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Tesi di Laurea

Microgrid development and integration: a real case analysis.

Relatore: Prof. Coppo Massimiliano
Tutor aziendale: Ing. I. Colombara Romeo

Laureando: Michael Maggiolo
Matricola: 2079470

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Abstract

Microgrids are an increasingly relevant solution for local energy management and optimization. This thesis discussed microgrids at a general level, covering their main advantages such as increased energy efficiency, reduced grid losses and the possibility of integrating renewable energies, and analysing possible disadvantages such as management complexity. Its main components are discussed and practical applications are explored, ranging from powering remote areas to ensuring stability in communities that need it, such as hospitals, campuses, military bases, ...

The second part of the thesis deals with the practical analysis of a microgrid on a campus in Vicenza, describing its compositions and operation. All the problems that may occur are analysed, such as load management in the event of faults or disconnection from the grid and the need for a stable, quality power supply to the campus. Finally, some improvements are proposed, including the implementation of a Battery Energy Storage System (BESS) and a new hot water storage tank on campus, with the aim of increasing the efficiency and resilience of the system.

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Introduction

The energy sector is going through a period of rapid evolution, with an increasing focus on the use of renewable sources and efforts to make energy production and distribution systems increasingly efficient and resilient. In this scenario, microgrids are playing an increasingly interesting and promising role. A microgrid is a local energy system that can operate both autonomously and in connection with the main grid, allowing for more flexible and sustainable energy management. Microgrids are composed of various components, such as generators, storage systems, control, monitoring, and protection devices, which work together to meet the energy needs of a specific area, which can be a single building, a neighbourhood or a community. Thanks to these local networks, it is possible to reduce distribution losses, easily integrate renewable sources such as solar and wind power, and respond quickly to breakdowns or emergencies, guaranteeing energy even when the main grid is unavailable. However, these networks present some operational difficulties, such as peak demand management, network stability, load management and coordination of different energy systems. In this thesis, an attempt is made to explore the concept of the microgrid, analysing its strengths and problems. After providing a general overview of the microgrid and its main components, a practical application will be examined in which the composition of the system, the difficulties encountered during its operation and the solutions implemented to improve it will be analysed: the optimization of energy management and the use of advanced storage technologies.

The aim of this work is to propose concrete approaches to make microgrid system even more efficient, sustainable and reliable, thus contributing to the global energy transition.

Chapter 1

Introduction to the micro-grid

1.1 Definition and concept of microgrid

In today's power grid, the electricity generated by the power plant is then distributed via hundreds of kilometres of transmission lines to end users. With the microgrid, on the other hand, the aim is to localise the consumption and production of electricity in the same area, usually by combining fossil fuel generators with renewable energy systems. Storage systems can also be envisaged in order to store electricity and cover any peaks in demand from the grid or any blackouts. We can therefore define the microgrid as an autonomous power grid that can produced energy locally independently and use it when it is required. It must be able to improve the performance, ecological footprint and resilience of the grid, while connecting, monitoring and managing the different distributed energy resources. The microgrid therefore includes the generation, distribution, consumption and storage of energy, requiring appropriate management through monitoring, control and automation systems.

The microgrid can either be connected to the public grid or operate in isolation. In fact, in the presence of a grid failure, for example due to a natural event, through appropriate load management it may be able to continue feeding it and, if necessary, to store electricity for the needed period of time.

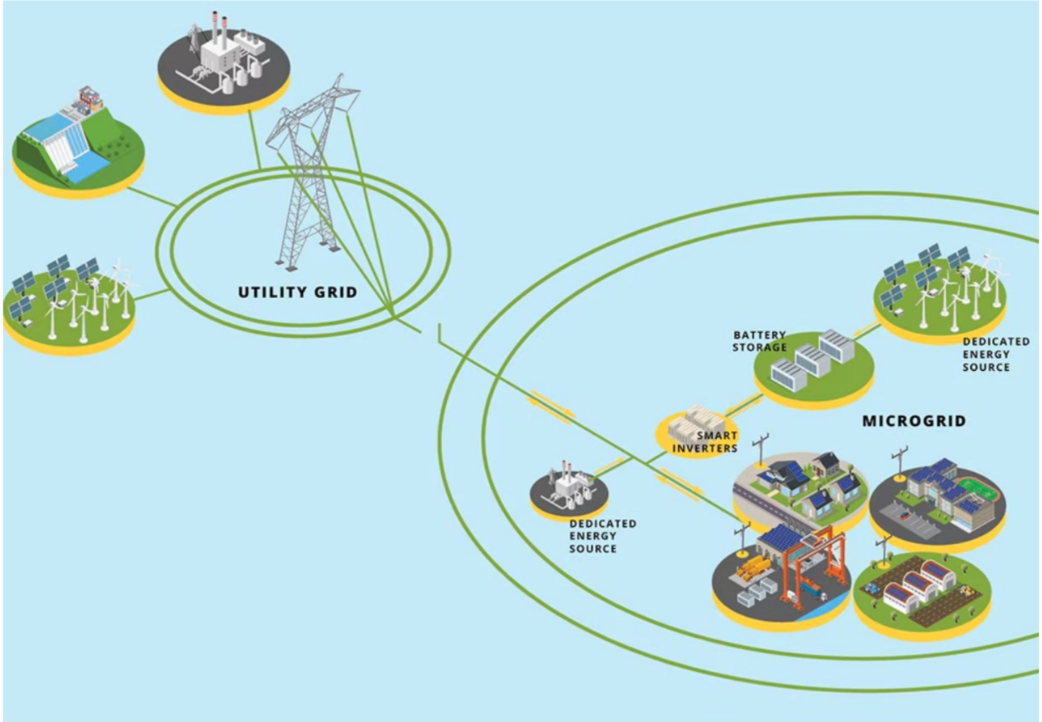

Fig.1 Example of a grid-connected microgrid[1]

1.2 Type of energy and potential application of the microgrid

The methods of power generation within the microgrid may vary from grid to grid and this is due to the evaluation of the generation sources that best suit the site. However, most microgrids are characterised by a core of one or more gas, biomass or methane-fuelled generators, to which renewable generation systems, such as hydro, solar and wind, are implemented.

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[1] Source: DigiKey: https://www.digikey.it/it/articles/using-electrification-more-efficient-sustainable-power-grids-part-1

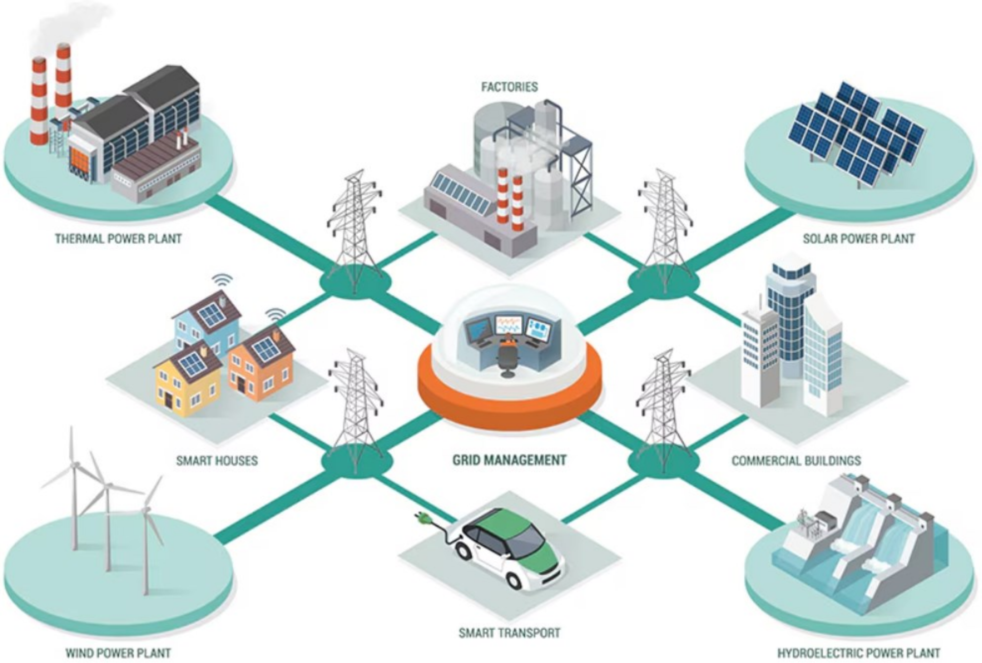

Fig.2 Representation of a microgrid and its components[2]

Having clarified the concept of the microgrid, the applications to which it is best suited are analysed below:

- **Utilities** like hospitals, data centres, military bases and telecommunication towers that need to optimise the stability and robustness of the power supply to protect themselves from potential blackouts;

- **Remote communities** to cope with any problems in reaching the national network and thus be as much autonomous as possible;

- **Smart cities, university campuses and research centres** whose aim is to reduce their environmental impact;

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[2] Source: https://www.digikey.it/it/articles/using-electrification-more-efficient-sustainable-power-grids-part-1

- **Industries and agricultural districts** which, by focusing on cogenerators for electricity and heat production and distributed generation sources such as solar photovoltaics, aim to lower their energy bills;

- **Commercial and industrial customers** who, in order to enjoy better electricity tariffs, aim to lower peak absorption from the grid;

- **Electricity market savvy customers** who aim to value their energy supply methods or remunerated services to the national grid and also minimise their energy bills.

