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*Modelling a 36kV utility-scale photovoltaic plant according to the Italian
Transmission System Operator grid code*

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Abstract

The Italian and European electricity generation mix is becoming increasingly dominated by renewable sources, driven by the need to reduce greenhouse gas emissions and pollutant levels. Photovoltaic generation is the leading technology in this transition: the maturity of the technology and the relocation of manufacturing outside Europe have lowered its cost to the point that plant sizes have grown steadily, from single-user installations to modern utility-scale photovoltaic fields.

This growth, however, is not free of drawbacks. The variability and uncertainty of the solar resource introduce several critical issues for the management of the transmission network, and these issues become more severe as the installed capacity increases, since inverter-based generation behaves differently from conventional synchronous power plants.

In recent years, the Italian Transmission System Operator has issued several updates to its Grid Code, together with a set of annexes dedicated to renewable sources, covering connection schemes and the tests required before a plant may be authorised to inject power into the network. Within this regulatory framework, the present thesis, developed during an internship at Gridshape, an electrical design company based in Padua, focuses on the development of a DIgSILENT PowerFactory® model — the software accepted by the TSO — of a case-study photovoltaic plant adopting the most recent connection concept defined by the TSO, namely the 36 kV scheme, so that all the requirements set out in the annexes can be studied and described.

The main reference is Annex A.68, which governs the connection of photovoltaic plants. The model makes it possible to derive the plant capability curves, both PQ and VQ, and to show through them how sensitive these curves are to variations in the internal topology, as well as how a plant can be modified when the requirements are not met. The analysis then moves to primary and secondary power regulation, and to the settings required on the Power Plant Controller to regulate active and reactive power under the different scenarios defined by the Grid Code. These scenarios are also reproduced in the test configurations prescribed by Annex A.18, which offer a clearer picture of plant behaviour under standard conditions. Finally, the use of a commercial PPC, permits to investigate some non-standard conditions of both the grid and the devices involved, in order to assess how the plant responds to situations that are not foreseen by the regulation but are closer to actual operating conditions.

Declaration of usage of generative AI and AI-assisted technologies

No generative AI and AI-assisted technologies were used to perform this project and to write the Thesis.

The author reviewed and edited the Thesis as needed and take full responsibility for its content.

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Introduction

The studies conducted in this thesis are done in a Paduan company, Gridshape, which is a young and dynamic electrical boutique, working in consultation and operating in the renewable energy production, energy storage systems (BESS), and electricity distribution and transmission grid connections sectors. It was created with the aim of leading the energy transition towards a sustainable future, with the focus into photovoltaic systems.

One important topic nowadays is climate change, with the focus on the pollution emitted, CO₂, which is a greenhouse gas, by human activities and the related global warming effect. The main sectors in which these emissions are concentrated are industrial plants, transportation, and electricity production.

The last one is the one in which the study is focused, because to reduce the pollution emissions of the electricity production, the solution is to abandon or at least reduce the older method of production, based on the use of fossil-fuels in steam or gas-cycle plants and move into exploiting more and better the renewables.

Inside the new renewable plant share, the one which has the highest power installed in Italy is the solar photovoltaic system (PV).

Considerable importance has the most recent study [1] conducted by the GSE (Gestore Servizi Energetici), the Italian public company, controlled by the Ministry of Economy and Finance, which has as the main task to promote sustainable development by managing state incentives and administrative practices for clean energy and energy efficiency. It shows that the new installations of PV are still under a constant development and the size of them is growing. Together to this, in 2024 about one fourth of the new installations were connected to HV transmission system.

Following the chapter of this thesis work, there will be in the first one an introduction on the Italian photovoltaic scenario, an explanation of the different HV available connections and an explanation on how a PV plant can work.

The second chapter is dedicated to giving a complete overview of the plant studied in all of its components and to describe the choice made for designing that plant, also discussing the assumptions made and the standard at which the design phase is referred.

Then the chapter is focused on describing the working philosophy of two key components of the modern photovoltaic plant, the power plant controller (PPC), and the integrated inverter controller, that together allows the control of the production following diverse types of setpoints. All these ideal components need to be implemented into the DIgSILENT Power

Factory[®] environment for doing the simulations and this chapter describes how to do and how the models used works.

The third chapter provides a study on the capability's curves, both the PQ and the VQ ones, starting from the description of the standards and the reference needed for the development. Then going into the detail of the analysis of the result obtained by the experimental simulation. Moreover, a part of the chapter is dedicated to the discussion of the methods available to reach the compliancy of that curves in the case of not respecting the requirements due to the characteristics of the plant in object.

Then going more in detail of the annex A.68 [8] of the Italian Grid Code, the fourth, the fifth and the sixth chapters, are dedicated to the deep study of the requirement and the development of the simulations required by the annex A.18 [9]. Each of them is dedicated on a single core event: one the active power control, one on the reactive power control, with the use of a reactive power reference or using a voltage reference, and the last is about the active power control with the purpose of helping the frequency stability of the grid.

The last chapter is instead dedicated to an even more experimental analysis by moving from the standards and considering some not theoretical but practical events that could interfere with the setting and the requirements previously chosen and described. To name but a few, the behaviour of the PPC in case of loss of some inverters of the plant and the response of the control strategy if the grid is weaker than the one considered.

Chapter 1:

Utility scale photovoltaic plant

The transition towards low-carbon energy production systems has a significant increase in the deployment of new photovoltaic (PV) installation. If countries want to satisfy the decarbonization targets, for sure, the expansion of the share of renewable energy sources in their electricity mix is needed. Inside the macro area of PV installation, utility-scale photovoltaic power plants have become one of the most effective technologies for delivering enormous amounts of clean electrical energy.

Ground-mounted photovoltaic systems represent the predominant solution for utility-scale applications due to their scalability, design flexibility, and high energy density.

Large-scale PV generation plant needs to be connected to a strong transmission system due to the high power in action and the intrinsically low stability of these types of plant. That because these systems have not rotating devices, which can help the electrical system providing inertia and also there is the issue related to the not available control of the sun light. For these reason large scale PV plants are typically connected to high voltage (HV) transmission system and due to the previous mentioned critical issue, the Italian transmission system operator “Terna”, set some requirement related to voltage regulation, frequency support, and power quality, that the plants need to satisfy.

This chapter provides an overview of ground-mounted photovoltaic systems, introducing their main components, operating principles, and typical configurations of the connections with the HV Italian system.

1.1 Italian photovoltaic scenario

Solar photovoltaic is one of the cheapest ways to produce electricity also in a large scale, because, thanks to the incentives taken place in Italy and Europe across the 2010s decade, this technology is nowadays mature enough to reach the big scale economy which result in a price reduction. According to the last available report from GSE [1], reported in Figure 1.1, the initial rapid growth was driven, amongst other things, by public incentive schemes, in particular the so called “Conto Energia”, started from 2005 to 2013 and it was an incentive mechanism in which there was an agreement between the GSE and the producer for buying the electricity produced in 20 years from PVs at a fixed price. this of course was a great advantage for the

producers, and help, year by year, to the installation increase of new plants. Then from 2022 there was a new acceleration thanks to other incentives like the 110% Super bonus (an incentive in which the State repays 1.1 times the costs for energy efficiency renovation, which include the installation of new system for self-producing electricity like PVs), and the DM FER-1 (incentives for reaching the 2030 targets about reduction of emissions).

Moreover, it is important to highlight that not only the number of plants is increasing, but also the size of new plant is a growing trend, indeed, compared with 2023 the new plant average size is increased of 69%, at about 23.8 kW. This is still a power related to the MV network, but the trend states that less “building” scale PVs are installed and instead ground-mounted, utility scale PVs are increasing.

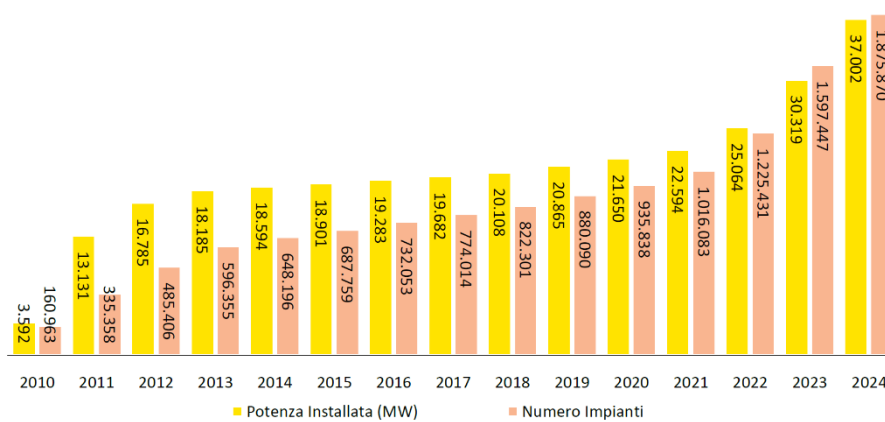


Figure 1.1 represents the annual trend of power installed (yellow bars) and the number of plants (orange bars) of the new Italian PV plants [1].

In the Italian scenario about 10.7% of the power of PVs is from HV connected plant, as seen in Figure 1.2, but interesting for the thesis study and the future development in this sector, is that in 2024 about 23.8% of newer installation are related to HV photovoltaic plant.

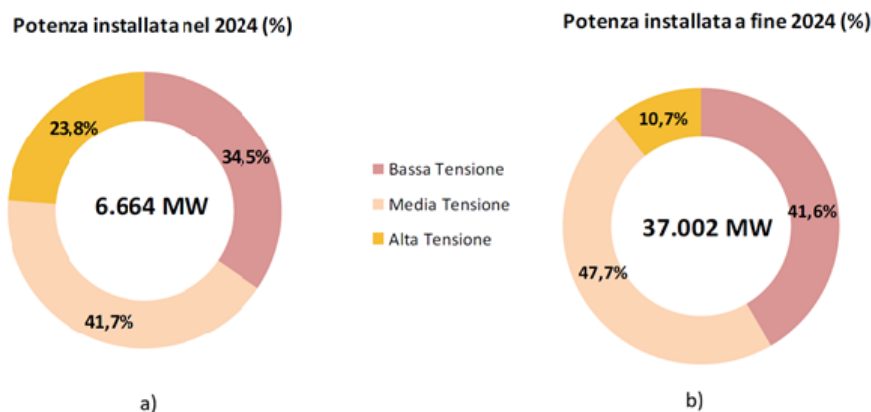


Figure 1.2 represents the share of new power installed in 2024 (a) and the share of power still installed until the end of 2024(b) [1].

This is not only an Italian trend but is still a global one. Figure 1.3 shows that the utility-scale PVs plants are growing year by year all over the world.

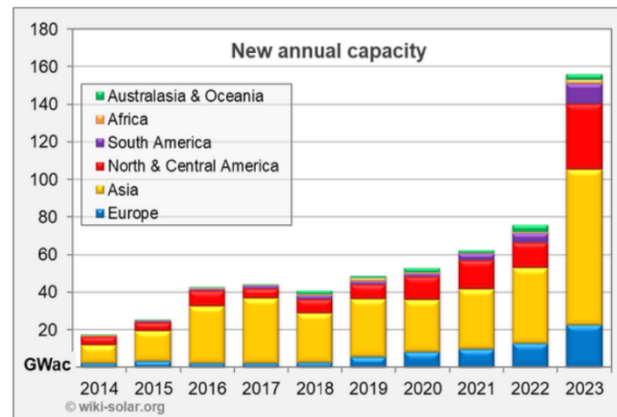


Figure 1.3 represents the annual variation of power installed only for utility-scale photovoltaic plants [2].

This because the benefits from strong economies scales are evident and by 2050 module's costs are expected to be about half of today's levels. This enables new additional investments in grid expansion and integration technologies such as storage, connectivity, and demand-response that increase the value of the solar assets, and according to IEA, global renewable power capacity is expected to double between now and 2030, increasing it by 4 600 GW. This is the equivalent of adding China, the European Union and Japan's actual power generation capacity combined to the global energy mix. Solar PV accounts for almost 80% of the global increase, followed by wind, hydropower, bioenergy and geothermal [3]. Taking all into account, last forecast speak that newer investment in this assets will be major focused into large power installations, the so-called utility-scale plant.

1.2 Type of HV connection according to Terna annex A.2

"To allow better integration of renewables through more efficient connection solutions to the national transmission grid consistent with the current size of the production plants, a new standard 36 kV connection solution has been identified". With these words, in August 2021, Terna, the Italian Transmission System Operator, announced the updated version of Annex A.2 [4] to the Grid Code "Guide to connection diagrams".

On 20 October 2021, Terna, through the "delibera 439/2021" of ARERA, define the new type of HV connection, the 36 kV standard, then called just "Type 2". It is designed to optimise the integration of renewables into the transmission grid, because it simplifies the procedure of connection and reduce the environmental impact of the substations.

The point is that the exponential growth of renewable plants in Italy is not only a problem related to the flexibility of the entire system, but also a physical problem of integrating all these new systems into the present network.

As shown by Terna, the requests for connection of PV system, on 28 February 2025 has overpassed the capacity of over 354 GW, with typical average power of these plants of 30 MW. The last point was the main problem, because before these integration in the Grid code, a plant with size of 30 MW should be installed into a bay of a conventional primary substation, sized for the 150-132 kV connection and an initial maximum power connection of about 200-250 MW, this means that all the equipment would be oversized, and the space occupied by such under-loaded bay would be used inefficiently. Moreover, each new plant requires a new bay in addition into the substation.

Instead with the 36 kV connection standard, more than one plant can be connected to the same 150-132 kV bay, so there is a creation of a “condominium like” connection, where for the single bay there may be more plants in parallel, also from different producers. That because now, the owner of the central transformer becomes Terna itself, instead of the different producers.

According to the A.2 annex [4], Terna state that each production plant can be connected directly to a 36 kV bay, which acts as a grid system, up to 100 MW. In this way, it is possible to provide the connection at a voltage level more appropriate to the average size of renewable production plants and at the same time free them from the authorization complexities brought by 150-132 kV bays. The voltage increase from 36 kV to higher levels is in fact conducted directly by Terna, no longer by the manufacturers.

Already in December of the same year, the transmission system operator recorded 1,400 connection requests at 36 kV, which about 40% of them are requested already presented, but for a higher voltage level connection.

For this type of connection, the unique standard configuration permitted by annex A.2 [4] is the “antenna” one, in which, as shown in Figure 1.4, the two existing lines from the National Transmission Network (NTN) are entering in an “in-out” connection on the TSO primary electrical substation (E.S.), and then from here, a line for the user connection.

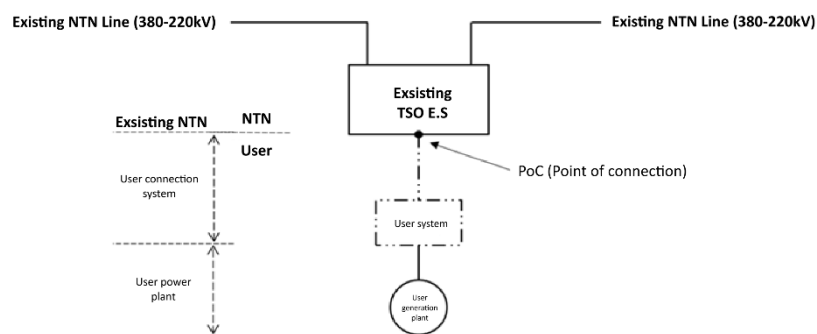


Figure 1.4 represent the antenna connection needed for the type 2 connection

In this substation there is a set of bays each of them dedicated to a single user, which exploit itself the antenna connection.

1.3 The 36 kV connection concept

Among the connection schemes depicted in Figure 1.4 and admitted in the Terna annex A.2 [4], the case study analysed in this document use the recent development in the renewable utility scale power plant of the 36 kV connection.

Generally speaking, the internal elements in a utility scale photovoltaic plant are intended to collect the power produced from the distributed generation inside the field zone, which is an area that for some tens of megawatts of modules installed could be several tens of hectares, to a single connection point.

The traditional system used also nowadays, for the connection of PV plant directly to 150-220 kV, is the one where the power distribution is carried at 20-30 kV in an internal subsystem. Instead, the type 2 connection use components that often are the same which would have been used in the traditional distribution network with only an increasing on the insulation level (if needed). The advantage is not only in the commercial availability of the components, but also on the lower Joule losses in the internal cable thanks to the presence of a lower current. The cross section of the conductors and the number of feeders required can be reduced with a non-negligible effect on the space occupied and on the overall cost of the plant. Moreover, a single transformation between the HV system and the LV inverters, avoid a median transforming stage, with the reduction of the related costs and losses.

As is often the case, these advantages are counterbalanced by some drawbacks that should have be considered in the design phase. An increase of voltage requires a higher insulation level for all the components, from the cable to the switchgear and also the windings of the transformers. The capacitive contribution of the cables is proportional to the square of the voltage, so the reactive contribution at low active power output is modified by the higher capacitance of the HV network cables as discussed in detail in the third chapter.

From the point of view of the regulation what makes this type of connection particular and interesting for the present study is the position of this concept between the border of the two standards. On one side the plant is in some sense “conventional” since it has an internal network similar to what is done in current practice for the distribution system but at the same time is connected to a transmission network with high voltage and so is subjected to the Grid Code defined by Terna and in particularly described in the annex A.68 [8]. As a result, the requirements verified in this work are all defined at the Point of Connection, which lies immediately downstream of the HV connection and is comparable to the collector of a

distribution network. Such a node would normally be a purely design-related matter, but in this case, it is governed by the rules set by the Transmission System Operator.

1.4 European and Italian regulatory framework

Before describing the technical solutions adopted in the plant, it is useful to clarify the regulatory context in which this design work sits, because every requirement discussed in the following chapters is a consequence of a hierarchy of documents produced at the European and national level.

The starting point is the Commission Regulation (EU) 2016/631, commonly identified as the Network Code Requirements for Generators, usually abbreviated as NC RfG. This regulation is directly applicable in all European Union Member States and establish a set of technical requirements for the connection to the grid of the generation unit. The regulation defines four types of generating units from letter A to D according to the maximum active power produced and the voltage level of the connection point. The classification is not only a formal distinction but include a set of different requirement, which becomes strictest control as the size and the voltage of the plant increases. Some of them are accepted at the European level, but other can be modified by the national TSOs.

For this reason, a photovoltaic plant designed for the Italian market could not be installed in a place different from the peninsula, since the capability and the settings related to the auxiliary services that it must provide could not satisfy the national regulation of the different State even if inside the EU.

In Italy, the specifications are provided by Terna which collected them in the Grid Code and its annexes, key documents for the design of the plants and also core documents for this thesis work. The annex A.2 [4] provides the admissible connection scheme and is the reference used in the present work to identify the topology of the case study plant. The annex A.68 [8] collects the technical requirement needed for the photovoltaic power plant, connected to high voltage and is the main standard reference for this thesis work. Finally, the annex A.18 [9] express the tests and the demonstrations needed for the approval and the connection of the plant and is used in this document as guide for the simulations in the software environment.

The regulatory path of a new plant is not limited to the technical requirements. After the connection request, the Transmission System Operator writes the Minimum General Technical Solution (STMG), which fixes the connection scheme and the point of connection; the design is then developed consistently with that solution and, before the start of the commercial operation, the plant has to be verified through the tests prescribed by the annex A.18 [9], whose positive outcome is a necessary condition for the definitive activation of the connection.

1.5 Photovoltaic power generation

Doing a step back, it is important to know how the photovoltaic generation is possible and which element and device participate in the design of a PV system.

The core of the system is the photovoltaic cell, it can convert the energy from the sun light into electricity, exploiting the so-called photovoltaic effect. Cells are arranged into strings, then a DC-DC converter manage the working point in terms of current, voltage and power produced by the string. After that is needed a link between the DC system and the AC grid, this is carried by the DC-AC inverter and the power transformers.

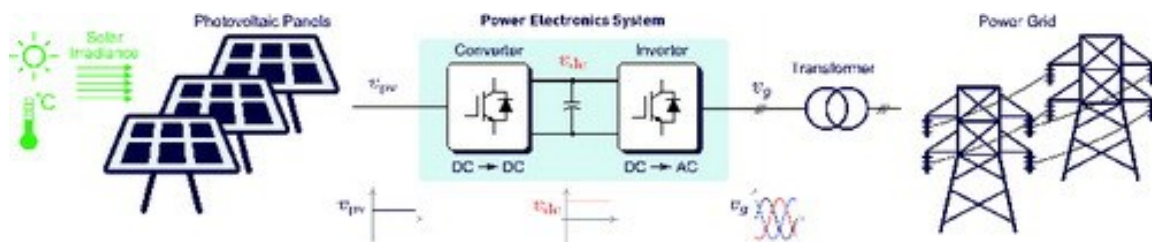


Figure 1.5 Scheme of how a utility-scale PV plant is built [15].

1.5.1 Photovoltaic cell

The photovoltaic cell is the basic building block of a PV system, it is made by silicon, which is a semiconductor, and when a beam of photons hits the cell surface, part is reflected, part pass through it without interaction and part is absorbed and generates electricity.

The physical principle under this effect is called “photovoltaic effect” and it is experimented thanks to the intrinsic design of the photovoltaic cell. It is made as a sandwich of two layer of the semiconductor, one n-doped and the other p-doped, this creates the so-called p-n junction. The junction is the site of an electric field of about 0.8 V that is present thanks to the abundance in the opposite direction of electrons (n-doped) and holes (p-doped), and the field maintain separated the charges due to the creation of a potential difference V_D .

When the light hits the cell, the energy of photon, if is enough, generates an electron-hole pair, which is then separated by the electric field of the p-n junction. The connection of the two side of the junction with an external conductor, establish a closed loop, in which thanks to the potential still present, a current start to circulate.

Knowing this behaviour, the equivalent circuit of the cell can be modelled, in first approximation as the one reported in Figure 1.6.

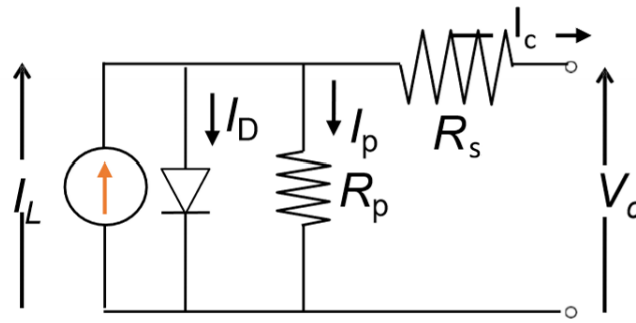


Figure 1.6 the simplified model of a photovoltaic cell

Here is represented an ideal current generator, responsible to the current from the sun, in parallel with a diode, responsible to the current generated by the p-n junction and two resistance, one in parallel, to consider the physical defects of the cell surface, and one in series to consider the real resistance still present in the p-n junction and the related not ideality of the diode.

$$I_c = I_L - I_0 \left(e^{\frac{q \cdot V_c - R_s \cdot I_c}{n \cdot k \cdot T}} - 1 \right) - \frac{V_c + R_s \cdot I_c}{R_p} \quad (1.1)$$

$$V_c = V_D - R_s \cdot I_c \quad (1.2)$$

The (1.1) relation define the behaviour of the current produced in the photovoltaic cell and together with the voltage behaviour (1.2), the power is shown in Figure 1.7.

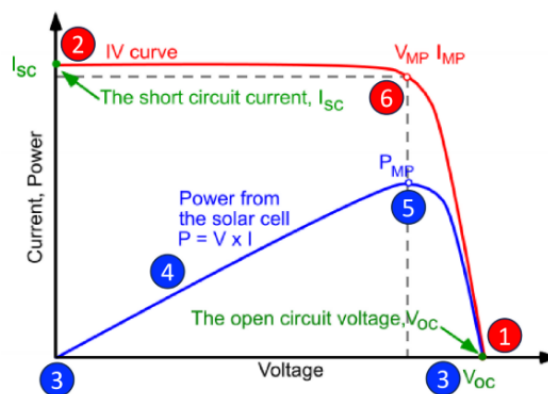


Figure 1.7 Current-voltage (I-V) characteristics for a PV panel showing the MPP.

The amplitude of the I-V characteristic curve of the photovoltaic cell varies from two extremes, the short circuit current I_{sc} at zero output voltage, where the terminals are short circuited and

the open circuit voltage V_{OC} at zero current where the terminals are opened. In both these working point, as described by the blue line, the power produced is null.

Instead interested in the producing point of view is the point in which the power is at its maximum value, the “Maximum Power Point” (MPP) and it is the preferable working point for the cell.

Moreover, the power generated by the cell is affected by the variation of the environment condition, specifically from the solar irradiance level and the ambient temperature. This is experienced by a significant voltage decreases at the temperature rising and instead the current is related to the solar irradiance facing the cell surface.

A single cell produces about 1 W, too little for a utility-scale plant. Cells are therefore connected in series, which keeps the current low, to form a module. Nowadays technology create inside a module, two submodules connected in parallel and the series of cell is made by three groups in parallel, needed to minimize the reduction of performances due to shadows on the module.

Due to the properties of non-linearity and environmental dependency of the PV cell, a Maximum Power Point Tracking (MPPT) algorithm is necessary to maximize the generated power.

1.5.2 DC-DC MPPT converter

Another fundamental device for a PV field is the MPPT. It is typically integrated in the inverter structure and is a technological device capable of defining new working point for the modules, different from the ideal one, to maintain all the operations at the highest power value instant by instant. To do this, the way is exploiting a DC-DC converter, typically a buck-boost one, able to change the output current and voltage.

The working principle of this device can be resumed as a variable resistance, indeed the control of the converter, through the duty cycle, can varies the resistance of the circuit and so if it is increased, also the voltage follows that trend, while current is reduced, following the famous Ohm’s law.

Moving it to a utility-scale PV plant, the scenario created is one in which tens or hundreds of modules are connected to the MPPT and deliver energy to the inverter. In ideal condition all should work at the MPP and so all is perfectly balanced. But if for some reason (shading, ageing, dirt...), one or more of the modules produce less or does not produce at all, a spread appears in the values of current and voltage, which are not in the MPP anymore.

For hitting the MPP point, the control logic is based on an algorithm loaded into a microcontroller or into a microprocessor and there are two main strategies.

