.56	11.11
1	1801	1.46	5.38
3		1.30	5.54
1	2001	2.83	-21.54
3		3.38	-22.08
4		1.24	-22.22
1	2002	1.23	-5.36
3		1.53	-5.52
1	2801	4.57	-10.68
3		5.09	-10.96
4		1.84	-11.11
1	32	2.13	10.65
3		2.72	10.97
1	1503	1.60	5.35
3		1.29	5.53
1	3506	1.57	-6.45
3		1.48	-6.64
1	3504	1.67	-3.22
3		1.55	-3.32

The overstressed sources are very small, so is very simple to reach the upper limit of active and reactive power and overcome it. Moreover, in this test case, the overstressed sources aren't near each other, so to solve the overstress the dispatcher has to install more than a current source. Furthermore, in the previous table, the value of the limit of reactive power related at some distributed sources is negative. This means that, for the grid, this sources have an inductive behavior. So that specific source absorbs a certain reactive power, in this test case. Furthermore in the second case there is a source, link at node 3503, that has a saturation with an active saturation power negative. So, in this case, that source as to absorb a certain value of active power.

TABLE 8.5: Overstressed power source at test case 42, using the radial grid.

Day time	Node	Overstressed	Apply limit
1 3	5	P/Pnom =3.09 A/Anom =2.05; P/Pnom =3.07 A/Anom =2.23	Psat=13.80kW Qsat =6.19kVAR; Psat=13.80kW Qsat =6.07kVAR
1 3	1501	A/Anom=1.51; A/Anom =2.04	Qsat =10.77kVAR; Qsat =11.06kVAR
1 3	1004	P/Pnom =2.76; P/Pnom =1.67	Psat=3.00kW; Psat=3.00kW
1 3	1005	P/Pnom =3.65; P/Pnom =1.93	Psat=3.00kW; Psat=3.00kW
1 3	1010	P/Pnom =4.75; P/Pnom =1.85	Psat=3.00kW; Psat=3.00kW
1 3	1602	P/Pnom =1.14; P/Pnom =1.45	Psat=5.00kW; Psat=5.00kW
1 3	1604	P/Pnom =1.14; P/Pnom =1.46	Psat=5.00kW; Psat=5.00kW
1 3	1606	P/Pnom =2.08; P/Pnom =2.29	Psat=3.00kW; Psat=3.00kW
1 3	2801	A/Anom =1.68; A/Anom =1.89	Qsat =-10.83kVAR; Qsat =-11.07kVAR
1	1503	A/Anom =1.35	Qsat =5.35kVAR
1	1801	A/Anom =1.32	Qsat =5.37kVAR
3	2001	A/Anom=1.30	Qsat =-22.16kVAR
3	3503	P/Pnom =1.75	Psat=-3.00kW

After that the peak value of the simulation, done with SUSI3, related at radial grid between the first and second case are compared in this graph. From this graph the optimal control gives the best results in terms of voltage deviation, distribution loss into the feeders, loss in power sources, the total power loss, maximum current stress into feeders and maximum power stress into sources. While the efficiency remains constant between the two cases. The only negative aspect is the maximum of the current stress into the sources. Moreover is important to consider that the over-stressed sources are very small so is simple to reach the upper limit of active and reactive power and overcome it. To solve this problem a solution is to install a fully controllable generator, close to the overstressed power sources, to support them at load balance and minimization of the total stress. Another solution is to increase the rated active and reactive power of those sources.

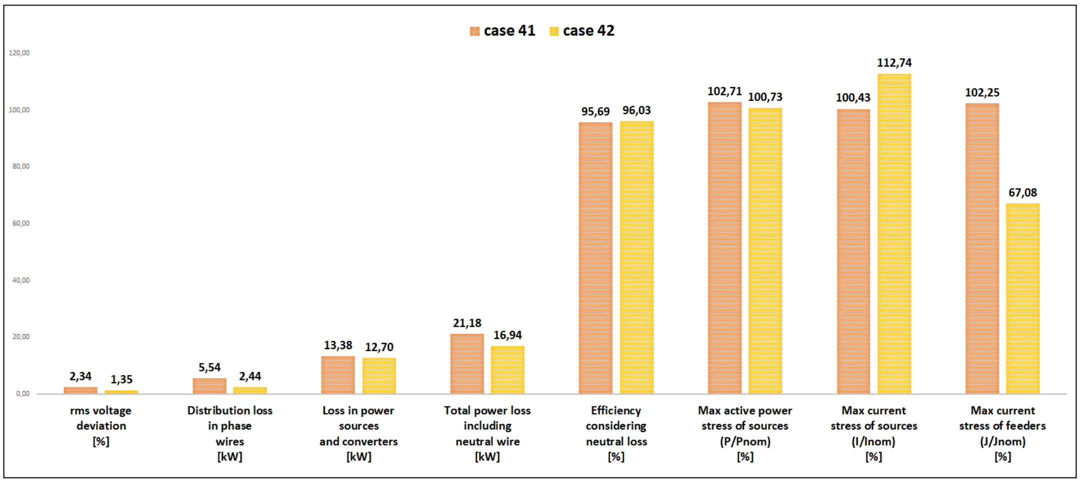

FIGURE 8.2: Comparison between the results of case 41 and 42.

So, for this test case in the radial grid, the optimal control gives the best results in terms of management the system under islanding operation.

8.3 Analysis of the results relative at meshed grid.

After that the results of the simulation, related at meshed grid, are reported in the following tables. At first the results of the voltage deviation are always much lower compared to the maximum value. This is a very good point, for this configuration of the meshed grid, because it confirms, another time, the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed generator, like the photovoltaic sources and the energy storage systems, can feed the local loads so there will be a lower flow of current into the grid. Furthermore the value of the voltage deviation, at first case, is greater compared to that at second case. This is because at second case the active and reactive power generated from the distributed sources is the results of an optimal control. That is a smart management of the sources that characterizes the smart grid. In particular the voltage deviation during the day is greater than that during the night. This is because during the night the load consuming decreases compared to that during the day.
Subsequently the power loss into phase wires and into the sources are considered. In particular the power loss into the sources, in the first case, is always greater compared to that at second case.

TABLE 8.6: Main results of the simulation, using SUSI3, of the meshed grid.

Test case	41	41	41	41	41	42	42	42	42	42
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099
rms voltage deviation / Vnom	0,83%	0,93%	0,19%	1,06%	0,38%	0,39%	0,68%	0,16%	0,73%	0,17%
P entering grid at node 0 [kW]	-0,16	0,16	0,00	0,19	0,07	-0,11	0,13	0,01	0,16	0,05
Q entering grid at node 0 [kVAR]	-0,01	0,04	0,03	0,05	0,02	-0,06	0,05	0,01	0,06	0,03
P absorbed by loads [kW]	226,88	221,13	196,09	194,64	57,13	227,04	221,12	196,08	194,60	57,09
Q absorbed by loads [kVAR]	113,94	110,99	100,09	99,25	29,20	113,95	111,10	100,10	99,32	29,19
P fed by sources [kW]	329,15	223,18	196,36	197,37	57,51	290,12	224,85	196,29	199,14	58,09
Q fed by sources [kVAR]	135,95	146,27	109,31	141,00	51,53	122,14	128,89	100,15	121,70	35,51
P returned to sources [kW]	100,05	0,00	0,00	0,00	0,00	62,22	2,50	0,01	3,03	0,87
Q returned to sources [kVAR]	21,70	34,89	9,17	41,26	22,27	8,10	17,52	0,01	22,07	6,28
P troughput-grid transport [kW]	189,66	143,28	98,79	164,29	57,41	174,02	141,63	108,27	158,31	54,44
Q troughput-grid transport [kVAR]	110,54	115,24	89,15	117,01	45,47	63,28	87,08	56,04	94,20	28,82
Distribution loss in phase wires [kW]	2,22	2,06	0,27	2,72	0,38	0,86	1,24	0,21	1,52	0,13
Loss in power sources & converters [kW]	25,81	10,15	7,31	10,37	2,74	22,03	10,05	6,85	9,38	1,85
Total power loss w/o neutral wire [kW]	28,04	12,21	7,58	13,09	3,11	22,88	11,28	7,06	10,90	1,98
Efficiency neglecting neutral loss (Total loss/power fed by sources)	91,48%	94,53%	96,14%	93,37%	94,59%	92,11%	94,98%	96,40%	94,53%	96,59%
Estimated loss in neutral wire [kW]	1,69	0,36	0,36	0,56	0,07	1,21	0,67	0,26	0,69	0,07
Total power loss including neutral wire [kW]	29,72	12,57	7,94	13,66	3,18	24,10	11,95	7,32	11,58	2,04
Efficiency considering neutral loss	90,97%	94,37%	95,96%	93,08%	94,47%	91,69%	94,68%	96,27%	94,18%	96,48%
Min node voltage vs Vnom	-2,36%	-1,91%	-0,57%	-2,25%	-0,80%	-0,84%	-1,20%	-0,58%	-1,02%	-0,39%
Node with minimum voltage	917	1605	3004	1601	1601	910	1605	3004	1605	1605
Max node voltage vs Vnom	1,75%	2,07%	0,42%	2,65%	0,95%	1,13%	1,48%	0,42%	1,71%	0,22%
Node with maximum voltage	1602	917	1605	917	917	1603	917	1605	917	917
Max active power stress of sources (P/Pnom)	100,22%	76,33%	49,76%	97,81%	34,60%	100,23%	108,25%	72,69%	104,61%	100,25%
Node with maximum active power stress	1603	917	1603	917	917	1603	1604	5	1604	5
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	117,85%	100,07%	83,01%	100,42%	114,36%	113,91%	119,80%	69,43%	99,59%	96,31%
Node with maximum current stress	1009	5	1107	2001	5	2801	1107	1501	1107	5
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	117,68%	91,93%	44,82%	119,76%	44,83%	59,29%	70,31%	43,40%	67,59%	17,71%
Branch with maximum current stress	7	7	68	7	7	30	68	28	7	28
Number of overstressed feeders (current)	1	0	0	1	0	0	0	0	0	0
Max stress	117,9%	100,1%	83,0%	119,8%	114,4%	113,9%	119,8%	72,7%	104,6%	100,3%

Moreover the value of the distribution loss in phase wires, in the first case, is greater compared to that in the second case. These two facts are due to the optimal control that exploit the distribution sources to feed the local loads. In this way the flow of current, into the grid, will reduce and, consequently, the power loss will reduce.
After that is important to analyze the results of the efficiency. The value of the efficiency is quite constant for each case and period and its value is very high. This is a good point for this configuration because the dispatcher can guarantee high value of power quality and reliability of the network. Furthermore the power loss into the feeders is always lower than the power loss into the sources. This happen because the distributed generators, such as the photovoltaic sources and energy storage systems, have to feed a lot of local loads, so those sources will be a reduction of flow of current into the grid. This leads to a decrease of the power loss into the feeders and an increase of loss in power sources, since those sources are more exploited by the optimal control. Moreover, from the analysis, a lot of distributed sources are overstressed and it causes an increase of the power loss into the sources. The power loss into the feeders remains very small because, in this test case, the distributed sources can feed the local loads, so the current flow into the grid will be lower compared to that in the previous test cases. Furthermore in the second case the value of the maximum power stress into the sources is always greater than that at first case. At last, in the fist case, the value of the maximum power stress of the sources is always lower compared to the value of current stress in the sources. While, in the second case, the value of the maximum power stress of the sources is always greater compared to the value of current stress in the sources. In the following table the overstressed sources are resumed.

TABLE 8.7: Overstressed power source at test case 41, using the meshed grid.

Day time	**Node**	**Overstressed A/Anom**	**Qsat [kVAR]**
1 3	5	2.81; 3.19	-14.88; -15.26
1 3	1107	1.66; 1.71	21.64; 22.15
1 3	1501	2.63; 2.52	10.73; 11.06

The overstressed sources are very small because they are property of the domestic or industrial end-user. So is very simple to overcome their upper limits of active and reactive power. In particular the overstressed sources, in this test case, are close each other, so, to solve this overstress, a solution is to install a new current source in a nearby node that become a new fully controllable node. Moreover that new current source will support the already existing generators at load balance and minimization of the total stress.

TABLE 8.8: Overstressed power source at test case 42, using the meshed grid.

Day time	Node	Overstressed	Apply limit
1 3 4	5	P/Pnom=5.15 A/Anom =1.47; A/Anom =1.62; P/Pnom =2.02	Psat=13.80kW Qsat =-6.39kVAR; Qsat =-6.35kVAR; Psat=13.80kW
1 3	1004	P/Pnom =2.61; P/Pnom =3.40	Psat=3.00kW; Psat=3.00kW
1 3	1501	A/Anom =1.46; A/Anom =1.37	Qsat =10.76kVAR; Qsat =11.07kVAR
1 3	1005	P/Pnom =3.87; P/Pnom =4.02	Psat=3.00kW; Psat=3.00kW
1 3	1010	P/Pnom =3.8; P/Pnom =4.38	Psat=3.00kW; Psat=3.00kW
3	3503	P/Pnom =1.11	Psat=-3.00kW
3	1107	A/Anom =1.26	Qsat =22.16kVAR

From the results of the two previously tables there are some sources with a negative limit of active and reactive power. The sources with negative active power limit, for the grid, has the same behavior of the loads. While the sources with negative reactive power limit , for the grid, has the same behavior of the inductance. Furthermore the number of overstressed power sources, in the first case, is greater compared to that at second case. After that the results of the simulation using Source Locator are reported in the following two tables. In particular there is only a feeder that has a current overstress.

TABLE 8.9: Result of the current stress into the feeders considering the meshed grid.

Test case	Period of the day	Branch number	Phase	Overstress J/Jnom
41	3	7	2	1,20

The proposed solution is to install a generator at node 9, that is a new fully controllable node. In particular the new current source has an apparent power equal to 50 kVA. With this solution is possible to control the current in the line 7 with a control factor that allow a reduction of the current in that line over fifty per cent. Otherwise is possible to exploit the fully controllable node that already exist. Indeed at node 917, that is a fully controllable node, the control factor is greater compare to that at node 9. So, another solution that gives best results than the previous one, is to install that generator at node 917. Another solution that gives best results than the previous one, is to install that generator at node 917.

TABLE 8.10: Results of the analysis made with Source Locator considering the meshed grid.

Fully controllable node	Power generate from that node [kVA]	Number of controlled branches	Total control factor J/Jnom	List of control branches (control factor)
917	47.14	17	10.06	24(1.21), 26(1.05), 23(0.84), 125(0.82), 22(0.81), 18(0.72), 9(0.70), 7(0.56), 132(0.49), 11(0.44), 10(0.43), 19(0.41), 3(0.40), 127(0.39), 17(0.32), 27(0.26), 4(0.22)
2803	47.14	6	3.96	7(2.07), 126(0.60), 3(0.58), 8(0.25), 132(0.25), 6(0.22)
9	16.67	3	2.18	37(1.09), 7(0.65), 3(0.43)
1602	5.55	2	0.85	14(0.51), 84(0.34)
1604	5.55	2	0.85	14(0.51), 86(0.34)

Subsequently is important to compare the results of the simulation, done with SUSI3, related at meshed grid, to understand if the optimal control gives the best results compared to the operative condition without optimal control.

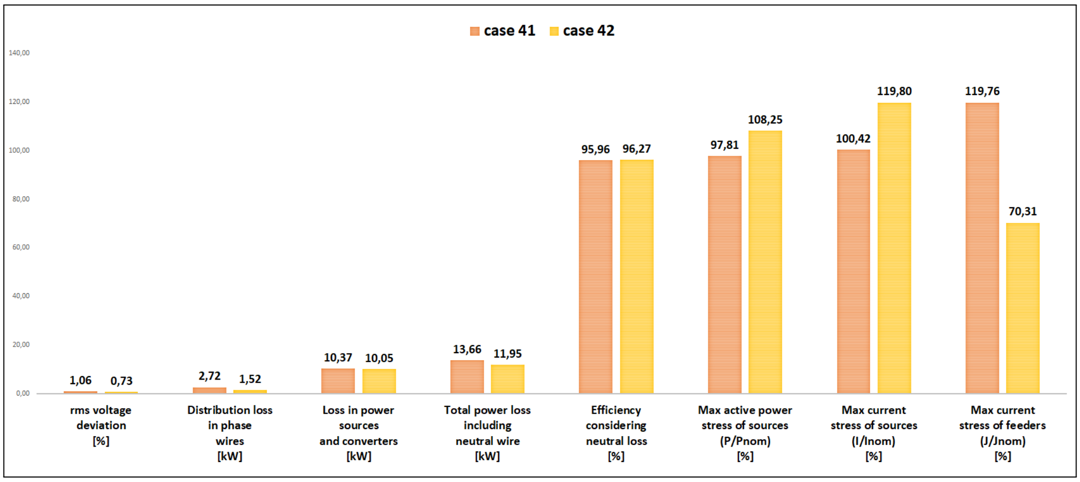

FIGURE 8.3: Comparison between the results of case 41 and 42.

In the previous graph the peak value of the results of the simulation, related at meshed grid, are compared. Considering the voltage deviation, the distribution loss in phase wires and the maximum current stress in feeders, the optimal control gives the best results. Furthermore the loss in power sources and the efficiency remain constant between the two cases. While the only two negative aspects of optimal control are maximum active power and current stress into the sources. This is because, with the optimal control, the distributed sources are more exploited compared to those at first case, in which the optimal control is off.
So the optimal control, in this test case considering the meshed grid, gives the best results in terms of management the system.

8.4 Comparison between the radial and meshed grid.

At last is important to understand which configuration of the distributed grid gives the best results for each case. In the following graph the peak values of the radial and meshed grid, related at case 41, are reported.