1.3 Market drivers and advantages

The emergence of microgrids is influenced by several factors:

- **Cyber security.** Power systems are increasingly dependent on modern communication technologies such as wireless, cloud computing, etc., thus making them vulnerable to cyber-attacks and hackers. This becomes important in special applications such as military bases or research laboratories;

- **Incentives.** More and more economic incentives are being made available by the state to invest in renewable energy production, energy efficiency, advanced energy infrastructure and electric vehicles;

- **Growing demand.** As the population continues to grow and the consumption per person of electricity increases, there is increased stress on the physical grid and the companies that handle it;

- **Reliable and secure power.** Some commercial and industrial environments such as research laboratories, data centres, national security infrastructures, military bases, etc., need a constant power supply, thus not allowing for blackouts or brownouts. Examples of such instances are data centres that process millions of transitions, or research laboratories that require a specific temperature and air quality to ensure compliance and therefore need a constant supply of power;

- **Altruism.** Organisations with a vision of a sustainable future and a strong commitment to green energy are directed towards renewable energy generation and microgrid solutions. Their doubts about the reliability of the main grid and the impact of fossil energy generation lead them to reduce their consumption and dependence on the main grid.

Having analysed the various factors influencing the choice of microgrids, all possible benefits they bring are assessed below.

Reliability

Consumers demand reliable, high quality and cheap electricity. They therefore need energy-efficient production and lighting lines that are always active. One solution for reducing costs and power losses could be microgrids, which would allow for more on-site energy production and storage.

Efficiency

To reduce costs, the first thing to do is to reduce consumption. A transparent system with advanced metering to promote savings and the implementation of other technologies, such as energy efficient lighting, variable frequency drives (VFD) on motors and upgrades of chillers and/or boilers will further improve energy efficiency. In addition, transmission and distribution line losses can be significantly reduced by increasing the amount of energy generated on site.

Security of supply

Natural disasters, acts of terrorism and other risk could affect the energy supply. Appropriate physical and informatic security measures must therefore be combined with an increase in on-site power generation in order to reduce these risks.

Sustainability

More and more organizations are taking an interest in renewable production, committing to long-term goals, regardless of expected time to recoup the investment. For example, a manufacturer might want to increase its sustainability index and reduce greenhouse gas emissions in its production processes.

Save money

Based on demand, the price of energy and other factors, operators, with the operators, with the help of sophisticated software, are able to optimise energy consumption, resulting in an economic return.

1.4 Social and environment costs and benefits

To gain a broader understanding of the impact of microgrids, the environmental and social costs associated with them must also be analysed. Although microgrids may represent the future, it is necessary to first analyse the environmental challenges that can be found, such as land use and resource consumption. An important role in the expansion of microgrids is also their social impact such as societal acceptance and fair distribution of energy. By correctly balancing the associated costs and benefits, microgrids can play a key role towards a more sustainable and resilient energy world.

Environmental costs and benefits

1. **Reduced carbon footprint**
   Unlike conventional power plants, microgrids by, using mainly renewable energy sources, are able to significantly reduce greenhouse gas emissions and carbon footprints, thus contributing to the fight against climate change. Furthermore, as seen in the previous points, with on-site generation and consumption, transmission losses can be minimised and efficiency improved.

2. Resource utilization and land use

Although the environmental benefits of microgrids are clear, the impact on resource use and land use must be considered as well. There can be negative environmental effects from the extraction and processing of raw materials to produce batteries, solar panels and wind turbines. Furthermore, the use of land for major renewable installations can damage local biodiversity and ecosystems. It is therefore necessary to minimise these impacts by choosing sustainable practices in order to produce and implement these technologies.

3. Lifecycle environmental impact

For a correct assessment of the environmental costs of microgrid, it is also necessary to analyse the entire life cycle of the components, from production to disposal. For example, irresponsible handling of rare earth mining for batteries can lead to pollution and environmental degradation. Furthermore, a further challenge comes with the disposal and recycling of damaged or obsolete components. To minimise the environmental footprint of microgrids, it is therefore necessary to develop sustainable recycling methods and promote a circular economy.

Social costs and benefits

1. Energy access and equity

By being able to operate independently of the main grid, microgrids can provide reliable and affordable accesses to remote and underserved communities, thus offering solutions to rural areas where the traditional grid is impractical or too expensive. This would foster economic development, improve education and quality of life.

2. **Community engagement and empowerment**

   Microgrids foster a sense of ownership and empowerment by involving local communities in their planning, implementation and operation. This not only ensures that energy needs and community preferences are met, but also promotes resilience and social cohesion, leading to better maintenance and management of the systems, ensuring their long-term success.

3. **Job creation and economic opportunities**

   The development and maintenance of microgrids, requiring skilled labour for tasks ranging from the installation of solar panels to the management of energy storage systems, can create jobs and stimulate economic diversification. Furthermore, additional jobs opportunities associated with decentralised systems can be created through training programmes and educational initiatives in this regard.

<u>Balancing environmental and social costs</u>

Balancing environmental and social costs is of primary interest for microgrid deployment. Politicians, communities and industry stakeholders must work together to address the following issues:

1. **Sustainable manufacturing practices**

   Promoting sustainable ethics and practices in the production of microgrid components is crucial. It is therefore necessary to minimise waste and emissions during production, responsibly source raw materials and ensure safe and environmentally friendly disposal methods.

2. **Holistic lifecycle assessment**
   The environmental impact of microgrids must be assessed with a holistic approach, considering the entire life cycle of the system components. Life Cycle Assessments (LCA) can be useful in identifying areas for improvement and developing more sustainable practices and technologies.

3. **Community centered planning**
   During the planning and implementation of microgrids, it is very important to involve local communities to address social costs. Such involvement ensures that community needs and preferences take priority, leading to more effective and sustainable energy solutions.

4. **Policy and regulatory support**
   To facilitate the growth of microgrids, supportive policies and regulations are needed, while also addressing environmental and social concerns. This includes incentives for the use of renewable, funding for research and development, and facilities to involve and protect the community.

Microgrids thus make it possible to address the dual challenges of climate change and energy accessibility. Through sustainable practices, global planning and collaborative efforts, it is possible to manage the environmental and social costs associated with these systems, although they cannot be ignored. In creating a resilient, inclusive and low-carbon energy future, microgrids can therefore play a crucial role, prioritising both social equity and sustainability.

Chapter 2

Components of a microgrid

2.1 Power sources

In a microgrid, energy can be generated from renewable and non-renewable sources. If the sources can be naturally and easily replenished, we speak of renewable sources, otherwise if they draw on more limited resources, we speak of non-renewable sources. Depending on various factors such as location, energy demand, peal management, economic factors and incentives, it is evaluated which sources are best installed in the microgrid and then how to plan their production in order to maximise their efficiency. The different renewable energy resources and their associated power generation systems are briefly analysed below.

Biomass

Energy from plants and plant-derived materials is called biomass energy, or "bioenergy". The use of biomass dates back to when people began to burn wood, which is still the most widely used source of biomass today, for heating and cooking food. Other resources can be: grassy and woody plants, food crops, oil-rich algae, residues from agriculture or forestry, and the organic component of municipal and industrial wastes. Due to the methane they contain, landfill flue gas can also be used as a biomass energy sources. Biomass can be used for fuels, power production, and products that would otherwise be made from fossil fuels. Bioenergy technologies are:

- **Biofuels.** They are created by converting biomass into liquid fuels to meet transport needs. They are transport fuels, such as ethanol and biodiesel.

- **Biopower.** Through one of three processes: combustion, bacterial decay and conversion to liquid/gaseous fuel, they convert renewable fuels from biomass into heat and electricity.