One is the so-called “Perturb and Observe”, where the algorithm increases the voltage, then a feedback control compares if this action corresponds to a power increasing, if true there is a continuous increasing otherwise the voltage is decreased.

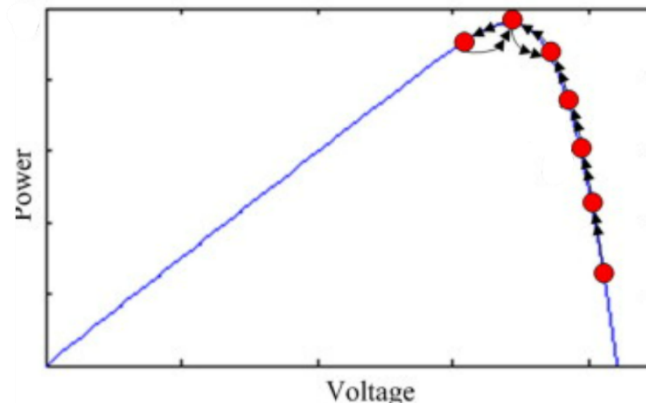


Figure 1.8: Improved strategy algorithm of the “Perturb and Observe” control developed for the MPPT [5].

As can be seen in the previous figure, since the perturbation is continuous, the true MPP is never reached: the operating point oscillates around it, within a band whose width depends on the settings of the DC-DC converter.

The latter is the “Incremental conductance”, where are measured the derivatives of current and power with respect to the voltage and so a real track of power curve can be design and so a real MPP can be achieved. The main drawback of this strategy is related to the slow reaction time and to the higher cost of the device compared to the other strategy.

Typically, at each DC-DC converter is associated a DC-AC inverter in order to directly produce electrical energy suitable for the grid connection, but since the MPPT has a fundamental role in the optimization of the efficiency of the power plant, different connection configurations can be used. The most natural one for the connection with the string is the “Conversion per module”, Figure 1.9a, where each module is connected to a MPPT, of course is the best in terms of performances, but considering a utility-scale plant, with hundreds of modules in the field, this solution is not economically sustainable. Another option is the “Conversion per string”, Figure 1.9b, where each string is connected to a different MPPT, in this way a shadow in one string does not affect the working point of the other. Nowadays the latter is improved by the adoption of multi-MPPT inverters, Figure 1.9c, where each inverter has multiple independent MPPT, so the basic principle remains untouched, but there is a reduction in cost and inverter installed in the whole field.

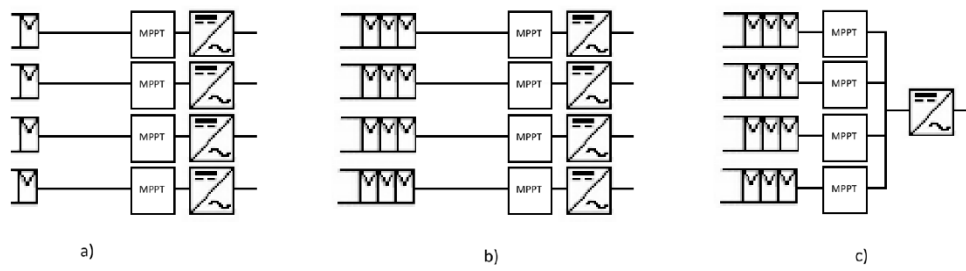


Figure 1.9 Three different configuration for the MPPT connection: “Conversion per module” a), “Conversion per string” b), “multi-MPPT inverter” c).

1.5.3 DC-AC inverter

As seen in the §1.1.1 the solar cells and then photovoltaic modules and strings, can be considered as a DC current source, but the transmission system and in general the electrical network is operating with an AC current and voltage, this means that a conversion circuits from a DC voltage source or a DC current source to an AC voltage and current is needed, and it is carried by the inverters. Moreover, inverters not only convert DC power to AC power, but are capable to gives that at required voltage and frequency.

For the photovoltaic application, the most used is the voltage–fed inverter (VFI) or a voltage–source inverter (VSI); these develop at the input terminals a constant voltage. Since the case-study is referred to a high-power installation, the focus of this introduction paragraph is on the three-phase inverters.

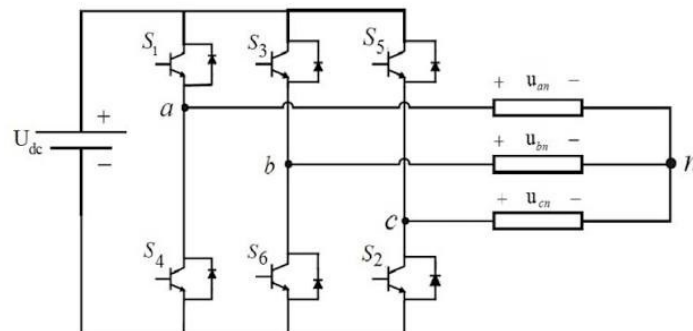


Figure 1.10 Layout of a three-phase inverter, with a DC voltage source, connected to a three-phase wye load [6]

Internally, they consist of three half-bridge legs connected in parallel, one per phase and, during the operation, each phase of the inverter is shifted by 120 degrees. So, at the end with six switching devices and six diodes, the converter can operate between the 180° and 120° conduction angle.

One of the most used strategy for the control of the inverters is the Pulse Width Modulation (PWM), where pulses have fixed frequency and scale, but with a variable pulse width. This is fundamental since it modulates the signal according to the requirement. Then this signal is

applied to the gate of the transistor and inverter reacts with a different opening and closing duty cycle.

The advantages of using this technique are related to the lower power dissipation, the easy implementation of the control and in the fact that output voltage lower order harmonics can be eliminated or minimized. The main drawback of this method is that Insulated Gate Bipolar Transistor (IGBT), the ones typically used in the inverter as the switching devices, are expensive and the turn-on and off rate is limited, so not too much frequency can be achieved.

The main basic idea of the PWM technique is to compare a carrier signal, usually a triangular one, with a specified frequency, with a reference signal having a lower frequency equal to the desired output frequency. If the output must be a sine wave, the reference signal must be a sinusoid at the required frequency.

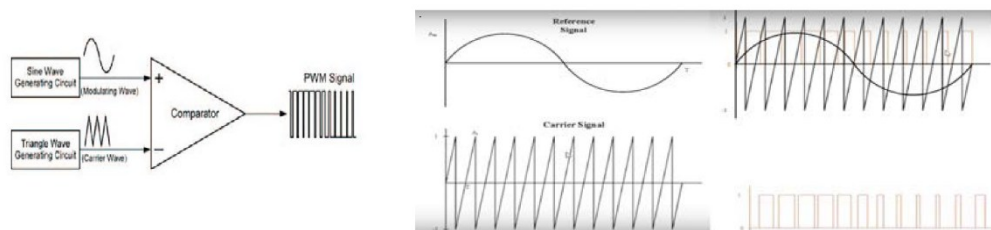


Figure 1.11 PWM strategy, from left to right, how modern electronic comparator produce the PWM output signal and then how the comparison is done analytically [6].

Chapter 2:

Study case PV plant and DIgSILENT Power Factory[®] models

When in 2021 Terna developed the Type 2 connection mode, one of the prototype plants under observation for this new connection was certainly the PV system, in particular utility-scale plants of an intermediate power installed for the HV level. Following this philosophy, the plant studied on this thesis work is a fictitious but realistic plant, with 30MW power installed. The choice is dictated by the average power of new connection requests previously mentioned and by the desire to use the most common, commercially available devices used in Gridshape's projects.

This chapter provides a complete overview of the plant studied and on the technical choices necessary for the development of the plant.

Then a further step is done by moving in the simulation environment, DIgSILENT Power Factory[®]. It is a power system analysis software application for use in analysing generation, transmission, distribution, and industrial systems. The aim is focussed initially to the static scenarios as the one needed for the capability curve in chapter 3, where the elements shown in the previous chapter are modelled and used as something "standard" which needs only to be tuned according to the tables presented. But then going more in detail on the power control system, also dynamic model are needed, together with the so-called RMS simulation, a tool in DIgSILENT Power Factory[®] that can be used to analyse mid-term and long-term transients under both balanced and unbalanced conditions, which incorporates also a graphical environments for creation of user-defined models, using DSL (DIgSILENT Simulation Language) or Modelica language.

For this reason, this chapter also provides the description of how the models are built and then implemented into the plant, starting from the simpler theoretical ones from WECC Solar Plant Dynamic Modelling Guidelines [7] to the more complex commercial ones.

2.1 Plant component overview

The single-line layout can be seen in Figure 2.1. It represents all the single line layout of the user plant, connected to the Point of Connection (PoC) modelled as an external grid.

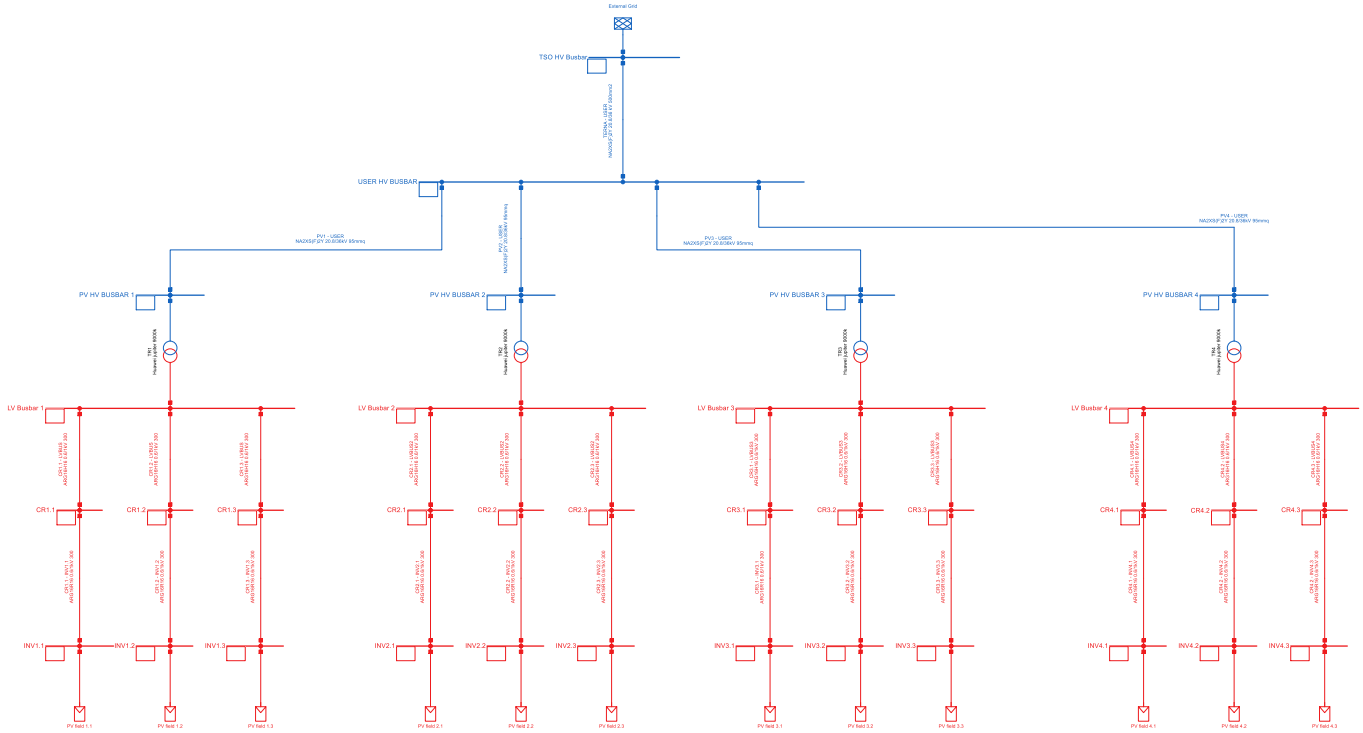


Figure 2.1 Single line layout of the case study plant realized using the software DlgSILENT Power Factory®

Since the plant is only a study case, not a real executive solution, every cable, inverter, transform used is sized with realistic data, but in an easy scalable way. For instance, the length of cable is appropriate for the extension of the possible photovoltaic field, but it is only an indicative number and the same is for the connection HV cables between the Terna substation and the user.

Focus of the document is the connection between a 36 kV PV plant with Terna substation and its necessary regulation to satisfy the requirements of the annex A.68 [8], using the software DlgSILENT Power Factory®. This means that the connection layout of the photovoltaic modules and in general the DC side of the inverters does not need to be considered since for the software is enough knowing quantity and size of the inverters. The unique data from the photovoltaic modules needed is related to the ratio between power installed DC and the output AC power from the inverter, but in this case, it is assumed equal or higher than one. It is a statement that can be acceptable since the inverter itself limit at the unit. The worst condition should be the one in which this ratio is less than the unit, because in this case the inverter output is limited by the DC power.

To respect the limit of nodes set by the educational edition of the software, and since the studies which will be carried out involves only powers and voltages, a first simplification can be made by grouping the inverters in 4 areas, each of them constituted by 3 subsystems of eight, eight and nine inverters respectively.

Such subdivision helps in the develop of the software model but considering that each group is supplied by a separated-full-loaded transformer, the solution adopted could not be so distant from a real plant.

2.1.1 HV cables

According to the idea of the Type 2 connection, the PoC is at 36 kV, with the charge of the transformation from 380-150 kV to 36 kV carried by Terna in their substation. This becomes an advantage since the user does not need his own one and the PV plant can be located also far from the primary substation. In fact, the connection can be carried by a HV Over Headline (OHL) or by a HV ground cable. The latter solution was chosen because overhead lines are less likely to be approved during the connection process, due to their environmental impact.

The solution presents a single cable, with a length of two kilometres, in order to represent the possible distance between the PV field and the TSO substation, made by a cable NA2XS(F)2Y 20.8/36 kV 500 mm², having an aluminium conductor, with core insulation in XLPE compound and metallic copper screen; adapted for the ground laying.

The cross-section, since the goal of the thesis work is not the sizing of conductors, is defined as the minimum one that satisfies only the ampacity criteria. If the plant will be constructed, the criteria for the sizing of the conductor would be the maximum admittable voltage drop and the thermal sizing.

The same type of cable, but with a cross section of 95 mm², is used for the connection between the collection cabin and the HV/LV transformers. In this case the average length is one kilometre by considering that the plant is dislocated in separated landscape, because one layout is that the overall necessary surface is about 360000 m² can be divided in four separated zones. In this case the length is a little overestimated to obtain a bigger incidence in the capability curve of the next chapter.

Since the main purpose of this document is the DIgSILENT Power Factory® model, fundamental for it are the electrical parameters of the HV cables reported in Table 2.1.

Table 2.1 Electrical parameters and characteristics of the HV cables used in the DlgSILENT Power Factory® model.

Description	Value
NA2XS(F)2Y 20.8/36 kV 500 mm²	
Nominal voltage [Uo/U]	20.8/36 kV
Nominal current (ground)	620 A
Conductor type	Aluminium
AC resistance at 20°C R1	0.0608 Ω/km
Direct sequence reactance X1	0.11 Ω/km
Zero sequence resistance R0	0.12 Ω/km
Zero sequence reactance X0	0.33 Ω/km
Capacitance C0	0.4 µF/km
Nominal short circuit withstand current (1s)	47 kA
NA2XS(F)2Y 20.8/36 kV 95 mm²	
Nominal voltage [Uo/U]	20.8/36 kV
Nominal current (ground)	254 A
Conductor type	Aluminium
AC resistance at 20°C R1	0.206 Ω/km
Direct sequence reactance X1	0.13 Ω/km
Zero sequence resistance R0	0.618 Ω/km
Zero sequence reactance X0	0.39 Ω/km
Capacitance C0	0.5 µF/km
Nominal short circuit withstand current (1s)	9.2 kA

2.1.2 HV/LV transformers

One distinctive feature of the 36 kV connection is the absence of a medium voltage section. This is advantageous because losses are reduced due to the voltage ratio of the transformers.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \quad (2.1)$$

$$\frac{I_p}{I_s} = \frac{N_s}{N_p} \quad (2.2)$$

As shown by (2.1) and (2.2), for the same secondary current and voltage, a higher primary voltage means a smaller turn ratio and so a higher current ratio, so I_s is smaller and according to (2.3) the losses are reduced.

$$P = 3 \cdot r \cdot I^2 \quad (2.3)$$

The drawback is related to the fact that not standard transformer can be used, but only one having the possibility to reach at the primary 36 kV and they are typically special types of MV/LV transformer, with limited apparent power and a high short-circuit voltage value. Under certain conditions this is a limitation, because the total power of the plant cannot be handled by a single transformer (in the study case is 30 MW, but according to [4] the maximum power for this connection is 100 MW) and so multiple, less power installation are needed, which if in terms of continuity of supplying and for distributed generation field can be the best solution, for the overall losses and for the capability curves of the plant is a limitation.

For this application, the choice fell on the quite common Huawei JUPITER-9000K-H0 Smart Transformer Station. Moreover, another limitation provided by that configuration is the fact that these transformers are equipped with just a No-load tap changer (NLTC), device, creating a limit for the voltage regulation during the high reactive power generation scenarios.

Since the main purpose of this document is the DIgSILENT Power Factory® model, fundamental for it are the electrical parameters of the transformer reported in Table 2.2.

Table 2.2 *Electrical parameters and characteristics of the transformers used in the DIgSILENT Power Factory® model.*

Description	Value
Huawei JUPITER-9000K-H0	
Nominal apparent power	9000 kVA
Nominal voltage HV side	36 kV ($\pm 2 \times 2.5\%$ NO-LOAD TC)
Nominal voltage LV side	0.8 kV
Vectorial group	Dy11
No-load losses	8 kW
Percentual short-circuit voltage	15%
Full load losses	50 kW
Cooling method	ONAN

2.1.3 LV cables

The LV cables are cables made typically in aluminium (cheaper and less attractive to thieves than copper) and here are chosen the ARG16H16 0,6/1kV 300 mm², they are unipolar cables, with external insulation of EPR and internal one in PVC, the double insulation is the minimum requirement for the direct ground laying.

The cross-section, since the goal of the thesis work is not the sizing of conductors, is defined as the minimum one that satisfies the ampacity criteria, equals to 300mm².

The length of the cable is assumed to be equal for all in first approximation and equal to an average value of 300 m. According to the previous assumption, each photovoltaic field should occupy an area around 90000 m², so in the most favourable condition a square surface with side of the previous mentioned 300 m. For all the possible layout of the field, if the Collection cabin is in the middle of the field, or if it is on one side of the plant, this length is overestimated and so can consider most of the possible configurations available for the PV field. It is important to take in consideration that these cables need to only connect the cabin to the inverter and not going around the area, so in real application the length is reduced as the inverter is closer to the collection spot.

Since the main purpose of this document is the DIgSILENT Power Factory® model, fundamental for it are the electrical parameters of the LV cables reported in Table 2.3.

Table 2.3 *Electrical parameters and characteristics of the LV cables used in the DIgSILENT Power Factory® model*

Description	Value
ARG16H16 0,6/1kV 300 mm²	
Nominal voltage [U ₀ /U]	0,6/1kV
Nominal current (ground)	454 A
Conductor type	Aluminium
AC resistance at 20°C R ₁	0.1 Ω/km
Direct sequence reactance X ₁	0.078 Ω/km
Zero sequence resistance R ₀	0.3 Ω/km
Zero sequence reactance X ₀	0.154 Ω/km
Capacitance C ₀	0.35 μF/km
Nominal short circuit withstand current (1s)	11.3 kA

2.1.4 Inverters

Last key elements for the plant development are the inverters. The choice was to recreate the most general layout, so are used the HUAWEI SUN2000-330KTL-H1, one of the most used for the utility scale solution. In this general layout, the inverters are chosen separated from the transformer, but in the market are available also solution with all the two devices jointed together in a single power station to perform the conversion and transformation of the electric power in a specific location. To reach the goal of the installed power, are used 100 inverters. This is a three-phase inverter, equipped with five separated MPPT, with the subdivision of the 300 kW power from the module in five separated groups, to maximize the productivity also with shadows.

Since the main purpose of this document is the DIgSILENT Power Factory® model, fundamental for it are the electrical parameters of the inverters reported in Table 2.4.

Table 2.4 *Electrical parameters and characteristics of the inverters used in the DIgSILENT Power Factory® model*

Description	Value
HUAWEI SUN2000-330KTL-H1	
Nominal apparent power	330 kVA
Nominal current	238.2 A
Nominal voltage	0.8 kV
Maximum short circuit current I_k	238.2 A
European Efficiency	98.8 %

2.2 Renewable Energy Generator/Converter Model REGC_A

REGC_A module is one of the possible Renewable Energy generator/converters designed by WECC and then accepted by ENTSO-E association. It represents the Generator/Converter (inverter) interface with the grid. It processes the active and reactive current command and outputs them into the grid model.

The model controls the inverter through the definitions of two currents, one for the active injection and one for the reactive injection and so unlike the traditional synchronous machines, it behaves as a controlled current source. There are two main control blocks, the High Voltage Reactive Current Management (HVRCM) and the Low Voltage Active Current Management (LVACM).

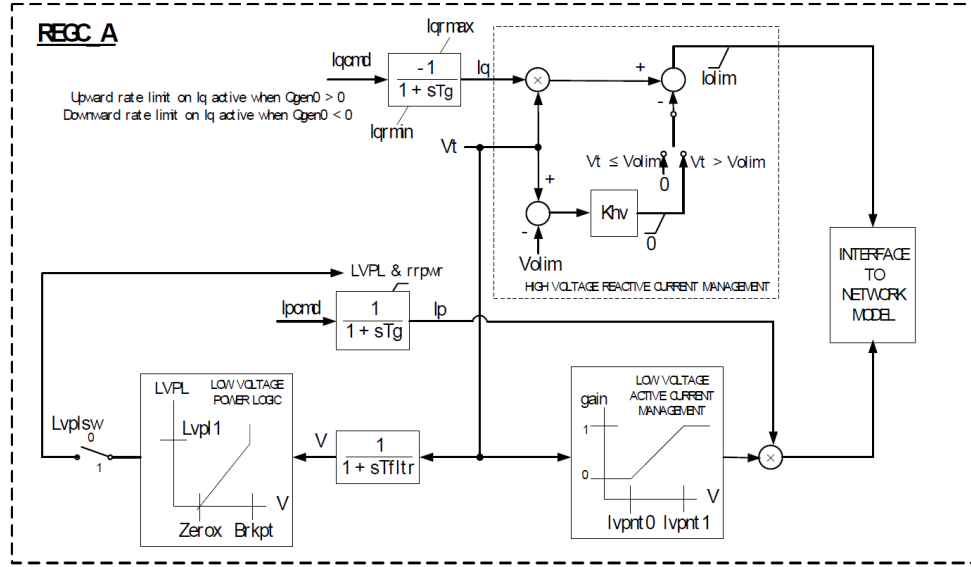


Figure 2.2 Theoretical logic scheme of the REGC_A controller according to [7]

The HVRCM works as stabilizer and as voltage safeguard during overvoltage events. From Figure 2.2, during nominal conditions, where V_t , the nominal voltage, remains inside the threshold, this block is passive and gives to the inverter only the signal of reactive current provided by the PPC. If instead the V_t voltage goes above the trigger threshold with value V_{olim} the block calculates the difference of the voltages and provides an extra reactive current proportional to the error multiplied by a defined gain Khv , as the (2.4) express, remaining inside the capability limit of the inverter defined as I_{olim} .

$$I_{qextra} = -khv \cdot (V_t - V_{olim}) \quad (2.4)$$

The LVACM block governs how the inverter behaves during undervoltage transients, because if the voltage is reduced, in order to maintain a specified power setpoint, the inverter should inject a current higher than the rated one.

As for the other block, under nominal voltage conditions, the active power injected is the one coming from the PPC, but if V_t become lower than the threshold of V_{t_filt} , the block follows a specified linear function to reduce the active current injection until the minimum value of voltage $Lvpl0$ is reach with a current equal to I_{pl} . At the end, the logic injects the minimum current between the one from this block and the one from PPC.

2.3 Commercial Solar Converter model in DIgSILENT Power Factory®

The producer of the inverter considered in this document, also provides its own dynamic model to be assigned to the block “*elmGenstat*” used in the simulation. Figure 2.3 shows that this frame is equipped with more modules than the ones needed, so the focus is only on “Plant control” (the link between PPC and the inverter), “Q_control” (the reactive power controller), “Udc_Control” (the active power controller), “Curr_control” (current controller) and “PQ and Ulv measurement” (measuring inverter bus blocks).

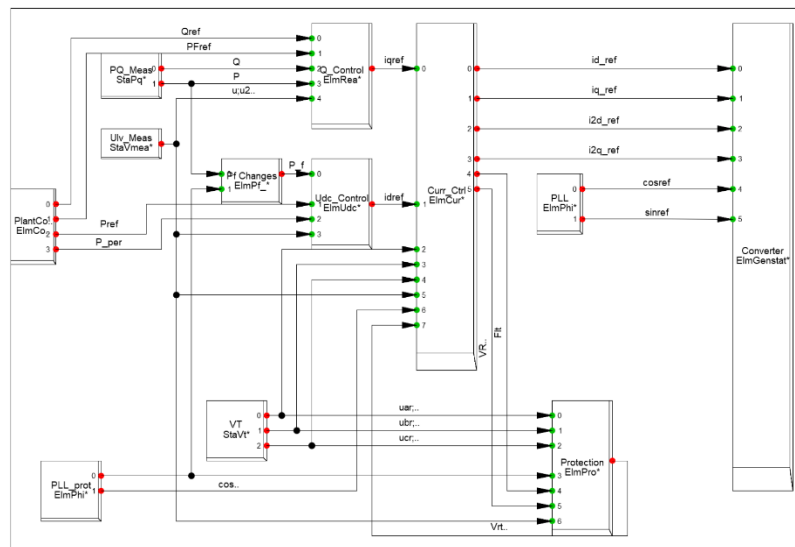


Figure 2.3 Internal logic scheme of a commercial inverter controller

From the link with the PPC, four signals come out: two related to the reactive power, Q_{ref} and PF_{ref} , which are the set-point value of reactive power and power factor, and two related to active power, P_{ref} and p_{per} , the set-point value of active power in Watts and in p.u. Signals are then processed inside the Q and P control blocks, where there is a logical switch, since the signal input can come from PPC, local controller or the protection module, and also from user settings. Then a divider block, together with the p.u. voltage measurement, derives the reactive and active current respectively, that as to be sent to the current control.