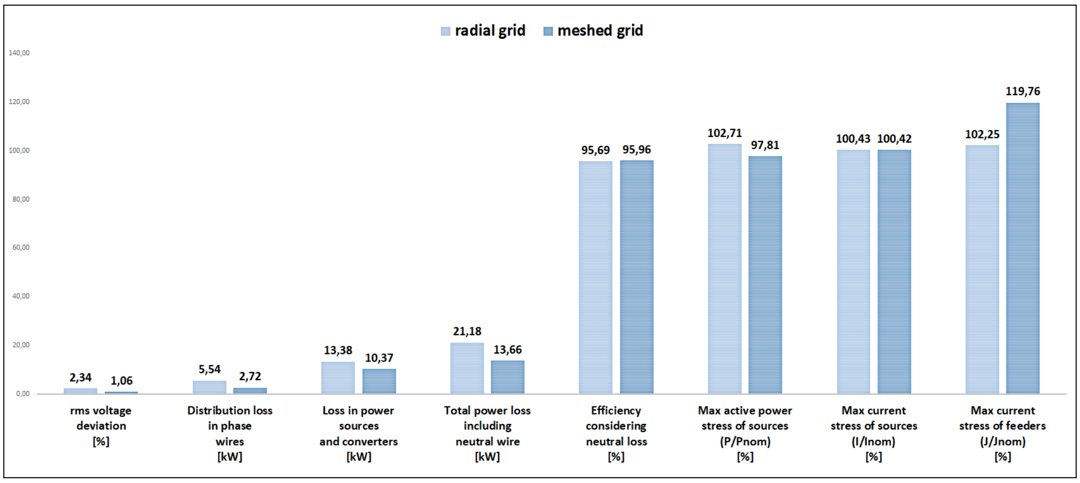

FIGURE 8.4: Comparison between the results of the radial and meshed grid at case 41.

From the previous graph, in the meshed grid, the voltage deviation, the distribution loss in phase wires, the loss into sources and the maximum of active power stress in sources, are lower compared to those at radial grid. Furthermore the efficiency and the current stress of sources remain constant between the two cases. The only negative aspect of the meshed grid is the maximum current stress into the feeders.
So, for the case 41, the meshed grid gives the best results, both considering the graph and the results reported in the previous tables, in terms of management the grid and power quality.
While the comparison between the peak value of radial and meshed grid, related at case 42, are reported in the following graph. In the meshed grid the voltage deviation, the distribution loss in phase wires and the loss into sources, are lower compared to those at radial grid. Furthermore the efficiency remain constant between the two configurations of the grid. While the negative aspects, related at meshed grid, are the maximum active power stress and current stress into the sources and the maximum current stress into the feeders. This happen because in the meshed grid the distributed sources are link to a greater number of loads compared to the number of loads in the radial grid. So in the meshed grid the distributed sources have to feed a greater number of loads and it bring to a greater stress of the sources and feeders. Also the distributed sources, that are overstressed, are very small, so it is very simple to reach the upper power limit and overcome it. As previously anticipated to solve these power overstress, of sources, a solution is to connect, in a nearby node, a new current source to support the already existing distributed sources. Rather than the value of the stress into the sources and the feeders are not so different, between

the radial and meshed grid related at case 42.
So the meshed grid gives the best results in terms of management and the power quality of the system.

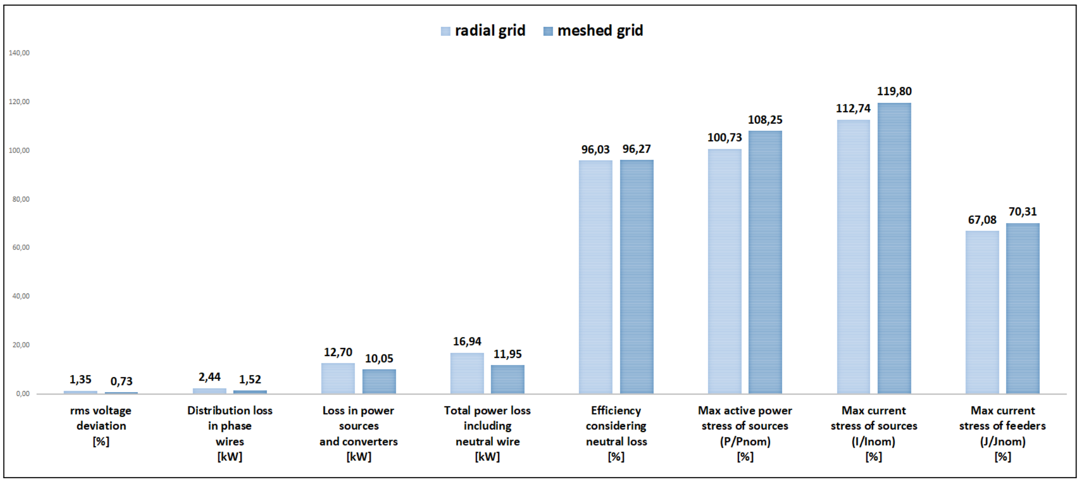

FIGURE 8.5: Comparison between the results of the radial and meshed grid at case 42.

In conclusion, considering the results reported in the previous tables and the graphs, the meshed grid, with optimal control, allows us a better management of the system.

Chapter 9

Battery recharge

At first this chapter deals with the description of the boundaries related at the test case defined for the radial and meshed network. This test case is related at an active grid in which the energy storage systems are under charge. Subsequently the results of the simulation are reported into the tables and they are used for make comparisons. The results come from the analysis, done with SUSI3 and Source Locator.

9.1 Description of fifth case.

In this test case the energy storage systems are under charge, so the rest of the sources have to feed them and also the loads. Among many strategies and approaches of accumulator battery charge, the main of them all are those involving charge with constant current and voltage and combined ones with switching the constant current and voltage during the charge. The charge process of energy accumulating batteries is not as simple as may seem. Even small undercharge may cause the next and next not in full charge which leads to the degradation of battery elements including the recent generations of Li-ion batteries. The small overcharge may cause the overheating and as a rule the small reduction of state of charge which leads again to the reduction of life time. In addition to that the main stages of charge should include both constant voltage and constant current charge. Also the approach may be alternating when either the voltage or current would be constant. The idea is not just to develop a rapid charger but also to get the maximally clear understanding of what stages are mains, and what are secondary. Which stages to be considered as invariable and which are optional. On each stage there will be positive and negative conditions. For instance the big current will be always the negative condition as it will be a reason of heating and finally of overheating. The time will always be the alternative value as the smaller time involves in better result and no overheating, however the longer process, the more commercial losses. Also the temperature will be a sensitive condition. If the temperature is low, then the ion exchange process may fail in some space of the battery, which may cause undercharge. If the temperature is high then it may cause the overheating which may cause in turn the failing of the ion exchange on electrodes and degradation of the element. One of the ways

for their improvements is the computer modeling of the charging processes and research of consequences of the rapid charge, at last on the level of main charge stages. There are many different strategies and approaches of accumulating battery charge today. The main of them are the charge with constant current, charge with constant voltage, and combined when both current and voltage are being variable during the charge.
So is very important to study the grid under this operative condition. Indeed the evolution, of batteries and energy storage systems, is very fast and in the next future the battery will cover an important role in the electric scenario.
In the first case, also called case 51, all sources generate active power and control the reactive power. Furthermore the energy storage systems absorb 20% of rated active and reactive power. At last the PCC_1 is the slack node. While the absorption, for each load, is calculated randomly using the formula described at the beginning.

TABLE 9.1: Boundaries of case 51.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources feed generated P All sources control Q Actual loads	-1		6	100	100	4	100	
UI absorb 20% of rated P and control Q	2	12				1	-20	
ES absorb 20% of rated P and control Q	2	11				1	-20	
PCCx slack nodes (reset bounds and power,limits)	2	10				-2		

While the second case, also called case 52, all sources control the active reactive power. Furthermore the energy storage systems absorb 20% of rated active and reactive power. At last the PCC_1 is the slack node. While the absorption, for each load, is calculated randomly using the formula described at the beginning.

TABLE 9.2: Boundaries of case 52.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources control P and Q Actual loads	-1		6	100	100			
UI absorb 20% of rated P and control Q	2	12				1	-20	
ES absorb 20% of rated P and control Q	2	11				1	-20	
PCCx slack nodes (reset bounds and power,limits)	2	10				-2		

9.2 Analysis of the results relative at radial grid.

In this section the results of the analysis, done with SUSI3 and Source Locator, are reported in these tables.

TABLE 9.3: Main results of the simulation, using SUSI3, of the radial grid.

Test case	51	51	51	51	51	52	52	52	52	52
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160
rms voltage deviation / Vnom	1,16%	1,95%	0,70%	2,48%	0,80%	0,90%	1,48%	0,50%	1,79%	0,52%
P entering grid at node 0 [kW]	-36,97	90,62	28,10	117,43	42,34	-16,05	62,66	11,96	81,21	16,91
Q entering grid at node 0 [kVAR]	8,32	-25,01	-12,05	-27,79	-18,01	-5,59	-13,98	-3,59	-13,52	-0,40
P absorbed by loads [kW]	228,57	225,12	199,60	199,54	58,72	227,09	223,48	193,96	194,90	57,37
Q absorbed by loads [kVAR]	121,82	112,68	103,44	98,51	29,96	113,70	106,01	97,16	92,80	28,02
P fed by sources [kW]	322,93	227,41	200,26	202,91	59,30	310,05	228,01	195,63	199,79	59,53
Q fed by sources [kVAR]	155,22	144,64	110,57	134,87	44,74	121,22	124,30	97,62	109,31	32,47
P returned to sources [kW]	92,42	0,00	0,00	0,00	0,05	81,73	3,01	1,26	3,05	1,95
Q returned to sources [kVAR]	32,36	54,38	18,83	60,03	32,20	12,51	30,83	3,87	27,90	4,65
P troughput-grid transport [kW]	179,32	143,67	97,58	167,56	58,75	185,55	133,24	98,82	148,42	53,09
Q troughput-grid transport [kVAR]	122,47	124,45	94,33	130,94	56,92	67,70	91,84	62,78	93,95	25,41
Distribution loss in phase wires [kW]	1,95	2,28	0,65	3,37	0,52	1,23	1,52	0,41	1,84	0,21
Loss in power sources & converters [kW]	23,44	8,60	8,51	7,86	2,61	21,85	10,53	8,17	8,16	1,60
Total power loss w/o neutral wire [kW]	25,39	10,88	9,17	11,22	3,13	23,09	12,05	8,58	10,01	1,81
Efficiency neglecting neutral loss (Total loss/power fed by sources)	92,14%	95,22%	95,42%	94,47%	94,73%	92,55%	94,72%	95,61%	94,99%	96,97%
Estimated loss in neutral wire [kW]	3,88	1,16	0,49	2,01	0,23	3,13	1,01	0,61	0,84	0,09
Total power loss including neutral wire [kW]	29,27	12,04	9,66	13,24	3,35	26,22	13,06	9,19	10,85	1,90
Efficiency considering neutral loss	90,94%	94,71%	95,18%	93,48%	94,34%	91,54%	94,27%	95,30%	94,57%	96,81%
Min node voltage vs Vnom	-1,36%	-2,21%	-1,43%	-2,98%	-0,89%	-1,14%	-2,02%	-1,05%	-2,55%	-0,83%
Node with minimum voltage	3004	1605	915	905	905	1605	1605	915	915	1603
Max node voltage vs Vnom	1,53%	1,47%	0,61%	1,72%	0,70%	1,50%	0,71%	0,44%	0,60%	0,51%
Node with maximum voltage	1009	33	5	33	5	3401	33	5	5	5
Max active power stress of sources (P/Pnom)	100,28%	29,85%	49,49%	19,94%	6,56%	100,89%	100,80%	104,08%	101,09%	99,94%
Node with maximum active power stress	3001	3501	3001	331	331	1005	5	911	5	902
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	108,22%	98,66%	115,92%	104,82%	100,47%	106,65%	113,22%	99,55%	100,57%	89,96%
Node with maximum current stress	3501	2001	1107	2002	5	2001	2001	5	5	902
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	57,54%	62,14%	54,72%	76,72%	48,75%	60,96%	90,73%	52,88%	75,15%	31,33%
Branch with maximum current stress	30	27	68	14	68	95	95	68	95	3
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0	0	0
Max stress	108,2%	98,7%	115,9%	104,8%	100,5%	106,6%	113,2%	104,1%	101,1%	99,9%

At first the results of the voltage deviation, in percentage, are always much lower compared to the maximum value. This is a very good point, for this configuration of the radial grid, because it confirms the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed photovoltaic sources can feed the local loads, so there will be a lower flow of current into the grid. It will bring to a reduction of the total power loss into the feeders and it is another benefit. In particular the voltage deviation, during the day, is greater compared to that during the night. This is because during the night the load consumption decreases compared to that during the day. Moreover the voltage deviation at the first case is greater compared to that at the second case. This is because in the second case all sources can control the generated active power. In this way all the distributed sources generate the active power obtained from an optimal solution. That is a smart management of the sources that characterizes the smart grid.
After in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power fed by sources and the power throughput grid transportation. Subsequently the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters. Also it makes an estimation of the power loss into neutral wires. In this test case the power loss into the sources is always greater than the power loss into the feeders. Moreover the power loss into the sources remains approximately constant between the first and second case. While the power loss in phase wires, in the first case, is greater compared to that at second case. These facts are a direct consequence of the optimal control of the active power generated, from all generators. Indeed in the second case the active power generate, for each sources, is the results of an minimization of the total stress. So SUSI3 calculates an optimal point in which there is a balance between the supply and demand and the total stress is minimized. Furthermore the distribution loss, during the day, is comparable with that during the night. This is because during the night the loads absorption and the photovoltaic generation falls so there will be an increase of current flows into the grid. At last the loss in power sources, during the day, is comparable with that during the night, for the same reason explain previously.
The calculation of the power loss is fundamental for the efficiency. The efficiency of a system is a very important parameter of the power quality that gives an idea of the management of the network. The value of the efficiency is high for each case and it is a good point for the management of the grid in this configuration. Furthermore the value of the efficiency, at first case, is lower compared to that at the second case, except for the first period of the day. This is because in the second case the active power generated from all the sources is the results of an optimization that minimize the total stress and, consequently, the power loss.
After that is important to understand where the sources overstress come from. From the results of the simulation, in the first case, the value of the current stress, into the

sources, is greater than the value of power stress. While, in the second case, the current stress and power stress, of sources, are practically the same. So, in this test case, the limitation of the sources is the value of current that can generate. To solve this active power and current overstress of the sources, a solution is to increase the rated active power of the overstressed sources. Another solution is to install a fully controllable generator in that node to support the already existing source at generation. Moreover the value of power of sources, at first case, is always lower compared to that at second case. While the value of current stress remain approximately constant between the first and second case, considering the same period of the day.
In the following table the overstressed sources are reported for each case.

TABLE 9.4: Overstressed power source at test case 51.

Day time	Node	Overstressed A/Anom	Qsat [kVAR]
1 2 3 4	5	6.44; 1.91; 8.26; 2.84	13.66; 14.22; 13.59; 15.31
1 3	1501	1.53; 1.87	10.78; 11.03
1 3	1107	2.55; 3.25	21.18; 21.82
1 3	2001	1.75; 1.74	21.29; 22.04

In particular all the overstressed sources are always very small because they are property of a domestic or industrial end-user. So, for this reason, is very simple, for those distributed sources, to reach the upper power limit and overcome it. A solution, to solve the power overstress, is to increase the rated active and reactive power of those overstressed sources. Otherwise the dispatcher has to install a new generator, that works as current source, close to the overstressed sources. In this test case the overstressed sources are very close each other, so is possible to solve the power overstress using a new current source, positioned in a strategic node. At last that node becomes a new fully controllable node.
Further more, from the comparison of these two tables, the values of overstress are very similar in some case. Also the overstressed sources, in the first case, are in common with those in the second case, except for the sources at node 2001. Moreover, from these two tables, the number of overstressed sources, in the first case, is lower compared to that in the second case. This is due to the optimal control that exploited more the overstressed sources to reduce the total stress. Indeed, in the second case, the optimal control is on, so it acts on the distributed renewable sources to reduce the flow of current into grid and, consequently, the total stress. As we will see later

the optimal control will reduce the stress into the feeders and will increase the stress of sources. Rather than the total stress will reduce ensuring the load balance.

TABLE 9.5: Overstressed power source at test case 52.

Day time	Node	Overstressed	Apply limit
1 2 3	5	P/Pnom =2.99 A/Anom =1.58; P/Pnom =1.48 A/Anom =1.29; P/Pnom =2.39 A/Anom =1.36	Psat=13.80kW Qsat =6.68kVAR; Psat=13.80kW Qsat =6.36kVAR; Psat=13.80kW Qsat =6.68kVAR
1 2 3 4	902	P/Pnom =3.25; P/Pnom =2.58; P/Pnom =4.18; P/Pnom =1.38	Psat=5.00kW; Psat=5.00kW; Psat=5.00kW; Psat=5.00kW
1 2 3	909	P/Pnom =1.18; P/Pnom =2.20; P/Pnom =1.46	Psat=3.00kW; Psat=3.00kW; Psat=3.00kW
1 3	1501	A/Anom =1.42; A/Anom =1.32	Qsat =10.86kVAR; Qsat =11.06kVAR
1 3	3503	P/Pnom =1.26; P/Pnom =1.74	Psat=-3.00kW; Psat=-3.00kW
1 2 3	910	P/Pnom =1.92; P/Pnom =1.25; P/Pnom =2.57	Psat=3.00kW; Psat=3.00kW; Psat=3.00kW
1 3	911	P/Pnom =1.79; P/Pnom =2.60	Psat=3.00kW; Psat=3.00kW
1 3	1004	P/Pnom =2.50; P/Pnom =1.47	Psat=3.00kW; Psat=3.00kW
1 3	1005	P/Pnom =1.42; P/Pnom =1.26	Psat=3.00kW; Psat=3.00kW
1 3	1010	P/Pnom =1.85; P/Pnom =1.49	Psat=3.00kW; Psat=3.00kW
1	1107	A/Anom =1.62; A/Anom =1.50	Qsat =21.23kVAR; Qsat =22.06kVAR

At last the current stress of feeders are resumed into the previous tables. The value of current stress of feeders, in the case 51, is approximately the same compared to that at case 52, except for the first period of the day. in that period of the day the maximum current stress of feeders, in the first case, is lower compared to that in the second case. Furthermore the value of current stress into the feeders, during the

day, is always greater compared to that during the night. This is because during the night the load consumption decreases compared to that during the day, so the current flows falls. This is a benefit that the distributed sources can bring with an appropriate algorithm. That is a smart management of the sources that characterizes the smart grid.
At last is important to compare the peak values of the results, relative the radial grid, between the case 51 and 52 to understand if the optimal control, of active power, gives the best results.