Geothermal

Geothermal energy is the heat from the earth. This heat is used to generate electricity, to heat buildings and for bathing. Derived from the Greek words geo (earth) and therme (heat), geothermal energy since it harnesses the heat constantly produced within the Earth is considered a renewable energy source. Many technologies have been development to harness geothermal energy such as:
-access through boreholes to steam or hot water reservoirs in the Earth's depths;
-geothermal reservoirs near the earth's surface, mostly in Alaska, Hawaii and western U.S.;
-shallow ground near the earth's surface that maintains a virtually constant temperature of 10÷16 °C.
All these geothermal resources can be utilised on both a small and large scale. A public company could generate electricity for its users by using

the hot water and steam from the reservoir to activate generators. The heat produced by geothermal energy can also be used directly for various purposes in buildings, industrial plants, agriculture and roads. Other use heat directly from the ground to provide heating and cooling for homes and buildings.

Geothermal applications are:

- **Heat pumps**. They provide heating and cooling of the environment using earth's surface temperature (10÷16 °C), being warmer than air above it in winter and cooler in summer.

- **Electricity production.** Electricity is produced using steam from hot water reserves beneath the earth's surface. The steam drives a turbine which, when connected to a generator, produce electricity. There are three types of geothermal power plants: dry steam, flash steam and binary cycle.

- **Direct use.** Heat is produced directly from the hot water inside the earth.

Hydropower

Hydropower, which is the oldest form of renewable energy in the world, is generated by the movement of fresh water. As far back as the ancient Greeks harnessed the power of rivers and streams to turn wheels and crush grain to make bread; today, the power of water is harnessed to generate clean electricity. With turbines properly coupled to generators, it is indeed possible to harness the power of water to produce electricity.

Furthermore, with pumped storage hydropower, it is possible to store excess energy and then use it during the night or in times of need. Hydropower can therefore, except for periods of severe drought, be considered a reliable source of energy.

Solar

Solar energy is a renewable energy source that can heat, cool and light homes and business. The energy from the sun that hits the earth in an hour is more than anyone in the world uses in a year. The most common technologies capable of converting sunlight into energy are: solar photovoltaics for electricity, passive solar design for space heating and cooling, and solar water heating. Solar photovoltaics and solar concentration technologies are used by developers and energy utilities to produce electricity on a large scale to power small towns and cities. Solar technologies are:

- **Solar photovoltaic technology.** Solar cells, also called photovoltaic cells, convert sunlight directly into electricity;

- **Passive solar technology.** Passive solar technologies convert sunlight into usable heat and cause air movement necessary for ventilation in order to cool and heat rooms without active electrical or mechanical devices.

- **Solar water heating.** Solar water heating enables the cost-effective generation of hot water for residential buildings by harnessing solar energy.

- **Solar process heating.** Solar process heating is used by commercial and industrial centres to ventilate and cool water and space heating in order to be more energy efficient.

- **Concentrating solar power.** The sun's heat is used to supply electricity to large power plants.

Wind

Wind energy can provide clean onshore and offshore electricity to remote farms, individual homes, small and large cities. Wind energy has been used since ancient times, where the power of the wind was harnessed by wind turbines built from abundant materials such as wood and reeds, which were woven into narrow blades and spun to power communities, pump water and grid grain. Today, turbines use modern, high-performance materials to generate clean, renewable energy in virtually all parts of the world.

Distributed wind energy powers remote and local communities

Distributed wind energy allows power to be produced on a smaller scale by one or more wind turbines whose capacity can range from one kilowatt to several megawatts. Although they can be connected to the electricity distribution grid, these generally terrestrial wind turbines can supply power to individual buildings or small communities, making them perfect for all application such as microgrids. This solution can also become essential for defence or natural disaster scenarios.

Marine energy

Marine energy, which is the energy generated by oceans waves, currents, tides and temperature changes, is the world's largest untapped source of renewable energy since oceans cover 70% of the planet's surface and retain about 95% of the earth's water. Marine energy can be generated both from oceans and from streams, rivers, lakes, estuaries and more. Marine energy is defined as:

- Waves, tides, and currents in oceans, estuaries, and tidal areas;
- Free flowing water in rivers, lakes, streams, and man-made channels;
- Changes in water temperature;
- Changes in salinity or pressure.

As previously mentioned, one or more of the renewable energy sources briefly outlined above may be present in a microgrid. The choice of which resources to use is linked to several factors, the main ones certainly being the location of the site, since this is linked to the presence or absence of the source or its efficiency, and the economic factor for an assessment of the convenience of the installation. Due to their availability and efficiency, the two most commonly used sources are solar and wind. The majority of microgrids provide for the integration of these resources with cogeneration and trigeneration plants in order to guarantee regular production even when these cannot cover all energy demand.

Cogeneration

Cogeneration enables the simultaneous production of electrical and thermal energy is a single plant. An engine powered by natural gas and/or diesel fuel connected to an electric generator is able to produce electricity. During operation, all the heat produced in the cylinders, exhaust gases and lubricating oil, which is normally dispersed into the environment, is instead recovered and converted into thermal energy thanks to special heat exchangers. In terms of efficiency, compared to the separate production of thermal and electrical energy, cogeneration allows a 30 to 40% reduction in fuel consumption and consequent savings in terms of emissions. Cogeneration is therefore perfectly suited to microgrids as, in addition to covering part of the electricity production, it is also able to supply hot water to the various consumers.

Trigeneration

Trigeneration enables the simultaneous production of electrical, thermal and cooling energy. The production of cooling energy is made possible by coupling the cogenerator with an absorption refrigeration unit, thus allowing part of the heat that would otherwise be dissipated into the environment to be transformed. In this way, it is possible to increase the hours of use and the economic advantage, which benefits the payback time of the investment. These absorption refrigeration units use hot or superheated water as the primary source. These units produce no climate-altering gas emissions, are zero-impact, and are capable of producing chilled water at an output temperature of 7°C in line with the requirements of most refrigeration systems. Trigeneration is therefore well suited to the microgrid, as it can guarantee chilled water that can be used for ambient, civil and industrial summer air conditioning.

2.2 Energy storages

Considering the arising trend of photovoltaic in the last years, it should be noted that the primary source of renewable energy is mainly available during daytime. Furthermore, photovoltaic and wind energy, whose growth represents one of the main goals in the ongoing energy transition, are by nature unpredictable and therefore not programmable. With the help of storage, i.e., energy storage systems, energy can be stored and potentially made available 24 hours a day. By storing electricity making it available when it is needed most, balancing supply and demand, storage systems are able to stabilise the grid. They are therefore crucial for the future of renewable energy. With the exception of pumped-storage hydroelectric systems, electro-chemical batteries are among the most widely used systems and are in the midst of a technological revolution: by introducing new materials and cutting-edge technological solutions, it is possible to ensure greater efficiency, lower costs and increasingly sustainable products.

In fact, as can be seen from the graph in the figure below, thanks to the development of new materials and technologies, the costs of batteries have been falling significantly over the past 15 years, facilitating their expansion. The development project for storage is very promising and the stock of electricity available in storage system is expected to triple from 4.67 TWh in 2017 to between 11.89 and 15.72 TWh in 2030.

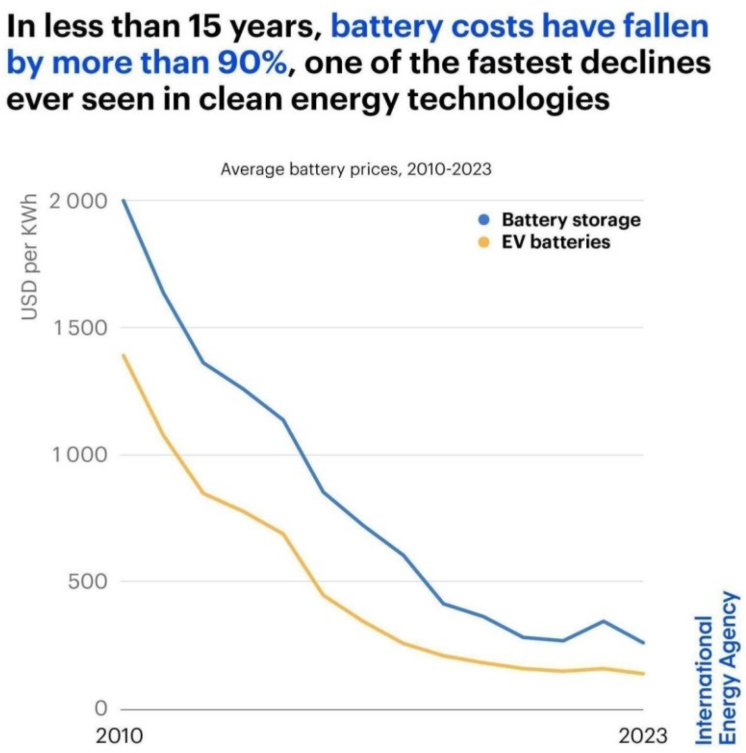

Fig.3 Average battery prices 2010-2023[3]

BESS (Battery Energy Storage System)

BESSs are systems in which individual or, more often, aggregated batteries are used to store the electricity produced by generation plants and subsequently make it available when needed. The basic components of a BESS are: the blocks formed by the batteries, the inverter to convert the direct current from the batteries to the alternating current from the grid (and vice versa), a transformer to adapt the system voltage to that of the grid, and finally auxiliary systems such as fire-fighting and cooling systems.