The Current controller is the core brain of the model because it is the REGC_A module of the previous paragraph, with the only addition of the signals from protection, which are not under observation. Inside this block there are also some limits related to the real inverter connected as for instance the maximum apparent power, current... all tuned by the user before the start of the simulation through the setting menu.

2.4 Renewable Energy Plant Control Model REPC_A

According to [7] the model REPC_A is used to represent the PPC, it can process voltage and reactive power output to emulate the reactive power and the voltage control at the plant level.

It also processes frequency and active power output to emulate the active power control.

The model incorporates a closed loop voltage regulation according to a specific voltage bus reference. Key feature of this loop is the line drop compensation, the voltage/reactive power droop response and the possibility to define a user-settable voltage deadband, a closed loop reactive power regulation with a user-settable dead band on the reactive power error signal and a governor able to control the frequency deviation in a user-designated bus. The frequency droop response is controlled by the action on active power on a user user-designated branch. Frequency droop control is capable of being activated in both over and under frequency.

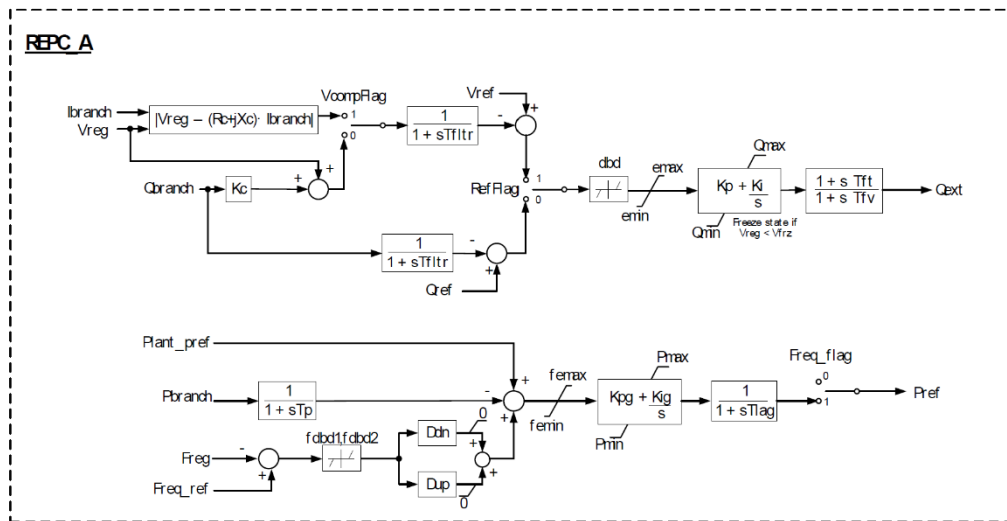


Figure 2.4 Theoretical logic scheme of the REPC_A controller according to [7]

In the reactive loop, the top one, the first phase is related to conditioning and compensation. Here the voltage measured from the busbar V_{ref} , and the reactive power measured Q_{branch} , are initialized and passes through a first order high-pass filters with time constant T_{filtr} to attenuates the high-frequency noise from the switching transient. Before the voltage block, the user can acts on a switch to choose two controller configurations, one where the voltage value derive from the action of an impedance compensation, by the automatic measurement of the current I_{branch} and so is related to the physic of the plant, or in the other, the voltage is obtained “virtually” by multiply the reactive power with a droop constant K_c .

The logical selector $RefFlag$ determines the operational state of the controller, when the logic state is one, the controller operates in voltage control mode (the Terna’s regulations Q(V), RegQ, RegV fast and RegV slow), where an external voltage reference set-point V_{ref} is compared with the previous measured one. When instead the logic state is zero, the controller

operates in reactive power control mode, here the error is calculated directly between the reference reactive power Q_{ref} and the one measured Q_{branch} .

When the two error signals are defined, they go into a deadband blocks, to filter it and then into a Proportional-integral PI block, defined by the gains K_i and K_p . In order to prevent that during severe grid fault the controller requests a boundless reactive power, are fixed the limits Q_{max} and Q_{min} . The final output signal, Q_{ext} , serves as the external reactive power reference command for the generators.

The bottom loop is the active power P and frequency f one, by which the plant contributes at the primary frequency regulation, emulating the behaviour of the traditional synchronous generator's-based plants.

Starting from the left bottom side, the controller calculates the frequency deviation of the measured value F_{reg} from the reference one F_{ref} . Also two deadbands (f_{dbd1} and f_{dbd2}) and two drops are implemented, because the response is different in over and under frequency, due to the fact that the active power injected by these types of plant is conditioned from the instant-by-instant environment conditions, so if in over-frequency conditions, the control of the inverter output reduces the power injected, in under-frequency conditions, not always the active power can be increased.

Through the droop block, the controller provides an active power signal, summed with the active power reference P_{plant_pref} , which can be imposed by Terna or the owner of the plant according to the operation regulations; and subtracted with the measured active power (at the PoC) signal P_{branch} . The result is an error which enters in a structure similar to the reactive power control, indeed a PI controller, with correctly tuned gains K_{pg} and K_{ig} , limited by the maximum and minimum value of the active power available, according to the capability curves, gives the output signal P_{ref} , used in the previous mentioned inverter controller.

2.5 Commercial PPC model in DIgSILENT Power Factory®

Moving inside the software environment, the way chosen to implement the REPC_A block is using a commercially available PPC block. Of course, the structure is a little bit different, with some extra features, required for the real application, as shown in the figure below.

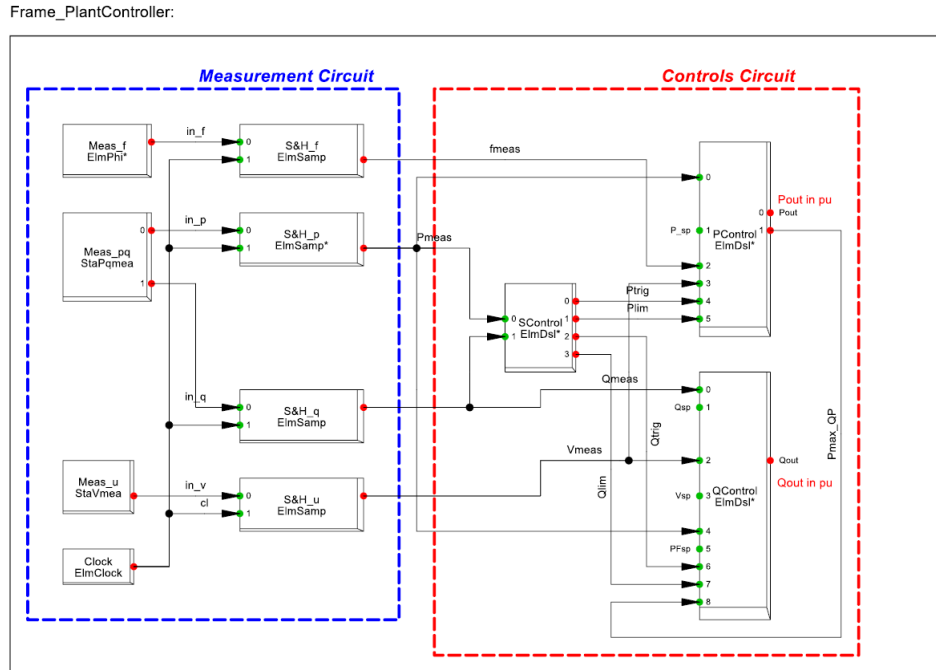


Figure 2.5 Internal logic scheme of a commercial PPC

The PPC represented is divided in two parts, one highlighted with blue dedicated to the measurement circuit, while the red one is for the effective PPC logic implementation.

In the “measurement circuit”, the four input are automatically obtained from three “virtual measurement device” implemented in the software, one for the frequency, one for the power, both active and reactive, and one for the voltage, all at the PoC busbar. There is also a tuneable clock, that together the respective “Sample and Holding” (S&H) blocks, allows the injection in the “Controls circuit” of measurement signals that are not continuously updated in the time (as the one provided by the software) but instead are discontinuous as the behaviour of a real measure instrument; the tuning is needed to define the deliverable sampling interval.

Inside the “Controls circuit”, the first block met is the “S_Control”, as the name says, it is the control block of the apparent power S, more in detail, it allows to set a limit on the S value and a priority, or for the active power or for the reactive, in this way the block provides a limit signal Q_{lim} or P_{lim} for the opposite power block with respect to the priority choice. The two blocks “P_Control” and “Q_Control” are based on the two sections of the REPC_A previously mentioned equipped with the different working mode in power regulation needed for satisfying the Terna requirements.

2.6 Modelling assumptions and simulation methodology

The results presented in the following chapters are the outcome of a custom model built to verify Grid Code compliance for 36 kV plants in general. Since this is a model, its underlying assumptions that must be stated explicitly, together with the domain of validity of the results. This section collects the hypotheses adopted in the construction of the DIgSILENT Power Factory model and the numerical settings used in the simulations.

The first choice concerns the type of analysis. The software will be used to study the electrical network in the load flow domain and in the RMS balanced dynamic domain. The load flow calculation is used in this work to obtain the steady state operating points, and therefore to build the capability curves at the point of connection. The RMS balanced dynamic simulation, instead, is the tool adopted for all the tests derived from the annex A.18 [9].

The second assumption made is in considering the balanced three-phase operation. All the network elements are described through their positive sequence parameters and the voltage source representing the external grid is assumed symmetrical. This hypothesis is consistent with the nature of the tests analysed, which are all defined as symmetrical variations of a set point, but it excludes from the analysis the unbalanced conditions. Moreover, the experience gained by the company and the constant contacts with the Terna's office, give greater weight to the choice, since the symmetrical representation is what really is expected for the connection agreement, even if behaviour of the plant in the working condition could be extremely different. A third aspect concerns the aggregation of the generating units. A utility-scale plant contains a large number of identical inverters. Each of them is connected to its own generator unit string and to a transformer. The detailed representation of every unit is possible but leads to a model whose computational cost is not justified by an appreciable improvement of the accuracy at the Point of Connection, because the units operate in parallel with the same control signal. In this work the plant is represented preserving the topology of the collector network, so that the contribution of the cables and of the transformers to the reactive balance and to the voltage profile is not lost, while the units belonging to the same section are described through equivalent generators. Moreover, the quantities analysed are power and voltages, that in an ideal symmetrical circuits are uniformly distributed along the parallel connection.

The external network is represented through a Thevenin equivalent generator, characterised by the rated voltage, by the short circuit power and by the resistance to reactance ratio at the point of connection. This representation is the standard one for the connection studies, but it deserves a remark: the equivalent source imposes the voltage and the frequency at the boundary of the model, and therefore the plant is always studied as a subsystem connected to a network whose behaviour is not influenced by the plant itself.

Moreover, since the plant is only a fictitious one and the purpose of this study is to create a model able to study all the same type of plant, the external grid is intended having infinite short

circuit power. In this way, none of the limitations identified in the following chapters can be attributed to the external transmission grid.

From the numerical point of view, every dynamic simulation is initialised through a load flow calculation, whose solution provides the initial state of all the dynamic models. Before the application of any event, a steady state verification is conducted in order to confirm that all the derivatives of the state variables are effectively null and that no internal signal is already in saturation.

Finally, since the focus is on the connection between the plant and the grid and not the plant design phase, some phenomena are not described, such as the variability of the solar irradiance, permitting to have in all the simulations the maximum power available on the direct current side and to maintain it constant during all the test periods. Or the thermal behaviour of the components and the consequent derating are neglected. The communication system between the controller and the units is represented through its equivalent delay and cycle time, and not through a detailed model of the protocol.

Chapter 3:

Capability curves at the point of connection

One of the core elements required for photovoltaic plants in order to obtain the approval of the connection agreement are the capability curves, and in particular the fulfilment of the requirements established in Annex A.68 [8]. Their importance derives from the fact that they constitute the formal and synthetic representation of the operating limits of the generation plant. They provide an overview of the admissible working region of the plant. In this sense, the capability curve is not merely a graphical output of a study, but a contractual document since the operating envelope that it delimits is the one against which the behaviour of the plant will be assessed throughout its service life.

From a technical point of view, the capability curve is the locus, in the active–reactive power plane, of all the operating points that the plant is able to sustain in steady-state conditions at the Point of Connection (PoC), once all the internal constraints have been considered. Through such curves it is therefore possible to define the maximum active power that can be delivered at the PoC and the maximum reactive power that can be exchanged with the network. Since the reactive capability of a plant is strongly dependent on the voltage at the connection busbar, the same procedure must be conducted in a voltage-reactive power plane, to define the voltage operating condition during maximum active power injection.

After illustrating how the capability curve can be obtained in the software environment, and which are the requirements that it be expected to satisfy, this chapter presents a simulation conducted on the specific case study plant. This approach makes it possible to demonstrate how the individual elements of the plant such as inverters, step-up transformers, collection cables, HV connection line and any compensation devices, can contribute to the final shape of the curves, and to quantify the extent to which each of them erodes the reactive capability theoretically available at the inverter terminals.

The purpose is not only to verify a posteriori whether the plant complies with Annex A.68 [8], but also to identify, at the design stage, how a plant will behave after the commissioning and what are the possible technical measures through which a non-compliant configuration can be brought back within the prescribed limits.

3.1 Curves generation and Terna requirements

The capability curve of a plant is the locus of permissible operating points for a specific plant in steady-state regime and under specific conditions. It maps the operational envelope within the complex power plane, where the horizontal axis is referred the reactive power output (Q , measured in Megavar) and the vertical axis defines the active power (P , measured in Megawatt). Mathematically, the fundamental boundary is governed by the apparent power equation (3.1).

$$S = \sqrt{Q^2 + P^2} = \sqrt{3} \cdot V_{PoC} \cdot I_{PoC} \quad (3.1)$$

The relation (3.1) gives a better understanding on the high potential of this curves. To build them, on all the available apparent power point, is needed to simulate all the different working point at which are associated different active power and voltage values and from here the needed of two separated curves, one at constant voltage (PQ) and one at constant active power (VQ).

From the second part of the equation (3.1) another key point is highlighted, the reference of where voltage and current are measured, the PoC. It is important because define at first the boundary of the plant, and then the fact that not only the generator units are considered, but all the elements in the system contribute to the final curve. As the plant size increases, in terms of number of generators and length and cross section of the cables, the contribution becomes more important also from the “not generating” elements.

Nowadays these curves are obtained from an algorithm, where several load flow simulations are launched and the values of voltage, active power and reactive power are collected, and plotted in the two previous mentioned curves.

The load flow (or power flow) simulation is one of the base technique for the steady-state power system analysis, planning, and real-time operational optimization. Its primary objective is to compute the complete voltage profile, both in magnitudes and phase angles of every bus within a transmission or distribution network under a specified set of operating conditions. Once the nodal voltages are determined, the active and reactive power flows through all transmission lines, transformers, and interconnectors can be derived. DIgSILENT Power Factory® can do this type of simulation through an iterative-mathematical solving process, by computing the generator, load and reference bus matrixes and then solve using an enhanced non-decoupled Newton-Raphson algorithm.

3.1.1 Terna requirements

From the very beginning of the design phase, where the connection request needs to be drafted, one element that can give a positive or negative outcome for that demand is the satisfaction of the requirements defined in the annex A.68 [8].

First of all, some definitions need to be mastered, since are not physical constraints, but working point by means of Terna based its further discussion and the setting for the limits. The fundamental quantity is the “nominal available active power of the PV plant (P_{nd})”, it is equal to the sum of the nominal active power of the single PV inverters installed, when they operate at power factor equal to 0.9. Another is the “maximum power of the PV plant (P_{max})”, the maximum active power which can be continuously injected into the grid in the standard working conditions (where the plant works at P_{nd}), considering the normal internal losses and the possible mandatory regulation limit set by the STMG of the plant. Both are expressed in Megawatt.

For the Type 2 connections, once the active power P_{nd} is defined, the reactive power minimum requirements are obtained, since they must be at least 35% P_{nd} , both in inductive and capacitive injection; this is shown in the following Figure 3.1a.

Instead for the construction of the V-Q curve, the limit is now 35% of the tangent of the shifting angle (the ratio between Q and P) at nominal voltage and is fixed at that value until $1.05 V_n$ and $0.95 V_n$, but than it can decreases until zero in a straight line, at the maximum admissible grid voltage of $1.1 V_n$ and $0.9 V_n$. The behaviour is depicted in the following Figure 3.1b.

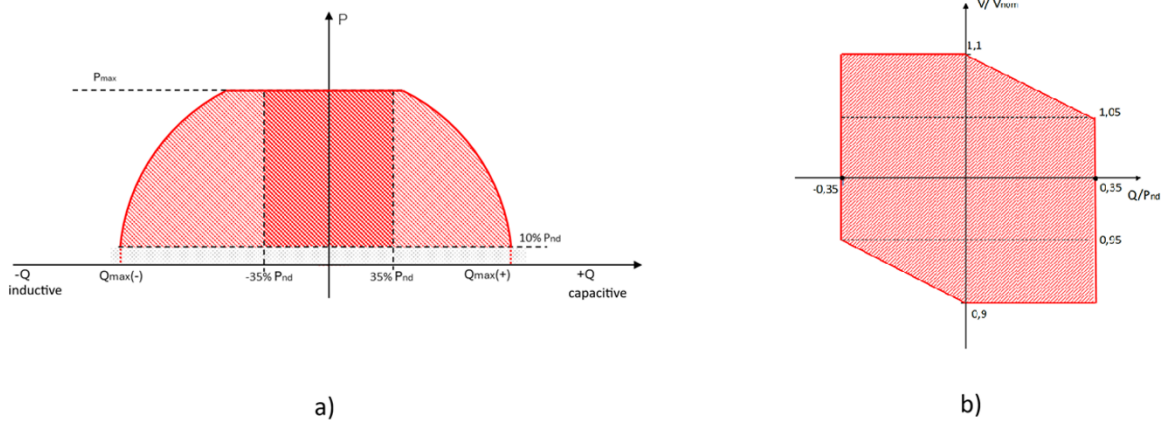


Figure 3.1 Terna requirement for the capability curves, according to annex A.68 [8] of the Italian Grid code, where the a) is for P-Q curve and the b) is for the V-Q curve.

The red areas are the minimum value of apparent power (for the P-Q curve) at which the plant must operate, to guarantee not only the active power injection, but also the reactive power support. From Figure 3.1a, it is possible also to see the definitions of maximum reactive power, in inductive and capacitive behaviour. It is the value of reactive power obtained following the natural “circular shape” of the capability of the plant (due to the generator capability of the inverters) at a corresponding value of 10% P_{nd} . Dually is for the V-Q curve, where the red is

the minimum requirement. The real capability curves must stay around this values and do not enter the red region in any point.

3.1.2 Reactive power capability in absence of active production

An important point that deserves a separate discussion is the reactive power exchange in the conditions in which the plant does not produce active power. It is crucial because the hours in which a photovoltaic plant does not produce, due to no light condition, is comparable with the hours of working. It is a huge amount with respect to traditional power plant and that are also the hours in which typically (evening and early morning) the nowadays electricity demand has its peak.

The condition of null active power is in fact the one in which the converters have the higher possibility to exchange reactive power, and in which the reactive capability of the plant is therefore theoretically maximum.

The exploitation of this availability, however, is not automatically satisfied because the presence of a voltage on the direct current side must be sufficient to allow the operation of the converter. Because also in absence of production, the converter requires to remain energised and controlled, drawing from the network the power necessary for their own operation and for the supply of their auxiliaries.

This mode of operation, in which the converters of a photovoltaic plant behave as a static compensator, has a cost in terms of the energy absorbed and produces a thermal stress of the components, comparable to the one of the ordinary operation, since the current that flows in the semiconductors is similar but of a reactive type and not by the active one.

This mode has, however, the advantage of permitting to a plant that theoretically is not capable, since no rotational machinery are present, to help the grid providing a service to the system beyond the mere injection of energy.

In the case study analysed in this work, the reactive balance in the absence of production is dominated by the capacitive contribution of the connection cables, which is present whenever the plant is energised and independent of the production. The consequence is that the plant, in this condition, presents a natural tendency towards the injection of reactive power, and that the control action necessary to satisfy a null reactive reference is not the absence of action but an inductive absorption from the converters.

3.2 Theoretical limits of the reactive power capability

The capability curve computed at the Point of Connection is the result of the superposition of several physical limits, each acting on a different portion of the plant. Before presenting the curves obtained for the case study, it is useful to identify these limits separately, because the interpretation of the shape of the curve and of its sensitivity to the topology of the plant derives directly from them.

The first and most evident limit is the apparent power of the converters. An inverter can exchange a combination of active and reactive power whose vectorial sum does not exceed in any point its rated apparent power. For this reason, the ideal inverter should have a capability which is the locus of the points represented by a portion of a circle in the active and reactive power plane.

A second limit comes from the direct current side and from the modulation. The alternating voltage that a voltage source converter can produce is bounded with the voltage available on the direct current link and by the maximum modulation point defined by the PPC. Since in a photovoltaic plant the direct voltage is imposed by the maximum power point of the array and depends on the irradiance and on the cell temperature, the reactive capability of the converter is not a constant property of the machine but a quantity that varies with the operating conditions of the generator. In the document all the capability curves are realized considering the ambient temperature of 30°C, but if the environmental conditions were different, the curves would also change in shape and amplitude.

The third contribution is related to the sum of all the other electrical element present in the network. Because the electrical machines like the transformers absorb a reactive power that grows with the square of the loading, being proportional to the short circuit reactance with the effect of subtracting reactive power from the amount produced by the converters.

The cables, and with a particular focus the high voltage ones, act in the opposite direction. A cable behaves as a distributed capacitance and generates a reactive power proportional to the square of the voltage applied and to the capacitance itself. This behaviour is present whenever the cable is energised, including the hours in which the plant does not produce, and constitutes a permanent offset of the reactive balance.

Then moving from the ideal to the real case, the active power axis is affected by the losses. The Joule losses in the cables and in the windings and the no load losses of the transformers reduce the active power available at the Point of Connection with respect to the one produced by the converters, and the reduction grows with the square of the current, therefore with the loading of the plant. For the sake of completeness, one should also consider the consumptions of the auxiliary systems which are constant in the time and becomes relevant in the conditions of low production, but since are not the focus of this work, for the time being, they are not counted.

A last limit is imposed by the voltage inside the network. The exchange of reactive power between two nodes connected by an inductive impedance requires a difference of the voltage amplitudes to permit the injection of reactive power towards the network, and it implies that the voltage at the terminals of the converters is higher than the voltage at the point of connection. This mechanism is the physical reason why the extension of the capability envelope cannot be obtained only by oversizing the converters, and why the choice of the transformation ratios and of the tap position of the transformers, discussed in the following section, has a direct effect on the shape of the curve.

The curve computed at the point of connection is therefore the envelope of all these limits, and its shape reflects which of them is binding in each region. At the end, a modification of the topology of the plant does not deform the curve uniformly but acts on the specific limit that is reflected in a given region of the curve, and this is why the same modification can be irrelevant in one portion of the plane and decisive in another.

3.3 Case study capability curves

Moving to the case study under investigation, as defined before at the §2.1.4, there are 100 HUAWEI SUN2000-330KTL-H1 inverters, and each of them has an apparent power equal to 330 kVA. Fundamental for the plot of the curves is the own generator's capability curves, different for the different inverter models. For the one used, the generator's capability is reported in Figure 3.2. Here, importance needs to be pay in the fact that there is not a single behaviour, the but the inverter active/reactive power production is related also to the voltage at the terminals.

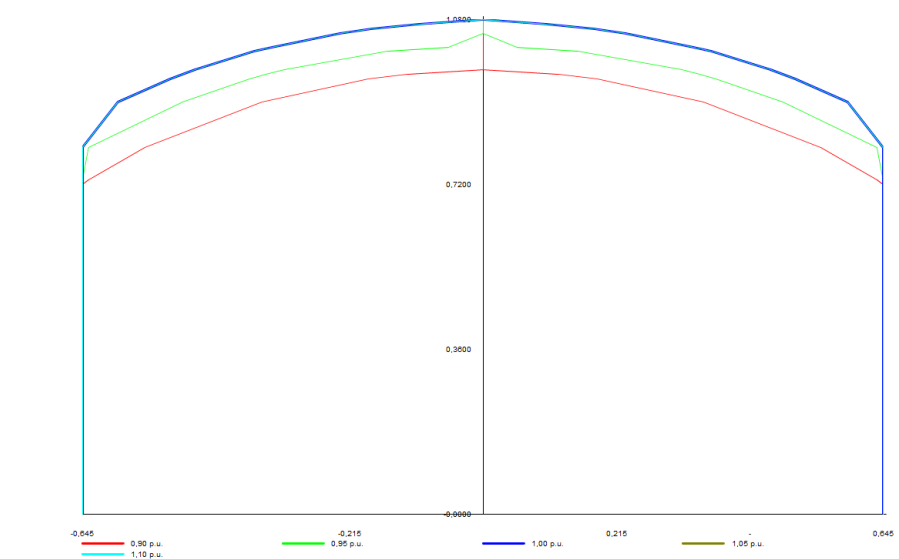


Figure 3.2 Generator's capability curve of the HUAWEI SUN2000-330KTL-H1 inverter at the variation of the terminal voltage

So, for a voltage above 1p.u., the maximum working point is at 1.08 nominal active power, but if the busbar voltage goes below that value, also the inverter production is limited, and this limitation becomes more and more severe as the voltage is reduced.

According to the Terna's definitions, the following relations (3.2), (3.3) express the value needed for defining the constraints for the capability curves, calculated instead in relation (3.4).

$$Pnd_{inv} = Sn_{inv} \cdot 0.9 = 0.33 \cdot 0.9 = 0.297 \text{ MW} \quad (3.2)$$

$$Pnd = Pnd_{inv} \cdot \#inverters = 0.297 \cdot 100 = 29.7 \text{ MW} \quad (3.3)$$

$$Qref = 0.35 \cdot Pnd = 0.35 \cdot 29.7 = 10.39 \text{ Mvar} \quad (3.4)$$

Then by lunching the algorithm previous mentioned, the result for the case study plant is reported in Figure 3.3, for the PQ curve and in Figure 3.4 for the VQ curve.