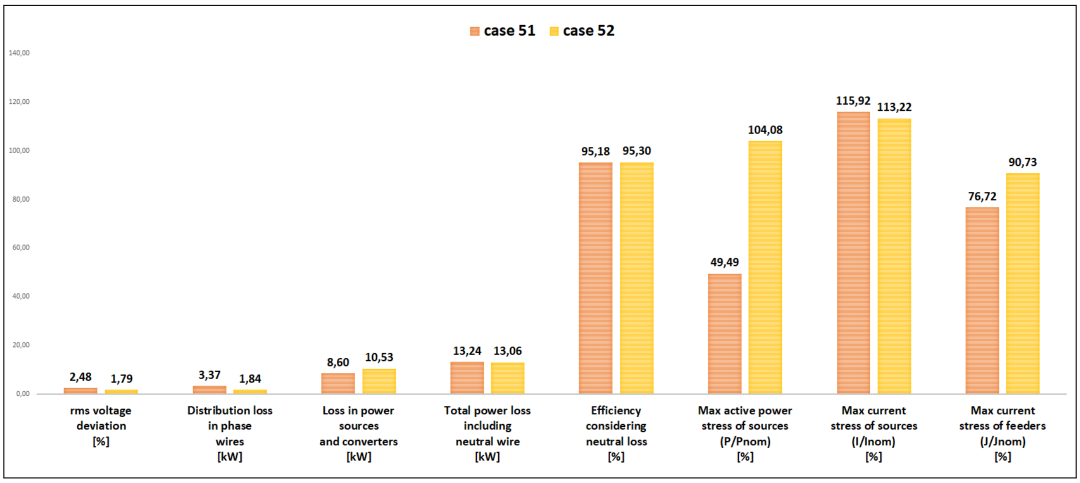

FIGURE 9.1: Comparison between the results of case 51 and 52.

From the previous graph the optimal control gives the best results in terms of voltage deviation, distribution loss in phase wires and maximum current stress into sources. Moreover the efficiency and the total power loss remain constant between the first and second case. While for the power loss of sources, the maximum power stress of sources and maximum current stress of feeders the best configuration of the radial grid is without control of the active power. Since the overstressed sources are always a small sources, the current stress into the sources is not a problem because it is easily solved adding a new generator in that node or in a near one.
So, for the radial grid, the optimal control gives the best results and it allows a better management of the system.

9.3 Analysis of the results relative at meshed grid.

In this section the results of the analysis, done with SUSI3 and Source Locator, are reported in these tables. At first the results of the voltage deviation, in percentage, are always much lower compared to the maximum value. This is a very good point, for this configuration of the radial grid, because it confirms the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed photovoltaic sources can feed the local loads so there will be a lower flow of current into the grid.

TABLE 9.6: Main results of the simulation, using SUSI3, of the meshed grid.

Test case	51	51	51	51	51	52	52	52	52	52
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099
rms voltage deviation / Vnom	0,91%	1,68%	0,62%	2,14%	0,72%	0,78%	1,24%	0,55%	1,62%	0,52%
P entering grid at node 0 [kW]	-33,51	96,48	30,57	121,90	43,17	-16,15	63,90	18,01	84,92	21,59
Q entering grid at node 0 [kVAR]	7,91	-12,68	-1,98	-11,87	-6,83	2,29	2,67	6,10	4,01	2,98
P absorbed by loads [kW]	231,53	228,24	201,72	202,39	59,70	226,28	221,66	198,49	197,90	58,46
Q absorbed by loads [kVAR]	115,06	107,01	97,82	93,65	28,50	115,13	109,33	98,65	96,15	29,09
P fed by sources [kW]	320,33	230,72	202,22	205,81	60,35	301,00	225,80	199,98	202,68	60,54
Q fed by sources [kVAR]	154,76	154,39	104,99	159,52	62,78	121,90	128,27	101,32	129,02	35,94
P returned to sources [kW]	87,43	0,26	0,00	0,43	0,14	73,89	3,07	1,15	3,21	1,92
Q returned to sources [kVAR]	38,86	57,65	8,81	73,91	40,61	6,21	17,69	2,42	30,68	6,64
P troughput-grid transport [kW]	188,21	156,23	108,84	171,44	59,73	183,49	131,85	104,31	150,66	54,01
Q troughput-grid transport [kVAR]	127,13	126,02	83,88	140,45	62,70	66,79	88,31	66,77	105,17	29,68
Distribution loss in phase wires [kW]	1,37	2,21	0,50	2,99	0,50	0,83	1,06	0,34	1,57	0,16
Loss in power sources & converters [kW]	23,36	12,26	7,72	11,95	3,43	19,82	10,04	7,01	9,37	1,38
Total power loss w/o neutral wire [kW]	24,73	14,47	8,22	14,94	3,93	20,65	11,11	7,35	10,95	1,54
Efficiency neglecting neutral loss (Total loss/power fed by sources)	92,28%	93,73%	95,94%	92,74%	93,49%	93,14%	95,08%	96,33%	94,60%	97,46%
Estimated loss in neutral wire [kW]	2,63	0,43	0,55	0,76	0,09	1,98	0,74	0,51	0,76	0,10
Total power loss including neutral wire [kW]	27,37	14,90	8,77	15,70	4,02	22,64	11,85	7,86	11,71	1,64
Efficiency considering neutral loss	91,46%	93,54%	95,66%	92,37%	93,34%	92,48%	94,75%	96,07%	94,22%	97,29%
Min node voltage vs Vnom	-0,93%	-2,34%	-0,80%	-2,70%	-0,95%	-1,04%	-1,92%	-1,52%	-2,11%	-0,79%
Node with minimum voltage	3004	1605	3004	1601	1601	3004	3004	3004	3004	3001
Max node voltage vs Vnom	1,63%	0,34%	0,37%	0,34%	0,15%	1,64%	0,19%	0,14%	0,07%	0,11%
Node with maximum voltage	3402	33	3402	2	2	3402	1009	1009	1009	5
Max active power stress of sources (P/Pnom)	100,06%	31,50%	49,59%	19,35%	6,58%	100,40%	108,80%	100,14%	105,53%	100,09%
Node with maximum active power stress	1604	1006	902	331	331	3402	1602	5	1602	5
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	115,28%	113,11%	99,56%	99,34%	99,89%	101,08%	114,79%	99,62%	109,99%	92,16%
Node with maximum current stress	2103	1503	5	1008	5	3506	1107	5	1009	5
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	62,95%	78,87%	54,91%	93,93%	49,08%	52,80%	52,59%	52,59%	56,93%	19,61%
Branch with maximum current stress	68	7	68	7	68	30	28	28	28	28
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0	0	0
Max stress	115,3%	113,1%	99,6%	99,3%	99,9%	101,1%	114,8%	100,1%	110,0%	100,1%

It will bring to a reduction of the total power loss into the feeders and it is another benefit. In particular the voltage deviation, during the day, is greater compared to that during the night. This is because during the night the load consumption decreases compared to that during the day. Moreover the voltage deviation, at first case, is greater compared to that at the second case. This is because in the second case all sources can control the generated active power. In this way all the distributed sources generate the active power obtained from an optimal solution that minimize the total stress into the network. That is a smart management of the sources that characterizes the smart grid.
After in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power feed by sources and the power throughput grid transportation. Subsequently the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters. Also it makes an estimation of the power loss into neutral wires. In this test case the power loss into the sources is always greater than the power loss into the feeders. This happen because the current flows into the grid is very small for the same reason explain before for the value of voltage deviation. This fact leads to a reduction of power loss in phase wires and an increase of power loss in sources. In particular the power loss into the sources at first case is greater compared to that at the second case. While the power loss into the feeders, in the first case, is greater compared to that at second case. This is a direct consequence of the control of the active power generate, from all generators. Indeed in the second case the active power generate, for each sources, is the results of an minimization of the stress. So SUSI3 calculates an optimal point in which there is a balance between the supply and demand and the total stress is minimized. Furthermore the distribution loss, during the day, is comparable with that during the night. This is because during the night the loads absorption and the photovoltaic generation falls so there will be an increase of current flows into the grid. At last the loss in power sources, during the day, is comparable with that during the night, for the same reason explain previously.
The calculation of the power loss is fundamental for the efficiency. The efficiency of a grid is a very important parameter of the power quality that gives an idea of the management of the network. The value of the efficiency is high for each case and it is a good point for the management of the grid in this configuration. Furthermore the value of the efficiency, in the first case, is lower compared to that at the second case. This is because in the second case the active power generated, from all the sources, is the results of an optimization that minimize the total stress and, consequently, the power loss.
After that is important to understand where the sources overstress come from. From the results of the simulation, in the first case, the value of the current stress is greater compared to the value of power stress. While, in the second case, the value of power

stress and current stress, of sources, are practically equal, considering the same period of the day. So, in this test case, the limitation of the sources are the values of current and power that can generate. To solve this active power and current overstress of the sources, a solution is to increase the rated active power of the overstressed sources. Another solution is to install a fully controllable generator in that node to support the already existing source at generation. In the following table the overstressed sources are reported for each case.

TABLE 9.7: Overstressed power source at test case 51.

Day time	**Node**	**Overstressed A/Anom**	**Qsat [kVAR]**
1 2 3	5	5.77; 1.73; 7.24; 2.54	14.48; 14.42; 14.71; 15.33
1 3	1107	1.92; 2.17	21.46; 22.05
1 3	1501	1.25; 2.10	10.73; 11.02
1 3	1009	2.09; 2.48	21.24; 21.95
1 3	1006	1.84; 1.29	10.57; 11.02
1 3	1007	1.69; 1.34	10.70; 11.03
1 3	1008	1.58; 1.22	10.76; 11.05
1 3	1004	1.70; 2.66	3.21; 3.29
1 3	1005	1.41; 1.78	3.23; 3.31
1 3	1010	2.03; 2.65	3.20; 3.29
1 3	2001	1.46; 1.42	21.54; 22.10

In particular the overstressed sources are always very small because they are property of domestic or industrial end-user. So is very simple to reach the upper limit of active and reactive power and overcome it. As anticipate before, a solution is to connect a new generator, in a new or already existing fully controllable node, close to those nodes in which there is the overstressed sources. In this test case the overstressed sources are very close each other, except for the generator at node 3503.

Apart from that generator, with only a new source, that works as current source, is possible to solve or reduce the power overstress of distributed sources. Indeed the new current source will support the local generators at load balance and minimization of the total stress.

TABLE 9.8: Overstressed power source at test case 52.

Day time	Node	Overstressed	Apply limit
1 2 3 4	5	P/Pnom =3.40 A/Anom =1.38; P/Pnom =1.11; P/Pnom =3.42 A/Anom =1.40; P/Pnom =1.17	Psat=13.80kW Qsat =6.39kVAR; Psat=13.80kW; Psat=13.80kW Qsat =6.32kVAR; Psat=13.80kW
1 2 3	902	P/Pnom =1.35; P/Pnom =1.42; P/Pnom =2.19	Psat=5.00kW; Psat=5.00kW; Psat=5.00kW
1 3	3503	P/Pnom =1.31; P/Pnom =1.83	Psat=-3.00kW; Psat=-3.00kW
1 3	909	P/Pnom =2.04; P/Pnom =2.70	Psat=3.00kW; Psat=3.00kW
1 3	910	P/Pnom =1.58; P/Pnom =2.02	Psat=3.00kW; Psat=3.00kW
1 3	911	P/Pnom =1.12; P/Pnom =1.60	Psat=3.00kW; Psat=3.00kW
1 3	1004	P/Pnom =1.39; P/Pnom =1.80	Psat=3.00kW; Psat=3.00kW
1 3	1005	P/Pnom =2.01; P/Pnom =2.00	Psat=3.00kW; Psat=3.00kW
1 3	1010	P/Pnom =1.78; P/Pnom =1.98	Psat=3.00kW; Psat=3.00kW
3	1107	A/Anom =1.29	Qsat =22.11kVAR

At last the current stress of feeders are resumed into the previous tables. The value of current stress of feeders, in the case 51, is always lower compared to that at case 52. This happens because at case 52 there the optimal control of active and reactive power generated from all sources is active and the distribution generators participate at load balance. This situation leads to a reduction of the current flows into the grid. So the feeders will be less stressed and the power loss will decrease compared to those at case 51. Moreover the value of current stress into the feeders, during the day, is always greater compared to that during the night. This is because during the night the load consumption decreases compared to that during the day, so the

current flows falls. This is a benefit that the distributed sources can bring with an appropriate algorithm. That is a smart management of the sources that characterizes the smart grid.
At last is important to compare the results, of the meshed grid, between the case 51 and 52 to understand if the optimal control of active power gives the best results.

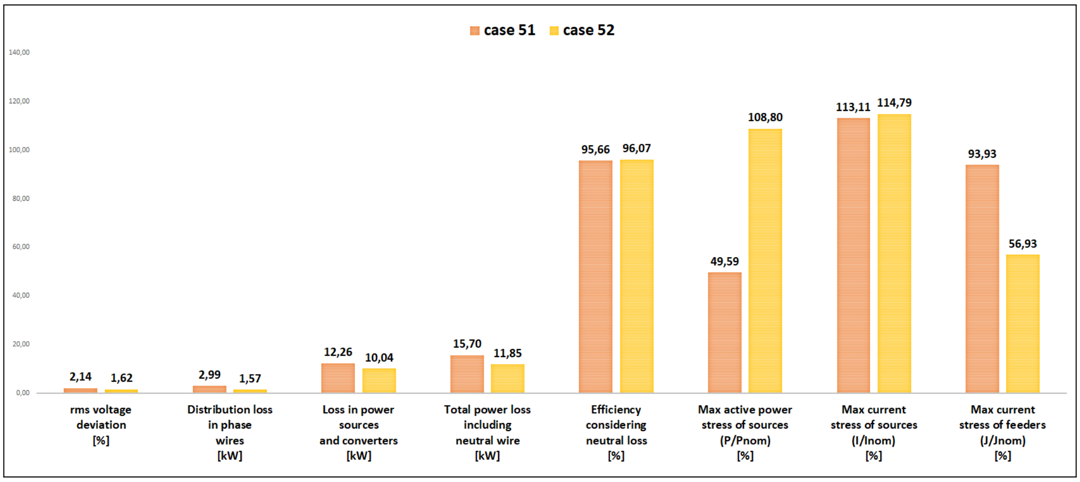

FIGURE 9.2: Comparison between the results of case 51 and 52.

From the previous graph the optimal control gives the best results in terms of voltage deviation, distribution loss in phase wires, power loss in phase wires, total power loss and maximum current stress of feeders. While there are no difference of the efficiency and maximum current stress of feeders between the two cases. Moreover the value of active stress into the sources, in the first case, is lower compared to that in the second case. Since the overstressed sources are always a small sources, the current stress into the sources is not a problem because it is easily solved adding a new generator in that node or in a near one as described above.
So, for the meshed grid, the optimal control gives the best results and it allows a better management of the system.

9.4 Comparison between the radial and meshed network.

At last is important to understand which configuration of the distributed grid gives the best results for each case.
In the following graph the peak values of the radial and meshed grid, related at case 51, are reported. From the previous graph, in the meshed grid, the voltage deviation and the distribution loss in phase wires are lower compared to those at radial grid. Furthermore the efficiency and the current stress and power stress of sources remain constant between the two cases. The negative aspects, of the meshed grid, are the maximum current stress into the feeders, the power loss into sources and the total power loss. Rather than, as previously described, the overstressed sources are very small, so is very simple to reach the upper limit of active and reactive power and

overcome it.
So, for the case 51, the meshed grid gives the best results, both considering the graph and the results reported in the previous tables, in terms of management the grid and power quality.

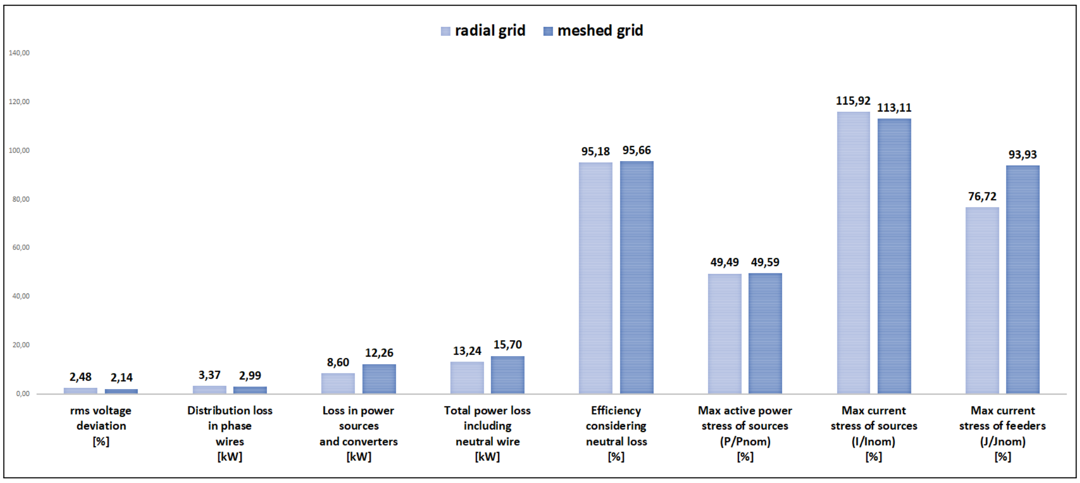

FIGURE 9.3: Comparison between the results of the radial and meshed grid at case 51.