These are also known as electrochemical energy systems. Other storage

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[3] Source: https://www.voronoiapp.com/energy/Battery-Costs-Have-Fallen-by-More-Than-90-Since-2010-1165

systems that can be found are:

- Gravitational energy systems, e.g., pumped storage hydroelectric power plants;
- Mechanical energy systems, such as compressed air or flywheel systems;
- Thermal energy systems, or Thermal Energy Storage (TES).

Based on the chemical elements used, batteries can be distinguished into:

- **Lithium-ion batteries**: generally using lithium combined with other elements, such as Nickel, Manganese and Cobalt used in NMCs or Iron and Phosphate in LFPs. Some more advanced research focuses on Lithium-Sulphur batteries. Lithium-ion batteries are the most widespread, cost-effective and also most efficient technology to date;

- **Lead-acid** and **Sodium-Sulphur batteries** can be found as alternatives to Lithium, while **Aluminium-Sulphur batteries** are still in research phase;

- **Flow batteries** are emerging and are a promising technology due to their longer life span. In them, unlike conventional batteries, the electrolytes are stored in separate reservoirs and then flow into a central cell where they react in the charging and discharging phases. The most common are **Vanadium batteries**; however, **Zinc-Bromine** and **Zinc-Iron** models are also being researched.

- **Solid-state batteries**: these use solid-state batteries electrolytes, such as synthetic or ceramic materials. Their cost is high, but they guarantee excellent performance.

Lithium batteries

Lithium batteries are the most widely used storage system in the world. These are based on different technologies where energy storage is characterised by the use of Lithium ions, positively charged particles that easily react with other elements. Lithium batteries consist of a positive electrode, the Lithium cathode, and a negative electrode consisting of a Carbon anode. Their charge and discharge operation are achieved through chemical reactions that store and return energy. Their modularity, high energy density and high charge and discharge efficiency, even over 90% at the level of a single module, are very interesting technological features that characterise them.

Over the past few years, NMC (Nickel Manganese Cobalt) technology has undergone a revolution term of increased production and a considerable drop in prices, which have fallen by more 85% since 2010. Researchers, due to the socio-political difficulties associated with finding certain materials such as Cobalt, are testing new innovative solutions in which the percentage of this is always lower or where Lithium is combined with other elements that are easier to find such as Silicon, or even Oxygen. In addition, processes are being investigated to "close" the production cycle by enhancing the recycling of more critical materials, giving increasing attention to end-of-life management. A major disadvantage of lithium batteries is their flammability; in the event of a fire, they continue to burn for 2-3 days. Installation must therefore take place in places that do not endanger buildings and any people inside them, respecting the minimum distances from the rest of the installation and any structures present.

Flow batteries

Flow batteries show great promise in the area of long-term storage (8-10 hours), which is crucial for managing electricity demand, reducing peak and stabilising grids. In these, unlike conventional batteries, liquid electrolytes are stored in separate reservoirs, and then flow (hence their name) into central cell, where they react in the charging and discharging phases. Flow batteries have numerous advantages:

- **Duration of stored energy.** They make it possible to cover periods even of many hours when there is no electricity production, such as overnight in the case of solar.
- **Use of common raw materials.** The most mature technology for example uses vanadium, a material found in important mineral reserves in Norway and Finland.
- **Easy recyclability.** Further reducing the use of raw materials.
- **High safety.** They reduce fire risks to zero and undergo minimal degradation to last at least 20 years.

Flow batteries are at the centre of strong commercial development. The aim is to increase their efficiency and decrease their costs, which are already falling sharply. To do this, the focus is on materials science, trying to further improve Vanadium batteries and studying other models including Zinc and Iron batteries. A new frontier capable of eliminating the need for raw materials of mineral origin is that which proposes models based on the use of organic material such as agro-food industry processing waste; although at the moment, for large-scale applications, they appear further away from commercialisation. In addition to cost, a further disadvantage of flow batteries is their size, as they take up a lot of space for medium to large installations and are therefore placed inside containers, making them difficult to install where space is limited.

Applications

BESSs are mainly used by electricity producers using wind and solar systems. Here, we speak of large BESS, often located close to transmission nodes or directly at generation plants. However, their applications are constantly increasing, and this is mainly linked to the growth of the prosumer phenomenon, i.e., self-producers of electricity, such as a private individual who, thanks to a solar photovoltaic system, is also able to generate energy as well as use it. In addition, a BESS can also be particularly advantageous for industries and commercial companies in order to ensure greater energy security, contribute to grid stability and at the same time secure an economic return. Finally, BESS are indispensable elements of microgrids and functional elements in smartgrids, i.e., smartgrids for electricity distribution. The main user systems of BESSs are photovoltaic systems; they generally use lithium-ion batteries because of their cost-effectiveness compared to alternatives, mainly due to a much better ratio of cost, efficiency and lifetime.

Advanages of storage systems

Storage systems can be used to store the energy generated and then release it to costumers at the required times, regardless of the time of day and weather conditions. In practice, storage is key to enabling the penetration of renewable energy sources into the energy system, reducing the use of fossil fuels and thus the emissions of greenhouse gases into the atmosphere. Energy storage systems can also cope with any imbalance between supply and demand in the market, making the grid more stable and greatly reducing risk of disruptions or blackouts. Energy storage can play a key role in companies where blackouts or grid outages would compromise production, leading to both practical and economic problems.

An example of this could be plastics processing companies, which, due to their extruders, require a continuous supply of power, which would otherwise create quite a few problems for the production line. BESS also have advantage of cost-effectiveness and, thanks to their modular design, enjoy great flexibility and scalability; in fact, by easily adding further battery blocks even to running plants, their capacity can be increased. In order to bring about a fair and safe energy transition, it is therefore important that the presence of BESS is increasingly widespread.

Future storage

In addition to the storage technologies just mentioned, gravitational, kinetic, mechanical and thermal energy storage solutions appear promising. These technologies are all complementary, as no one is better than the other in all respects, but each suits certain requirements.

Mechanical energy storage systems can be CAES, which use compressed air, or LAES, which use compressed air and cooled to liquefaction. In both technologies, it is possible to replace air with other gases, in particular carbon dioxide. The energy stored during compression is then released by driving a turbine to release a fluid at high speed. In this system, it is also possible to store heat and cold generated during the compression and expansion phases, thus improving efficiency.

Kinetic energy storage systems are flywheels, where a rotating cylinder at high speed is driven and slowed down by an electric motor: during breaking, the motor absorbs the energy released by the cylinder and transmits it to an electricity generator. This technology is suitable for cases where a high discharge speed is required, but they are difficult to compete with due to their high cost.

Another type of storage is gravitational storage, where potential energy is stored by lifting large masses and then dropping them, transforming the energy available in the form of electricity thanks to a generator. Thanks to sophisticate control systems, it is possible to release energy continuously and effectively, even over long discharge durations. Gravitational storage can be seen as a variant of hydroelectric storage, where turbines are driven by dropping previously pumped water from a lower basin to an upper basin. The latter is the most widespread energy storage system in the world date.

Finally, another important storage systems are thermal energy storage (TES) system. Such systems convert electricity into heat during the charging phase and then store it. Subsequently, in the discharge phase, thanks to a thermodynamic cycle, the heat is again converted into electricity. From a technical-economic aspect, this type of storage is at its best when it directly utilises the stored heat. Charging generally takes place via resistors, while in newer systems, the heat pump principle is exploited. Instead, the storage medium ranges from molten salts, rock-and-cement based solid systems to fluid sand beds or phase change systems.

Another solution for storage could be electric cars. They remain unused 90% of the time. By exploiting this, the car could be used to store electricity and, if necessary, to return it. This solution is especially favourable for homes with a photovoltaic system: excess electricity is stored by electric car and used during the night or during times when the system is unable to produce. To realise bi-directional charging requires an app to set the battery discharge rules and a specific charging station, the cost of which is still high at present. In the coming years, however, as demand and suppliers increase, the cost will probably fall. However, this system has the advantage of offering a much larger storage capacity compered to normal domestic batteries (up to 6/7 times higher) and of increasing the efficiency of the photovoltaic system on its own consumption. In the future, therefore, electric cars could play a key role in a stable and sustainable energy system. In this way, thousands of electric cars all together would be able to store electricity from sustainable sources and thus become a huge decentralised storage unit.