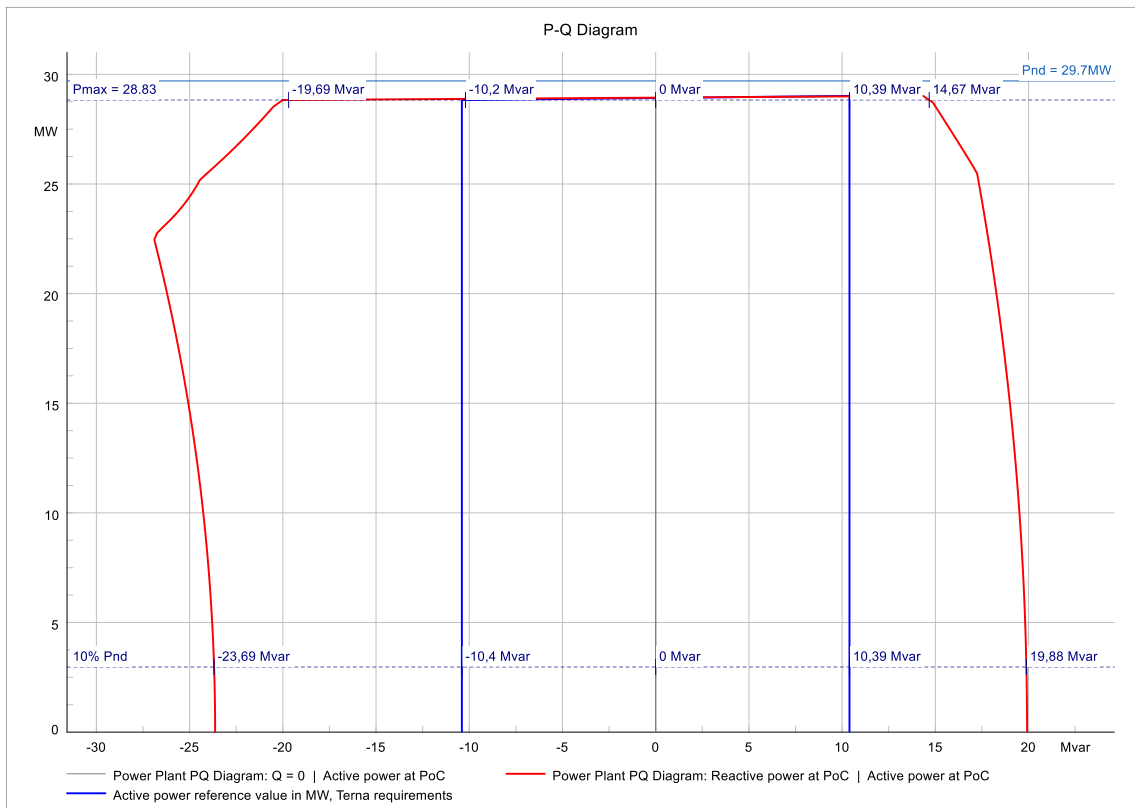


Figure 3.3 P-Q capability curve of the case study plant

From Figure 3.3, the result line is the red one, and the blue is the requirement set by Terna, from the top to the bottom, the Pnd horizontal line is light blue one, while the blue dotted ones are respectively the Pmax one and the 10%Pnd one.

As then resumed in the following Table, even if the Pnd value is already a limit compared to the possible active power injection by the inverters, the losses inside the plant define as maximum active power delivery, one which is lower the Pnd and it is called Pmax. This value is not perfectly constant in the upper part of the chart, so the lowest value has been taken, as conservative purpose. In this maximum conditions, the most severe one, the reactive contribution is naturally reduced due to the limit imposed by the maximum apparent power capable from the inverter, the reactive capability is anyway widely satisfied.

Table 3.1 Power values reviews, obtained from the case study P-Q capability curve

Parameter	Value	Requirement
Pnd	29.7 MW	-
Pmax	28.83 MW	-
Qind min	-16.96 Mvar	10.39 Mvar
Qcap min	14.67 Mvar	10.39 Mvar
10% Pnd	2.97 MW	-
Qind @10%Pnd	-23.69 Mvar	10.39 Mvar
Qcap @10%Pnd	19.88 Mvar	10.39 Mvar

The behaviour of the curve is no more similar to the generator's curve previously reported. This is because the action of the intrinsic cable inductance and capacitance limit or help the generator contribution.

In Figure 3.4, the red line represents the limit of reactive power injection at the variation of PoC voltage, the blue line, as for Figure 3.3, is the requirement previously described and finally the green lines are the limits defined by the recommended setting for the protections indicated by the annex A.68 [8]. More in detail, the acceptable overvoltage is less than 1.15 p.u, while the undervoltage is higher than 0.95, the plant is so able to provide reactive power at all the necessary voltage levels but also can sustain the reactive power of the grid in more critical conditions. The behaviour is more favourable in case of overvoltage, since by nature of the intrinsic structure of generators, PVs try to “increase voltage” instead of reducing it.

The lower portion, at around 0.8 p.u., shows a non-physical condition in which no inductive reactive power is available, but instead that left side limit is shifted into the capacitive side. This is a simulation artefact, caused by the fact that the generator capability is defined only down to 0.9 p.u. and then the software needs to interpolate it as the voltage is reduced. However, this doesn't represent an issue for the validation of the result achieved because that part is in a

condition that the plant never experience, since before reaching 0.8p.u. (in reality not below 0.85 p.u.) the protections open the circuit and the inverter's production is stopped.

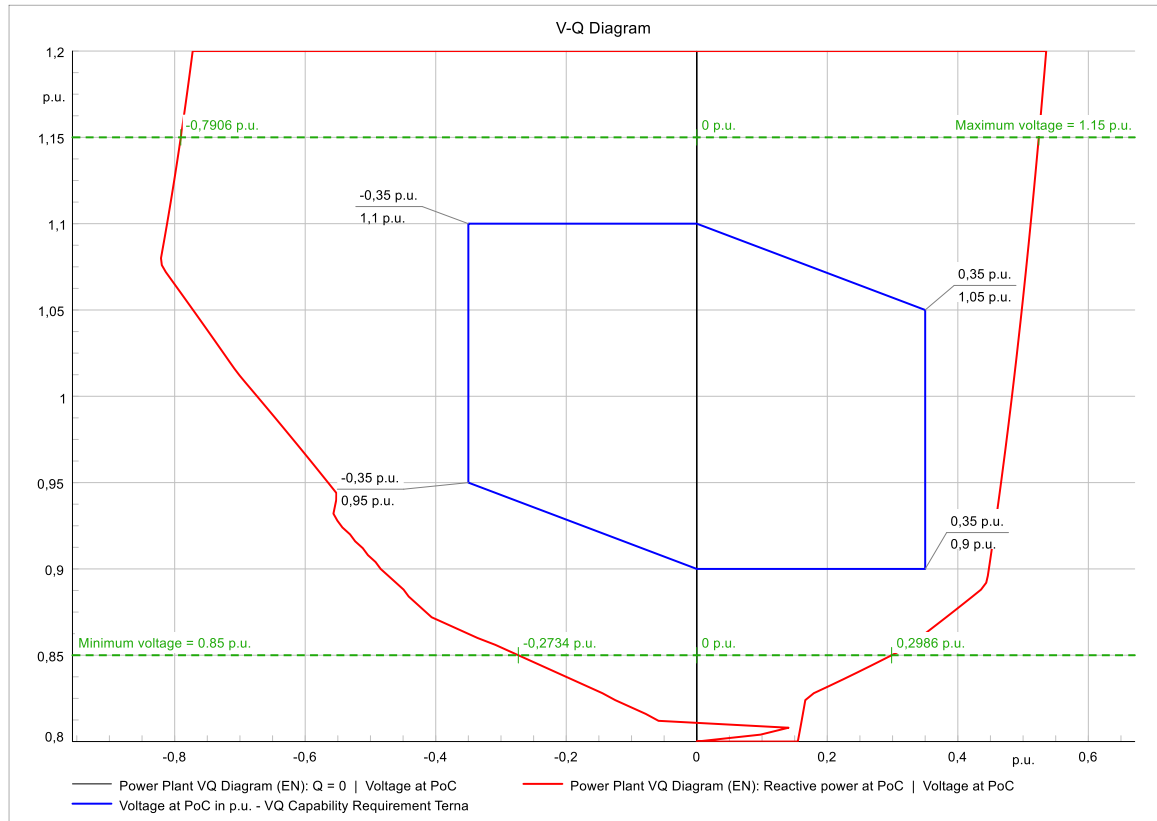


Figure 3.4 VQ capability curve of the case study plant

3.4 Influence of the plant element on the curve and regulations

According to the study shown in the previous paragraph, the capability curve plot is not only the sum of the generator's capability curves, but also considers the influence of the cables, their length, and electrical parameters, associated to the cross section.

Considering, in first approximation, the lines with the method of the concentrated parameters, each conductor is electrically made by a series impedance, made by the sum of the kilometric resistance and the kilometric inductive reactance, multiplied by the length, and a shunt impedance, made by the sum of the kilometric conductance (for sake of simplicity, equal to zero) and the kilometric capacitance, multiplied by the length.

In both the terms, common constant is the length, so as it increases, also the longitudinal reactance increases and the total impedance is higher causing an increase of the inductive voltage drop, that in the PV system could be beneficial because the VQ curve is shifted down, so the requirements are easier to be achieved. But increasing the length also increases the shunt

capacitance which, particularly for buried cables (whose capacitance is higher than that of overhead lines), shifts the capability curve by adding a constant capacitive reactive power, so the final curve is shifted towards right.

Moreover, a higher length influence the total resistance, at which are associated the Joule losses of the plants, this means that the apparent power limits are reached with a lower reactive power and so the curve is deformed and also that part of the active power can no more be injected into the grid, experiencing a reduction of the maximum active power P_{max} .

These effects are more severe as the electrical parameters are higher or with a longer length.

The critical point is on the HV conductors, since typically, even if the resistance and the reactance is lower, the capacitance is bigger compared with the low voltage cables.

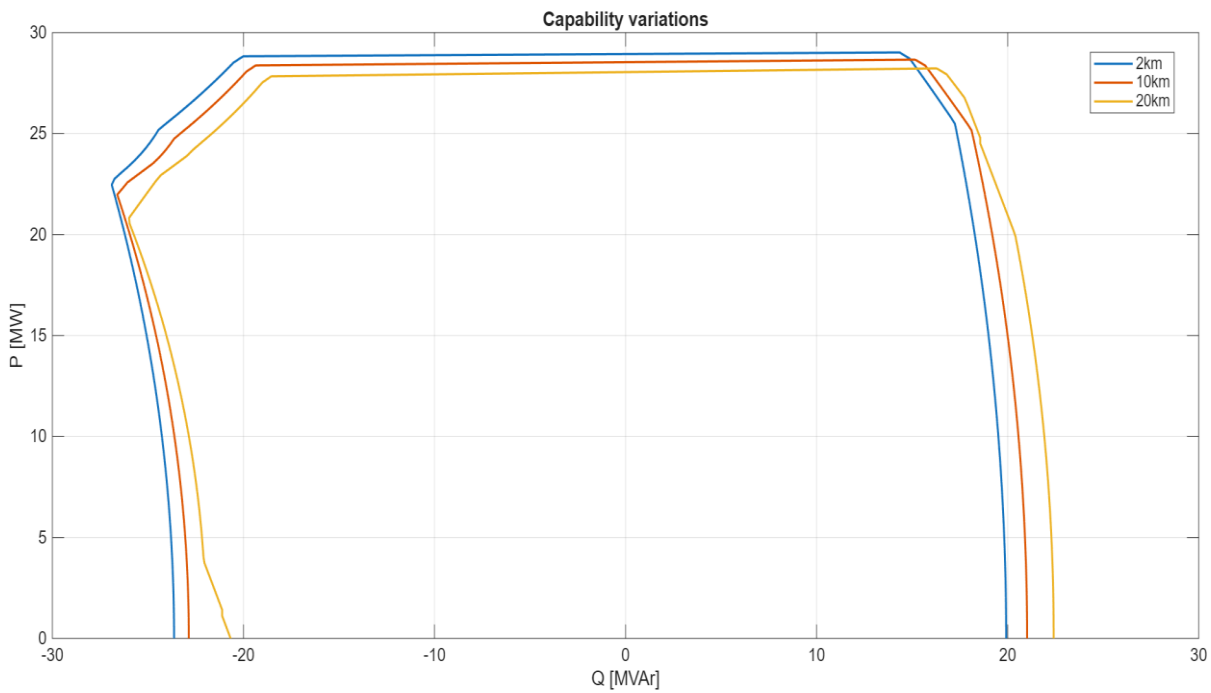


Figure 3.5 Comparison between different length of the HV cable and its influences on the P-Q capability curve

The effects mentioned above can be demonstrated in Figure 3.5, where there are three capability curves obtained only by changing the length of HV cable. The choice is based on the fact that the MV field cable length is almost fixed for a standard rectangular shape PV field (different length derived only from strange shape of the field), while the one that can change mostly is the HV cable since is related to the distance of the collection cabin with the substation where there is the PoC.

Especially in Type 2 plants, this is a big issue, because it is true that the voltage level is reduced, so also the cable insulation is thinner and the capacitance is reduced, but this plants are typically connected through insulated cables with a consistent distance from the substations.

This problem, for the traditional Type 1 connections can be overpassed by modifying, in the design phase, the vcc parameter of the HV/MV transformer, reducing it, that gives an effect also on the internal impedance reduction and, by accepting and higher short-circuit current downstream, the amount of available reactive power is increased (the plot is a larger curve). But fixing the PoC immediately downstream the HV/MV transformer, as the annex A.2 [4] describes, this useful adjustment cannot be applied, since that transformer lies outside the plant boundary and the HV/LV transformer placed in this scenario are typically “standardized” by the manufacturers, following the MV/LV ones. A regulation of vcc is not so easy to achieve in this specific case.

In this type of plant, three strategies can be used to permit the compliance with the requirements without limiting the maximum power P_{max} exchanged with the grid, because it is the more immediate and does not require external elements, but of course imply a reduction on the revenue from the plant.

The first is to subdivide the overall PV plant in more inverters of the same size, in order to reduce the percentual active power loading on each inverter. Doing this a portion of the available apparent power of the inverters is released from the active power loading and instead can be used for the reactive power supply. This solution can be phased only if the PV field is correctly designed with a ratio between the active power of the DC side and the on the AC side higher than the unit. This situation means a higher P_{nd} , since is related to the apparent power installed in the field, and also a higher reactive power requirement. It is overpassed since now the possible active power can be exploit and so the curve can reach a higher top limit for P_{max} , but to respect the STMG agreement, it must be limited at a specified power, which following the envelope of the curve certainly provides a higher reactive power.

The second solution provides an increase of the cable’s cross-sections, in order to obtain more favourable series coefficients that help to reduce the internal losses. This enlarges the curve but as previously mentioned, moves the curve towards the capacitive behaviour. In any case this solution is helpful only for small variations.

The third instead consists in adding shunt reactors in the HV side of the plant. In this way part of the excess capacitive behaviour is directly compensated by this reactors. They do not work by enlarging the capability but just move the curve towards the inductive side. This solution is particularly suitable for the previous mentioned situation, in which due to long lines the PQ capability curve is unbalanced towards the capacitive behaviour, but in terms of width, the curve must be already sufficient.

Chapter 4:

Active power control

One of the milestones of the power control functions implemented in the Power Plant Controller (PPC) is the active power control, also referred as production control. This function represents the interface between the physical capability of the generating units and the operational requirements imposed by the TSO, and it is therefore one of the most critical elements in the assessment of the compliance of a photovoltaic plant with the grid code.

Under normal operating conditions, the objective of this function is to guarantee the injection into the grid of the maximum active power available from the photovoltaic modules and subsequently converted by the inverters, so that the energy yield of the plant is not unnecessarily curtailed. The control action of the PPC, in normal conditions remains inactive as long as the plant is not required to limit its output.

Nevertheless, the design of a grid-connected generating plant cannot be limited to the maximisation of the production. Modern transmission systems, require that each generating system must be able to modulate its output on demand, in order to contribute to the management of congestions, to the balancing of the system and, more generally, to the maintenance of the operational security of the network. For this reason, the plant must be able to follow an external active power set point imposed by the TSO, reducing the injected power below the available one whenever a curtailment order is received.

To reach the fulfilment of this requirement, a sufficiently prompt dynamic response is necessary, in order to reach the new operating point within the time limits imposed by the Grid Code and on the other hand, an adequate steady-state accuracy must be ensured, avoiding permanent offset. At the end, the tuning of the regulator is therefore the result of a compromise between them.

In order to verify if this requirement is satisfied by the plant under study, the behaviour of the active power has been reproduced in the simulation environment, imposing step variations of the set point and observing the resulting transient and steady-state response.

The adopted procedure reproduces, in a virtual environment, the field test that must actually be conducted before the system is put into operation, in accordance with the prescriptions of Terna Annex A.18 [9].

4.1 Rapid reduction of the production and test description

According to annex A.68 [8] the photovoltaic system must be capable of tracking changes in the reference signals whilst operating at its maximum performance, but it must also be designed to track linear power ramps with gradients specified by the TSO, depending on any specific services that may be activated. In order to ensure the grid stability, the TSO may request a temporary reduction in the injection of active power or the possibility to suspend the injection into the grid. The reduction must take place without any deliberate delay in activation, and the command signal comes to the plant as a remote signal sent from a remote managing centre of the TSO.

The plant control system must allow the active power to be limited to a percentage of P_n . The plant must reduce its injection to a value below the limitation threshold within no more than 2 seconds of receiving the command signal. Throughout the duration of the limitation, the plant must remain below the limitation threshold. A tolerance of 1% of P_{nd} shall be permitted.

One other requirement is represented by the possibility to reduce the output in steps of no more than 5% of the system's rated power.

The limitation is then evaluated according to the annex A.18 [9] and in particular with the test called PPM-PLIM. PPM is the acronym given by A.18 [9] for the power plants within the meaning of European Regulation (EU) 2016/631, which are inverter-based power plants.

If the test had been done in a real plant, the system should be able to produce, according to the ambient conditions, at least 60% of the nominal power, but since this document is based on a software simulation, the test is carried out at 100% of the nominal power.

The test consists of, starting from the nominal power, maintaining it for 2 minutes, then reduces it by changing the external setpoint of 20%, then after a waiting of 2 minutes, the reduction and the wait is repeated until the setpoint is equal to 20% of the nominal power. After that, the set point must be raised at the nominal value, and after the wait, moved at 30% in a single step variation.

During the previously described procedure, some quantities must be recorded, in particular the active power from the plant, the setpoint and the reactive power.

One minute after that the limitation signal has arrived (in order to permit the complete limitation and the maintenance of the setpoint), the active power average must be calculated to compile the Table 4.1 set out below, where it is possible to observe the actual deviation from the setpoint. Then some considerations and observation must be done in relation to the response signal at the step variation from 100% to 30%.

4.2 PPM-PLIM – Active power limitation

To reproduce in the software environment the power profile, is necessary to move, from the steady state condition to the time-variable calculation through the RMS tool. It is a tool that can be used to analyse mid-term and long-term transients under both balanced and unbalanced conditions, incorporating a simulation scan feature. In particular with the simulation event tool, the profile is recreated.

Before launching the simulation, one key aspect is the calibration of the gains in the PPC, both the active power one and the reactive one, that, as regards the plant in question is done according to [A.1] and [A.2], where, on the $P_Control$ block is activated the mode P_en dedicated to the setpoint follow and the gains are respectively 0.00001 for the integral and 0.001 for the proportional. Instead in the $Q_control$ block, every mode is shut down since it must only follow the zero reactive injection without establish a different working point on the reactive side. Moreover, since with a variation of active power corresponds a change also in the reactive one, the gains are set as 0.0065 for the integral and 0.0545 for the proportional.

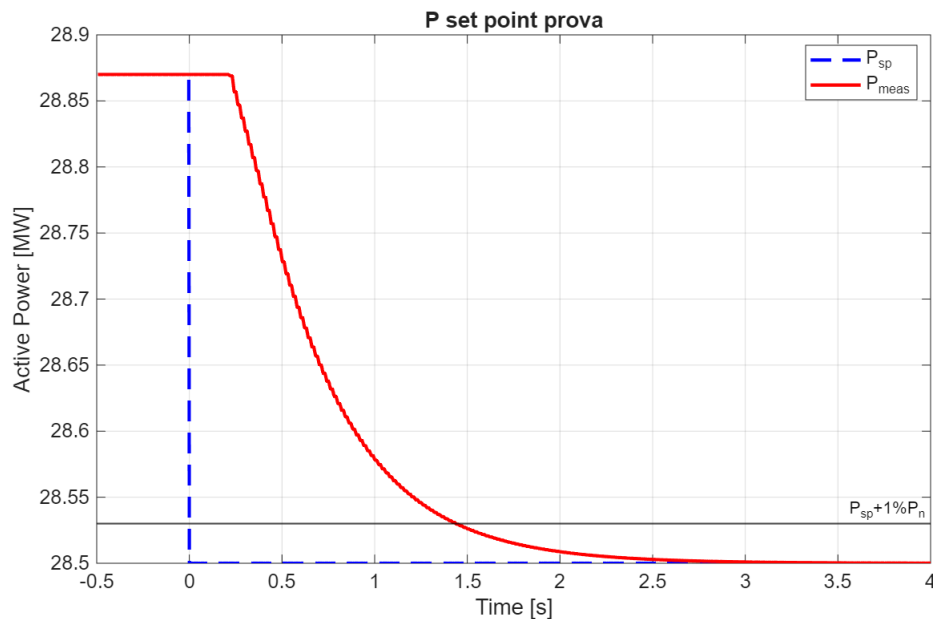


Figure 4.1 Active power response of the case study plant at the step variation of the setpoint

The previous mentioned gains values are obtained through an iterative way, from the observation of the response of the plant at a limited step variation, in a short-time simulation, according to the limitations defined by the annex A.68 [8]. More in detail, is requested that a limitation defined by the TSO of any percentage must corresponds to a limitation of active power injection, with a power lower than the setpoint (with 1% tolerance) in two seconds. Moreover, is defined that the maximum power reduction step size must be 5%. On this basis, a

set of simulations were run until the gains given above were obtained, and the response is the one in Figure 4.1, similar as possible to a first order response.

The idea was, from the maximum power, P_{max} , the most difficult condition since reactive power is subject to quotas, acting the reduction of the maximum step and maintain the response inside the threshold or, if possible, reduce it to a “safer” time, in order to avoid any possible extra delay not yet considered. The result is that the 1 % tolerance is reached in 1.4 s, with no overshoot. A faster response could easily be achieved, but there are two competing objectives, speed is required, but more important is the stability, and so only with a trade-off between them the control strategy is robust. That trade-off is reached only by correctly adjusting the previous mentioned gains.

Defined the active power control gains, also the ones related to the reactive power control must be obtained.

The approach is the same, by means of an iterative way. However, the requirement for this first test is not defined as the active power, but only at level of the “Fixed Q” mode, explained in the next chapter.

For this reason, the test is based on a step variation of 50% of the available reactive power, the maximum size of the step variation described in the annex A.18 [9].

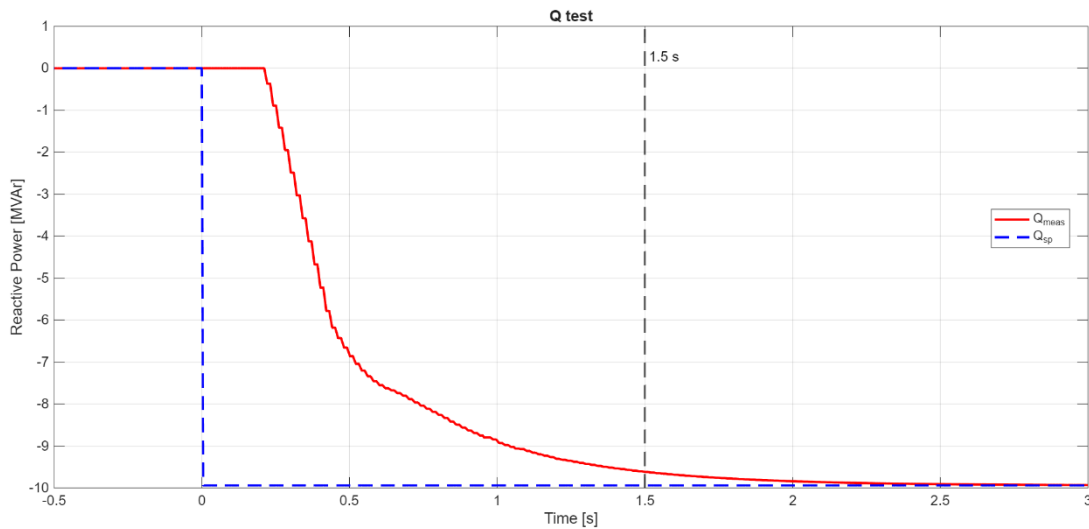


Figure 4.2 Reactive power response of the case study plant at the step variation of the setpoint

Figure 4.2 shows the final behaviour after having defined the reactive power gains. With respect to the mode “Fixed Q”, the controller is not able to satisfy the minimum threshold of 1.5 seconds for completing the variation, but it is achieved in about 2 seconds. That does not necessarily imply a restriction on the working capability but instead is a characteristic of the plant and is related to the choice of losing a little of reactivity in favour of a more stable response. Analysing the curve presented, it is possible to observe in the very beginning of the response, that the behaviour is not as “linear” as the active power response, but some fluctuations are present.

They are related to a high proportional gain, but the reduction of it implies a slower response. Moreover, a less rapid action has also the positive action of reducing the spike during active power variation.

In any case, the time goal defined previously, are the minimum one, that considering the theoretical nature of the study is challenging for the analysis of the PPC. But Terna fixed a range in which the operation can be phased, and if the minimum time needed by the plant is inside this range, the only point is to report it in the Operating regulation for power generation plants (RdE).

One key aspect that will be constant in all the following simulations, is that after the trigger event of changing the setpoint, a delay time of 200ms is applied before the correction started. This in the software environment is defined in the PPC settings sheets [A.1] and [A.2] and it considers the time delay for communication of signals between PPC and inverters which instead in a real circuit is related to the distance and the type of communication between them.