While the comparison between the peak value of radial and meshed grid, related at case 52, are reported in the following graph.

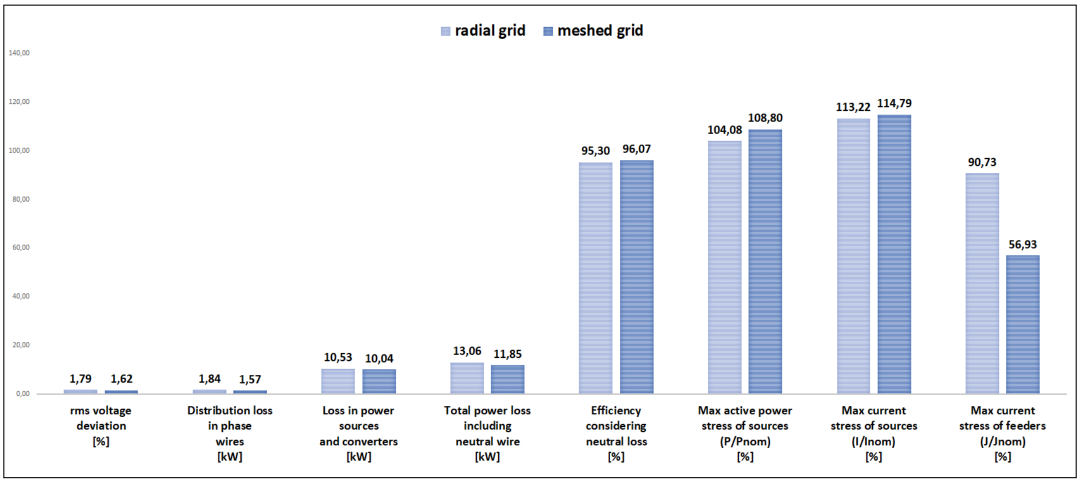

FIGURE 9.4: Comparison between the results of the radial and meshed grid at case 52.

In the meshed grid the voltage deviation, the distribution loss in phase wires, the loss into sources and the total power loss, are lower compared to those at radial grid. Furthermore the efficiency, the active power stress and current stress of sources remain, approximately, constant between the two configurations of the grid. While the maximum current stress of feeders, in the meshed grid, is lower compared to that in the radial grid. This is due to the new paths that, the meshed grid, introduce into the system. Indeed with the addition we create new paths in which the current

can flow. So, generally, the concentration of the current will reduce and this lead to a reduction of the current stress of feeders.
So the meshed grid gives the best results in terms of management and the power quality of the system.
In conclusion, considering the results reported in the previous tables and the graphs, the meshed grid, with optimal control, allows us a better management of the system.

Chapter 10

Demand Response

At first this chapter deals with the description of the boundaries related at the test case defined for the radial and meshed network. This test case is related at an active grid under demand response conditions. Subsequently the results of the simulation are reported into the tables and they are used for make comparisons. The results come from the analysis done with SUSI3 and Source Locator.

10.1 Description of the sixth case.

In this test case both grids are work under demand response conditions. Demand Response is going to become a part of the system operations in the smart grid driven restructured power system around the world in the near future. Demand response implementations are more active at the retail level than the wholesale level. To enhance competition at the retail level, separate entities called retailers have also come into the scenario. The increased retail level competition is associated with a variety of problems which can be categorized as market based and network based problems. The former problems occur when the generators or the retailers face financial risks caused by spot price volatility in the wholesale electricity market. The latter problems occur when TSO and DSOs have to maintain reliable power supply during times of peak demand or low operating reserves or when constrained networks are operating at their limits. Traditionally, problems of the latter type have been handled single sidedly, by the generating utilities who have to either ensure a security margin of generation to be always available to be dispatched when asked to do so by the ISO or in the opposite case have to reduce generation to bring the network from a constrained state to the normal state. A resource which is left unused is the demand side resource which can also be helpful in such situations. Demand Side Management is a global term that includes a variety of activities such as: load management, energy efficiency, energy saving. The problems mentioned above can be categorized as short term problems whereas problems such as environmental effects of burning coal to produce electricity can be categorized as long term problems. Demand Side Management schemes like energy efficiency and energy saving schemes are potential inhibitors of such problems whereas the short term problems can be tackled by efficient load management programs which are collectively referred to as Demand Response. According to Federal Energy Regulatory Commission, Demand Response is defined as a changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. The end-use customers can also be the customers who are participating in the wholesale market operations. Based on how the changes in electric usage are implemented the demand response can be classified as shown in the following figure. Besides the motivations as to why involve demand side into the operational aspects of the system other benefits of demand response are listed below:

1. Demand response can reduce system peak load in the long term and therefore postpone the need for building new power plants, leading to considerable environmental impacts.

2. TSO can benefit from DR by being able to improve reliability of the transmission network. Improved network reliability results from reducing the probability of forced outages when system reserves fall below desired levels. By reducing electricity demand at critical times, like when a generator or a transmission line is unexpectedly lost, DR dispatched by the TSO can help to return system reserves to pre-contingency levels.

3. DSO can use demand response for managing network constraints at the distribution level, like relieving the voltage constrained power transfer problem, relieving congestion in the distribution substations and simplifying outage management and improving the quality of supply. During incidents of congestion or peak periods Demand Response relieves the components of the network from the undesirable stress. This way a gain in service quality and reliability is achieved. The load curtailment during incidents is expected to reduce the monetary global value of the non-supplied load.

4. In order to cover most of these risks the retailers can ask their consumers to reduce their consumption during the times when spot prices are most volatile and reach their peaks, provided the customers can receive financial reward for such decrease in consumption.

5. The short term impacts of demand response on electricity markets leads to financial benefits of both the utility and the consumers.

6. Deployment of new technologies like, distributed generation, for example solar, small wind, geothermal, and storage also motivate the inclusion of demand response as a key component for the smart grid.

In the following figure is represent an example of smart demand response. In that figure are highlighted the communication links between the distributed generations and the centralized control and the communication between the loads and the distributed pinning control. The pinning control is a feedback control strategy for synchronization and consensus of complex dynamical networks composed of a series of TCL aggregators. The TCL aggregators, those are aggregate thermostatically controlled loads, are good candidates for providing load following services in power systems. So the analysis of this operative situation is very important because it will be expected in the next future.

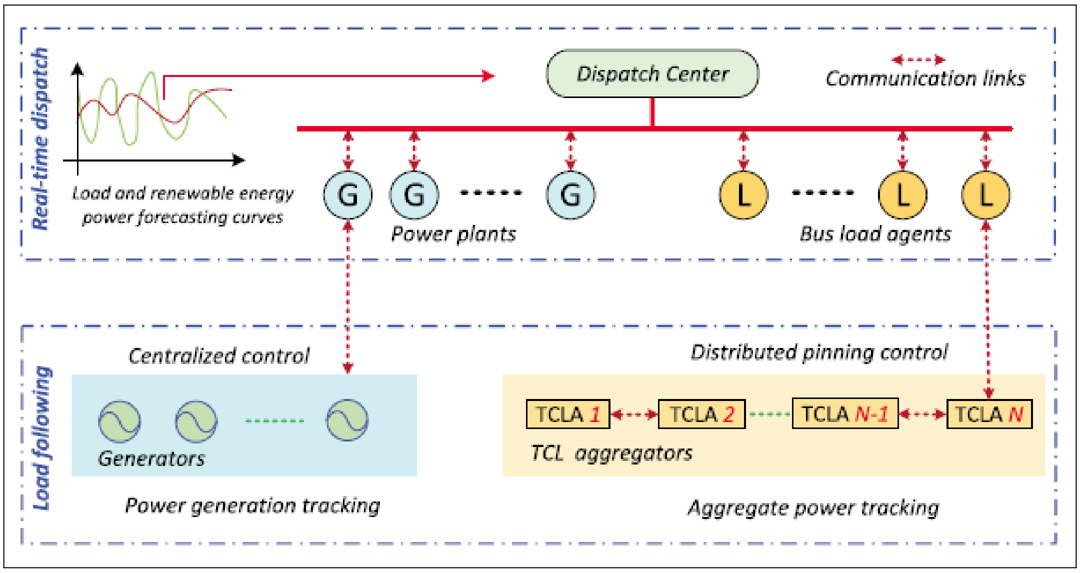

FIGURE 10.1: Demand response load following structure of source and load systems.

The first case, also called case 61, all sources feed generated active power and control the reactive power. Furthermore at PCC_0 returns 50% of rated active and reactive power and the PCC_1 with the energy storage system, that is voltage source, are the slack node. While the active and reactive power of the load are calculated with the formula described at the beginning.

TABLE 10.1: Boundary of case 61.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P	Source bounded Q
All sources feed generated P All sources control Q Actual loads	-1		6	100	100	4	100	
PCC0 returns 50 kW and 50 kVAR	1	0				9	-50	-50
PCCx slack nodes	2	10				-2		
UI slack nodes (reset bounds and power limits)	2	11				-2		
ES unbounded	2	12				1		

The second case, also called case 62, all sources control the active and reactive power. Furthermore at PCC_0 returns 50% of rated active and reactive power while the PCC_1, with the energy storage system that works as voltage source, that is voltage sources, are the slack node. While the active and reactive power of the load are calculated with the previous formula.

TABLE 10.2: Boundary of case 62.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P	Source bounded Q
All sources control P and Q Actual loads	-1		6	100	100			
PCC0 returns 50 kW and 50 kVAR	1	0				9	-50	-50
PCCx slack nodes	2	10				-2		
UI slack nodes (reset bounds and power limits)	2	12				-2		
ES unbounded	2	11				1		

The third case, also called case 63, all sources feed generated active power and control the reactive power. Furthermore at PCC_1 returns 20% of rated active power and 30% of rated active power and the PCC_0 with the energy storage system, that is voltage sources, are the slack node. While the active and reactive power of the load are calculated with the previous formula.

TABLE 10.3: Boundary of case 63.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P [%]	Source bounded Q [%]
All sources feed generated P All sources control Q Actual loads	-1		6	100	100	4	100	
PCCx return 20% of rated P and 30% of rated Q	2	10				3	-20	-30
UI slack nodes (reset bounds and power limits)	2	11				-2		
ES unbounded	2	12				1		

The fourth case, also called case 64, all sources control the active and reactive power. Furthermore at PCC_1 returns 20% of rated active power and 30% of rated active power and the PCC_0 with the energy storage system, that is voltage sources, are the slack node. While the active and reactive power of the load are calculated with the previous formula.

TABLE 10.4: Boundary of case 64.

Case description	Boundary type	Number of bounded entity	Load bound code	Load bounded P [%]	Load bounded Q [%]	Source bound code	Source bounded P[%]	Source bounded Q[%]
All sources control P and Q Actual loads	-1		6	100	100			
PCCx return 20% of rated P and 30% of rated Q	2	10				3	-20	-30
UI slack nodes	2	11				-2		
ES unbounded	2	12				1		

10.2 Analysis of the results of cases 61 and 62, related at radial grid.

In this section the results of the analysis, done with SUSI3 and Source Locator, are reported in these tables.
At first the results of the voltage deviation, in percentage, are always lower compared to the maximum value. This is a very good point, for the radial grid, because it confirms the advantages of the distributed generations also under demand response conditions. Indeed the voltage deviation is small because the distributed generators, such as the distributed renewable sources and energy storage systems, can feed the local loads so there will be a lower current flow into the grid. It will bring to a reduction of the total power loss into the feeders and it is another benefit. In particular the voltage deviation, during the night, is comparable with that during the day. This is because during the night the load consumption and the photovoltaic generation decreases compared to that during the day. So the load will be feeded by the PCC_s and the energy storage systems and it will bring to an small increase of voltage deviation. Moreover the voltage deviation, in the first case, is always greater compared to that at the second case. This is because in the second case all sources can control the generated active power. In this way all the sources generate the active power obtained from an optimal solution. That is a smart management of the sources that characterizes the smart grid.
After in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power feed by sources and the power throughput grid transportation. Subsequently the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters. Also it makes an estimation of the power loss into neutral wires. In the cases 61 and 62, the power loss into the sources is always greater than the power loss into the feeders. This happen because the current flows into the grid is very small, for the same reason explain before for the value of voltage deviation, and the distributed sources are so exploited. Furthermore, from the results of the simulation, a lot of distributed sources are are exploited a lot, so there will be an increase of power loss into sources. In particular the power loss into the sources, at first case, is always greater compared to that at the second case. Also the distribution loss in phase wires, in the first case, is greater compared to that at second case. These two facts are a direct consequence of the optimal control of the active power generated, from all generators. Indeed, in the second case, the active power generated, for each sources, is the results of an minimization of the stress and, consequently, the power loss. So SUSI3 calculates an optimal point in which there is a balance between the supply and demand and the total stress is minimized. Moreover the distribution loss and the loss in power sources, during the day, are comparable, respectively considering the same period of the day, with those during the night.

TABLE 10.5: Main results of the simulation, using SUSI3, of the radial grid, related at case 61 and 62.

Test case	61	61	61	61	61	62	62	62	62	62
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160
rms voltage deviation / Vnom	1,68%	3,32%	2,32%	3,56%	2,72%	1,71%	2,81%	1,99%	2,94%	2,22%
P entering grid at node 0 [kW]	-50,30	-49,56	-49,63	-49,54	-49,60	-50,31	-50,20	-50,05	-50,21	-50,08
Q entering grid at node 0 [kVAR]	-50,02	-49,93	-50,00	-49,95	-50,01	-50,02	-50,16	-50,08	-50,16	-50,10
P absorbed by loads [kW]	245,34	239,97	212,01	211,47	61,92	245,73	230,69	203,60	204,05	59,82
Q absorbed by loads [kVAR]	107,64	113,45	101,15	101,10	29,49	107,76	111,18	99,48	98,80	28,73
P feed by sources [kW]	338,65	363,33	306,11	340,45	161,50	336,48	336,54	287,45	312,91	142,67
Q feed by sources [kVAR]	153,98	212,93	177,69	203,29	131,11	161,26	190,39	157,65	176,86	115,62
P returned to sources [kW]	90,55	112,69	89,79	116,49	93,62	88,34	99,02	80,95	101,11	79,11
Q returned to sources [kVAR]	94,11	143,22	123,09	145,43	147,24	101,26	124,85	105,71	123,51	133,77
P troughput-grid transport [kW]	191,51	282,42	204,70	307,35	160,11	206,85	247,04	190,08	267,81	136,69
Q troughput-grid transport [kVAR]	159,63	216,26	190,28	218,84	171,77	158,25	189,58	161,90	191,03	156,99
Distribution loss in phase wires [kW]	2,76	10,66	4,31	12,49	5,96	2,42	6,84	2,90	7,74	3,74
Loss in power sources & converters [kW]	24,58	25,98	19,64	27,67	16,11	25,82	22,39	18,24	22,94	14,48
Total power loss w/o neutral wire [kW]	27,34	36,64	23,95	40,16	22,07	28,23	29,23	21,14	30,68	18,22
Efficiency neglecting neutral loss (Total loss/power feed by sources)	91,93%	89,92%	92,18%	88,20%	86,34%	91,61%	91,32%	92,64%	90,19%	87,23%
Estimated loss in neutral wire [kW]	2,26	2,20	2,24	2,58	2,02	3,00	3,13	2,47	3,07	2,06
Total power loss including neutral wire [kW]	29,60	38,84	26,19	42,74	24,09	31,24	32,36	23,61	33,76	20,28
Efficiency considering neutral loss	91,26%	89,31%	91,44%	87,45%	85,09%	90,72%	90,39%	91,79%	89,21%	85,79%
Min node voltage vs Vnom	-0,55%	-0,17%	0,00%	-0,26%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Node with minimum voltage	901	1605	0	1602	0	0	0	0	0	0
Max node voltage vs Vnom	2,76%	5,88%	3,73%	6,60%	4,11%	3,10%	5,19%	3,25%	5,39%	3,93%
Node with maximum voltage	2103	917	917	917	2803	3402	917	917	917	1602
Max active power stress of sources (P/Pnom)	102,01%	181,77%	102,07%	207,58%	112,04%	107,01%	141,23%	102,52%	163,21%	103,11%
Node with maximum active power stress	3501	2803	2803	2803	2803	1602	2803	3503	2803	3503
Number of overstressed sources (power)	0	1	0	1	1	0	1	0	1	0
Max current stress of sources (I/Inom)	118,56%	130,48%	106,87%	147,81%	103,76%	117,78%	103,53%	101,54%	115,76%	118,90%
Node with maximum current stress	32	2803	1107	2803	3501	1107	2801	2002	2803	1801
Number of overstressed sources (current)	0	1	0	1	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	85,85%	155,16%	114,92%	164,87%	113,12%	69,82%	134,66%	97,29%	142,08%	95,00%
Branch with maximum current stress	19	27	27	27	27	27	27	27	27	27
Number of overstressed feeders (current)	0	5	1	7	1	0	1	0	3	0
Max stress	118,6%	181,8%	114,9%	207,6%	113,1%	117,8%	141,2%	102,5%	163,2%	118,9%

This is because during the night the absorption, of the loads, and the photovoltaic generation fall so there will be an increase of current flows into the grid. Those are some benefits that the photovoltaic sources and energy storage systems, with an appropriate algorithm, can bring into the grid, also in a demand response operative condition. That is a smart management of the sources that characterizes the smart grid.

The calculation of the power loss is fundamental for the efficiency. The efficiency of a system is a very important parameter of the power quality that gives an idea of the management of the network. The value of the efficiency is small for each case and it isn't a good point for the management of the grid in this configuration. Moreover the value of the efficiency, in the first case, is always lower compared to that at the second case. This is because, in the second case, the active power generated from all the sources is the results of an optimization. Furthermore the value of the efficiency of this test case are lower compared to that at the first test case. This is because at the first test case the distributed sources didn't participate at generation so the stress into the sources was very small consequently the power loss, into the sources, in the first test case, is lower compared to that at this test case. In this test case the sources are very stressed so there will be an increase of power loss into the sources and a reduction of the power loss into the feeders because the current flow, into the grid, decrease. So the increase of the power loss into the sources is greater compared to the reduction of the power loss into the feeders, between the first test case and this test case, and this situation involves in a sensible reduction of the efficiency.