2.3 Control and monitoring devices

Control and monitoring of a microgrid is a fundamental aspect of microgrids. They make it possible to optimise the operation of the microgrid, increasing its efficiency and productivity, as well as to monitor the utilisation of the various sources, power flows with the grid, and to operate maintenance and modification commands for the various variable. Some control and monitoring methods are analysed below.

SCADA

SCADA, which stand for Supervisory Control And Data Acquisition, as is easily understood from the definition has the objective of supervising, controlling and acquiring data. SCADA software generally fits into a structure that provides:

- One or more interconnected computers with the function of supervision and, in particular, of human-machine interface;
- Peripheral units that, thanks to sensors and actuators, interface directly the process;
- A transmission network that, thanks to multiple transmission media and communication protocols, ensures the appropriate exchange of information between peripheral units and supervisory PCs.

SCADA software refers to the integrated working environment that offers everything necessary for the realisation of SCADA applications used by supervisory computers, in order to perform the typical functions of such systems:

- **Supervision.** It allows the operator to monitor the state the process is in and to check its evolution by examining the sequence of states. In fact, it is realised thanks to a human-machine interface (HMI), the efficiency of which increases as it provides the operator with a schematisation of the process, its evolution and variations with respect to the expected development. Of great importance is the graphical representation, which makes it possible to translate process status information into a visual language that is easy for the operator to understand.

- **Control.** This is the ability of the control system to act on the analysed process in order to vary its evolution according to preestablished rules or decisions made by the operator. Given that real-time control is generally the responsibility of PLCs, the control of a SCADA system means the intervention aimed at varying the course of the process itself, such as for example sending a certain processing recipe or choosing the temperature at which the process is to operate.

- **Data acquisition.** Basically, it is the transmission of information from peripheral devices to the supervisory PCs, but also the transmission of information in the opposite direction, without which it would not be possible to control the process to the supervisory system, i.e., to direct its progress by acting on the values of the variables that characterise it. This is the main function of a SCADA system, as it provides the supervisory system with all the information on the status of the process by putting it in communication with the process, in order to make it possible to observe it. Data acquisition must ensure the precise transmission of information between supervision and process, in a system characterised by a multiplicity of different means of transmission and communication protocols.

SCADA Software

SCADA software is the development environment that enables the realisation of SCADA HMI supervision applications. There are different types of SCADA software, made by different manufactures, resulting in significant differences in price and size. The choice of software to be used depends on complexity of the application to be developed, any costumer requirements, the budget available and the performance required, as well as personal preference. It must also be considered that the longer the learning time, the greater the complexity of the software. In general, for large installations and cost, the choice of complex software can be justified, as license costs and development time would be irrelevant. For medium/small installations, on the other hand, the use of low-cost SCADA software with shorter learning times is recommended.

Nowadays, most industrial companies use SCADA applications, as they provide an essential aid for companies, regardless of their size and business sector. Thanks to SCADA software, it is therefore possible to realise complex SCADA applications easily and intuitively. The main advantage they bring is the replacement of humans in the execution of many tedious and repetitive tasks, leading to increased productivity, better and faster alarm management, and a considerable reduction in the danger of potentially hazardous situations for the environment. So, SCADA application:

- provide a wealth of information;
- they offer a concise and intuitive view of the plant;
- they grow and adapt easily as the company grows;
- they allow centralised control of distributed realities.

Microgrid controller

Microgrid controllers aim to optimise power consumption, reducing costs and minimising environmental impact. It therefore allows consumers to have control over their energy operations, minimising peak period operations, reducing consumption from the grid and maximising self-generation of energy. In this way, consumers are able to actively participate in the energy market. To optimise, it is therefore necessary to connect different types of technical resources as seen in Fig.4.
Through active participation, using exchange and demand response schemes, new revenue streams can be created. All the resources of the various sites are linked so as to gain greater control and optimise the sites through data analysis. It is also possible to minimise operations during peak periods and reduce the amount of energy fed into the grid. In addition, CO_2 emission can be reduced, without compromising grid stability, by integrating renewables to a greater extent.

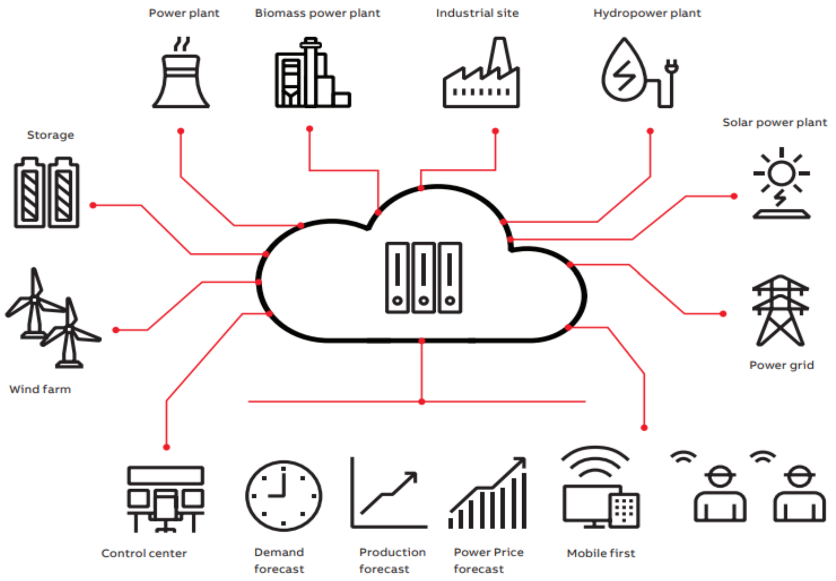

Fig.4 OPTIMAX Overview[4]

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[4] Source: S. Ghettini (2023). OPTIMAX Microgrid Controller. ABB Digital Solutions.

Microgrid controllers need to be connected to the grid in order to operate and optimise the flow of data in real time. The controller controls and optimises the energy system according to the optimisation objectives, considering the technical constraints of the various technical resources. The optimisation objectives are:

- **Minimization of energy costs.** Considering the cost for its own production and the variable price of electricity supply, the system is optimised so as to minimise the total net cost of power purchase. Revenues from feeding excess electricity into the grid and grid delivery obligations must also be considered in the cost analysis. Based on the associated costs, it is decided when to store/discharge energy, when to feed electricity into the grid and when to reduce the power absorbed by loads.

- **Peak shaving.** To maximise the reliability of the microgrid in a forward-looking manner, the amount of energy that can be taken from the grid is limited. Energy consumption can be limited by how the grid connection is designed or by contractual conditions. The controller provides several functions for this purpose:
  - By shifting the operation of a flexible consumer, the peak load can be reduced;
  - To have enough energy available before a peak occurs, predictive balancing of storage is performed;
  - Local generation flexibility is utilised to avoid peaks;
  - Starting an additional local generator if necessary.

- **Maximisation of self-consumption & grid-independency.** Another objective of the system is to try to cover the energy needs of the microgrid as much as possible with the energy generated by it and to minimise the electricity fed into the grid. By doing so, independence from the purchase of electricity from the grid is also maximised. By increasing self-sufficiency, a more sustainable and reliable energy consumption can be achieved, while also saving on purchasing costs. To cover the needs of the microgrid, electricity produced by the local generation source is mainly used. In the absence of storage systems, any surplus is fed into the grid, however, if the generation source in the microgrid cannot meet the energy demand, it is purchased from the grid. By considering the available demand and quantity of generated energy, the system can be optimised in real time and with foresight.

- **Minimize CO_2 emissions.** This aims to improve sustainability and reduce costs. The various CO_2-emitting resources may be weighted with a cost factor. In doing so, the optimiser will preferably use emission-free resources.

Inverter

An inverter is an electric device capable of converting direct current into a grid-compatible form of alternating current. This conversion processes can be divided into three main stages:

- **DC-AC Conversion** where direct current is converted into a form of alternating current that is suitable for grid;
- **Voltage control.** The inverter checks the compatibility between the voltage of the output AC current and the mains voltage;

- **Frequency control**. The inverter checks the compatibility between the frequency of the output AC current and the frequency of the electricity grid.

There are mainly two types of inverters in the photovoltaic industry: central inverters and string inverters. Central inverters manage the energy produced by all panels in the photovoltaic system, while string inverters manage the energy the energy produced by the group of photovoltaic panels managed in series. In addition to the above applications, inverters can be used for a variety of functions, including control and monitoring. Some of the functions in which inverters can be applied will be analysed below.

Off-grid inverters.

They are used and designed to power remote areas where there is no connection to the electricity grid (i.e. islanded mode). These inverters convert solar energy into alternating current to power electrical equipment. Thanks to the presence of a storage system, these inverters are also able to operate in the absence of sunlight. In this case, the solar energy is stored in batteries, but these increase the cost of the system and require careful management.