After that, the test setpoint model is simulated, obtaining the result in Figure 4.3

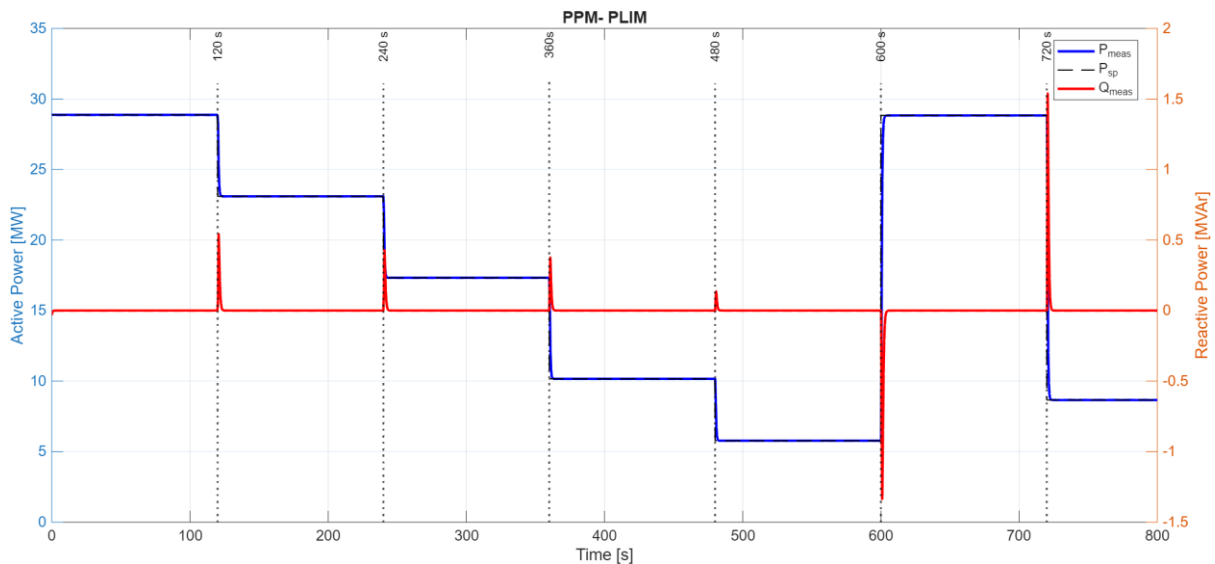


Figure 4.3 Active and reactive power response of the case study plant at the variation profile defined by the annex A.18 [9]

On the previous picture it is possible to see in blue the profile defined by the annex A.18 [9] while with red the response in terms of active power measured at the point of connection PoC of the plant. It is important to note that the time scale with full scale at 800 seconds and the variation required for the active power, two seconds, are in two different order of magnitude, so the non-overlapping of the two curves when the setpoint changes could not be appreciated. It represents a good point since this means that the plant, in general, is able to follow a step response which is more severe than the one during the normal working Terna can ask to the PPC without seeing a consistent deviation from the setpoint.

The third line, the green one, is instead representing the reactive power at the PoC, and it is important to highlight that from the beginning of the simulation, the set point for the reactive power taken is equals to zero but is clear that when there is the step variation on the active power side, the reactive power also reacts, with a variation that grows with the size of the active power step. The most severe is a transient peak of reactive power followed by its return to zero during the step change.

The reason this behaviour happens, can be conducted at internal structure of the three-phase inverter chosen and on how it regulates active and reactive power. In such inverter, the regulation is obtained through the two theoretically independent regulation of direct and quadrature current, and the Park transformation (4.1) and (4.2), define two voltages, one for the quadrature and one for the direct control side [12].

$$v_d = R \cdot i_d + L \frac{di_d}{dt} - \omega L \cdot i_q + e_d \quad (4.1)$$

$$v_q = R \cdot i_q + L \frac{di_q}{dt} + \omega L \cdot i_d + e_q \quad (4.2)$$

These two equations mathematically proof that through the internal inductance ($-\omega L \cdot i_q$ and $+\omega L \cdot i_d$) the two terms related to the direct and quadrature component are not independent one to each other. When the active power experience a fast variation as the step one present in this type of test, it induces on the control loop of the inverter a step decreases on the direct current and thanks to the $+\omega L \cdot i_d$ and the high time derivative terms, this correction acts also with an instantaneous dynamic perturbation on the quadrature voltage equation. This means that not directly but also the quadrature side of the controller experience the step variation done only in the direct side.

Then in the quadrature side the zero-set point is no longer respected since this variation on voltage is reflected on a variation on reactive power. But due to the delay of the measurement system of the controller of the inverter, for some instant typically less than 200 milliseconds, which represent the maximum updating interval for the measurement according to the Terna standard, the controller is not able to see that there is that variation from the setpoint and so the reactive power still rise with the previous mentioned law. Only when the not permitted value is detected, the controller, through the PI system, reduce the reactive power injection to the zero-set point.

This is why, in this and in the other next simulations, even if the variation concerns active power only, the reactive PI gains also have to be tuned, otherwise a prompt system cannot be able to correctly clear the peak formed in a small time. But instead, it can reach extremely high peaks and also be maintained for seconds causing overloading of the plant components and injecting

on the grid a not required impulsive reactive power, which could vary the voltage at that specific busbar.

According to the annex A.18 [9], from the simulation done, the following Table 4.1 contains the data required for determining if the test result is positive or negative.

Table 4.1 table for the verification of the active power limitation

Limit active power value		Actual active power value		Deviation	
Pset [MW]	Pset [%]	P [MW]	P/Pmax [%]	P-Pset [MW]	(P-Pset)/Pmax [%]
28.830	100%	28.83	100%	0	0%
23.064	80%	23.064	100%	0	0%
17.298	60%	17.298	100%	0	0%
11.532	40%	11.532	100%	0	0%
5.766	20%	5.766	100%	0	0%

The values reported are the means of the ones measured after a minute from the set point variation instant in the interval of the next minute. Since the data are recorded from a simulation, the arithmetic mean is equal to the single value detected, because the transition phase between two states happens in a faster time. If instead the mean were calculated in a real plant, the value could not be constant in the minute since some variations can arise due to changings in the external grid electrical parameters variations.

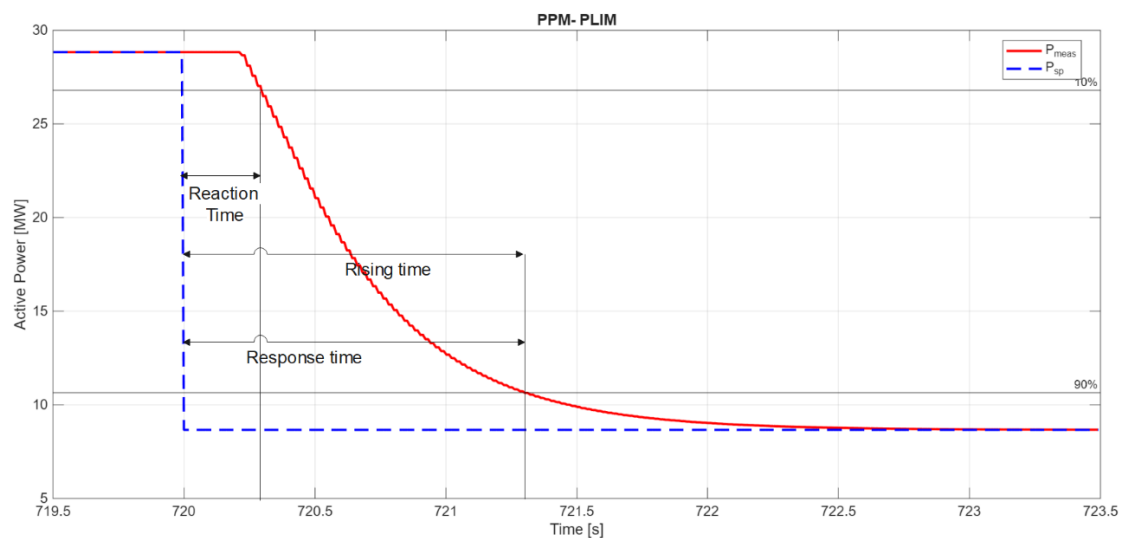


Figure 4.4 Analysis of the characteristics of the dynamic response of the active power limitation

Table 4.1 and Figure 4.4 describe exactly the purpose on how the active power controller is set, more in detail, the deviation from the active power setpoint is zero and this is due to the choice of self-imposing a stricter limitation in the response time, by limiting it at 1s, instead of 2s. The regime state is reached before the measurements are valid for the Table 4.1.

Moreover, Figure 4.4 shows that also with an extraordinary step variation with an amplitude equals to 70% of the active power, the controller architecture is still robust, because also in this case the time needed for achieving the regime is lower than the limit of 2s, but compared to Figure 4.1.

Having regard to the data collected and the considerations made in the previous paragraphs as regards active power limitation, the controller can be considered correctly designed and tuned. The structure thus created in the software environment constitutes a solid base for the development of the next tests, but also can be re-used for this specific test, but with different plant layout or components.

Chapter 5:

Reactive power control

Photovoltaic generation is now widespread but only partly controllable since it depends on weather conditions. During hours of high irradiance and low demand the power, the Point of Connection of a generating plant becomes an element that actively influences the voltage profile of its feeder. The effect is more evident in the distribution network, where the equivalent power of the grid is lower than the HV ones.

In traditional generation plants since they have not priority of dispatch, they would simply be stopped in case of production not needed. But for PV plant, the latest versions of the standards relating to the connection of new PV plants, including the annex A.68 [8], described that among the services required, reactive power control occupies a position of particular relevance.

Unlike synchronous generators, where reactive exchange is governed by the field current and by the thermal limits of rotor and stator, in a converter, the reactive power is available instantaneously specifically during hours of partial irradiance. When the active power produced is lower, part of the apparent power that constitute the rated size of the converter, can be allocated to the injection of reactive power into the grid.

The provision of the service is not, however, free of drawbacks, which a rigorous treatment must make it explicit. The delivery or absorption of reactive power occupies a share of the converter capacity, potentially subtracting it from active power production during hours of maximum irradiance, the increase in total current entails additional losses in the converter, in the transformers and in the internal collection network.

The present chapter sets out to analyse the strategies that Terna has identified for reactive power control for the PV system, they involve not only a reactive power setpoint but also a voltage setpoint. Then according to annex A.68 [8], through the communication mean, the TSO can require different type of regulation, in terms of time and methodology of intervention.

Going forward in the chapter, the case study plant, with the same settings used for the active power limitation, simulates all this different methods according to the test required in the annex A.18 [9].

5.1 Voltage and reactive power control modes

The photovoltaic plant must be prepared in order to regulate, through different control rings, the voltage and the reactive power exchanged with the grid, according to external setpoint defined by the TSO.

In every control mode of this chapter, in terms of voltage or reactive power, the maximum precision must be not lower than 1% of the maximum reactive power available while the maximum overshoot permitted is less than 5% and it is permitted only within the first two seconds after the activation of the limitations.

There are five modes expected by the annex A.68 [8], three of them acts through a direct voltage setpoint, one with an indirect voltage setpoint, and the latter exploit a direct reactive power setpoint. All of them must be implemented in the PPC control strategy, since they come into the plant by means of the RTU (connected at the inverter through the PPC) and they are independent one to each other, so the network operator can ask to control the reactive power only with one of the five strategies at the same time.

The first is the “Q(DV)” mode, where the plant must elaborate an error of voltage as the difference (ΔV or DV) between the setpoint defined by the TSO, from the external grid, and the actual voltage value at the PoC and then calculate a corresponding reactive power to be injected into the grid.

The voltage of the external grid must stay in an interval between 0.95 p.u. and 1.05 p.u. and knowing this range, the reactive power value can be determined knowing that it must be proportional to a specific curve expressed as $Q=f(\Delta V)$. The TSO set according to the site conditions the value of maximum voltage and minimum voltage which must be reported in the operating regulations (RdE) for which the controller can act and indirectly fix the limit on adding reactive power in the grid. Moreover, the Network operator could ask also to implement a dead band around the reference voltage in order to limit the phenomena of unbalances and to permit at the controller to not regulate too many times around the equilibrium point and so maintain the grid more stable also during very brief transient variations.

Related to this mode there are the other two modes, the “RegV fast” and the “RegVslow”, here after a variation in the voltage error ΔV , the plant must react with the injection of reactive power, in a response time range variable between 1.5 s and 22 s in the first case, while for the second one the time is between 25 and 500s.

These modes are related to the control of the voltage in a direct way, since the setpoint is given in voltage value, but the mode “RegQ” permit, from a setpoint provided in terms of reactive power, that the controller’s response is practically seen as an increase or decrease of reactive power in that moment available, but deriving from the variation of the reference voltage in the “RegVfast” mode. In this condition the controller need the “conversion” using droop curve but

in a reverse way and for this reason the response time range is between 3s and 20s. Slower than in the standard “RegVfast” mode.

The last mode is the “FixedQ” mode, the faster one, since the set point is provided directly as a reactive power value and so to fulfil the requirement, the PPC, just varies the reactive power injected without acting on the voltage setpoint. A faster response means that the time target range is between 1.5 s and 20 s.

To verify that this modes are implemented in the PPC, the annex A.18 [9] provides two distinct types of tests, one is called “PPM-LIMQ – capability curves and reactive power control”, while the second is the “PPM-V – voltage control”.

The first one has the purpose of evaluating the absorption or emission of reactive power from the plant and to evaluate the static and dynamic characteristic of the control mode implemented in the PPC. With the focus on the “FixedQ” mode the reactive power set point is changed according to a ramp with gradient of 40% per minute, in the initial part, and a second part where the variation is instead done in a step way. Between one variation and the next there is a one-minute settling period for assessing the controller and at the +100 % and –100 % points, however, this period must be 60 minutes. The test must be carried in three different active power injection condition, to cover a wider application range, at the maximum, at 20% and at 40% of the power. When the scenario conditions are in the maximum active power, the values at 100% and -100% of reactive power must satisfy the capability curve and at the same time are the extreme values previously defined in the capability curves at the Chapter 3.

The results of this test define if the maximum error on the control strategy is below the maximum tolerance permitted in the CdR, define if the step variation do not cause undamped variations of reactive power and then define if the time of reaction and response are following the CdR.

The second test, instead, has the purpose of evaluating the static and dynamic characteristic of the voltage control modes and in this case the test is done by defining a voltage set point which is in the initial part a ramp with a gradient of 2% per minute and the last part is a step variation of the voltage setpoint. The test can be used to evaluate the different voltage control modes, both the faster and the slower one, with the only variation related to the time scale of the test.

After the elaboration of the data measured it is possible to obtain an XY graph with active power in the ordinate axis and voltage on the horizontal one, which, by means of the linear regression of the curve, for the overvoltage and undervoltage condition, and to define the actual droop curve of the plant, which must be transmitted to the control room of the Network operator, needed for the grid managing operations. Moreover, all the result can give information about the compliance of the control strategy in terms of voltage on for the reaction and response time and the compliance about the not generation of undamped voltage oscillation during the step variations.

5.2 PPM-LIMQ – capability curves and reactive power control

The different control strategies, both the active and the reactive power ones, are simulated just in a single way which means that the set point can be defined or as an active power or as a reactive power or as a voltage, so according to the modality, only a mode is imply in the plant control strategy, this to permit the focus only in one perturbation in the response. But there is also the possibility that two of them are combined so a set point of active power with a set point of reactive power or voltage, for this reason is important that the PPC used in the plant must be set in order to satisfy the required times all of these modes, without having a change on the settings, but just a change on the modality.

For this reason, moving to the software environment, the settings defined at the previous chapter are not changed, but to perform the simulation defined at the previous paragraph, is added a block between the power plant controller setpoint input and the simulation setpoint defined in the DIgSILENT Power Factory[®] RMS interface, to create a custom gradient ramp on the setpoint.

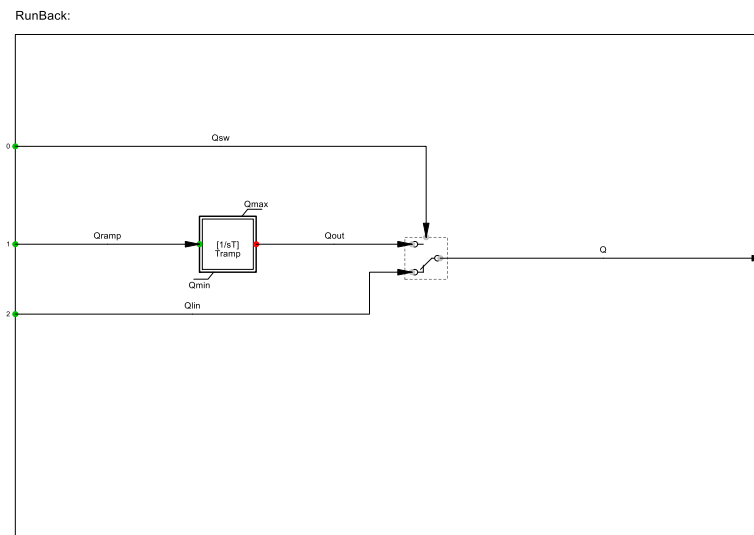


Figure 5.1 Reactive power setpoint generator system; produce both a set and a ramp variation

According to Figure 5.1, this custom block is an integral logical block connected to a switch. The input signal, for starting the ramp, can arrive from Q_{ramp} , and passes through the integrator which by means of the time constant $Tramp$, the block starts to increase the output value with the specified gradient. Instead, if the desired setpoint is linear, the one used in the step variation, the input must be Q_{lin} . The connection with the PPC is through the switch governed by the Q_{sw} signal. All these signals can be controlled from the DIgSILENT Power Factory[®] RMS interface and allows to shape the setpoint curve as requested in the annex A.18 [9].

Before moving to the simulation test, it is important to define the maximum values of active and reactive power according to the ones obtained through the capability studies done at chapter 3, Whilst the maximum active power is unique, the same cannot be said for reactive power,

since according to the sign, the value changes, for this reason, the value chosen is 19.88 Mvar, the minimum one for safety.

Only for simulation purposes, the long stops at 100% reactive power do not last one hour, but instead just two minutes.

Figure 5.2 shows the data measured during the first test of the “Fixed Q” mode.

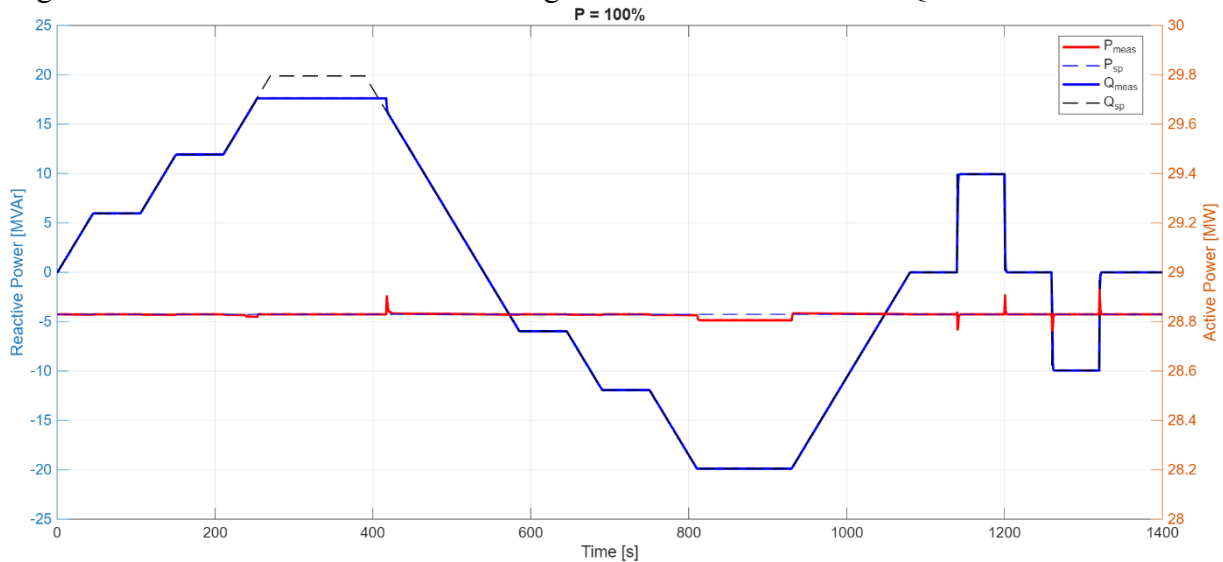


Figure 5.2 “Fixed Q” – first test with active power at 100%Pmax

Here, and in the following figures, the reactive power is depicted in green, while the active power is the red line. The black dotted one is the reactive power setpoint.

The first test give the chance to note that during the capacitive behaviour (positive reactive power, according to the generator convention), at maximum power, the system is not able to provide the maximum reactive power, previously defined according to the Terna’s definitions, even if, during the simulation a maximum overload of 110% is permitted.

Moreover, when the ramp setpoint is decreasing, the actual reactive power does not decrease immediately but remains unchanged for a few seconds. This is due to the absence of an anti-windup block in the “*Q_control*” system.

This omission does not necessarily mean that is necessary to add that block, because the issue arises only in the most critical condition, maximum power requested at maximum production scenario, and is solved within the maximum time threshold for the “FixedQ” mode of twenty seconds. The anti-windup block is a block that, defining the maximum value of reactive power, permit to interrupt the calculation of the error in the PI of the PPC. That because here the problem is related to the fact that the integrator goes in saturation area and it take some interaction to provide a correct updated value.

Continuing with the curve observation, another key point is in the opposite sign maximum reactive power point, in inductive behaviour, here the active power is reduced from 28.83 MW to 28.81 MW. The reduction is done by the “*S_control*” block’s logic because its purpose is to

limit the overall apparent power within the maximum tolerable by the components of the plant. The limitation can be actuated because even if the main priority is the active power injection, in this modality fundamental is also the reactive power support, and the value required can be achieved with a limitation on active power lower than the 1% admitted fluctuation, equals to 0.288 MW.

This system did not intervene in the previous focus-case because in that situation the reactive power requested could not be obtained with an active power limitation below the 1%.

As described in the chapter 4, at a variation of active power, it corresponds a variation in the reactive power emission/absorption due to the non-independency between the two control systems, and in this control mode, this behaviour is confirmed but, in a mirror-like manner, since the variation is actuated in the reactive power. In any case the resultant peaks are below the maximum admitted threshold.

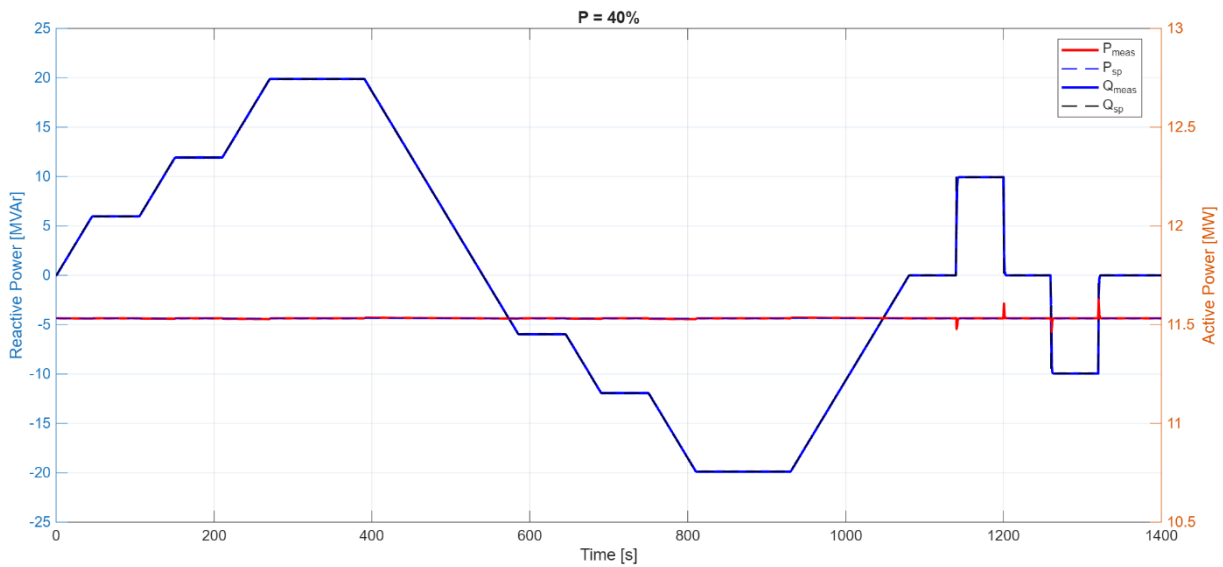


Figure 5.3 “Fixed Q” – second test with active power at 40%Pmax

In Figure 5.3 and 5.4 is depicted the behaviour of the system during the “FixedQ” control for active power at 40% and 20% of the maximum value. According to what obtained in the capability curves, the limitations experimented in the previous test are no longer required and the only not linear points are represented by the peaks points of the active power during the variations of the reactive setpoints, especially in the step variations.