After that is important to understand where the sources overstress come from. From the results of the simulation, into the sources, the value of the current stress is comparable with the value of power stress. So, in this test case, the limitation of the sources is the value of current and active power that can generate. To solve this active power and current overstress of the sources, a solution is to increase the rated active power of the overstressed sources. Another solution is to install a fully controllable generator in that node to support the already existing source at generation. Furthermore the value of power and current stress of sources, in the first case, is always greater compared to that at second case. This is because the power flow related at second case is the result of an optimization to minimize the total stress. For the case 61 and 62 the tables of the power limits for each overstressed source aren't reported because there are a lot overstressed sources. Rather than, all overstressed sources are very small because they are property of domestic or industrial end-user, so is very simple to reach the upper limit, of active and reactive power, and overcome it.

Subsequently the current stress of feeders are resumed into the previous tables. The value of current stress of feeders, in the case 61, is always greater compared to that at case 62. This happens because at case 62 there the optimal control, to minimize the total stress, of active and reactive power generated from all sources is on and the distribution generators participate at load balance. This situation leads to a reduction of the current flows into the grid. So the feeders will be less stressed and the power

loss will decrease compared to those at case 61. Furthermore the value of current stress into the feeders, during the day, is always greater compared to that during the night. This is because during the night the load consumption decreases compared to that during the day, so the current flows falls. This is a benefit that the distributed sources can bring with an appropriate algorithm. That is a smart management of the sources that characterizes the smart grid.
After that the overstressed feeders of case 61, with the related value of overstress, are reported into the following table. The number of current overstress of feeders is quite high in some period of the day. Also the the overstressed feeders are in common between the different period of the day and they are close each other. So with a smart decision concerning where to install a fully controllable generator is possible to solve all this current overstress. In particular that node will be the new fully controllable node, if it was not before.

TABLE 10.6: Results of current stress into the feeders considering the radial grid, related at case 61.

Test case	**Period of the day**	**Branch number**	**Phase**	**Overstress J/Jnom**
61	1	27	1	1.17
			2	1.31
			3	1.55
61	1	29	3	1.16
61	1	125	3	1.13
61	2	27	3	1.15
61	3	27	1	1.35
			2	1.44
			3	1.65
61	3	29	3	1.24
61	3	125	1	1.09
			2	1.19
			3	1.21
61	4	27	3	1.13

The results resumed into the following table are related at the analysis with Source Locator in which the new generator, that works as current source, has an apparent power equal to 50 kVA. The proposed solution is to install this generator in the node 31 that is near the previous overstressed lines. With that solution is possible to control the total current into the overstressed lines 27 and 29, but is not possible to control the current into the line 125. Another solutions have been tried to solve the current stress in all the overstressed lines together without success. The proposed solution gives the best results in terms of control of the current into the lines that are overstressed. So, to solve the current overstress into the feeders 125 is possible to increase its section, so the ampacity will increase.

TABLE 10.7: Results of the analysis made with Source Locator related at case 61.

Fully controllable node	Power generate from that node [kVA]	Number of controlled branches	Total control factor J/Jnom	List of control branches (control factor)
31	50.00	16	19.05	112(3.04), 27(2.03), 6(1.60), 7(1.60), 3(1.57), 29(1.52), 24(1.28), 26(1.28), 23(0.89), 10(0.87), 22(0.86), 18(0.86), 5(0.50), 4(0.50), 2(0.33), 1(0.33)
917	47.14	12	8.19	24(1.21), 26(1.21), 23(0.84), 125(0.82), 10(0.82), 18(0.81), 22(0.81), 126(0.51), 6(0.44), 7(0.44), 5(0.14), 4(0.14)
2803	47.14	8	8.31	6(2.07), 7(2.07), 3(1.87), 5(0.65), 4(0.65), 1(0.39), 2(0.39), 126(0.23)
1602	5.55	6	1.35	14(0.51), 84(0.34), 11(0.14), 13(0.13), 6(0.11), 7(0.11)
1604	5.55	6	1.35	14(0.51), 86(0.34), 11(0.14), 13(0.13), 6(0.11), 7(0.11)

After that the overstressed feeders, related at case 62, are reported in the following table. In this case the overstressed feeders are the same at those of the case 61. Furthermore the value of current overstress is less in the second case as the number of overstressed lines. This is because, in the second case, the optimal control, of the total stress, acts on the active power generated by the distributed sources to reduce the total stress. In this way the flow of active power, into the grid, will decrease and, consequently, the current stress of feeders.

TABLE 10.8: Results of current stress into the feeders considering the radial grid, related at case 62.

Test case	Period of the day	Branch number	Phase	Overstress J/Jnom
62	1	27	3	1.35
62	3	27	3	1.42
62	3	29	3	1.07
62	3	125	3	1.08

In the following table the result of the analysis with Source Locator are reported. Those results are obtained considering a new generator, that will works as current source, link in a fully controllable node, with an apparent power equal to 50 kVA, like in the previous case. The proposed solution is to install that generator at node 31. In this situation with the new generator is possible to control totally the lines 27 and 29, while there is no solution to control the current into the line 125. Another solutions have been tried to solve the current stress in all the overstressed lines together without success. The proposed solution gives the best results in terms of control of the current into the lines that are overstressed. So, to solve the current overstress into the line 125 is possible to increase its section, so the ampacity will increase. So from the previous results of Source Locator the new generators, linked at node 31, can control the current into the branches 27 and 29 in both cases 61 and 62. While it cannot control the current into the line 125 in both cases.

TABLE 10.9: Results of the analysis made with Source Locator, considering the radial grid, related at case 62.

Fully controllable node	Power generate from that node [kVA]	Number of controlled branches	Total control factor J/Jnom	List of control branches (control factor)
31	50.00	16	19.05	112(3.04), 27(2.03), 6(1.62), 7(1.62), 3(1.54), 29(1.52), 24(1.28), 26(1.28), 23(0.89), 10(0.87), 22(0.86), 18(0.86), 5(0.50), 4(0.50), 2(0.32), 1(0.32)
917	47.14	10	7.91	24(1.21), 26(1.21), 23(0.84), 125(0.82), 10(0.82), 18(0.81), 22(0.81), 126(0.51), 6(0.44), 7(0.44)
2803	47.14	8	8.30	6(2.07), 7(2.07), 3(1.86), 5(0.65), 4(0.65), 1(0.39), 2(0.39), 126(0.23)
5	5.11	3	0.72	36(0.31), 6(0.20), 7(0.20)
1602	5.55	2	0.85	14(0.51), 84(0.34)
1604	5.55	2	0.85	14(0.51), 86(0.34)

At last is important to compare the results of the result of radial grid between the case 61 and 62 to understand if the optimal control of active power gives the best results. The following graph shows the comparison of the peak value of the results, relative at radial grid, of cases 61 and 62.

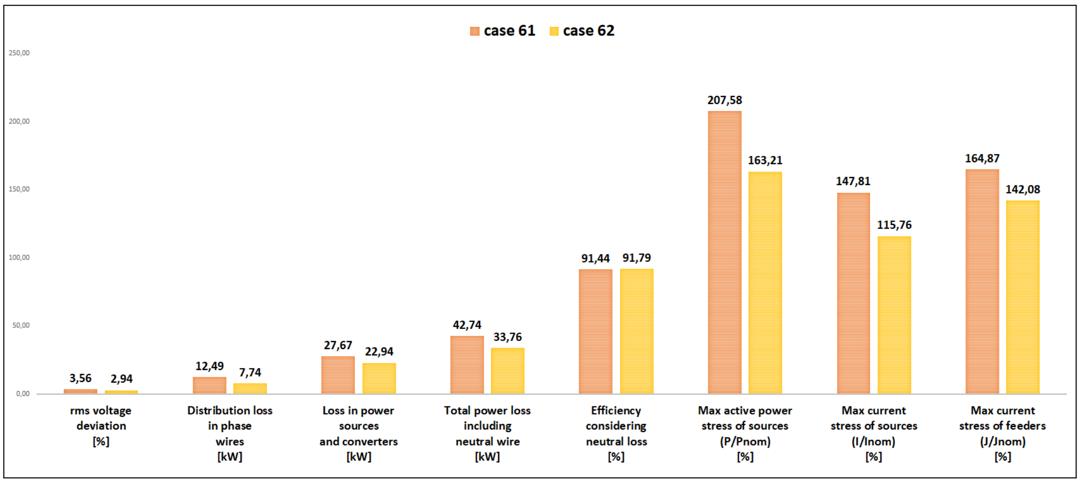

FIGURE 10.2: Comparison between the results of case 61 and 62.

From the previous graph the optimal control gives the best results in terms of the voltage deviation and all the rest of the electrical quantities considered in the previous graph. In particular only the efficiency remains constant between the two cases. Moreover the optimal control of the active power brought a reduction of the peak value of the maximum active power stress of source and it is a very good point. Also the optimal control has reduced the peak of maximum current stress of sources and feeders, so it leads a lot of benefits into the system.
So, for the radial grid, the optimal control of the active power gives the best results

in terms of management of the system. Those are benefits that characterize the smart grid.

10.3 Analysis of the results of cases 63 and 64, related at radial grid.

After that the results of the simulation with SUSI3 and Source Locator, related at case 63 and 64 are reported in the following table. At first the results of the voltage deviation, in percentage, are always much lower compared to the maximum value. This is a very good point, for this configuration of the radial grid, because it confirms the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed generators, such as the photovoltaic sources and the energy storage systems, can feed the local load so there will be a lower flow of current into the grid. Moreover the voltage deviation at the case 63 is always greater compared to that at the case 64. This is because in the case 64 all sources can control the generated active power. In this way all the sources generate the active power obtained from an optimal solution. That is a smart management of the sources that characterizes the smart grid. At last the voltage deviation, during the night, is comparable with that during the day. This is because during the night the load consumption and the photovoltaic generation decreases compared to that during the day. So the load will be feeded by the PCC_s and the energy storage systems and it will lead to an small increase of voltage deviation.
Subsequently in the following table the main power flow are reported. In the cases 63 and 64, the power loss into the sources is always greater than the power loss into the feeders. This happen because the current flows into the grid is very small for the same reason explain before and the distributed sources will be more exploited. Furthermore the power loss into the sources, in third case, is always lower compared to that in the fourth case. Moreover the distribution loss in phase wires, in the third case, is greater compared to that in fourth case. This happen for the same reason explain previously. At last the distribution loss in phase wires and the loss in power sources, during the day, are respectively comparable with those during the night. This is because, during the night, the loads absorption and the photovoltaic generation falls so there will be an increase of current flows into the grid.
The calculation of the power loss is fundamental for the efficiency. The efficiency of a system is a very important parameter of the power quality that gives an idea of the management of the network. The value of the efficiency is high for each case and it is a good point for the management of the grid in this configuration. Furthermore the value of the efficiency, in the third case, is always greater compared to that in the fourth case. This is because, in the fourth case, the optimal control exploits more the distributed sources compared to the third case. So the reduction of the power loss into the feeders, due to the optimal control, is lower compared to the increase of the loss in power sources.

TABLE 10.10: Main results of the simulation, using SUSI3, of the radial grid, related at case 63 and 64.

Test case	63	63	63	63	63	64	64	64	64	64
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160	0,160
rms voltage deviation / Vnom	2,47%	0,97%	0,29%	1,10%	0,37%	2,28%	0,72%	0,27%	0,70%	0,18%
P entering grid at node 0 [kW]	-79,67	47,04	4,18	56,47	22,06	-60,13	27,52	2,63	31,93	2,87
Q entering grid at node 0 [kVAR]	-58,49	-5,53	1,68	-8,69	-7,79	-66,04	-4,85	-7,43	-6,52	-6,99
P absorbed by loads [kW]	252,74	225,86	203,28	200,98	59,14	246,67	232,07	209,05	206,41	60,61
Q absorbed by loads [kVAR]	115,04	105,94	94,22	92,19	27,35	108,72	110,94	98,53	97,69	28,92
P feed by sources [kW]	396,16	227,32	203,70	202,94	59,49	370,01	233,14	212,04	207,65	60,78
Q feed by sources [kVAR]	179,41	124,31	103,76	114,91	45,79	172,95	118,07	98,73	110,50	33,90
P returned to sources [kW]	138,82	0,01	0,01	0,04	0,04	119,70	0,00	2,57	0,00	0,00
Q returned to sources [kVAR]	118,35	23,21	9,42	30,47	26,05	126,26	11,59	7,44	18,87	11,89
P troughput-grid transport [kW]	246,34	149,35	108,02	169,35	59,25	239,18	147,69	122,82	162,32	56,10
Q troughput-grid transport [kVAR]	184,95	100,48	82,05	104,02	49,22	181,19	74,20	68,17	91,94	33,79
Distribution loss in phase wires [kW]	4,59	1,45	0,41	1,92	0,31	3,65	1,07	0,41	1,24	0,17
Loss in power sources & converters [kW]	27,34	8,92	7,09	8,49	2,49	26,55	10,30	9,32	10,00	1,93
Total power loss w/o neutral wire [kW]	31,94	10,37	7,49	10,42	2,80	30,20	11,37	9,74	11,23	2,10
Efficiency neglecting neutral loss (Total loss/power feed by sources)	91,94%	95,44%	96,32%	94,87%	95,29%	91,84%	95,12%	95,41%	94,59%	96,55%
Estimated loss in neutral wire [kW]	3,47	0,72	0,68	0,93	0,12	3,27	1,26	0,83	1,08	0,10
Total power loss including neutral wire [kW]	35,41	11,09	8,18	11,35	2,92	33,47	12,63	10,57	12,32	2,19
Efficiency considering neutral loss	91,06%	95,12%	95,99%	94,41%	95,08%	90,95%	94,58%	95,02%	94,07%	96,39%
Min node voltage vs Vnom	0,00%	-2,95%	-0,66%	-3,40%	-1,15%	0,00%	-2,05%	-0,64%	-1,41%	-0,36%
Node with minimum voltage	0	1601	1601	1601	1602	0	1605	1502	1605	1605
Max node voltage vs Vnom	4,18%	0,70%	0,54%	0,98%	0,47%	3,95%	0,54%	1,20%	0,78%	0,61%
Node with maximum voltage	1602	917	1006	917	5	3507	917	5	2803	5
Max active power stress of sources (P/Pnom)	102,57%	50,84%	49,79%	70,61%	23,68%	103,63%	109,61%	101,15%	101,18%	100,51%
Node with maximum active power stress	1006	2803	1005	2803	2803	1604	1604	5	1604	5
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	116,17%	115,15%	82,86%	100,46%	100,41%	110,79%	106,11%	119,20%	119,92%	99,90%
Node with maximum current stress	1901	2002	1501	2801	5	3402	1107	5	1107	5
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	116,26%	65,23%	46,72%	83,42%	32,60%	114,05%	65,17%	68,64%	68,71%	31,05%
Branch with maximum current stress	27	14	95	14	3	27	68	3	68	3
Number of overstressed feeders (current)	1	0	0	0	0	1	0	0	0	0
Max stress	116,3%	115,2%	82,9%	100,5%	100,4%	114,1%	109,6%	119,2%	119,9%	100,5%

Rather than the differences between the values of efficiency, considering at the same period of the day, are very small, so it is possible to neglect these differences. At last the efficiency, during the day, is compared with that during the night. This happens because during the night the load absorption and the distributed generations falls, so there will be a reduction of power loss into the sources. Furthermore there will be an increase of current flows into the grid that brings at an increase of power loss into the feeders. This situation involves into a value of efficiency that is very similar in between the day and the night.
After that is important to understand where the sources overstress come from. From the results of the simulation, into the sources, the value of the current stress is greater compare to the value of power stress. Moreover both stress of sources are very high and close to the upper limit. So, in this test case, the limitation of the sources are the values of current and active power that can generate. Furthermore the value of power stress of sources, in the third case, is always greater compared to that at fourth case. While the value of the current stress of the sources between the case 63 and 64, are approximately similar. This is because the power flow, related at fourth case, is the result of an optimization for the minimization of the total stress. In the following tables are reported the overstressed sources.

TABLE 10.11: Overstressed power sources at case 63.

Day time	Node	Overstressed A/Anom	Qsat [kVAR]
1	5	4.71	14.32
1	1501	1.98	10.72
1	2801	1.78	-10.79
1	2001	1.66	21.53
1	1107	1.29	21.38

In particular, from the comparison of these two tables, we note that the overstressed sources, in the third case, are overstressed also in the fourth case. Moreover in the last case, there are some overstressed sources that do not appear in the previous table. So the number of overstressed sources, in the third case, is lower compared to that at fourth case. This happen because the optimal control acts on the distributed sources to reduce the total stress, so the distributed sources will be more exploited. Furthermore the overstressed sources, in both cases, are always very small because they are property of end-user, such as industrial or domestic. Consequently is very simple to reach the upper limit of active and reactive power and overcome it. Also the overstressed sources are very close each other, except for the sources at node 2001 and 2801. So, to solve this overstress of sources, a solution is to install a new generator, that works as current source, in a node close to the overstressed sources to support them at load balance and minimization of the total stress. The node, in which we will link the new generator, will be a new fully controllable node.

TABLE 10.12: Overstressed power sources at case 64.