Grid-connected inverters with storage function.

Used in grid-connected systems equipped with a storage system. These inverters convert the electrical energy generated into alternating current and store it in batteries for future use.

Inverters with feed-in limitation function.

Used in grid-connection systems, they monitor energy production and limit the feeding of surplus into the grid. This function is very useful in all those installations where electricity production may exceed the consumption of the house or company. In this case of energy fed into the grid, the limiting function avoids overloading the grid and also reduces the risk of damage to electrical equipment.

Inverters with feed-in management function.

Used in grid-connected plants to monitor energy production and to regulate it in order to improve the feed-in of energy to the grid. This function is very useful in all those installations where electricity production may exceed the consumption of the company or community where it is located. In this case of energy feed-in, the feed-in management function avoids overloading the grid and also maximises the utilisation of energy produced.

Inverters with voltage conversion function.

Used in grid-connected photovoltaic systems using modules with high output voltages. Inverters convert the direct voltage produced by photovoltaic modules into grid-compatible alternating current. This function makes it possible to use photovoltaic modules with high voltages, which may have higher efficiency and lower costs compared to modules with lower output voltages. However, this function can cause reductions in system efficiency and increased system complexity.

CCI (Central Plant Controller)

The grid operator (Terna), in order to guarantee the security of the national electricity system in accordance with European regulations, needs to observe and monitor production plants above 1 MW. For these plants, it is mandatory to install the Central Plant Controller (CCI). This device is necessary to allow the exchange of data between the production plants, distributors and Terna; these data collected on the production plant are used by Terna to feed, together with other data (such as weather forecasts, time series, etc.), a central algorithm for estimating real-time production for each generation plant.

2.4 Protection devices

A further fundamental aspect of microgrids is the protection system, i.e., the set of electrical devices and safety technologies designed to protect people and equipment in the event of faults or abnormal operation of electrical system. The choice of such a system depends on the characteristics of the plant, the type of industrial process and its need for service continuity, the characteristics of the machines, the state of the neutral, the levels and durations of fault currents, etc.

The protection system has the objectives of:

- Limiting damage to people and plant;
- Allowing different operating conditions (e.g. switchgear devices operating a topology change);
- Guaranteeing continuity of service in plant areas where the fault is not present;

- Activating the planned automatisms.

For active users such as microgrids where both energy production and utilisation systems are present, the following devices must be provided:

- **Main device (DG).** It ensures the separation of the entire installation from the grid.
- **Interface device (DDI).** It ensures both the operation of the microgrid in parallel with the grid and the separation of a portion of it (privileged loads and generators), guaranteeing their operation in isolation;
- **Generator device (DDG).** Capable of excluding individual generating groups from the grid.

Main device (DG). Consisting of a general switch-disconnector immediately downstream of the point of delivery and a main switch located immediately downstream of the switch-disconnector or a switch in a withdrawable design capable of disconnecting the entire microgrid from the grid.

Main protection systems (SPG). It is associated with the Main Device and consists of:

- Current transformers/transducers (and, if necessary, voltage transducers) and their connection to the protection relay;
- Main protection relay (PG) and its power supply;
- Circuit breakers opening circuits.

Main protection (PG). The protection relay with its power supply must guarantee the following functionalities in terms of protection (listed with reference to the respective ANSI code):

- Overload, I>, 51;
- Polyphase short-circuit (delayed), I>>, 51;
- Polyphase short-circuit (instantaneous), I>>>, 50;
- Single phase ground fault, I_0>(51N);
- Single phase double ground fault, I_0>>, 50 N;
- Ground fault directional for compensated neutral 67 NC or insulated neutral 67 NI.

Interface device (DDI). It consists of a three-pole switch with a deenergised opening trip and two insulating switches, one downstream and one upstream of the switch, or a three-pole switch in a withdrawable version with a de-energised opening trip.

Interface Protection Systems (SPI). It is associated with the interface device, and consists of:

- Voltage transformers/transducers and their connection to the protection relay;
- Interface Protection Relay (PI) and its power supply;
- Circuit breaker opening circuits.

Frequency, voltage and if necessary homopolar voltage relays are provided in the Protection System. The following protection functionalities involving voltage must be ensured in such a system:

- Maximum voltage (no intentional device), 59.S1, 59.S2;
- Minimum voltage (tipic delay: 300 ms), 27.S1, 27.S2;
- Maximum frequency (without intentional delay), 81>S1, 81>S2;
- Minimum frequency (without intentional delay), 81<S1, 81<S2;
- Maximum homopolar voltage V_o on MV side (delayed), 59 V_o;
- Protection against network loss. This value is agreed between the

distributor and the user depending on the characteristics of the distribution network.

Generator protection device (DDG). Its opening leads to the separation of the generator group in the case of unintentional islanding from the mains. It consists of a three-pole circuit breaker with opening trip and a disconnector on the mains side of the circuit breaker or a three-pole circuit breaker in a withdrawable version of opening trip.

Component of the protection system

The protection system consists of all those components that guarantee grid protection, such as: measuring and protective transformers, protective relays, switching devices, signalling and control circuits. Below is a brief description of the various components.

Protection relays

Protection relays have the task of disconnecting the system within the time limits set by the standards by opening the DDI if the measured electrical quantities are below or above the limit values set by the standards. In systems connected to medium voltage, the interface protections are equipped with an additional control. Groups of voltmetric transformers send signals to the medium-voltage protections in order to implement the voltmetric unlocking protection. Since interface protection relays have a function very closely linked to the security of the national electrical system, they must be periodically checked by means of field inspection procedures as stipulated in the relevant resolutions and regulations. In these checks, the correct setting of the interface protection, the correct operation by checking the protections and tripping times, and the correct intervention of the DDIs must be verified.

Switching devices

The main types of closing and opening devices for electrical circuits used in medium voltage networks are:

- **Circuit breakers.** Device capable of closing and interrupting short-circuit currents;
- **Contactors.** Device capable of carrying out numerous manoeuvres and interrupting limited short-circuit currents;
- **Disconnectors.** These are switch-disconnectors capable of opening or closing rate currents with a high-power factor.
- **Fuses.** Specially designed and proportioned fuse elements are able to open circuit where it is located, interrupting the current if it exceeds the set value for a given amount of time.

Current and voltage transformers

Current and voltage transformers are used within installations to:

- Reduce the system's voltage and current values in such a way that measurement and protection equipment can detect them;
- Make the protection and measurement secondary circuits galvanically independent of the power primary circuit, while at the same time providing operators with greater satisfy (there must always be a grounded winding point in the transformer secondary

circuit).

Transformers are used to translate current and voltage values from the power circuit to the measurement circuit. According to standards, they can be divided into two types:

- **Measuring transformers.** They are connected to measuring instruments such as amperemeters, wattmeters, converters, etc. in installations where current and voltage reach incompatible values. They have the peculiarity of saturating for values slightly higher than the primary current values so as to ensure protection of the instrument in the event of a short circuit.
- **Protection transformers.** They are connected to protections, as protective relays, in systems where current and voltage reach incompatible values. They have the property that they do not saturate until the tripping of the protection for the maximum short-circuit current is guaranteed.

Signal and control circuits

Signal and control circuits play a fundamental role within the microgrid as they enable communication between the different components of the system, including protection devices. Fundamental characteristics that the circuits must have been safety, reliability flexibility and speed. A malfunction or incorrect installation of the signalling circuits can compromise the correct operation of the entire microgrid, which is why it is essential to correctly choose the types of circuits and their characteristics that best suits each system. For the standardization of substation automation and the definition of communications protocol to ensure communication between substations, reference is made by IEC

61850. This standard was created with the help of modern data transmission standards and network protocols specifically designed to define general requirements regarding construction, design and environmental conditions for communication and automation equipment and systems in substations and power plants. Some of the main points of the standard are:

- Time accuracy not exceeding ±1 μs;
- Precise time synchronisation;
- Redundancy of connections without losses, aiming to ensure correct and continuous operation of the system;
- Protection of the station network from cyber-attacks;
- Real-time information exchange and processing, without the need for protocol converters or supervisor interpretation;
- Interoperability, so as to ensure the proper functioning of equipment of different operators.