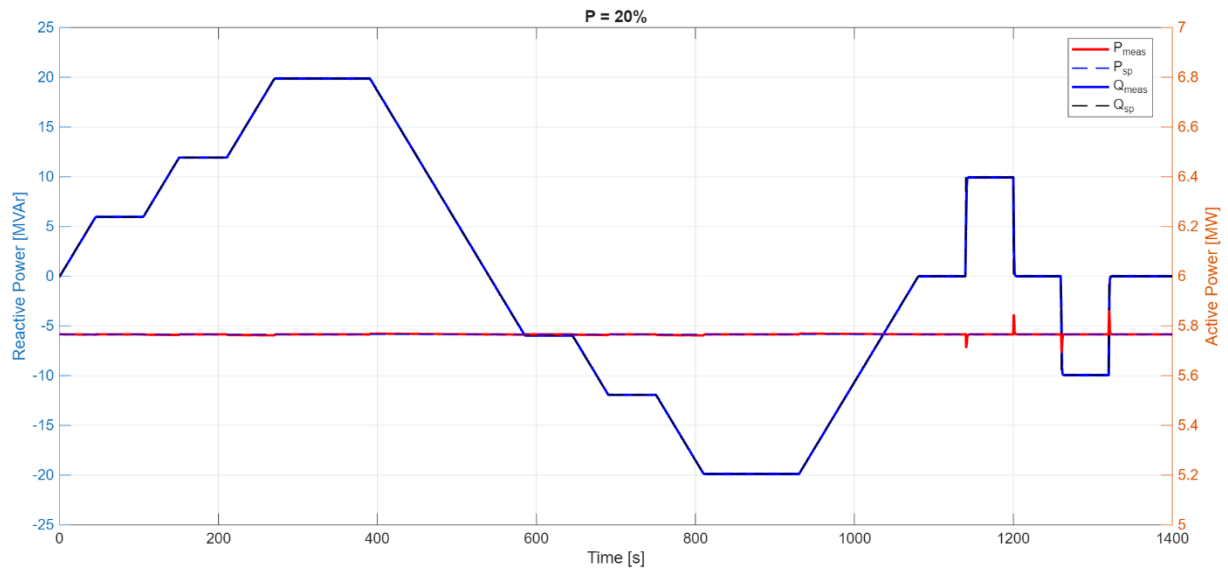


Figure 5.4 “Fixed Q” – third test with active power at 20%Pmax

Table 5.1 table for the verification of the capability curves

P	P/Pn	Q	Q/Qn	Qrif	Qrif/Pn	Q-Qrif	(Q-Qrif)/Pn
[MW]	[%]	[MVar]	[%]	[MVar]	[%]	[MVar]	[%]
28.83	100%	5.9640	30%	5.964	30%	0.00	0%
		11.9280	60%	11.928	60%	0.00	0%
		17.6161	88%	19.88	100%	-2.2639	-7.852%
		-5.9640	30%	-5.964	30%	0.00	0%
		-11.9280	60%	-11.928	60%	0.00	0%
		-19.88	100%	-19.88	100%	0.00	0%
11.532	40%	5.9640	30%	5.964	30%	0.00	0%
		11.9280	60%	11.928	60%	0.00	0%
		19.88	100%	19.88	100%	0.00	0%
		-5.9640	30%	-5.964	30%	0.00	0%
		-11.9280	60%	-11.928	60%	0.00	0%
		-19.88	100%	-19.88	100%	0.00	0%
5.766	20%	5.9640	30%	5.964	30%	0.00	0%
		11.9280	60%	11.928	60%	0.00	0%
		19.88	100%	19.88	100%	0.00	0%
		-5.9640	30%	-5.964	30%	0.00	0%

P	P/Pn	Q	Q/Qn	Qrif	Qrif/Pn	Q-Qrif	(Q-Qrif)/Pn
[MW]	[%]	[MVar]	[%]	[MVar]	[%]	[MVar]	[%]
		-11.9280	60%	-11.928	60%	0.00	0%
		-19.88	100%	-19.88	100%	0.00	0%

According to the previous figures and the table 5.1, the reactive power regulation in “FixedQ” mode may be considered fulfilled unless the maximum reactive power level at maximum power production. This anyway should not be seen as a breach of the CdR, but rather as the demonstration of the limits highlighted in the capability curves of Figure 3.3.

5.3 PPM-V – voltage control

As the previous one, in the PPM-V test, a custom block is required for developing the ramp setpoint signal required. It is exactly the same as the one shown in Figure 5.1 and reported in the annex [A.3], with the difference that the signals are in terms of voltage, measured in p.u., and no longer as reactive power measured in MVar. The output signal from the block is still connected to the “*Q_control*” block of the PPC, but in this case to the voltage setpoint port.

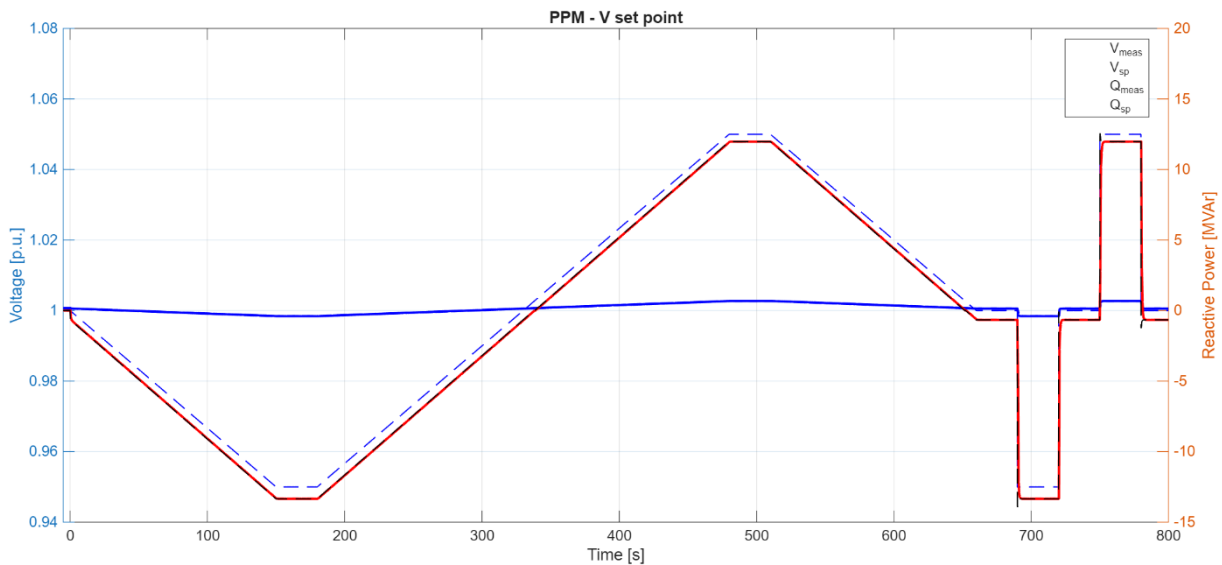


Figure 5.5 Voltage control test – *Q(DV)* mode. Voltage and reactive power plot

As regards the voltage, it is measured at the “USER HV BUSBAR”, which can be seen in Figure 2.1, just below the high voltage cable connection and then reported at the PoC voltage. Just for simulation purpose, in the RMS environment, the reference voltage of the grid must be provided by an external ideal voltage source and if the measurement point were located at same point as the IVS is connected, the value will be always one, with no possibility of regulation by

the PPC. But the IVS is used only as a “power source” needed for the correct initialization of the simulation. The main issue of this configuration is that moving the measurement point away from the PoC, is deleted from the measure the voltage drop on the cable and for this reason a “shift” on the result plot must be done, to consider it. In particular it is possible to see that in the very beginning of the curve of Figure 5.5, the voltage at the HV busbar is 1.002 p.u. instead of 1.000 p.u. due to the voltage drop absence.

As previously mentioned, the settings related to the PI’s gains are unchanged but is changed the working mode from the previous paragraph. Here is added the droop setting and the possible addition of deadband. Since the deadband is an instrument available in the PPC but not expressly required by Terna grid code, it is set on an extremely low value: 0.001 p.u.

According to the plant configuration, the droop value must be increased from the default value at 7.5% in order to not provide undamped voltage or reactive power oscillations.

Under the previous assumptions, Figure 5.5 shows the behaviour of the voltage and the reactive power during the test. The voltage does not reach the setpoint value, but it does show the maximum capability of the plant to support the grid voltage when required, by just injecting or absorbing reactive power. The test is carried in the mode “Q(DV)”, but according to the gains set, the same test can be carried for the “RegVfast” and “RegVslow” modes, where the unique changes are related to the time of intervention.

One key aspect that is reflected in this control mode, is the strength of the grid at which the plant is connected.

The relation between the power exchanged at a node and the voltage of that node can be derived considering the voltage variation across an impedance. In a high voltage network the reactance dominates over the resistance, and therefore the sensitivity of the voltage to the reactive power is equal to the ratio between the reactance of the equivalent network and the voltage, which is inversely proportional to the short circuit power at the point of connection.

The short circuit ratio can be defined as the ratio between the short circuit power at the point of connection of the grid and the rated power of the plant and it measures how much the network is able to absorb the reactive power injected without an appreciable variation of its voltage.

A strong network, characterised by a high short circuit ratio which means that an important reactive exchange produces a modest voltage variation, and therefore the plant has to move a large amount of reactive power in order to change only a little the voltage at the PoC node. Instead, in a weak network the opposite happens. A small reactive variation produces a significant voltage variation, and the regulation reaches its objective with a limited action.

The grid studied here is extremely strong. During voltage regulation the controller gains are tuned to this network sensitivity. A characteristic that produces a well damped response in a strong network, when applied in a weak network, results in an excessive loop gain and therefore in an oscillatory or unstable behaviour. Conversely, a conservative setting adopted for the weak

network condition produces, in a strong network, a response that is so slow that it may not satisfy the response time prescribed by the test procedure.

This explains why the droop slope of the characteristic is not fixed by the regulations but is selected on the basis of the actual short circuit power at the PoC and why the value declared by the Transmission System Operator for that node is a design datum as important as the rated power of the plant.

It is important also to highlight that, the setpoint curve provided from the TSO is only the blue one, related to the voltage, while the black one is an internal signal generated by the PPC itself and it matches the one provided less than at the step variations, points of the maximum stress. However, thanks to the PI response time, the sag created in the single step does not influence the behaviour of the reactive power.

If instead the goal was studying the behaviour during the “RegQ” mode, the test gives information also about this mode, since at a specific voltage setpoint is associated a specific reactive power according to the droop coefficient.

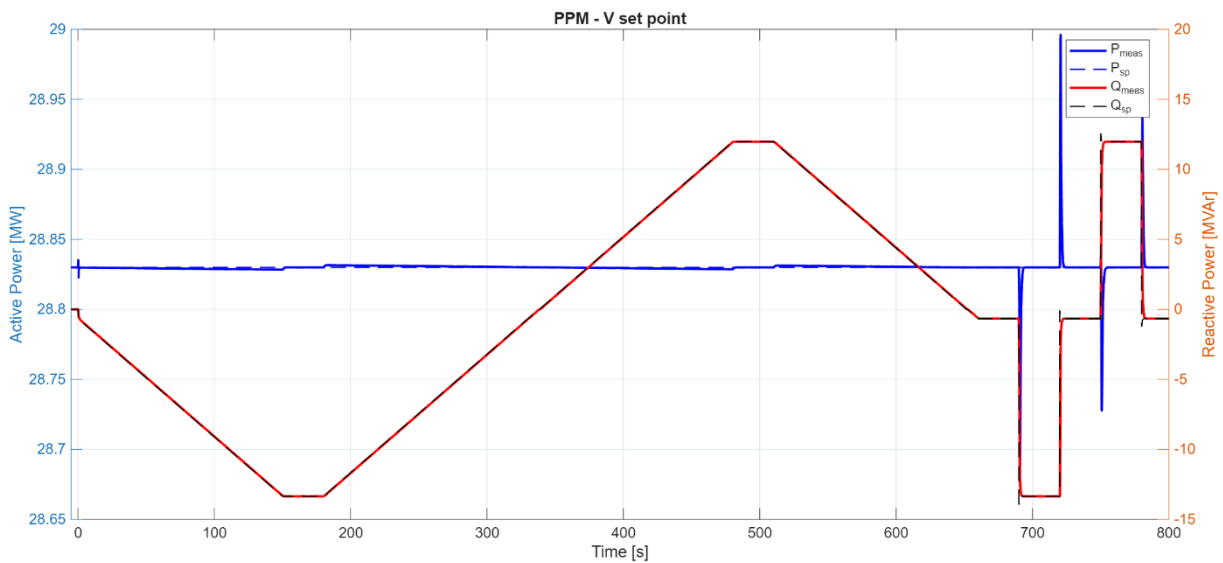


Figure 5.6 Voltage control test – $Q(DV)$ mode. Active and reactive power plot

In Figure 5.6 is instead represented the behaviour of the active power at the variations of reactive power from the voltage one. Here peaks of active power are not present, in the ramp region, since the reactive power gradient is small, so the interconnection between the two controllers follow a derivative of the inductance smaller with respect to the other tests. Instead in the step variations, bigger variations are required compared to the test for the “FixedQ” mode, and this means a bigger peak for the active power. The higher peak is for the restoration of the reactive power step point at the instant 720 seconds, but also in this case the maximum values below the threshold of 1% for the instability of the active power.

From the data recorded and with main focus on the ramp variation part, the annex A.18 [9] requires elaborating them, to calculate the regression in the overvoltage and undervoltage conditions, and to represent them in a reactive power-voltage graph as illustrated in Figure 5.7.

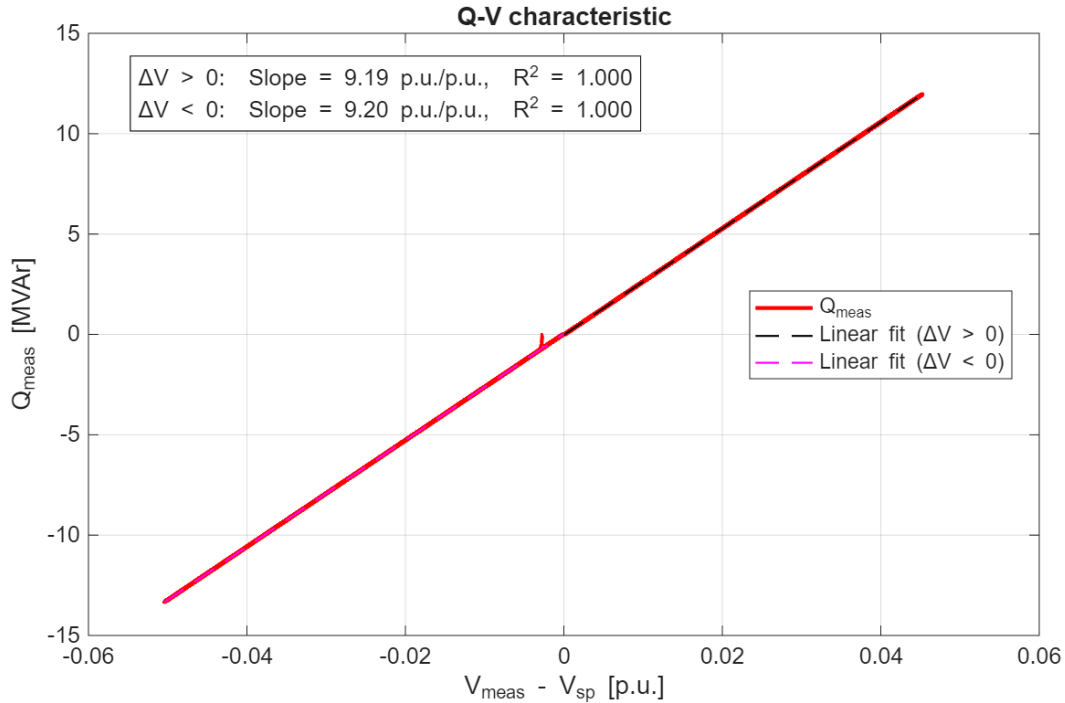


Figure 5.7 Static voltage regulation curve implemented in the power generation fleet control system

By the previous Figure, the slope is 9.20% in both the voltage conditions, it seems to be inconsistent with the droop value set in the PPC since it was 7.5%, but the actual slope is referred only to the difference between the measured voltage and the setpoint, and not to the ratio active power – actual voltage.

The maximum reactive power reached is 11.98 MVar, while the minimum is -13.34 MVar with the generator convention.

About the deadband, it is by choice, not included in the simulation in order to see the behaviour of the controller in the most extreme conditions, however, thinking about a possible commercial use of this model, the implementation of the deadband is possible and it is reflected with a flat response in the reactive power – voltage, while in the voltage setpoint plots, there would be a lack of sensitivity until the specified value of the voltage.

Chapter 6:

Frequency and active power control

The requirements described in this chapter address a problem that concerns the system as a whole and the plant is merely the means of meeting it.

The frequency of an AC system is a phenomenon determined by the balance between generated and absorbed power. In a system dominated by synchronous machines, the kinetic energy stored in the rotating masses acts as a buffer with respect to the imbalances provoked when the demand exceeds the generation. The deficit is initially covered by the deceleration of the rotors, which release a part of their kinetic energy, and the frequency decreases with a rate of change that is inversely proportional to the total inertia of the system. This behaviour for the traditional plant, in normal conditions is not a regulation, because no control system is involved, but it provides the time interval during which the regulation systems can intervene and therefore determines the depth of the frequency excursion following a disturbance.

The progressive substitution of the synchronous generation with renewable inverter based generation modifies this picture in a substantial way. A photovoltaic plant does not contain rotating masses and the not coupling with the network means an absence in the natural contribution to the inertia of the system.

As the share of renewable inverter based generation grows, the total inertia of the system decreases, the rate of change of frequency following a given imbalance increases and the time available for the regulation systems is reduced.

For this reason, is requested to the PV plant to contribute to the frequency control, in order to maintain it at least equivalent to the one historically provided by the conventional plants. This is the origin of the requirements of frequency-dependent active power modulation described in the chapter.

The plant is not able to provide inertia, but can instead, through a controlled action, modify its active power as a function of the frequency deviation.

The obligation to reduce the power in the presence of an over frequency is the most immediately achievable from of contribution, because it does not require any reserve since the plant simply produces less than what would be available and the regulation can be done with the same time as the active power regulation described in Chapter 4. It at the end is a better behaviour in the time scale, compared with the traditional generation.

The symmetrical requirement, the increase of the power in the presence of an under frequency, presents instead a structural issue, because a photovoltaic plant normally operates at the

maximum power point and therefore does not have any upper margin in order to be able to increase its production in response to an under frequency event. The plant, instead, has to operate permanently below the available power, keeping a reserve that is not delivered and is therefore not remunerated by the sale of energy. This is the reason the test procedure that verifies this functionality is executed with an active power set point reduced with respect to the rated one, in a way that makes the reserve available.

6.1 Frequency-dependent active power control

This regulation is needed in order to help the frequency control of the electrical system and since the time involved are so smaller, all the actions described in the following paragraphs must be done in an automatic way using the internal control system of the PPC. The PV plant must be able to modulate the active power exchanged and so help in the frequency control of the grid.

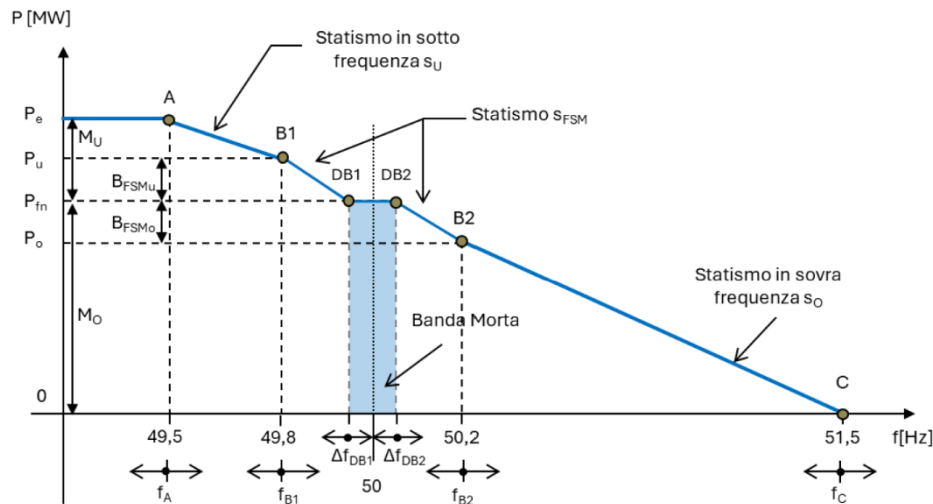


Figure 6.1 $P(f)$ curve for a PV plant according to the Terna annex A.68 [8]

According to Figure 6.1, there is the creation of three regions in the $P(f)$ curve: one around the nominal frequency called the FSM; one in the under frequency condition, when the frequency is under a certain threshold, identified as LFSM-U and the over frequency zone for frequency above a certain threshold, called LFSM-O.

6.1.1 Tuning around the nominal frequency (FSM)

The control system must respond when the grid frequency lies within the range f_{B1} – f_{B2} by varying the exchanged active power in proportion to the frequency error, taking priority over any other active power setpoint imposed.

In this mode, there must be implemented also a deadband with the two different bands, one for the under frequency and the other for the over frequency side.

6.1.2 Under frequency tuning (LFSM-U)

The PV plants connected to HV grid, must provide support in the grid also during under frequency events. For this reason, they must be able to increase their active power injection through the “*limited frequency sensitive mode under frequency system*”. The internal structure of PV systems, and of inverter-based generation in general, does not allow active power to be increased freely, since the production is related only to the environmental conditions and for this reason a certain margin called M_U must be maintained only to provide it during this specific events. The action of this mode has the priority on all the other setpoints and when activated the plant must provide an active power proportional to the error of the frequency with a statism defined by the TSO.

6.1.3 Over frequency tuning (LFSM-O)

The PV plants must provide support during over frequency transitory events, by reducing the injected power according to the frequency error. Such modality is called “*limited frequency sensitive mode over frequency system*”. When the frequency is above 51.5 Hz, the control system must detach the plant from the grid, by imposing a setpoint of zero active power injection.

The test illustrated in the annex A.18 [9], has the purpose of evaluating the static and dynamic characteristic in the frequency control domain, acting on the PPC. Such test must be conducted with a setpoint of active power equals to 70% of the nominal one, needed to guarantee a sufficient reserve of 30% of the nominal active power, to be able to develop during the under frequency regime.

The test consists in the simulation of specific frequency profiles, both with ramp and step variation, and then measure the active power injected into the grid, derived from the automatic variation of the setpoint of the PPC, since it must work in the P(f) mode.

In the model of the PPC used for this document development, the P(f) mode, active power mode for frequency response, could work with two distinct modes, a static and a dynamic one. The main difference is related to the reference active power at which the equations (6.1) and (6.2) are referring, or the maximum and the minimum respectively for the static mode, or the active power setpoint defined in the initialization, for the dynamic mode.

$$(P_{ref} - P_{min})/(f_2 - f_1) \quad (6.1)$$

$$(P_{min} - P_{ref})/(f_3 - f_4) \quad (6.2)$$

(6.1) and (6.2) express respectively the rate in MW/Hz of reduction/increase for the over frequency and under frequency scenario, respectively.

The following Figure 6.2 shows how the two behaviour works at the variation of frequency between the minimum allowed, f_4 , and the maximum, f_2 . For the simulations of the further paragraph, the dynamic mode is the one chosen, since it gives a closer behaviour to the one requested by Terna and reported in Figure 6.1.

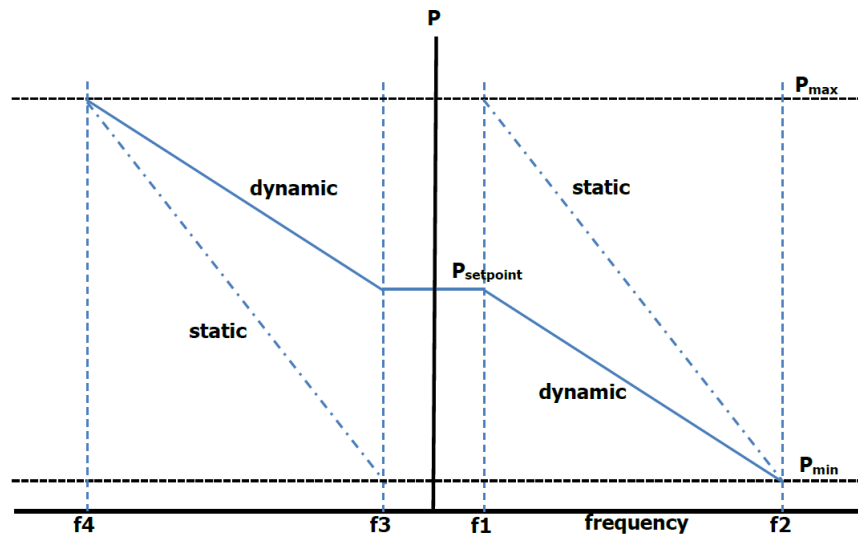


Figure 6.2 Illustration of the calculation of the static and dynamic ramp rates for $P(f)$ control

Other required settings are about the definitions of the frequency f_3 and f_1 , maximum and minimum frequency point for the under and over frequency control, respectively. Such points indirectly define also a deadband around the nominal frequency. In the setting table of the active power controller [A.1] must be define also the f_5 point, threshold where the power-to-zero strategy starts.

6.2 PPM-FSMLFSM – Frequency control

Different from the other Chapters, in this simulation, the setpoints that create the required profile of frequency is no more produced by an external block, connected directly to the PPC inputs, but instead is required a custom model for the ideal voltage generator.

In Figure 6.3 is represented such custom model, which can be able to modify the output frequency and voltage, both express in p.u., of the voltage generator. Both are built with the same basic concepts: core element is an integrator needed for the ramp signal production (as

the ones already used and represented in Figure 5.1), connected to a summation point. Then the signal passes in a switch, since the model can use or the external generated signal (ramp or step generator) or providing a quantity measured anywhere in the circuit and then connected to “y1” or “y2” if it is a frequency or a voltage quantity.

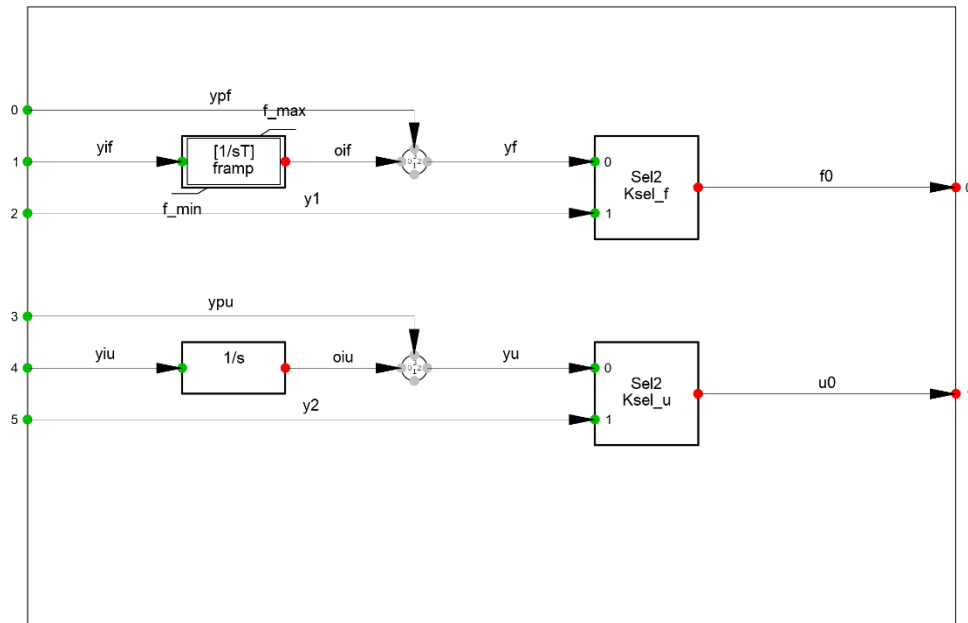


Figure 6.3 custom model of the control system of the ideal voltage generator for the frequency ramp generation

Moving to the simulation, the previous mentioned limit points, for the frequency proportional response are defined according to the default values set by the annex A.68 [8], which define an under frequency region between 49.5 Hz and 49.8 Hz and the over frequency region between 50.2 Hz and 51.5 Hz. The “f3” point is a 51.5 Hz.