Day time	Node	Overstressed	Apply limit
1	5	P/Pnom =4.26 A/Anom =2.07	Psat=13.80kW Qsat =6.68kVAR
1	1501	A/Anom =1.66	Qsat =10.81kVAR
1	1004	P/Pnom =1.80	Psat=3.00kW
1	1005	P/Pnom =1.46	Psat=3.00kW
1	1010	P/Pnom =2.45	Psat=3.00kW
1	2001	A/Anom=1.71	Qsat =21.62kVAR
2	5	P/Pnom =1.32	Psat=13.80kW
3	5	P/Pnom =4.29 A/Anom =2.05	Psat=13.80kW Qsat =6.68kVAR
3	1004	P/Pnom =1.72	Psat=3.00kW
3	1010	P/Pnom =1.28	Psat=3.00kW
3	1005	P/Pnom =2.25	Psat=3.00kW
3	1501	A/Anom =1.27	Qsat =11.07kVAR
3	2001	A/Anom =1.38	Qsat =22.15kVAR
3	2801	A/Anom =1.31	Qsat =-11.09kVAR
4	5	P/Pnom =1.44 A/Anom =1.22	Psat=13.80kW Qsat =6.45kVAR

Otherwise, to solve this overstress of the sources, a solution is to increase the rated active power of those sources.
Subsequently the current stress of feeders are resumed into the previous tables. The value of current stress of feeders, in the case 63, is very similar to that at case 64. Furthermore the value of current stress into the feeders, during the day, is always greater compared to that during the night. This is because during the night the load consumption decrease compared to that during the day, so the current flows falls. This is a benefit that the distributed sources can bring with an appropriate algorithm. That is a smart management of the sources that characterizes the smart grid.
At last is important to compare the results, between the case 63 and 64, to understand if the optimal control gives the best results. In particular, in the following figure, is reported the comparison of the peak value of the results of the simulation, done with SUSI3, considering the radial grid, between the third and fourth case. From the following graph, in the third case, the value of voltage deviation, distribution loss in phase wires and the maximum current stress of feeders, are lower compared those in fourth case. While, in the third case, the loss in power sources, total power loss and the maximum of active power stress of sources are lower compared to those in the fourth case. At last the efficiency and the maximum current stress of sources

remain constant between the two cases. In particular, as previously described, the increase of he active power stress of sources is due to the optimal control. Similarly the reduction of the current stress of feeders.

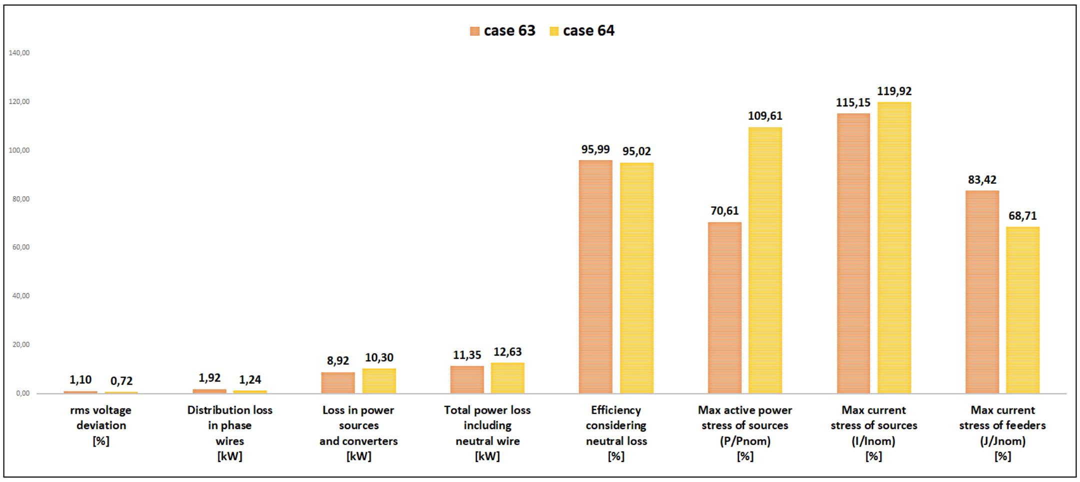

FIGURE 10.3: Comparison of the results between the case 63 and 64, considering the radial grid.

Moreover we have to consider that the overstressed sources are very small so it is very simple to reach the upper limit and overcome it.
So, for the radial grid, the optimal control, of the active power, gives the best results in terms of management of the system. Those are benefits that characterize the smart grid.

10.4 Analysis of the results of cases 61 and 62, related at meshed grid.

In this section the results of the analysis, done with SUSI3 and Source Locator, are reported in these tables. At first the results of the voltage deviation, in percentage, are always lower compared to the maximum value. This is a very good point, for this configuration of the meshed grid, because it confirms the advantages of the distributed generations also under demand response conditions. Indeed the voltage deviation is small because the distributed sources, such as the renewable generations, can feed the local loads so there will be a lower flow of current into the grid. Moreover the voltage deviation, in the first case, is always greater compared to that at the second case. This is because in the second case all sources can control the generated active power to feed the local loads, so the flow of current will decrease. That is a smart management of the sources that characterizes the smart grid. At last the voltage deviation, during the night, is comparable with that during the day. This is because, during the night, the load consumption and the photovoltaic generations decreases compared to that during the day because the load will be feeded by the PCC_s and the energy storage systems.

TABLE 10.13: Main results of the simulation, using SUSI3, of the radial grid.

Test case	61	61	61	61	61	62	62	62	62	62
Day time	0	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099
rms voltage deviation / Vnom	1,64%	2,32%	1,74%	2,58%	1,86%	1,40%	1,99%	1,60%	2,05%	1,69%
P entering grid at node 0 [kW]	-50,22	-49,83	-49,83	-49,84	-49,83	-50,18	-50,21	-50,27	-50,19	-50,25
Q entering grid at node 0 [kVAR]	-49,92	-50,15	-50,09	-50,17	-50,10	-49,99	-49,89	-49,92	-49,89	-49,90
P absorbed by loads [kW]	225,13	235,30	207,01	207,27	60,91	224,78	231,28	208,29	206,11	60,48
Q absorbed by loads [kVAR]	114,19	114,39	102,10	101,89	29,64	113,98	115,98	103,69	103,56	30,41
P feed by sources [kW]	327,83	322,13	280,77	311,90	131,62	307,19	310,62	279,59	286,32	129,26
Q feed by sources [kVAR]	171,17	234,58	176,35	238,80	170,03	161,06	207,43	171,85	205,69	151,60
P returned to sources [kW]	100,47	80,60	71,12	96,75	66,98	80,91	74,80	69,16	74,95	66,04
Q returned to sources [kVAR]	104,54	165,90	121,97	180,79	187,79	95,38	138,47	116,07	149,02	168,75
P troughput-grid transport [kW]	190,74	240,28	177,91	278,64	129,98	180,64	218,63	176,75	240,15	123,10
Q troughput-grid transport [kVAR]	165,16	241,50	193,73	256,32	212,05	145,96	207,47	179,59	220,97	193,18
Distribution loss in phase wires [kW]	2,24	6,24	2,63	7,87	3,73	1,51	4,53	2,14	5,26	2,75
Loss in power sources & converters [kW]	25,40	24,48	18,68	28,20	18,83	23,77	23,29	18,53	24,16	16,83
Total power loss w/o neutral wire [kW]	27,63	30,71	21,31	36,07	22,56	25,28	27,82	20,67	29,42	19,57
Efficiency neglecting neutral loss (Total loss/power feed by sources)	91,57%	90,47%	92,41%	88,44%	82,86%	91,77%	91,04%	92,61%	89,72%	84,86%
Estimated loss in neutral wire [kW]	2,32	2,01	1,66	2,72	1,27	1,69	1,71	1,43	1,91	1,45
Total power loss including neutral wire [kW]	29,95	32,72	22,97	38,79	23,83	26,97	29,53	22,10	31,34	21,02
Efficiency considering neutral loss	90,86%	89,84%	91,82%	87,56%	81,89%	91,22%	90,49%	92,10%	89,06%	83,74%
Min node voltage vs Vnom	-0,20%	-0,83%	0,00%	-0,97%	0,00%	0,00%	-0,22%	0,00%	-0,12%	0,00%
Node with minimum voltage	915	1605	0	1602	0	0	1605	0	1603	0
Max node voltage vs Vnom	3,14%	3,95%	2,88%	5,29%	2,96%	2,53%	4,01%	2,89%	4,15%	2,45%
Node with maximum voltage	3402	2803	917	2803	917	3402	917	917	917	1602
Max active power stress of sources (P/Pnom)	102,20%	119,88%	61,00%	175,84%	67,81%	102,45%	102,49%	103,18%	109,01%	102,33%
Node with maximum active power stress	1902	2803	2803	2803	917	1004	3503	1604	2803	3503
Number of overstressed sources (power)	0	1	0	1	0	0	0	0	0	0
Max current stress of sources (I/Inom)	119,64%	102,62%	117,15%	127,31%	116,72%	115,63%	114,33%	101,42%	102,33%	102,20%
Node with maximum current stress	1605	3505	1503	2803	1107	1503	1006	5	3507	3505
Number of overstressed sources (current)	0	0	0	1	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	63,60%	111,89%	69,47%	117,77%	98,70%	67,83%	118,35%	68,77%	125,97%	73,15%
Branch with maximum current stress	7	7	7	26	7	17	7	7	7	30
Number of overstressed feeders (current)	0	3	0	2	0	0	2	0	2	0
Max stress	119,6%	119,9%	117,2%	175,8%	116,7%	115,6%	118,4%	103,2%	126,0%	102,3%

After in the previous table the main power flow are reported. The main power flow are the follows: the power entering at node 0 or PCC_0, the power absorb by loads, the power feed by sources and the power throughput grid transportation. Subsequently the power loss are reported for each case and period of the day. In particular the program gives the results relative at power loss in phase wires, in sources and converters. Also it makes an estimation of the power loss into neutral wires. In the cases 61 and 62, the power loss into the sources is always greater than the power loss into the feeders. This happen because the current flows into the grid is very small for the same reason explain before for the value of voltage deviation. Furthermore the power loss into the sources and the distribution loss in phase wires, in the first case, are always greater compared to those in the second case. This is a direct consequence of the control of the active power generated, from all generators. Indeed in the second case the optimal control exploited more the distributed sources to reduce the total stress compared to that at first case. Those are some benefits that the photovoltaic sources and energy storage system, with an appropriate algorithm, can bring into the grid, also in a demand response operative condition. That is a smart management of the sources that characterizes the smart grid. At last the distribution loss, during the day, is comparable with that during the night. While the loss in power sources, during the day, is comparable with that during the night. These two facts are due to the reduction of the absorption and also the photovoltaic generation falls. So there will be an increase of flow of current into the grid.
The calculation of the power loss is fundamental for the efficiency. The efficiency of a grid is a very important parameter of the power quality that gives an idea of the management of the network. The value of the efficiency is small for each case and it isn't a good point for the management of the grid in this configuration. Furthermore the value of the efficiency, in the first case, is always lower compared to that at the second case. This is because, in the second case, the active power generated from all the sources is the results of an optimization to minimize the total stress and, consequently, the power loss. So the active power generated from all the sources satisfy the load balance and minimize the stress into the network.
Subsequently is important to understand where the sources overstress come from. From the results of the simulation, into the sources, the value of the current stress is very similar at the value of power stress, except for the second period of the day. So, in this test case, the limitation of the sources is the value of current and active power that can generate. To solve this active power and current overstress of the sources, a chance is to increase the rated active power of the overstressed sources. Another solution is to install a fully controllable generator in that node to support the already existing source at generation. Furthermore the value of power stress of sources, in the first case, is always greater, except for the second period of the day, than that at second case. While the current stress of sources, in the first case, is always lower compared to that in the second case, except for the second period of the day. This is because the power flow, in the second case, is the result of an optimization for the

minimization of the total stress. For the case 61 and 62 the tables of the power limits for each overstressed source aren't reported because there are a lot of overstressed sources that are property of end-user.
At last the current stress of feeders are resumed into the previous tables. The values of current stress of feeders, in the case 61, are similar at those related at case 62. Furthermore the value of current stress into the feeders, during the day, is always greater compared to that during the night.
Subsequently the overstressed feeders of case 61, with the related value of overstress, are reported into the following table. The number of current overstress of feeders is very small in all period of the day. Also the the overstressed feeders are close each other, so with an intelligent decision concerning where to install a a new generator, that works as current source, is possible to solve all these current overstress.

TABLE 10.14: Results of current overstress into the feeders, considering the radial grid, in the case 61.

Test case	Period of the day	Branch number	Phase	Overstress J/Jnom
61	1	7	1	1.07
			2	1.12
			3	1.12
61	3	26	2	1.18
61	3	125	2	1.17

TABLE 10.15: Results of the analysis, done with Source Locator, considering the meshed grid, in case 61.

Fully controllable node	Power generate from that node [kVA]	Number of controlled branches	Total control factor J/Jnom	List of control branches (control factor)
917	47.14	23	10.95	24(1.21), 26(1.05), 23(0.84), 125(0.82), 22(0.81), 18(0.72), 9(0.70), 7(0.57), 132(0.49), 11(0.44), 10(0.43), 3(0.41), 19(0.41), 127(0.39), 17(0.32), 27(0.26), 4(0.21), 29(0.19), 8(0.18), 6(0.15), 13(0.12), 126(0.11), 129(0.11)
28	16.67	18	5.43	105(1.01), 7(0.72), 3(0.46), 24(0.43), 26(0.37), 23(0.30), 22(0.29), 9(0.27), 18(0.25), 8(0.20), 11(0.17), 6(0.17), 127(0.15), 19(0.15), 10(0.14), 126(0.12), 17(0.11), 131(0.11)
2803	47.14	10	4.48	7(2.07), 126(0.60), 3(0.57), 8(0.25), 132(0.25), 6(0.21), 4(0.15), 131(0.14), 2(0.12), 1(0.12)
5	5.11	3	0.64	36(0.31), 7(0.20), 3(0.13)

The results, resumed into the previous table, are related at the analysis, done with Source Locator, in which the new generator has an apparent power equal to 50 kVA. The proposed solution is to install this generator in the node 28 that is near the previous overstressed lines. With this solution is possible to control the total current into the overstressed lines 7 and 26, but is not possible to control the current into

the line 125. To solve the current overstress into the feeders 125 is possible to increase its section, so the ampacity will increase. Otherwise the new generator, link at node 917, can control all the overstressed lines with a control factor that is capable to reduce the current overstress. In this way with a new fully controllable current sources is possible to eliminate all the current stress into the feeders and support the distributed sources at generation.
After that the overstressed feeders, related at case 62, are reported in the following table. In this case the overstressed feeders are the same at those of the case 61. The difference between the first and second case is the value of overstress. Indeed the current overstress is lower compared to the previous case and the number of overstressed lines is lower.

TABLE 10.16: Results of current overstress into the feeders, considering the radial grid, in the case 62.

Test case	Period of the day	Branch number	Phase	Overstress J/Jnom
62	1	7	3	1.13
62	3	7	1	1.15
62	3	7	3	1.16

TABLE 10.17: Results of the analysis, done with Source Locator, considering the meshed grid, in case 62.

Fully controllable node	Power generate from that node [kVA]	Number of controlled branches	Total control factor J/Jnom	List of control branches (control factor)
917	47.14	17	10.08	24(1.21), 26(1.05), 23(0.84), 125(0.82), 22(0.81), 18(0.72), 9(0.70), 7(0.56), 132(0.49), 11(0.44), 10(0.43), 19(0.41), 3(0.41), 127(0.39), 17(0.32), 27(0.26), 4(0.22)
2803	47.14	6	3.95	7(2.07), 126(0.60), 3(0.57), 8(0.25), 132(0.25), 6(0.21)
9	16.67	3	2.17	37(1.09), 7(0.65), 3(0.43)
1602	5.55	2	0.85	14(0.51), 84(0.34)
1604	5.55	2	0.85	14(0.51), 86(0.34)

The results resumed into the previous table are related at the analysis with Source Locator in which the new generator has an apparent power equal to 50 kVA. The proposed solution is to install this generator, that will work as current source, in the node 9 that is near the previous overstressed line. With this solution is possible to control the total current into the overstressed lines 7. Otherwise the new generator, link at node 917, can control all the overstressed lines with a control factor that is capable to reduce the current overstress. In this way with that new current sources is possible to reduce all the current overstress into the feeders and support the distributed sources at generation in a better way compared to the previous solution.
At last is important to compare the results, between the case 63 and 64, to understand if the optimal control gives the best results. In particular, in the following

figure, is reported the comparison of the peak value of the results of the simulation, done with SUSI3, considering the meshed grid, between the first and second case.

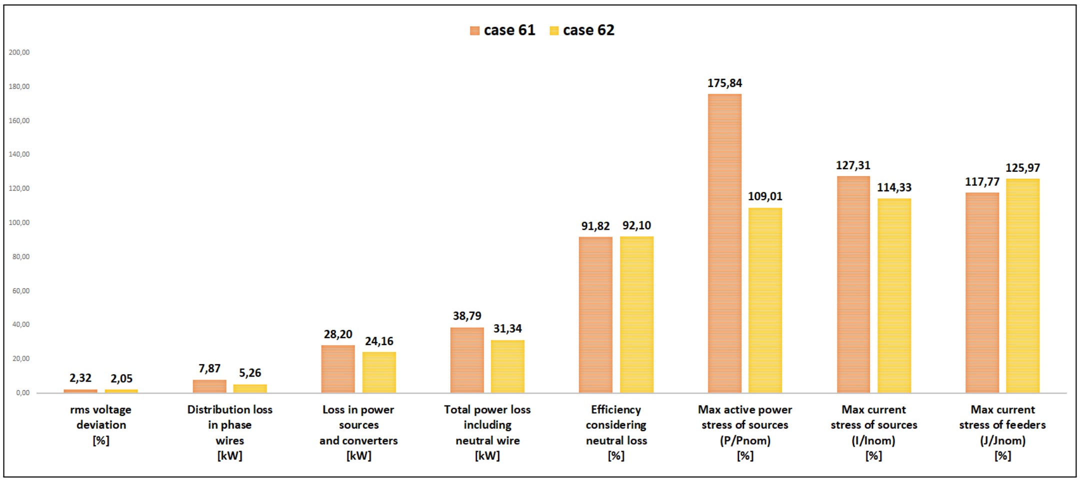

FIGURE 10.4: Comparison of the results between the case 61 and 62, considering the meshed grid.