The neutral state

Knowing in detail how the neutral is operated is essential in order to be able to detect earth faults in a network and thus carry out effective protection. It is possible to detect earth faults by making measurements of voltage and/or homopolar current, and therefore knowing the existence and magnitude of these parameters is essential to be able to choose and adjust the protection system. In contrast to protections for overload or polyphase shorth-circuit, protections that detect earth faults generally do not receive signals (pf voltage or current), which, on the contrary, only occur in the event of an earth fault in the network. For this reason, the protection system to be provided is very simple and generally only requires a threshold (voltage or current) with respectively short tripping times. It is possible to determine the types of protection that can be associated by analysing the various types of neutral status. This neutral may be army:

- **Isolated with respect to ground.** In these networks, no homopolar current circulation is intentionally generated (via grounding system) in the presence of a fault between a phase and ground. There is, however, a homopolar current in the system which is connected to the phase-ground capacitances of machine and pipes. Therefore, it is not easy to detect earth faults by using selective protections that measure the fault current. The fault can only be detected by measuring the homopolar voltage, which is zero in the absence of a fault and different from zero in presence of a fault. Since the homopolar voltage protection is not selective, it is not capable to detecting the location of the fault, but is only capable of detecting presence of the fault without indicating its location.

- **Solidly grounded.** In this mode, the single-phase fault current is of the same order of magnitude as the short-circuit current for polyphase faults. Consequently, it is possible measuring the homopolar current (or by using the phase protection, omitting the homopolar protection).

- **To ground via resistor.** It provides a safe current in the event of a fault and subsequently enables selective network protection. Depending on the value of the resistor installed, higher or lower values of the fault current can be achieved, however:

- the lower the fault current, the less damage to machines;
- the higher the fault current, the greater the chance that the fault will be identified as a fault (and protection will be required with less sensitivity).

- **To ground via impedance.** It allows the capacitive currents in the network to be compensated and thus, in the event of a fault, the current to be reduced to relatively small values and with a fault angle almost equal to zero (compensated network).

Selectivity

When an event (in the sense of a fault, overload or other) is detected by the protection element installed immediately upstream of the fault itself, while all other protections do not intervene since they are not involved, this is called selectivity. A selectivity technique that is often applied in microgrids is zone selectivity. Zone selectivity is generally realised through the dialogue between the electronic circuit breakers, which, when they detect that a setting threshold is exceeded, are able to correctly identify the fault and cut power only to the affected zone. This can be achieved in two ways:

- Information related to exceeding the current setting threshold is sent from the measuring devices to the supervisory system, which then has the task of identifying which protection must intervene;
- When current values above their setting are detected, all protections, by means of a direct connection or a bus, send a blocking signal to the hierarchically superior protection (upstream with respect to the direction flow) and, before intervening, check

> that a similar blocking signal has not arrived from the downstream protection; in this way, only the protection immediately upstream of the fault intervenes.

The second methodology is characterized by having shorter tripping times. Zone selectivity is mainly used where high current ratings and short-circuit ratings are present, with non-derogable requirements for both safety and service continuity. Example of selectivity are often found in primary and secondary distribution boards, and immediately downstream of transformers and generators.

Chapter 3

Configuration and typologies of microgrid

3.1 Off-Grid (islanded mode)

Off-grid microgrids are independent energy systems not connected to the main grid. Such configuration is generally adopted in remote areas, small islands, mobile facilities or in all areas where access to the main grid is difficult. Because they are not connected to the grid, off-grid systems are totally independent and have to generate all the energy they need themselves. Such plants are often equipped with battery storage systems to ensure a continuous supply that would otherwise not be possible due to the intermitted nature of renewable energy sources. Off-grid systems, as they are not connected to the grid and therefore do not make it possible to exchange energy with it, once all self-consumption needs have been met and all storage systems have been fully charged, they should either dissipate excess energy or reduce amount of energy produced to keep the balance between production and demand. To ensure efficient energy use and reduce waste, off-grid applications therefore require efficient energy use and management strategies. In fact, the most common solution involves the combination of electricity production from renewable sources and fossil fuels (programmable), such as cogenerators or tri-generators, with storage devices in order to cope with the intermittent nature of clean energy sources and ensure constant energy availability.

Fig.5 Off-grid operation [5]

3.2 On-grid (grid-connected mode)

Unlike off-grid microgrids, which are based on islanded operation, on-grid microgrids are connected to the grid and allow to combine the internal electricity production with supply from the main grid. On-grid systems, being connected to the grid and thus allowing to exchange energy with it, once all self-consumption needs have been met and any

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[5] Source: https://www.fortresspower.com/microgrids-help-community-reach-energy-goals/

storage systems have been fully charged, are able to sell the excess energy back to the grid, thus also providing an economic return. It can easily be seen, therefore, that the exchange of energy to/from the grid is the main difference from the previously analysed system type. As with off-grid systems, however, this type of microgrid also produces energy mainly from renewable sources, typically complemented by a fossil source system such as cogenerator or trigenerator in order to cope with the intermittent nature of clean energy sources and thus guarantee energy availability. On-grid microgrids have the advantage of being able to guarantee a constant availability of energy even when access to the main grid is not possible, thanks to the self-generation systems in it. The most important challenge of these systems, however, is their integration with the existing grid infrastructure. This requires careful project planning and coordination with the local utility company to ensure that the microgrid does not cause disruptions to the wider grid system.

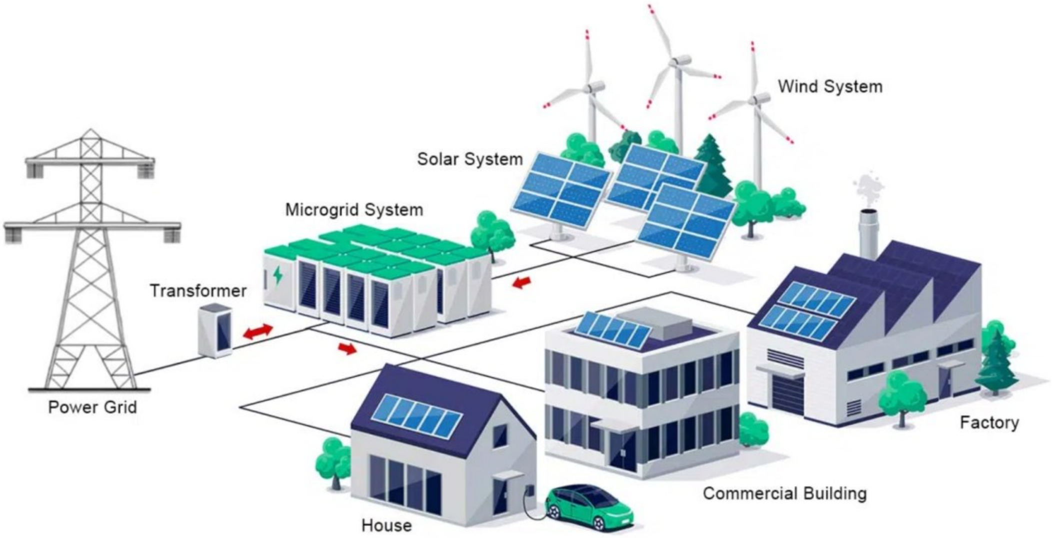

Fig.6 On-grid operation[6]

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[6] Source: https://flyfinebattery.com/microgrid-system-solution/

Chapter 4

Illustration of the analysed plant

4.1 Description of the analysed plant

The analysed plant is located in Vicenza, in the Veneto region, within a campus covering 58 hectares. The plant is a perfect example of a grid-connected microgrid. In fact, the microgrid typically imports about 100 kW of electricity from the national grid, to complement the energy production from a 7.8 MW trigeneration plant and a 3.4 MW photovoltaic plant installed on the roofs of some of the 34 buildings on the campus. The campus is supplied by the local distributor via a medium-voltage line at a voltage of 20 kV. To further improve the microgrid, a 3 MW and 4.5 MWh BESS is being installed to make the plant more efficient. Thanks to the advanced automation and monitoring technologies used, the plant is able to optimise exchange of energy, guaranteeing high standards of efficiency. The figure below shows the representation of the campus with its buildings and medium-voltage substations. The three trigenerators, each with 2.6 MW, are installed inside buildings 11, while 3.4 MW photovoltaic system is divided among the buildings characterised by the colour blue. As far as the cabins are concerned, it is possible to see the POD in red, which allows the exchange of energy with the grid, while for the power supply within the campus, the cabins are designed with letter "A" in orange and with letter

“B” in green, according to the ring line to which the cabin itself is connected (it is possible to see the distinction between the two rings in the figure below right (in red)). In green are the connection lines of the microgrid to the grid.