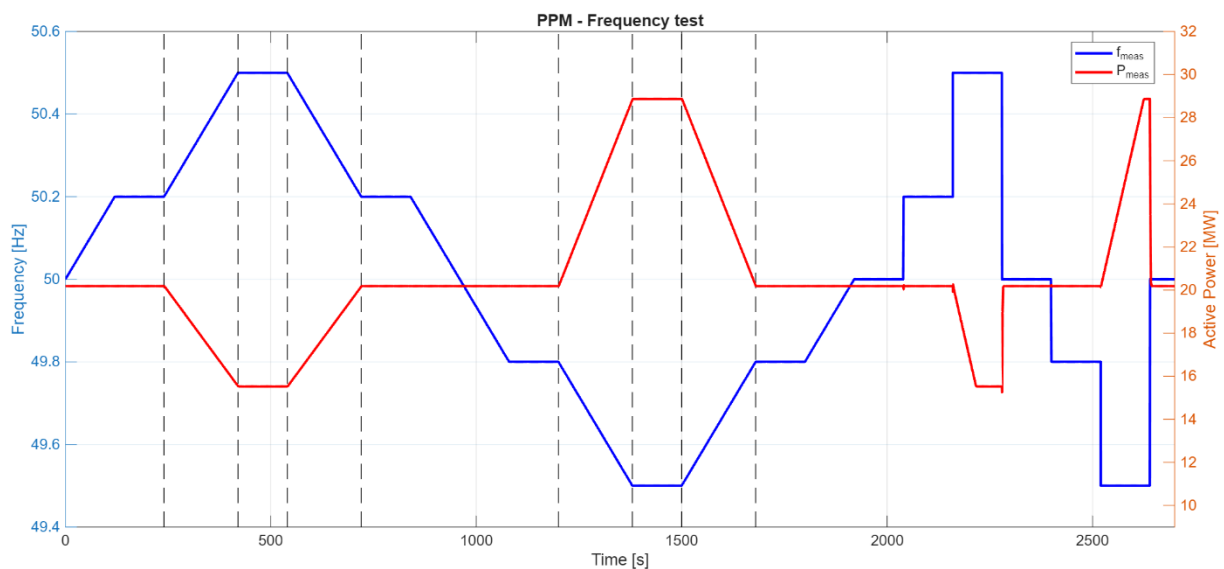


Figure 6.4 frequency control test. Frequency and active power curves

Figure 6.4, represent the profile defined for the frequency variations, where in the ramp phase the gradient is 0.1 Hz/min. The PPC acts by modulating the active power only in the zone inside the under or over frequency event, creating a factual deadband in the other side.

During the first over frequency event, the value reached is 50.5 Hz, well below the maximum allowed and the plant responds by limiting the active power to about 15 MW, roughly 52 % of the maximum value. In the under-frequency event, by contrast, the minimum allowed frequency of 49.5 Hz is reached and so the response from the PPC is to give to the grid all the available power, that during the simulation, not physically related to the solar radiation, corresponds to the maximum active power P_{max} .

As in the other scenarios, the most critical phase is the step variation. Here, a ramp limiter for the active power is set at 6MW/min by default in the PPC. It is necessary to prevent possible impulsive active power events during frequency step oscillations, which can be harmful at the grid stability, since the two quantities are intricately linked one to the other.

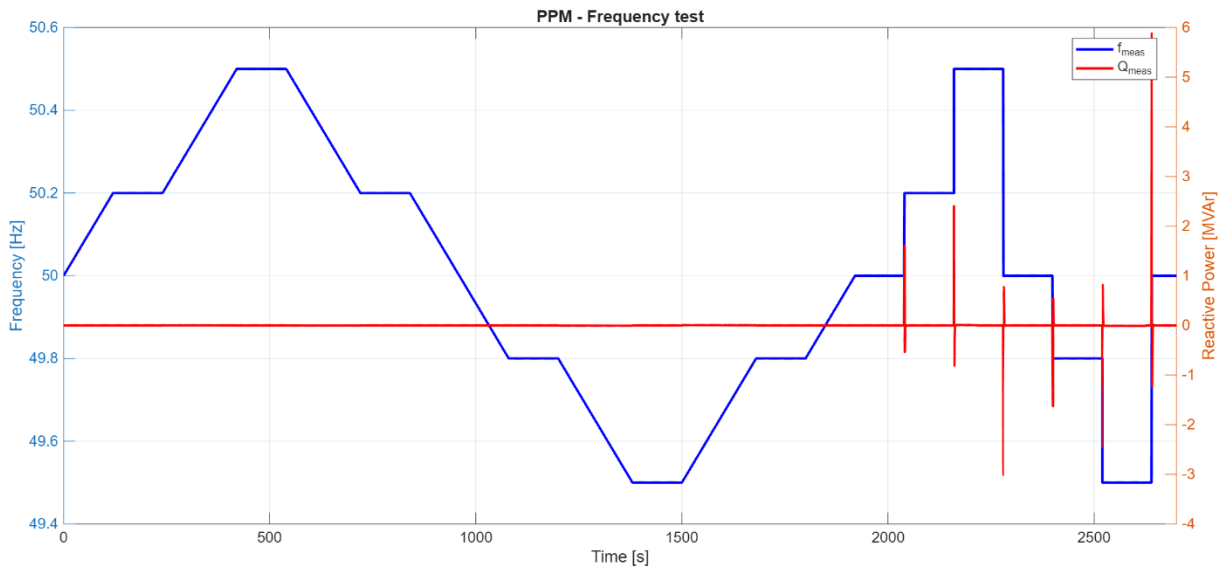


Figure 6.5 frequency control test. Frequency and reactive power curves

Considering instead the reactive power - frequency graph, in Figure 6.5, as experienced with the active power, after a step variation on frequency, the reactive power also changes but, in this case, the variation is not damped by the PPC and appears as an impulsive transient. In theory the reactive power should remain at zero, the setpoint defined in the initial conditions, but due to the previous mentioned link in (4.1) and (4.2) relations, the impulsive action is justified. The main issue depicted in the plot is that, during the step variation between the deepest under frequency value and the restoration, the plant is experiencing the most critical active power variation, correctly limited in a ramp. In the reactive power side of the PPC, this

signal does not come as a ramp and the natural response is the impulsive one, with a peak of 6 MVar, about 20% of the available active power.

Deviating briefly from the route set out in the annex A.18 [9], a study can be conducted on the behaviour outside the test, in particular in the over frequency region. Here, as described in the previous sections, upon reaching the upper limit fixed at 51.5 Hz, is requested to stop completely the production. Figure 6.6 allows to understand that as the frequency increases, the active power is reducing until the point “ f_2 ” which is overlapping with the upper limit. This point triggers a number of actions on the inverters, since the PPC issues a zero setpoint, but also the internal protection control system of the inverters acts since the point is in a “emergency” frequency value. The result is zero power output, imposed not only by the control logic but also by the physical opening of the circuit, so that the plant no longer reacts even if the frequency keeps rising.

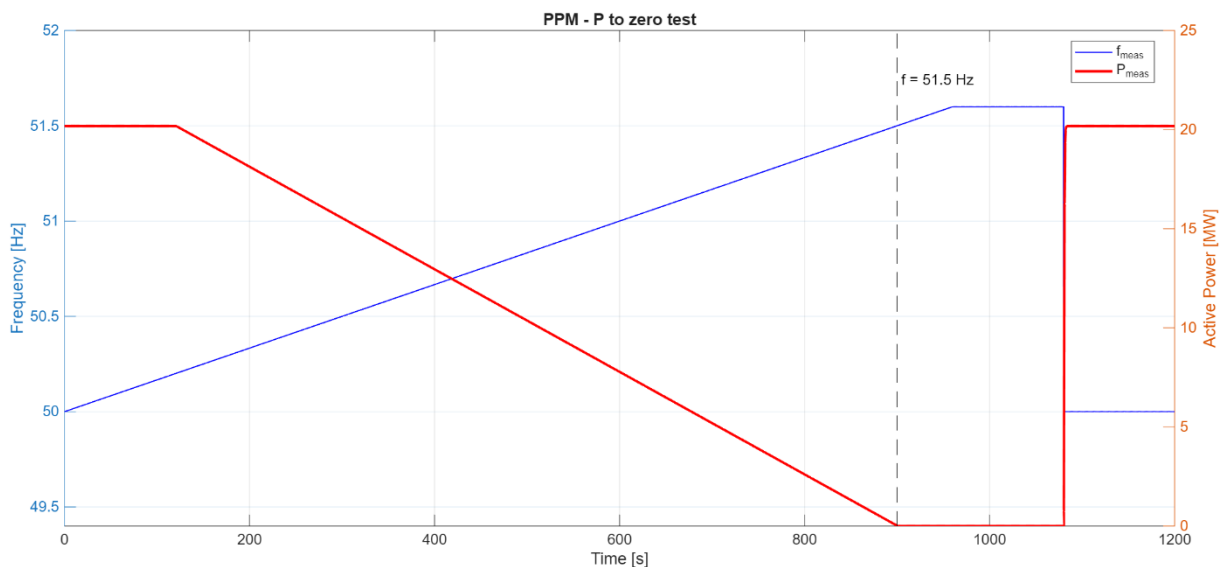


Figure 6.6 frequency control test in over frequency region. Frequency and active power curves

Instead, when the frequency returns inside the acceptable range, the active power is restored starting from zero, according to the control settings defined in the chapter 4, for this reason here there is no ramp increasing but only a fast follow of the setpoint produced.

The annex A.18 [9] requires the creation of a plot of the linear regression of the ramp variation part, where on the vertical axis is reported the active power and on the horizontal axis the frequency. Such graph is reported in Figure 6.7, where, according to the purpose of the present document, is not only represented the linear regression of the simulated scenario (blue line), but

also other two conditions, obtained by changing the regulation curve point that delimits the deadband.

The blue curve represents the linear regression with the default values reported in the Terna annex A.68 [8], instead the green one has the deadband limited between 49.9 Hz and 50.1 Hz; the red one has the deadband limited between 49.95 and 50.05, the minimum allowed position.

Each of the curve in Figure 6.7 perfectly matches the one required and reported in figure 6.1. The shape is not perfectly equal since the curves are based on the previous mentioned test and the under frequency part is limited at 49.5 Hz, but the limit of the available power “ P_e ” can be defined as the maximum power point depicted that corresponds to the maximum power P_{max} . The same can be considered for the over frequency side, where instead the test does not deal with points at a frequency less than 50.5 Hz.

However, all the three curves are completely compliant with the requirements from the annex A.68 [8].

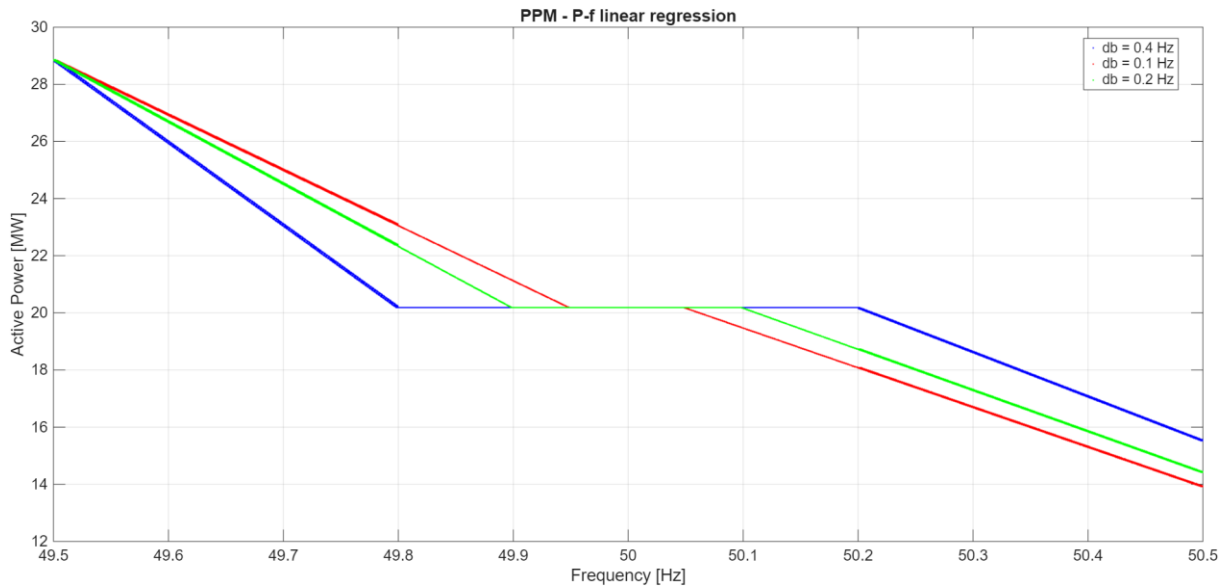


Figure 6.7 Linear regression of three possible settings for the regulation curve of the plant. active power – frequency graph.

Chapter 7:

External event influence

The annex A.68 [8] of the Terna Grid Code defines the prescriptions analysed in the previous Chapters by considering the grid in the theoretical condition reported in Chapter 2. They are certainly far from a real application and for this reason the behaviour of the plant could be different.

The main goal of this Thesis work is at first the creation of the model which can be used for the analysis of the compliancy of a particular PV focused plant to such requirement, but then, since the model would be applied to a real situation, after the approval phase such plant should pass to the commissioning phase. It means that the plant which will be build is expected to function as the model state. However, the use of the previous mentioned assumption could arise the possibility that the expected behaviour is not equal to the truth.

Moreover, the creation of a software model, gives the chance of knowing in advance how the plant behaves in the not ideal conditions or after a not normal event.

For this reason, this Chapter has the main purpose of illustrating some possible critical working condition, studying, and analysing how the model and so how the plant could respond in this conditions which are outside the regulation but closer to the real behaviour of the plant.

The first part is related to the study of one of the most probable issue in a PV utility scale plant, the loss of communication between PPC and the local controller of the inverter. The study is conducted because, not only this particular event can happen frequently, but also involves the injection of power in the grid and in general all the electrical operations required between the plant and the grid.

The second part, instead, is dedicated to the analysis of the behaviour of the case study plant in the PPM-V test, when it is connected to a grid which is not ideal. Particular attention is done to this specific case study since the strength of the equivalent grid at which the plant can be connected is crucial for all the auxiliary function of the plant (support of voltage, injection of reactive power...) and the one under analysis is the more evident.

7.1 Signal communication issue

About 50% of the issues that involve a loss of production in a photovoltaic plant can be attributed to the inverters. The loss of communication between the inverter and the control system is a very frequent problem [11], constantly ranking among the first causes of service tickets in photovoltaic systems as Figure 7.1 express.

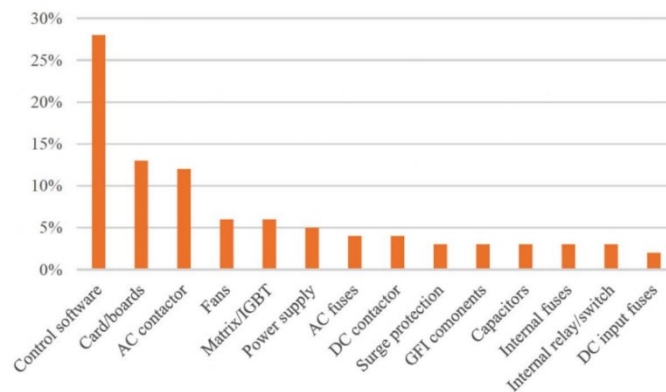


Figure 7.1 Frequency of tickets for each failed component of PV inverter [11]

It is important to note that a considerable number of tickets, about 27% is opened only for control software troubles, and they are entirely communication issue. Moreover, since this problem is just at a software level, the action is not destructive and result in a loss of communication between PPC and inverter.

The issue of communication influences the inverters both if they are connected together through wi-fi protocol both if are connected with the serial protocol RS485. The first is influenced by external wi-fi router of other infrastructures that could interfere with the internal network of the plant. The latter can have issues related to the poor electromagnetic compatibility of the signal cables due to the natural electromagnetic disturbances produced by the plant.

These events are critical for the active power managing, but at the same time, do not affect the health of the plant since no components are destroyed. Such events are typically monitored constantly by the PPC and immediately reported through a dedicated alarm.

Using the model developed, the connection issues can be simulated and analysed. It could have a key role, since such issues could be transitory, if generated by a momentaneous disturbance or in general the solution at the problem is not requested to be immediate.

In order to prevent such event, two different strategies can be adopted and must be activated separately in the inverter software, during the commissioning: “Hold Last State” and “Safe Shutdown”.

7.1.1 Hold Last State

From a power systems engineering perspective using the “Hold Last State” strategy over alternatives has the main advantage of eliminating revenue losses during minor telemetry dropouts by maintaining bulk energy injection into the transmission or distribution grid.

The action permit also to mitigates voltage spikes which instead are introduced in the other mode. The strategy consists in holding the last setpoint obtained. The issue of this strategy is related to the fact that during the communication loss, the capability of the plant is reduced, since a part of the inverters cannot be modify their power injection both active and reactive.

The test is conducted by considering the most critical condition, the maximum active power state.

Then is simulated the previous explained PPM-PLIM, the results are than reported in Figure 7.2.

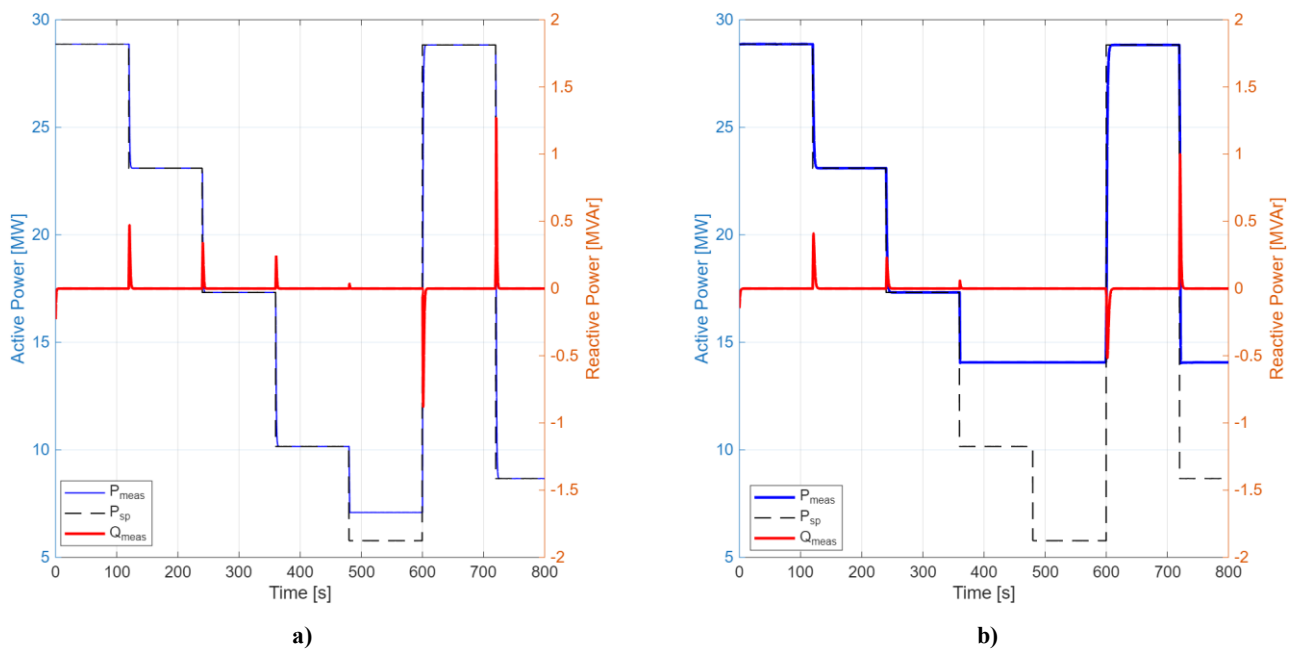


Figure 7.2 Active and reactive response of the plant after the loss of communication in Hold Last State
Mode a) represent the one group inverter loss. b) represent the half inverters loss

In Figure 7.2a is reported the curve, if the loss involved one group of 25 inverters. The result is that due to the imposed maximum generation on such inverters, the minimum step cannot be reach, but in all the values, the setpoint is reached.

Instead, in Figure 7.2b, the loss is more severe, involved half of the inverter. Here a bigger part of the lower side of the active power plain is not available, since the minimum active power is 14.7 MW, equal to the 15 MW from the lost inverters and the loss in the cables. This implies that all the still working inverters are stopped, while produce energy only the lost ones.

About the reactive power, since the inverters lost have a fixed only active power injection, is related only to the healthy inverters, so as the number of detaching increases, the peak of reactive power becomes smaller.

At the end, this strategy is used when the goal is to maintain a good active power injection, a low reactive fluctuation, but accepting that the plant cannot contribute to the reactive power support.

7.1.2 Safe Shutdown

This technique is used when the several strings are connected to the same inverter and frequent decrements are requested by the TSO. In this way all the not communicant inverter are shut down automatically entering in a certain way in a “safe protection” mode. The passage between the actual production and the zero state can be, in a stepped way or an instantaneous modification.

According to the layout presented in the second Chapter, to conduct this simulation, in the most critical condition of instantaneous shutdown, is not possible to shut off just a single inverter, but instead the minim number is eight. It is not a problem since permit to better appreciate the instantaneous variation of the active power.

All the simulations reported in the next figure starting with the maximum active power available and the reactive power is set to zero to permit the maximum active power injection.

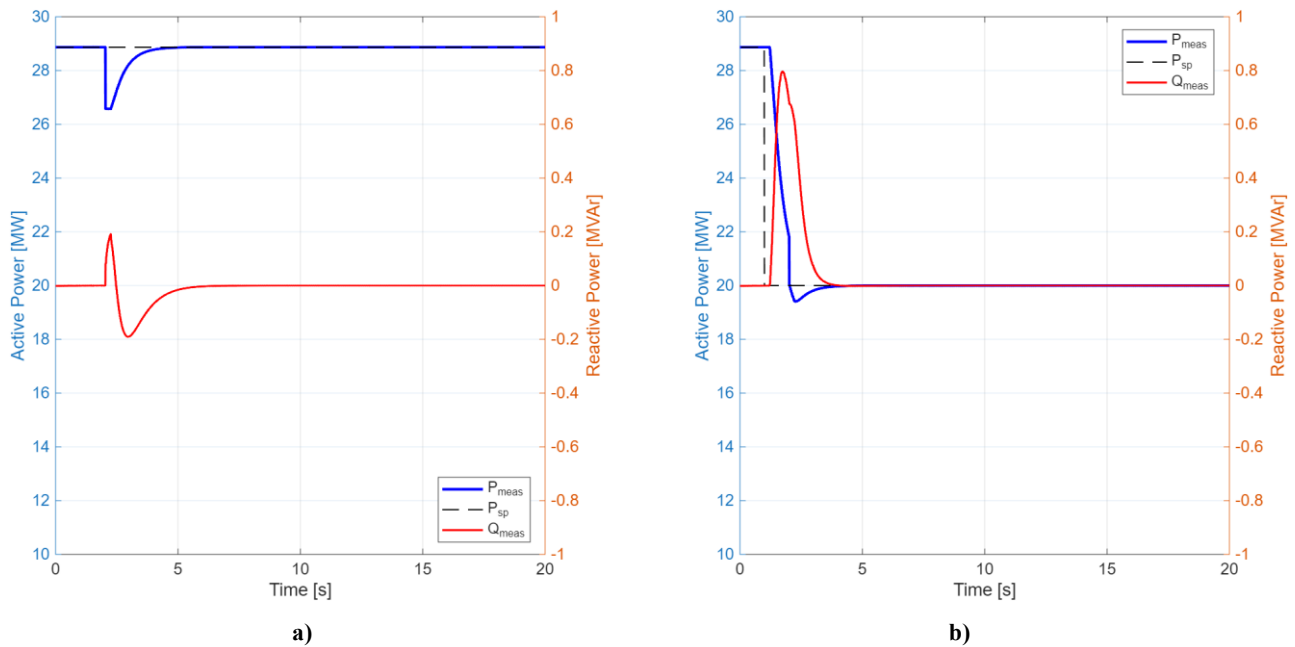


Figure 7.3 Active and reactive response of the plant after the loss of eight generating unit at time 2s. a) represent the maximum power setpoint. b) represent when the event happens in the step variation

Figure 7.3a shows the loss of one group of eight inverters during the maximum active power injection. Here the instantaneous loss is limited only at about 2.4MW during the normal operation of the plant. The PPC can restore the required active power by requesting to the other inverters the injection of a higher power, reaching their limit of 110% the active power fixed by the generator capability curve of Figure 3.2. That is a working phase that could be sustained only for a limited period since it is a condition of huge stress for the electronic components and at the same time is a condition outside the Terna requirement, since here no reactive power is available and no reserve of active power can be injected.

Figure 7.2b, instead shows the case where the same loss of eight inverters happens, instead, during a step variation, from the maximum power to 20 MW. This is a critical time coincidence that must be considered. When the loss happens, at the two second instant, the internal delay of 200 ms, permit at the plant to continuing the reduction even if the setpoint is already overpassed. But after the delay time, when the error is bigger than the expected one, the PPC acts a corrective action, with opposite sign to reach the selected setpoint. This corrective action is in terms of time and amplitude equal but with opposite sign with respect to the normal regulation acted after a step variation of the setpoint.