From the previous graph the optimal control gives the best results in terms of voltage deviation, distribution loss in phase wires, loss in power sources, total power loss, maximum active stress and current stress of power sources. While the efficiency and the maximum current stress of feeders remain constant between the two cases.
So, for the meshed grid, the optimal control, of the active power, gives the best results in terms of management of the system. Those are benefits that characterize the smart grid.

10.5 Analysis of the results of cases 63 and 64, of the meshed grid.

In this section the results of the simulation, done with SUSI3 and Source Locator, related at case 63 and 64 are reported in the following table. At first the results of the voltage deviation, in percentage, are always much lower compared to the maximum value. This is a very good point, for this configuration of the meshed grid, because it confirms the advantages of the distributed generations. Indeed the voltage deviation is very small because the distributed generators, like the photovoltaic sources and the energy storage systems, can feed the local loads, so there will be a lower flow of current into the grid. Moreover the voltage deviation, in the case 63, is greater compared to that in the case 64, except for the second period of the day. This is because in the case 64 all sources can control the generated active power. In this way all the sources generate the active power obtained from an optimal solution. That is a smart management of the distributed sources that characterizes the smart grid. At last the voltage deviation, during the night, is comparable with that during the day.

TABLE 10.18: Main results of the simulation, using SUSI3, of the meshed grid.

Test case	63	63	63	63	64	64	64	64	64
Day time	1	2	3	4	0	1	2	3	4
Tolerance on line impedance accuracy	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mean impedance of node-to-node paths [Ohm]	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099	0,099
rms voltage deviation / Vnom	0,77%	0,23%	0,87%	0,30%	2,19%	0,64%	0,26%	0,64%	0,19%
P entering grid at node 0 [kW]	34,25	7,40	38,22	13,93	-76,02	26,66	6,28	29,04	7,09
Q entering grid at node 0 [kVAR]	0,49	4,86	-0,87	0,55	-57,84	-2,24	-1,05	1,71	-0,90
P absorbed by loads [kW]	231,35	207,36	204,89	60,18	225,30	235,13	208,83	209,03	61,67
Q absorbed by loads [kVAR]	105,95	93,89	93,34	27,70	116,06	102,69	91,04	90,85	26,94
P feed by sources [kW]	232,64	207,61	206,64	60,40	361,86	236,15	210,01	210,19	62,26
Q feed by sources [kVAR]	121,55	100,50	122,67	41,77	181,12	119,10	91,34	111,87	32,38
P returned to sources [kW]	0,00	0,00	0,00	0,01	133,91	0,01	0,88	0,01	0,46
Q returned to sources [kVAR]	15,17	6,56	29,66	14,00	118,79	18,31	1,27	20,63	6,29
P troughput-grid transport [kW]	150,53	103,98	173,58	60,31	233,17	145,67	114,36	165,37	57,87
Q troughput-grid transport [kVAR]	82,75	77,56	97,12	35,63	168,04	79,61	55,48	88,53	27,63
Distribution loss in phase wires [kW]	1,29	0,25	1,74	0,22	2,65	1,01	0,30	1,15	0,13
Loss in power sources & converters [kW]	9,08	6,56	9,39	1,48	26,28	10,20	7,99	10,59	1,68
Total power loss w/o neutral wire [kW]	10,37	6,81	11,14	1,69	28,93	11,22	8,29	11,74	1,81
Efficiency neglecting neutral loss (Total loss/power feed by sources)	95,54%	96,72%	94,61%	97,20%	92,00%	95,25%	96,05%	94,41%	97,09%
Estimated loss in neutral wire [kW]	0,38	0,24	0,71	0,09	1,91	0,50	0,46	0,59	0,07
Total power loss including neutral wire [kW]	10,75	7,05	11,84	1,78	30,85	11,72	8,75	12,33	1,88
Efficiency considering neutral loss	95,38%	96,60%	94,27%	97,05%	91,48%	95,04%	95,84%	94,13%	96,98%
Min node voltage vs Vnom	-2,19%	-0,55%	-2,58%	-0,92%	0,00%	-1,53%	-0,60%	-1,16%	-0,35%
Node with minimum voltage	1605	3005	1606	1606	0	1605	1803	1605	1605
Max node voltage vs Vnom	0,87%	0,26%	1,15%	0,36%	3,27%	0,93%	0,50%	0,81%	0,23%
Node with maximum voltage	917	32	917	917	3507	917	1603	917	5
Max active power stress of sources (P/Pnom)	51,54%	49,64%	67,60%	23,69%	102,84%	100,63%	100,40%	100,41%	100,20%
Node with maximum active power stress	917	2304	917	2803	3503	1010	1010	5	5
Number of overstressed sources (power)	0	0	0	0	0	0	0	0	0
Max current stress of sources (I/Inom)	100,04%	76,73%	100,16%	58,43%	118,17%	99,72%	100,76%	114,19%	95,66%
Node with maximum current stress	5	1501	5	1501	1605	5	5	1501	5
Number of overstressed sources (current)	0	0	0	0	0	0	0	0	0
Max current stress of feeders (J/Jnom)	58,66%	45,68%	72,64%	24,29%	68,97%	45,72%	47,60%	64,14%	17,40%
Branch with maximum current stress	28	28	28	14	17	95	95	68	95
Number of overstressed feeders (current)	0	0	0	0	0	0	0	0	0
Max stress	100,0%	76,7%	100,2%	58,4%	118,2%	100,6%	100,8%	114,2%	100,2%

After in the previous table the main power flow are reported. In the cases 63 and 64, the power loss into the sources is always greater than the power loss into the feeders. This happen because the current flows into the grid is very small for the same reason explain before. Furthermore a lot of distributed sources are overstressed so there will be a certain power loss into the distributed sources. In particular the power loss into the sources, in third case, is always lower compared to that at the fourth case. While the distribution loss in phase wires, in the case 63, are always greater compared to that at case 64, except for the second period of the day. This happen because the optimal control exploits more the distributed sources to reduce the total stress. So it acts on the distributed resources to minimize the flow of current into the grid, so, consequently, the distributed resources are used for feed the local loads. In this way the distribution loss in phase wires will decrease, while the loss in power sources will increase. At last the loss in power sources, during the day, is comparable with that during the night, for the same reason explain before.
The calculation of the power loss is fundamental for the efficiency. The efficiency of a grid is a very important parameter of the power quality that gives an idea of the management of the network. The value of the efficiency is high for each case and it is a good point for the management of the grid in this configuration. Furthermore the value of the efficiency, in the third case, is always greater compared to that in the fourth case. This is because in the fourth case the active power generated from all the sources is the results of an optimization, so the distributed sources will be more stressed than those at third case. moreover, in the fourth case, the power loss of distributed sources will increase. At last the efficiency, during the day, is compared with that during the night. This happens because during the night the load absorption and the distributed generations falls, so there will be a reduction of power loss into the sources. Furthermore there will be an increase of the flow of current into the grid that leads at an increase of power loss into the feeders. This situation involves into a value of efficiency that is very similar in between the day and the night.
After that is important to understand where the sources overstress come from. From the results of the simulation, into the sources, the value of the current stress is greater compare to the value of power stress, in the third case. While in the fourth case the values of current and power stress of sources are approximately equal, considering the same period of the day. So, in this test case, the limitation of the sources is the value of current that can generate. To solve this current overstress of the sources, a solution is to increase the rated active power of the overstressed sources. Another solution is to install a fully controllable generator in that node to support the already existing source at generation. Furthermore the value of power stress of sources at third case is always lower compared to that at fourth case. While the value of the current stress of the sources between the case 63 and 64, are about similar, except during the night and in the second period of the day. At last the current stress of feeders are resumed into the previous table. The value of current stress of feeders, in the case 63, is very similar to that at case 64. Furthermore the value of current

stress into the feeders, during the day, is always greater compared to that during the night. This is because during the night the load consumption decrease compared to that during the day, so the current flows falls. This is a benefit that the distributed sources can bring with an appropriate algorithm. That is a smart management of the sources that characterizes the smart grid.
In the following tables the overstressed sources are reported. From those results the value of overstress into the sources at case 63 is lower compared to that in case 64. Furthermore the number of overstressed sources, at case 63, is greater compared to that at case 64, because the optimal control exploits more the distributed resources compared to those in the third case.

TABLE 10.19: Overstressed power source at case 63.

Day time	Node	Overstressed A/Anom	Qsat [kVAR]
1	5	1.36	14.91
1	1501	1.94	10.74
1	1107	1.44	21.54
1	2001	1.41	21.62
3	5	1.53	15.28
3	1107	1.23	22.14
3	1501	1.75	11.06
3	2001	1.50	22.14

In particular the overstressed sources are always very small because they are property of end-user, such as domestic or industrial. So it is very simple to reach the upper limit of active and reactive power and overcome it. Moreover the overstressed distributed sources are very close each other, so with a new generator is possible to reduce the overstress of those overstressed sources. Indeed if the dispatcher decides to connect a new generator, that works as current source, close to the overstressed sources, is possible to support the nearby overstressed sources at load balance and minimization of the total stress. In particular the node, in which we decide to link the new current source, will be a new fully controllable node. Otherwise is possible to increase the rated active and reactive power of those overstressed sources. Furthermore the overstressed sources of the third case are overstressed also in the fourth case. While in the case 64 appear overstressed sources that in case 63 aren't overstressed. This happen because the optimal control exploit more the distributed sources to minimize the total stress. In this way the flow of current, into the grid, will decrease as the current stress of feeders. While the active power stress of distributed sources will increase due to the optimal control. At last a very important results is that the overstressed sources are always the same generally. So if we chose a solution to reduce the overstress of sources, in the worst case, consequently, in the other cases, the overstress of sources will decrease. In this way with only a new current source is possible to reduce the overstress of distributed resources in different cases and different period of the day.

TABLE 10.20: Overstressed power source at case 64.

Day time	Node	Overstressed	Apply limit
1	5	P/Pnom =5.04 A/Anom =1.43	Psat=13.80kW Qsat =6.46kVAR
1	1501	A/Anom =1.37	Qsat =10.90kVAR
1	1602	P/Pnom =1.15	Psat=5.00kW
1	1604	P/Pnom =1.15	Psat=5.00kW
1	1004	P/Pnom =1.32	Psat=3.00kW
1	1005	P/Pnom =2.02	Psat=3.00kW
1	1010	P/Pnom =2.81	Psat=3.00kW
1	1606	P/Pnom =1.44	Psat=3.00kW
1	1107	A/Anom =1.25	Qsat =21.54kVAR
1	2001	A/Anom =1.33	Qsat =21.50kVAR
1	3503	P/Pnom =1.20	Psat=3.00kW
2	5	P/Pnom =1.59	Psat=13.80kW
2	1010	P/Pnom =1.26	Psat=3.00kW
3	5	P/Pnom =5.43 A/Anom =1.40	Psat=13.80kW Qsat =6.47kVAR
3	1004	P/Pnom =1.43	Psat=3.00kW
3	1005	P/Pnom =2.31	Psat=3.00kW
3	1010	P/Pnom =2.78	Psat=3.00kW
3	1602	P/Pnom =1.13	Psat=5.00kW
3	1604	P/Pnom =1.14	Psat=5.00kW
3	1606	P/Pnom =1.21	Psat=3.00kW
4	5	P/Pnom =1.85	Psat=13.80kW

At last is important to compare the results, between the case 63 and 64, to understand if the optimal control gives the best results. In particular, in the following figure, is reported the comparison of the peak values of the results of the simulation, done with SUSI3, considering the meshed grid, between the third and fourth case. From the previous graph the optimal control gives the best results in terms of voltage deviation, distribution loss in phase wires and maximum current stress of feeders. While the efficiency and the total power loss remain constant between the two cases. Moreover, in third case, the loss in power sources, the current stress and power stress of sources are lower compared to those at fourth case. This is because the optimal control, of the active power, exploits more the distributed sources to reduce the flow of current into the grid. Consequently the distributed resources are more stressed in reverse of the feeders that will be less stressed. Rather than the distributed sources are very small so it is very simple to reach the upper power limit and overcome it.

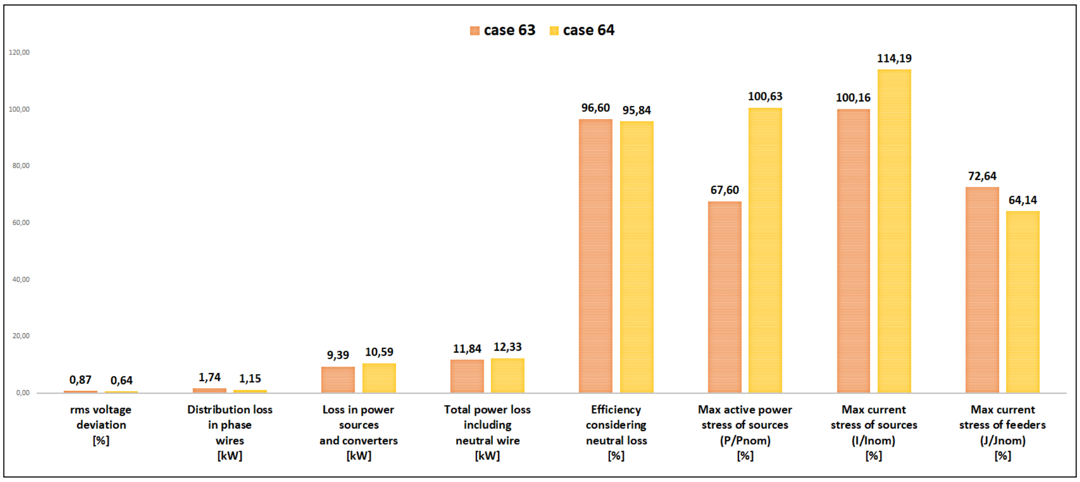

FIGURE 10.5: Comparison of the results between the case 63 and 64, considering the meshed grid.

So, for the meshed grid, the optimal control, of the active power, gives the best results in terms of management of the system. Those are benefits that characterize the smart grid.

10.6 Comparison between the radial and meshed network.

In this section a comparison of the peak value of results relative the analysis done with SUSI3, between the radial and meshed grid, for each case, is reported. In the following graph the first case is considered.

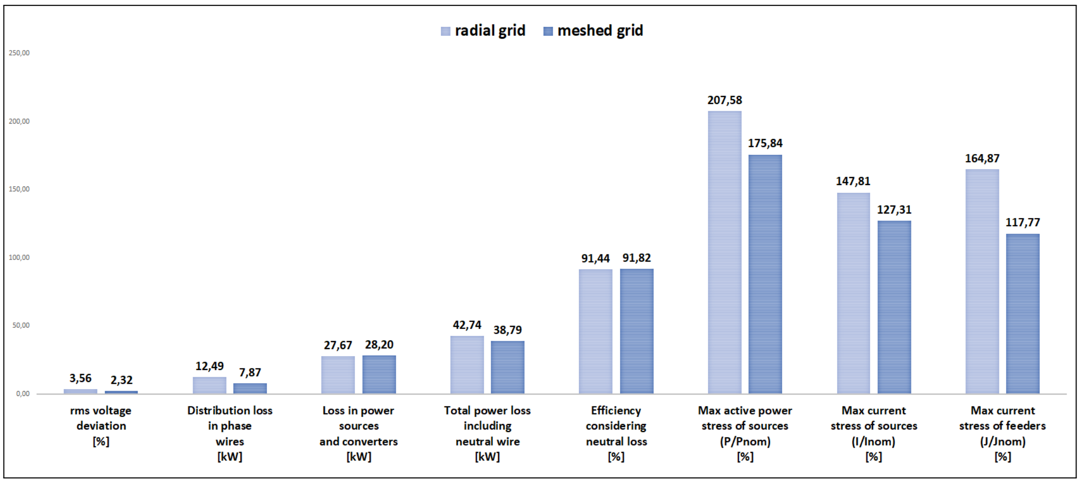

FIGURE 10.6: Comparison of the results between the radial and meshed grid, case 61.

From the previous graph the meshed grid gives the best results, in terms of voltage deviation, distribution loss, total power loss, current stress and power stress into the

sources and current stress of feeders. In particular, in the meshed grid, the current stress decreases because the added lines offer new path in which the current can flow, so th stress of the feeders will decrease. Moreover the added lines approaching a greater number of distributed sources with the loads, so there will be more support between the distributed sources. While the loss in power sources and the efficiency remain constant between the radial and meshed grid.
So, in this case, we obtain the best results, considering the previous graph and the results reported in the following table, with the meshed grid because it allows a better management of the system.
In the following graph the second case is considered.

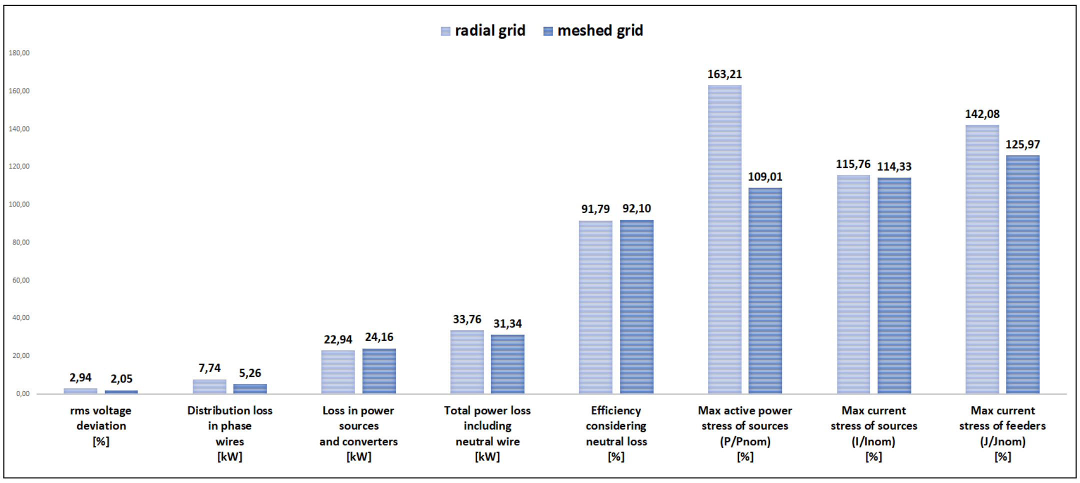

FIGURE 10.7: Comparison of the results between the radial and meshed grid, case 62.

From the previous graph the meshed grid gives the best results, in terms of voltage deviation, distribution loss, total power loss, power stress into the sources and current stress of feeders. In particular, in the meshed grid, the current stress decreases because the added lines offer new path in which the current can flow, so th stress of the feeders will decrease. Moreover the added lines approaching a greater number of distributed sources with the loads, so there will be more support between the distributed sources. While the loss in power sources, the efficiency and the maximum of current stress of sources remain constant between the radial and meshed grid.
So, in this case, we obtain the best results, considering the previous graph and the results reported in the following table, with the meshed grid because it allows a better management of the system.
In the following graph the third case is considered. From the following graph the meshed grid gives the best results, in terms of voltage deviation, distribution loss, current stress and power stress into the sources and current stress of feeders. In particular, in the meshed grid, the current stress decreases because the added lines offer new path in which the current can flow, so th stress of the feeders will decrease. Moreover the added lines approaching a greater number of distributed sources with the loads, so there will be more support between the distributed sources. While

the loss in power sources, the total power loss and the efficiency remain constant between the radial and meshed grid.

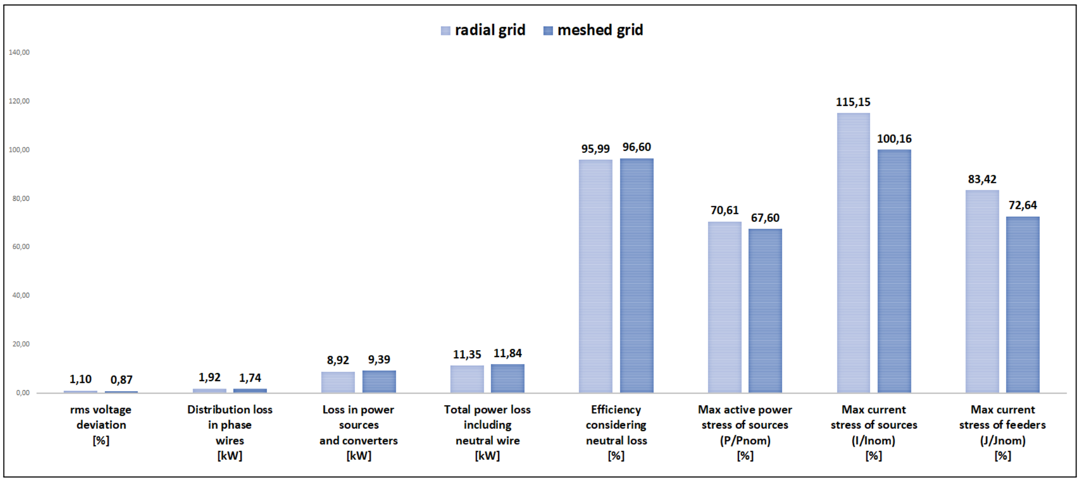

FIGURE 10.8: Comparison of the results between the radial and meshed grid, case 63.

So, in this case, we obtain the best results, considering the previous graph and the results reported in the following table, with the meshed grid because it allows a better management of the system.
In the following graph the fourth case is considered.

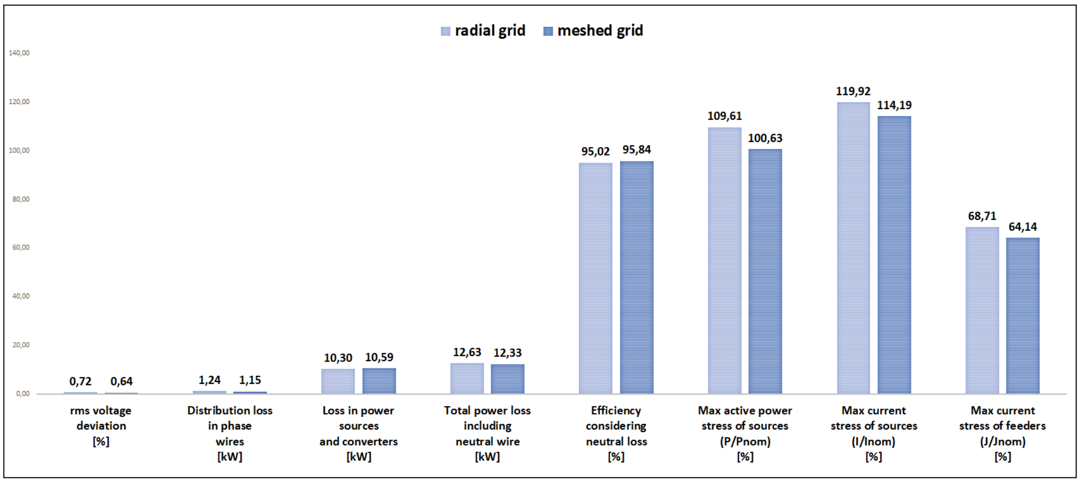

FIGURE 10.9: Comparison of the results between the radial and meshed grid, case 64.

From the following graph the meshed grid gives the best results, in terms of voltage deviation, distribution loss in phase wires, current stress and power stress into the sources and current stress of feeders. In particular, in the meshed grid, the current stress decreases because the added lines offer new path in which the current can flow, so th stress of the feeders will decrease. Moreover the added lines approaching a greater number of distributed sources with the loads, so there will be more support between the distributed sources. While the loss in power sources, the total power

loss and the efficiency remain constant between the radial and meshed grid.
So, in this case, we obtain the best results, considering the previous graph and the results reported in the following table, with the meshed grid because it allows a better management of the system.
In conclusion the best configuration of this grid is that meshed with the optimal control of the active power on, because we obtain a better management of the system.

Chapter 11

Conclusion

This chapter deals with the considerations about the results reported in the previous chapter.

11.1 General considerations about the results.

In this section general considerations about the results reported in the previous chapters are reported. In particular for all the cases the optimal control, in the meshed grid, allows a better management of the system.
The meshed grid allows a better management of the grid because it will introduce new paths in which the current can flow, so there will be a better distribution of the current into the network. Indeed with these new paths the current will be more widespread and this involves in a better management of the system in terms of a reduction of the voltage deviation, distribution losses and the current stress of feeders. Indeed the flow of current, into the network, is more widespread and will reduce, due to the presence of the new lines, so the electrical quantities, first mentioned, will decrease. Furthermore these new paths approaching the loads with the distributed renewable sources more compared to the radial grid. So a distributed source will see a greater number of loads. That will lead to a different results that are important to evaluate. The first one is that the distributed source will be more stressed in terms of active power and, consequently, the internal active power losses of that sources will increase. Indeed if that source supplies a greater number of loads it has to increase the generated active power up to the upper limits of active and reactive power of the inverter. So that sources will generate the maximum active and reactive power and the rest of the active power will be distributed between the rest of the nearby sources. The second results is that the distributed sources will be more close each other, so there is a better management of the distributed generation. This is an important fact because is fundamental that the distributed sources help each other at generation of active and reactive power. Furthermore this will lead to a reduction of the stress, in terms of the active and reactive power, of the sources. So the increase of the active power stress of sources, due to a greater number of loads to be fed, is counterbalanced by the support of a greater number of nearby sources. These are the advantages due to the meshed grid.

The optimal control allows to generate, in an optimal way, the active and reactive power. Indeed the algorithm calculates the active and reactive power, that each source has to generate, minimizing the cost function and taking into account the upper limits of active and reactive power of each sources. In some cases it will lead to an increase of the active and reactive power generated by a sources and it will increase the active power stress of that source. However, from the results, the increase of the active power stress is generally not so high so is not a problem. To solve the increase of the active power stress of source a solution is to introduce a new current source in the network, with a given apparent power. That new source will be connected to a node close to the overstressed sources to support those overstressed sources at generation. So the optimal control allows a better management of the grid because it is possible to generate the active and reactive power in an optimal way.

11.2 Future developments of the algorithm SUSI3.

In conclusion is important to consider the future perspectives of this algorithm for the calculation of the optimal power flow. Differently from the other algorithm, in SUSI3 the cost function is the sum of the total stress into the sources. In the future version of this algorithm will be include, into the cost function, a component that taking into account the cost of generation of each source, such as described in the following formula. Moreover will be fundamental taking into account the temporal change of loads. Indeed for now the algorithm calculates the optimal power flow considering in stationary system in which the loads do not vary. In the next version will be fundamental to vary loads with the time to consider how respond the network. So the cost function will be the following.

$$C_i(p_i(t), q_i(t), t) = \Phi_{total} + \Psi_{generation} \tag{11.1}$$

Where the Φ_{total} is the total stress into the system and the $\Psi_{generation}$ is the economic cost function. At last will be necessary consider all the new directive of energy that are coming out to achieve the goals of increasing power generated by renewable sources, increasing the efficiency and to create a new global market of energy. Indeed there will be new rules in the market of energy that SUSI3 has to consider to calculate the optimal power flow of the innovative system.

Appendix A

Manual of SUSI3

A.1 Node description matrix.

Dnode is a N x 26 matrix, where N is the number of grid nodes. Each node is described by a row of the matrix, and includes the following elements:

1. Node number: this is an integer positive (0=none).
2. Category: this is an integer positive (0=none), which defines the category of node (pure load, PCC, voltage source, prosumer, etc.). Category definition is free and may be useful because output data aggregate by category.
3. Connection: this is an integer non-negative, which defines how the load/source is connected. For single-phase grids the connection is always from phase to neutral, while in three-phase grids we have the following options:
   (a) 0 means that the load/source is three-phase three-wire (delta-connection or wye connection w/o neutral);
   (b) 1 (or 10) means that the load/source) is single-phase, connected from phase 1 to neutral; similarly for 2 (20) and 3 (30);
   (c) 12 (or 21) means that the load/source is single-phase, connected line-to-line from phase 1 to phase 2 (or vice-versa); similarly for 23 (32) and 31 (13);
   (d) 4 (or 40) means that the load/source is three-phase four-wire (wye connection to neutral).
4. Group 1: this an integer positive, which allows nodes to be grouped according to different properties (e.g., location in the grid). Output data aggregate by group.
5. Group 2: same as Group1, allowing another aggregation of nodes.
6. Type: there are three options for this integer number (-1, 0, +1):
   (a) type = 0 means that a pure passive load is connected to the node;
   (b) type=1 means that a voltage source (+ passive load) is connected to the node;

   (c) type=-1 means that a current source (+ passive load) is connected to the node.

7. Control bound (ctrl): this integer code (values: 0, 1, 2, 3) describes the control properties of the entity connected to the node:
   (a) for pure loads (type=0)
      i. ctrl=0 (default) means that load obeys shedding/reduction commands on both active and reactive power;
      ii. ctrl=1 means that active power absorption is fixed, while load obeys to shedding/reduction commands on reactive power;
      iii. ctrl=2 means that reactive power absorption is fixed, while load obeys to shedding/reduction commands on active power;
      iv. ctrl=3 means that both active and reactive power absorption are fixed, and the load ignores power shedding/reduction commands;
   (b) for voltage sources (type=1)
      i. ctrl=0 (default) means that the source can control both d-axis and q-axis voltages (case of grid-tied voltage-source inverters);
      ii. ctrl=1 means that the voltage fed by the source is fixed on the d-axis, while can be regulated on the qaxis;
      iii. ctrl=2 means that the voltage fed by the source is fixed on the q-axis and can be regulated on the d-axis (case of tap changers);
      iv. ctrl=3 means that the voltage fed by the source is fixed on both d-axis and q-axis (case of power transformers).
   (c) for current sources (type=-1)
      i. ctrl=0 (default) means that the source can control both the currents on d-axis (active current) and on the q-axis (reactive current);
      ii. ctrl=1 means that the current on the d-axis is fixed, while the current on the q-axis can be regulated;
      iii. ctrl=2 means that the current on the q-axis is fixed, while the current on the d-axis can be regulated;
      iv. ctrl=3 means that both currents on the d-axis and q-axis are fixed, and no control is possible.

8. Rated P load (kW): rated active power of the load connected to the node (0=none). The power represents the total of all connected phases.

9. Rated Q load (kVAR): rated reactive power of the load connected to the node (0=none). The power represents the total of all connected phases.

10. Actual P load (kW): actual active power absorbed by the load connected to the node (0=none). The power represents the total of all connected phases.

11. Actual Q load (kVAr): actual reactive power absorbed by the load connected to the node (0=none). The power represents the total of all connected phases.

12. Reduction of load power absorption at daytime 1 (%).

13. Reduction of load power absorption at daytime 2 (%).

14. Reduction of load power absorption at daytime 3 (%).

15. Reduction of load power absorption at daytime 4 (%).

16. Rated P source (kW): rated active power of the source connected to the node (0=none).

17. Rated Q source (kVAR): rated reactive power of the source connected to the node (0=none).

18. Voltage difference on d-axis (% value vs rated line voltage): this quantity, defined only for voltage sources, is used if the fix voltage impressed on the d-axis by the voltage source connected at the node does not coincide with the d-axis voltage impressed at reference node. This may be useful in case of multiple PCCs to analyze the effect of tap changers.

19. Voltage difference on q-axis (% value): same as above for the q-axis.

20. Source efficiency: this is the efficiency of the source (including the converter interface) at rated power, and serves to estimate the power loss occurring in the sources in the various operating conditions. For this purpose, the source is modeled with the equivalent series resistance computed in rated conditions.

21. Actual P source (kW): actual active power fed by the source connected to the node (0=none). This is useful to represent the behavior of distributed power sources. The power represents the total of all connected phases.

22. Actual Q source (kVAR): actual reactive power fed by the source connected to the node (0=none). This is useful to represent the behavior of distributed power sources. The power represents the total of all connected phases.

23. Reduction of source power generation at daytime 1 (%).

24. Reduction of source power generation at daytime 2 (%).

25. Reduction of source power generation at daytime 3 (%).

26. Reduction of source power generation at daytime 4 (%).

A.2 Boundary description matrix.

Dbound is a M x 10 matrix, where M is the total number of boundaries. Each boundary defines a matrix row, and includes the following elements:

1. Case number: this positive integer identifies the test case to which the boundary refers. I fact, each test case is defined by a set of boundaries, that share the same case number.
2. Boundary type: this integer number identifies the entity to which the boundary applies
   (a) type=0 means that the boundary applies to a specific branch;
   (b) type=1 means that the boundary applies to a specific node;
   (c) type=2 means that the boundary applies to a specific category of nodes;
   (d) type=3 means that the boundary applies to a specific group of nodes;
   (e) type=-1 means that the boundary applies to all nodes (but reference node);
   (f) type=-2 means that the boundary applies to all categories of nodes;
   (g) type=-3 means that the boundary applies to all groups of nodes.
3. Bounded entity: this integer identifies the branch/node/category/group to which the boundary applies. Note that node 0 is the reference node.
4. Bounded phase(s): this option applies only to branches, and the number identifies the phase, or phases, subject to the boundary. This allows, for example, binding to zero the current in a specific phase of a branch. Setting this parameter to 1 binds phase 1 (same for 2 and 3), setting to 12 binds phases 1 and 2 (same for 23 and 31), while setting it to 0 (default) binds all phases.

Load boundary / Branch boundary (power): The following three items refer to the boundary applicable to the load(s) connected to the bounded node(s) / branch.

5. Boundary code: this integer defines the function of the boundary (0=none)
   (a) code=1 means that the bounded quantity is the active power absorbed by the load and that the boundary is expressed as percent of rated load active power (percent value is given in field 5);
   (b) code=2 means that the bounded quantity is the reactive power absorbed by the load and that the boundary is expressed as percent of rated load reactive power (percent value is given in field 6);
   (c) code=3 binds both active and reactive power as percent of rated load power (fields 5 and 6);
   (d) code=4,5,6 is the same as above, but the boundary is given as percent value of the actual load power, as defined in matrix Dnode;

(e) code=7,8,9 is the same as above, but the boundary is given in absolute terms (kW, kVAr).

The same codes apply to branches too. However, the values in fields 5 and 6 always refer to absolute quantities (kW, kVA).

6. Bounded active power: the meaning of this value (%Prated, %Pactual, kW) depends on the previous code.
7. Bounded reactive power: the meaning of this value (%Qrated, %Qactual, kVAR) depends on the previous code.

Source boundary / Branch boundary (balance): The following three items refer to the power boundary applicable to the source(s) connected to the bounded node(s) / branch.

8. Boundary code: this integer defines the function of the boundary (0=none)
   (a) code=1 means that the bounded quantity is the active power fed by the source and that the boundary is expressed as percent of rated source active power (percent value is given in field 9);
   (b) code=2 means that the bounded quantity is the reactive power fed by the source and that the boundary is expressed as percent of rated source reactive power (percent value is given in field 10);
   (c) code=3 binds both active and reactive power as percent of rated source power (fields 9 and 10);
   (d) code=4,5,6 is the same as above, but the boundary is given as percent value of the actual power fed by the source, as defined in matrix Dnode;
   (e) code=7,8,9 is the same as above, but the boundary is given in absolute terms (kW, kVAR).
   (f) code=-1 resets all boundaries previously defined for the same node(s) in the same test case;
   (g) code=-2 defines the current node as a slack node; this command is only applicable to sources and has a twofold effect: first, it resets any previous constraints set for the node(s) in the same test case; second, it removes any power and current limitations.

The same codes apply to branches too, with a different meaning.

- code=1 (or 4 or 7) means that the active power must balance in the phases defined in field 4;
- code=2 (or 5 or 8) means that the reactive power must balance in the phases defined in field 4;

- code=3 (or 6 or 9) means that both active and reactive power must balance in the phases defined in field 4.

9. Bounded active power: the meaning of this value (%Prated, %Pactual, kW) depends on the previous code. This field is unused for branches.
10. Bounded reactive power: the meaning of this value (%Qrated, %Qactual, kVAr) depends on the previous code. This field is unused for branches.

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