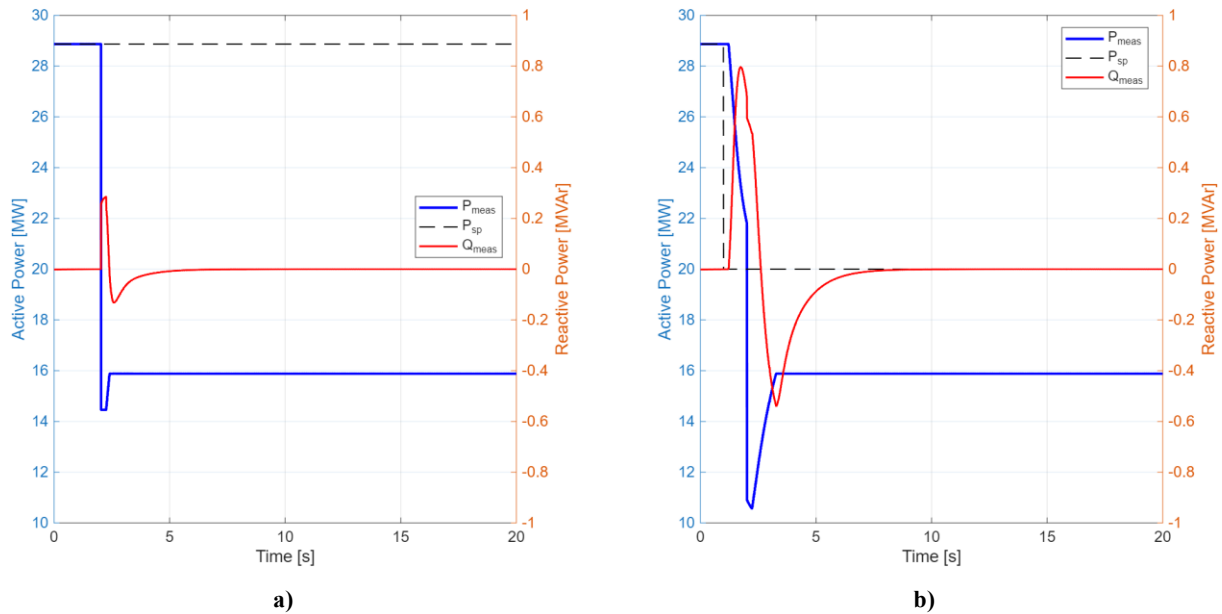


Figure 7.4 Active and reactive response of the plant after the loss of half of the generating unit at time 2s. a) represent the maximum power setpoint. b) represent when the event happens in the step variation

Figure 7.4a, instead shows the case where the loss is more severe and involves two full collection cabin, so are shut off simultaneously 50 inverters, half of the total. The result is completely different from the previous case.

Before the error between the measured active power and the setpoint was small and the PPC reacts with the response previously defined, since a reserve on the healthy inverters is available. Instead, now, the sum of the controllable inverters' power is lower than the required one and

the error becomes big. Also, the topology of the plant is changed, also modifying the relation with the gains of the PI controllers.

All together the result experiments a faster increase of power, reaching the 110% loading, with a quasi linear increase, due to the fact that the integrative gain is no more correctly tuned and has only a limited impact on the control phase. Nevertheless, the power is not physically available, so the setpoint cannot be reached.

In Figure 7.4b, the event is of the same type of Figure 7.3b, but with the loss of half of the generating park. The control strategy follows exactly the same behaviour of the previous event, but with a faster action, considering the higher distance from the setpoint, due to the different relationship with the gains. Also in this configuration, the setpoint is not physically achievable.

For what concern the reactive power, as the Park transformation [12] express, the instantaneous variation of active power triggers a variation in the reactive power that for the case of Figure 7.3 is limited at 0.2 MVar, while in Figure 7.4 it can achieve 0.4 MVar.

During the step response, the natural increase of reactive power is 0.8 MVar, but in the first case, due to the loosing of inverters, it is reduced from the lower contribution available. Instead, when the inverters lost are more, not only there is a reduction in the peak proportional to the number of inverter lost, but also a peak of the opposite sign is necessary to return to the setpoint value and that is proportionally bigger thanks to the newer gain relationship.

At the end, the possible loss of communication between inverters and PPC is not a mere loss of money due to the lower injection in the grid of active power but can mine also the stability of the grid itself. Moreover, the reduced productivity also implies an overloading and so a reduction of the health inverters that try to maintain the setpoint imposed, causing premature ageing, reducing their lifetime. The problem becomes more severe due to the involvement of the reactive power. It is aggravated from the fact that most of the communication issues are software side, and the detaching could be temporally or intermittently. Such peaks of reactive power, which could also change in sign during the operation, injecting in the grid disturbances of reactive power that acts certainly against the stability. In extraordinary events this can be reflected to the network at which the plant is connected, with the tripping of HV breakers and in general action of control of the other device in the network.

7.2 Stability of the grid

According to the traditional generation scenario, based on synchronous generators, the stability of the grid was obtained through the correct managing of rotating mass, governors, and excitation systems. In 2021 the IEEE/CIGRE joint task force revised and extended the classification by maintaining the three classical contribution (Rotor angle, Frequency, Voltage) but added two new categories: converter driven and resonance [13].

Focusing on the first of these two new categories, the converter-driven stability is based on the action on the internal control-loop of the plant, distinguished between the one of the PPC and the one of the inverters. That consent opens an innovative approach at the grid stability, since nowadays the frequency stability is a matter related to the speed of the inverter controls and is no more related to the rotor kinetic energy.

Voltage stability is increasingly a small-signal interaction between the inverter's phase-locked loop (PLL) and the grid impedance at low short-circuit ratio, no more the definition of a working point in a Q-V curve as done in the past.

For this reason, in a real executive project, has a key role also the electrical parameters of the grid at which the plant will be connected. Not only for the limit of power exchanges but also for the control logic.

This paragraph investigates on how the short circuit parameters modify the control response of the case study plant.

Doing a step behind, a grid can be considered “weak” or “strong” according to its amount of apparent short circuit power available at the PoC with the plant, considering the grid as a Thevenin's equivalent generator.

$$S_{sc} = \sqrt{3} \cdot V_n \cdot I_{sc} = \frac{V_n^2}{Z_{th}} \quad (7.1)$$

According to (7.1), S_{sc} , behaves inversely to the network's internal impedance, so high short circuit power implies a low impedance, and a strong grid, capable to absorb a significant current injection and react at the variation with a minimum deviation from the nominal voltage. The weak grid is instead the vice versa.

From the “Conventional minimum and maximum values for short-circuit current and short-circuit power in the relevant network with voltages of 380, 220, 150 and 132 kV” [14], Terna provides the values of maximum and minimum short circuit power at all the primary substation PoC of Italy.

To permit a clear visualization of the effects in the following studies, are chosen the highest and the lowest value, of Italian substation suitable for the connection of a similar power PV plant, all are reported in the following Table 7.1.

Table 7.1 Highest and lowest values of short circuit power at the PoC of the Italian primary substations [14]

Area	Substation	Voltage	Maximum short circuit power	Minimum short circuit power
		[kV]	[MVA]	[MVA]
M	Turbigo.ST	380	35819	18761
V	Adria Sud	132	2559	1546

The first one, “Turbigo.ST”, is the substation with the highest maximum short circuit power in Italy in January 2026, since it is the one connected to the Turbigo powerplant, a thermoelectric unit of about 1GW, the fourth in Italy per power installed and is located in the industrial area near Milan, a very energy-intensive zone.

The other, “Adria Sud”, is a substation under development works due to the increasing of PV and renewable energy plant in general in that area. The equivalent Thevenin’s generator gives a weaker grid with respect to the first, but still suitable for the PV connection (that will be also the first substation in Italy that accept the new type 2 technology presented in this document). With the data obtained, the focus is on the behaviour of the controller in the voltage setpoint mode, at the connection with different external grids.

All the substations selected are at a voltage different from the one in object since nowadays no substations in Italy follows such specific, and for this reason, the data reported, in the simulation environment are reported to 36kV.

As done in Chapter 5, the setpoint varies the voltage reference at which the PPC try to reach, and the focus is on the ability of the plant of moving the voltage at the PoC busbar.

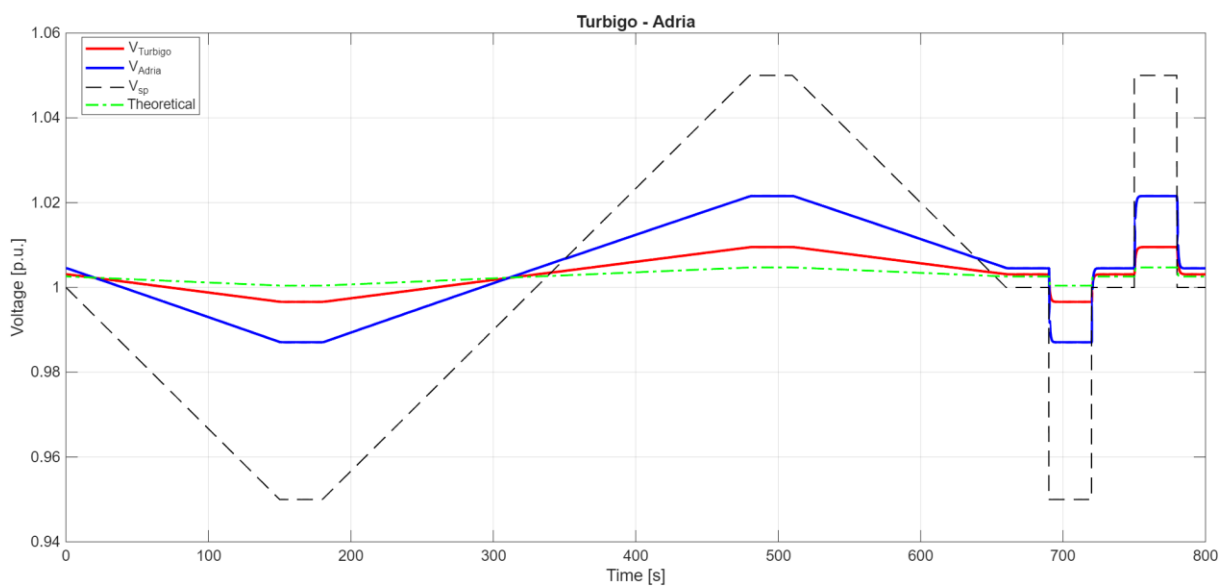


Figure 7.5 Response of the PPM-V test if the plant will be connected to Turbigo.ST and Adria Sud substations

In Figure 7.5 is represented the behaviour of the voltage at the PoC of the case study plant if will be connected to different substations. Considering the first case, the connection with Turbigo.ST is shown with the red line. The behaviour corresponds to what expected, in particular, a strong grid means a low propensity to react at variation. In fact, when the set point change is at the top and bottom limit, the action on the busbar voltage is limited, with a maximum excursion of 0.009p.u. from the unit. It corresponds to an insensibility of the grid from the point of view of instability generated from the PV plant, but at the same time, in case of variation of the voltage, grid side, the plant is not able to restore the voltage.

The blue line is instead representing the behaviour of the voltage if the connection would be realized in the Adria Sud substation. This is the most plausible behaviour, since the substation in exam is one of the one of those that in 2027 – 2028 will host a plant with comparable size using the same type of connection. Here the response is better amplified giving a suitable support in the voltage regulation, but at the same time the variation of voltage forms the plant side, does not impact so much in the grid behaviour [10]. Such response is confirmed by the fact that the plant can reach about half of the voltage required alone and must be consider that inside the substation, there is not only such plant that contribute to the voltage regulation.

At the end, all the two lines are extremely far from the one reported in green of the study in Chapter 5, since than one was done considering a fictitious – infinite short circuit power equivalent grid at the PoC.

Not the case in exam, since the two substations are enough strong to accept such plant, but for small issues, related to the voltage and reactive power stability, a compromise can be achieved by tuning differently the droop in the PPC response. The idea is to increase it, in order to have a more inclined curve that means, for the same voltage error ΔV , a lower amount of reactive power. The main drawback is that in such way the peaks of voltage are avoided, but instead the reactive is injected in continuous step variations, which corresponds to a not constant active power injection, which is instead the first objective of the plant.

At the end, this study demonstrates that not only the plant must be compliant with the Terna's requirement, but in real application, it forms with the already existent grid a unique element that must be correctly tuned in order to satisfy the requirements.

Conclusions

The objective of this thesis was the construction of a DIgSILENT Power Factory® model of a utility-scale photovoltaic plant connected to the HV transmission system, through the recently introduced 36 kV standard. The model is extended also to the creation of case study scenarios in the software environment to verify the compliance of the plant with the technical prescriptions of the Annex A.68 by means of the tests prescribed by the Annex A.18.

The case study is a fictitious but realistic plant with installed power of 30 MW, selected because its size and its connection scheme reproduce the average of the connection requests currently submitted to the Italian TSO, and because the Type 2 connection places the plant in a peculiar position, not already available in the actual Italian generation park.

The verification was carried starting from the steady-state load flow calculation, used to build the capability curves at the Point of Connection, both in the active-reactive and in the voltage-reactive plane. Then the balanced RMS dynamic simulation was the tool adopted for all the tests derived from the Annex A.18. The core elements of control architecture were first described through the theoretical WECC models REGC_A and REPC_A and then implemented through the commercial dynamic models of the inverter and of the power plant controller, which is the configuration that a real compliance study would adopt. To fulfil the required test profile, development of custom DSL block was necessary, one for the generation of the ramp and step set points of reactive power and voltage, and one for the control of the ideal voltage source, needed to impose the frequency profile of the PPM-FSMLFSM test.

As regards the capability curves, the case study plant satisfies the requirements of the Annex A.68 with a wide margin. Against a reactive requirement of 10.39 MVar, derived from the available active power of 29.7 MW, the plant exchanges 14.67 MVar in capacitive behaviour and 16.96 MVar in inductive behaviour at the maximum active power of 28.83 MW.

The analysis also showed that the curve at the Point of Connection is not the mere sum of the capability of the converters but instead takes into account the losses of the network (reduces the maximum power), the shunt capacitance of the high voltage cable (introduces a permanent capacitive offset), and the reactance of the transformers and of the cables (reduces the reactive power availability). A sensitivity analysis was conducted, and it identified in the length of the high voltage cable, one of the dominant parameter of a Type 2 connection capability curve.

The correct performances obtained are consequences of the ideal hypothesis made, but if needed, the correction usually adopted in the traditional schemes, the reduction of the short-circuit voltage of the step-up transformer, is not available, since that machine lies outside the plant boundary. Three measures were therefore discussed, the reduction of the active loading

of each converter, the increase of the cable cross-sections and the installation of shunt reactors on the high voltage side.

The dynamic tests confirmed the adequacy of the control structure. The active power limitation reaches the tolerance band of 1% of the rated power in 1.4 s against a prescribed limit of 2 s and without overshoot, and the same behaviour is maintained for a step of 70% of the rated power, which is far more severe than any curtailment order expected in normal operation.

The reactive power control in “FixedQ” mode reproduces the reference over the whole tested range, with the single exception of the extreme capacitive point at maximum production, where only 88% of the reference is reached. This deviation is not a deficiency of the regulator but the same limit already visible on the capability curve. The voltage control test returned a static characteristic with a slope of 9.20%. Finally, the frequency test showed a response fully compliant with the $P(f)$ characteristic of the Annex A.68 in all the three regions FSM, LFSM-U and LFSM-O, and for the three admissible positions of the dead band, together with the correct actuation of the power-to-zero strategy above 51.5 Hz.

Beyond the single verifications, two results of general character emerged from the work. The first is the coupling between the active and the reactive channels of the regulation. The Park equations show that the direct and quadrature axes are linked through the internal inductance, and every simulation confirmed that a fast variation imposed on one quantity produces a transient on the other. The practical consequence is that the reactive gains have to be tuned even in the tests that concern the active power only, and that a ramp limitation imposed on the active power is not reflected on the reactive channel, which remains the least protected part of the architecture. The second result is that the settings obtained are not a property of the plant alone. The analysis conducted with the short-circuit powers declared by Terna for two real substations showed that, with the same controller settings, the plant is almost unable to influence the voltage of a strong node such as Turbigo, provides an effective and well damped support at Adria Sud. The plant and the network therefore constitute a single system, and the short-circuit power declared for the point of connection is an extremely important design datum.

Some developments can be built on the structure created. The first is modelling the plant is all the components a so permitting a finer regulation on all the power aspects and also of the possible real events that can happens. The second is the extension of the model also to the protection coordination system and the response of the plant under short circuit events; it is not required in a so detailed way by the Terna annexes but constitute a good chance for simulating all the possible conditions at which the plant may be subjected in its whole life. Finally, a further implementation consists in extending the model to the traditional Type 1 connection, where the point is just modifying the requirement values. Or, more challenging, also the extension to the other inverter based renewable generation plant: BESS and wind farms. That because all the tests conducted are valid for all the European Regulation (EU) 2016/631 power plants.

The model developed in this work is therefore proposed not as the description of a single plant but as a reusable tool: the topology, the components and the controller settings can be replaced while the test procedures, the custom blocks and the post-processing remain unchanged, so that the compliance of a new 36 kV photovoltaic plant with the Italian grid code can be assessed at the design stage, when the corrective measures identified in this thesis are still economically viable

Nomenclature

V_D	=	Potential difference in the semiconductor's PV cell [V]
I_C	=	Cell current [A]
I_L	=	Ideal generator's current of the PV cell [A]
I_0	=	Dark saturation current of the diode model [A]
q	=	Magnitude of electron charge [$1.6 \cdot 10^{-19}$ C]
V_C	=	PV cell voltage [V]
R_S	=	Series resistance for the cell model [Ω]
n	=	Coefficient dependent on generation and recombination phenomena [-]
k	=	Boltzmann's constant [$8.617 \cdot 10^{-5}$ eV/K]
T	=	Absolute cell temperature [K]
R_P	=	Parallel resistance for the cell model [Ω]
I_{SC}	=	Short Circuit current of the cell [A]
V_{OC}	=	Open Circuit voltage of the cell [V]
R_l	=	Kilometric direct sequence resistance [Ω/km]
X_l	=	Kilometric direct sequence reactance [Ω/km]
R_0	=	Kilometric zero sequence resistance [Ω/km]
X_0	=	Kilometric zero sequence reactance [Ω/km]
C_0	=	Kilometric capacitance [$\mu\text{F}/\text{km}$]
U_0	=	RMS voltage between conductor and earth potential [V]
U	=	RMS voltage between two conductors [V]
V_p	=	Primary voltage [V]
V_s	=	Secondary voltage [V]
N_p	=	Primary turns [-]
N_s	=	Secondary turns [-]
I_p	=	Primary current [A]
I_s	=	Secondary current [A]
P	=	Generic active power [W]
r	=	Generic resistance [Ω]
I	=	Generic current [A]
I_k	=	Maximum short circuit current [kA]
I_{qextra}	=	Extra reactive current contribution [A]
khv	=	Gain of the HV block of the REGC_A [-]
V_{olim}	=	Over voltage trigger value[V]

Q_{ref}	=	Reference reactive power [MVar]
P_{ref}	=	Reference active power [MW]
Q	=	Generic reactive power [VAr]
S	=	Generic apparent power [VA]
V_{PoC}	=	Voltage at the Point of Connection [V]
I_{PoC}	=	Current at the Point of Connection [A]
P_{nd}	=	Available active power [MW]
P_{nd_inv}	=	Available active power per inverter [MW]
S_{n_inv}	=	Nominal apparent power [MVA]
v_d	=	Direct component of the busbar voltage [V]
R	=	Equivalent plant resistance [Ω]
i_d	=	Direct component of the busbar current [A]
L	=	Equivalent plant inductance [H]
I_q	=	Quadrature component of the busbar current [A]
e_d	=	Direct component of the grid voltage [V]
e_q	=	Quadrature component of the grid voltage [V]
$\#inverters$	=	Number inverters in the plant [-]
P_{min}	=	Minimum active power [MW]
P_{max}	=	Maximum active power [MW]
f_1	=	Minimum over frequency limit [Hz]
f_2	=	Maximum over frequency limit [Hz]
f_3	=	Maximum under frequency limit [Hz]
f_4	=	Minimum under frequency limit [Hz]

Acronyms

PV	=	Solar Photovoltaic system
HV	=	High Voltage system
MV	=	Medium Voltage system
IEA	=	International Energy Agency
GSE	=	Gestore Servizi Energetici – Energetic Services Manager
NTN	=	National Transmission Network
MPP	=	Maximum Power Point
MPPT	=	Maximum Power Point Tracker
DC	=	Direct Current

AC	=	Alternating Current
IGBT	=	Insulated Gate Bipolar Transistor
PWM	=	Pulse Width Modulation
VFI	=	Voltage Fed Inverter
VSI	=	Voltage Source Inverter
PoC	=	Point of Connection
OHL	=	OverHead Lines
TSO	=	Transmission System Operator
RMS	=	Root Mean Square
NLTC	=	No Load Tap Changer
ONAN	=	Oil Natural Air Natural
REGC	=	Renewable Energy Generator Converter
WECC	=	Western Electricity Coordinating Council
ENTSO-E	=	European Network of Transmission System Operators for Electricity
HVRCM	=	High Voltage Reactive Current Management
LVACM	=	Low Voltage Active Current Management
S&H	=	Sample and Hold
STMG	=	Soluzione Tecnica Minima Generale - Minimum General Technical Solution
PQ	=	Active power P and reactive power Q cartesian plot
VQ	=	Voltage and reactive power Q cartesian plot
PPC	=	Power Plant Controller
BESS	=	Battery Energy Storage System
ARERA	=	Autorità di Regolazione per Energia Reti e Ambiente - Italian Regulatory Authority for Energy, Networks and Environment
EU	=	European Union
DSL	=	DIgSILENT Simulation Language
XLPE	=	Cross-linked Polyethylene
EPR	=	Ethylene Propylene Rubber
LV	=	Low Voltage
PVC	=	PolyVinyl Chloride
REPC	=	Renewable Energy Plant Controller

RdE	=	Regolamento di esercizio - Operating regulation for power generation plants
RTU	=	Remote Terminal Unit
PPM	=	Generation Plant according to the European regulation EU 2016/631 []
IVS	=	Ideal Voltage Source
FSM	=	Around Nominal Frequency Regulation
LFSM-U	=	Under frequency regulation
LFSM-O	=	Over frequency regulation
CdR	=	Codice di Rete – Italian Grid Code
IEEE	=	Institute of Electrical and Electronics Engineers
CIGRE	=	Conseil International des Grands Réseaux Électriques - International Council on Large Electric Systems

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Appendix A: Settings and blocks

user-defined

The full settings of the PPC controllers are reported here for completeness.

[A.1] P_Control settings of the PPC

Name	Value	Unit	Description
Tdel	0,2	[s]	(Communication Delay)
Kp	0,00001	[-]	(Proportional Gain)
Ki	0,044	[-]	(Integral Gain)
Kd	0	[-]	(Derivative Gain)
Td	0,1	[-]	(Derivative Time)
P_en	1	[0/1]	Active Power Control, 1=Enable)
P_Slimit	28,83	[MW]	(Active Power rating of plant)
f_en	0	[0/1]	(Frequency Response, 1=Enable)
f1	50,5	[Hz]	(Over Frequency at Pmax)
f2	51	[Hz]	(Over Frequency at Pmin)
f3	49,5	[Hz]	(Under Frequency to begin U/F control)
f4	47	[Hz]	(Under Frequency at Pmax)
f5	51.5	[Hz]	(P to 0 for f>=f5)
Pf_RUset	1	[MW/min]	(P(f) Up Ramp Rate)
Pf_RDset	1	[MW/min]	(P(f) Down Ramp Rate)
PfRamp_En	0	[0/1]	(P(f) Ramp mode: 1=Enable)
of_hold	0	[0/1]	(P(f) Overfreq hold 1=Enable)
P_f_mode	0	[0/1]	(0=Static,1=Dynamic P(f) rate)
RUset	6	[MW/min]	(Up Ramp Rate)
RDset	6	[MW/min]	(Down Ramp Rate)
PRamp_En	0	[0/1]	(Active Power Ramp Control, 1=Enable)

Name	Value	Unit	Description
Pzero	0	[0/1]	(Plant Shutdown 1=Enable)
FSM_on	0	[0/1]	(FSM active 1=Enable)
f_insens	100	[mHz]	(FSM frequency response insensitivity)
s1	6	[%]	(FSM droop)
FSM_fis_step	1	[0/1]	(Step after freq insensitivity 1=Enable)
Vrt_min	0,85	[p.u]	(VRT minimum voltage trigger)
Vrt_max	1,1	[p.u]	(VRT maximum voltage trigger)
P_min	0	[p.u]	(Inverter/Turbine Pmin)
P_max	1	[p.u]	(Inverter/Turbine Pmax)
FSM_P_lim	10	[%]	(Active power range to Pmax)

[A.2] Q_Control settings of the PPC

Name	Value	Unit	Description
Tdel	0,2	[s]	(Communication Delay)
Kp	0,0065	[-]	(Proportional Gain)
Ki	0,0545	[-]	(Integral Gain)
Kd	0	[-]	(Derivative Gain)
Td	0,1	[-]	(Derivative Time)
Q_en	0	[0/1]	(Q Control, 1=Enable)
Qmin	-30	[MVar]	(Q Min of plant)
Qmax	30	[MVar]	(Q Max of plant)
Vmin	0,9	[p.u]	(Minimum voltage setpoint)
Vmax	1,1	[p.u]	(Maximum voltage setpoint)
Vdb	0,001	[p.u]	Voltage deadband
QV_en	0	[0/1]	(Voltage Control, 1=Enable)
QV_Droop	0,075	[-]	(Voltage Control Droop)
PF_en	0	[0/1]	(PF Control, 1=Enable)
Vrt_min	0,85	[p.u]	(VRT minimum voltage trigger)
Vrt_max	1,1	[p.u]	(VRT maximum voltage trigger)
QP_en	0	[0/1]	(Q(P) mode, 1=Enable)
Q_min	-1	[p.u]	(Inverter/Turbine Qmin)

Name	Value	Unit	Description
Q_max	1	[p.u]	(Inverter/Turbine Qmax)

[A.3] Voltage setpoint block