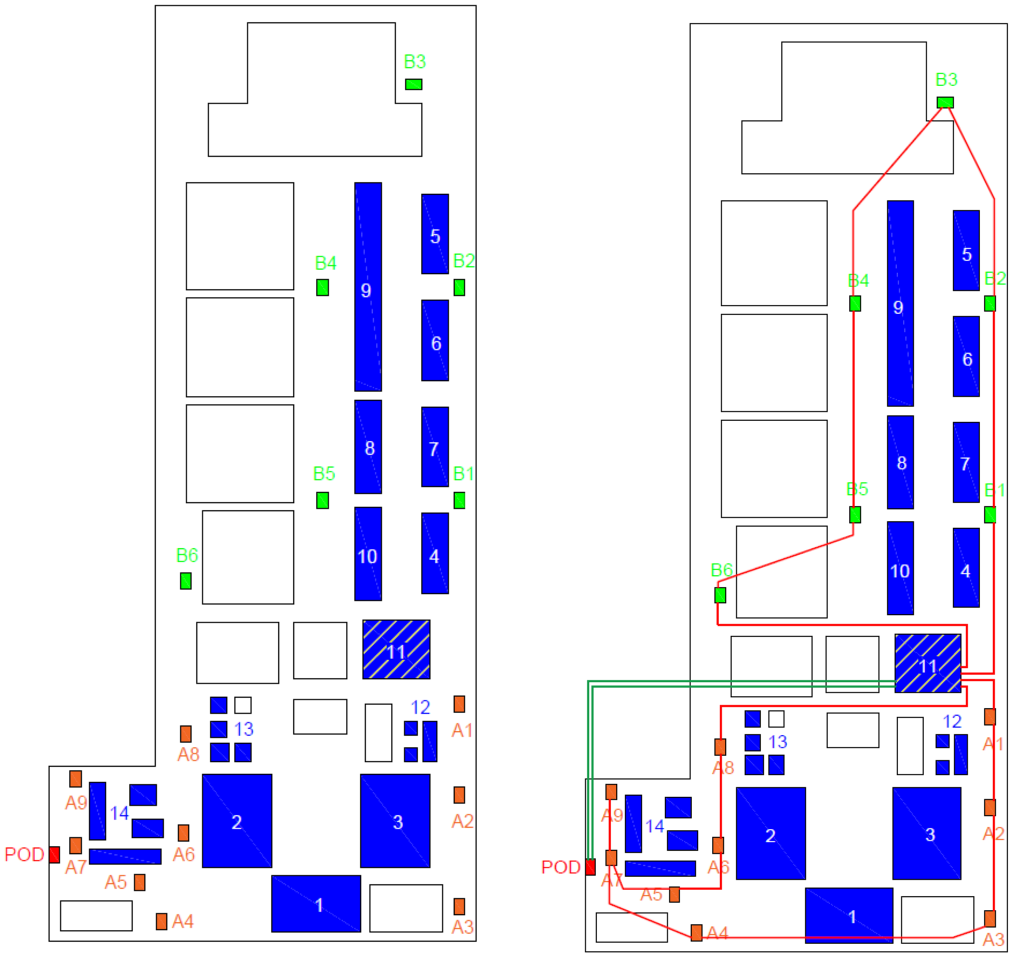

Fig.7 Campus plans

4.2 Components of the analysed plant

Generators

As mentioned in the previous section, the campus manages to cover part of its energy needs thanks to the presence of a photovoltaic system and three trigenerators. With a look at the numbering of the buildings in the previously illustrated floor plan and the aid of the following table, it is possible to see the share of electricity supplied by the photovoltaic system of each individual building.

	BUILDING N°.	**PV**	**TRIG.**
	-	**[MW]**	**[MW]**
	1	0.20249	-
	2	0.2923	-
	3	0.29023	-
	4	0.32658	-
	5	0.32658	-
	6	0.32658	-
	7	0.32658	-
	8	0.1939	-
	9	0.298	-
	10	0.19868	-
	11	0.0768	7.8
	12	0.064165	-
	13	0.108865	-
	14	0.3589	-
TOT.	-	3.4	7.8

Tab.1 Power generated in each building.

The table below shows the electrical specifications of the polycrystalline silicon photovoltaic modules installed in the system.

ELECTRICAL SPECIFICATIONS			
PERFORMANCE AT STANDARD TEST CONDITIONS (SCT: 1000 W/m2, 25 °C. AM 1.5 G SPETCTRUM) [1.]			
Nominal Power (+5/-0 W)	Pn	W	255
Short Circuit Current	Isc	A	8.9
Short Circuit Voltage	Voc	V	37.83
Current at MPP	Impp	A	8.37
Voltage at MPP	Vmpp	V	30.77
Efficiency	η	%	≥15.3
PERFORMANCE AT NOMINAL OPERATING CELL TEMPERATURE (NOCT: 800 W/m2, 45±3 °C. AM 1.5 G SPETCTRUM) [2.]			
Short Circuit Current	Isc	A	7.18
Short Circuit Voltage	Voc	V	34.99
Current at MPP	Impp	A	6.56
Voltage at MPP	Vmpp	V	28.92
1. Measurement tolerances STC: ±3% (Pmp); ±10% (Isc, Voc, Imp, Vmp) *2. Measurement tolerances NOCT: ±5% (Pmp); ±10% (Isc, Voc, Imp, Vmp)*			

Tab.2 PV Electrical Specification [7]

The photovoltaic production systems of individual buildings are connected to the respective substations directly at low voltage, unlike the trigenerators, which are connected directly to medium voltage with the help of 11-20 kV step-up transformers.

Fig.8 PV photographic survey

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[7] Source: Design documents provided by the customer on the analysed installation.

Within the photovoltaic system there are 204 inverts, whose task is to convert the direct current produced by the PV units into alternating current that can be used by the grid.

Fig.9 Photographic survey of PV inverters

As far as trigeneration is concerned, there are three Wartsila generating set with dual-fuel, gas and diesel, four-stroke engines in the plant. Methane gas is supplied by the local operator at a pressure of 0.7-5 bar, and thanks to a pressurisation system, the cogenerators are supplied at 8 bar. Unlike gas, diesel is delivered to the campus via tanker trucks and stored in special tanks. The engine is a medium-speed 4-stroke marine type, providing reliable and sustainable flexibility to optimise operation. These engines operate on the basis of lean combustion, thus reducing peak temperatures and significantly lowering NO_x emissions, and also meeting the most stringent limits through exhaust gas treatment. The Wartsila generating set is extremely reliable thanks to its fuel flexibility and continuous fuel switching.

The installed model operates at a frequency of 50 Hz, the specifications of which follow:

TECHNICAL DATA 50 Hz/750 rpm	
Power, electrical [kW]	2579
Heat rate [kJ//Kg]	8347
Electrical Efficiency [%]	43.1

***Tab.3 Motors technical data*[8]**

Hot water on campus is produced at temperature from 74°C to 91°C by three hot water boilers, two steam-hot water exchangers and water-to-water heat exchangers, all operating in parallel. The boilers, thank to special pressure reducers, are supplied at 0.4 bar. Hot water for the heat exchangers and steam for the heat exchanger are generated from the waste heat of the trigeneration units. The system is sized to operate with two active boilers and one backup boiler and heat exchangers. It is programmed to first generate hot water with the help of the waste heat from the trigenerators and then operate the boilers. If the trigenerator is operating at maximum power, it is able to supply 1200 kW of energy in the form of heat from the fuel gases, and approximately 800 kW from the engine cooling jacket. When the trigenerators are in operation, the waste heat recovery boilers operate to produce steam at 690 kPa for use with the double-acting steam absorption unit or steam/hot water

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[8] Data taken from the site: https://www.industrialmarinepower.com/w%C3%A4rtsil%C3%A4-34df-main-technical-data-wartsila-6l34df-9l34df-16v34df-20v34df---/

exchangers. To produce low-temperature hot water at 91°C for space heating, water-to-water heat exchangers recover heat from the water in the engine cooling jacket. If the steam cannot be used, the engine exhaust is automatically diverted to the atmosphere. If the low-temperature hot water cannot be used, the water in the cooling jacket is diverted to remote heat sinks. By recovering the additional excess heat produced by the trigeration system, it is also possible to produce chilled water. The water is generated by two 3000 kW centrifugal chillers and one 2560 kW absorption chiller to be distributed to the system and the thermale storage tank at 5°C. The return chilled water is at 13°C. In the event that no steam is available, or it more recovery seam is required for heating, the plant operator can only operate the centrifugal chillers. The plant operator is also able to determine which chillers to activate and when to charge the tank. With outside temperatures below 10°C, the chillers are switched off and the demand for chilled water is generated by plate heat exchangers using the cold condenser water from the evaporative towers. The cooling towers are sized for water leaving at 30°C, water entering at 35°C and a wet bulb ambient temperature of 24°C. Condensation water to the three chillers is supplied by three equally sized forced-air cooling towers.

Storage systems

Storage systems are designed to store energy in order to use it at later times when demand exceeds production or when supply is interrupted. On campus, there are three diesel storage tanks, one chilled water storage tank , two ambient temperature water storage tanks for sanitary and fire-fighting use. A 900 m^3 hot water storage tank and BESS are installed.

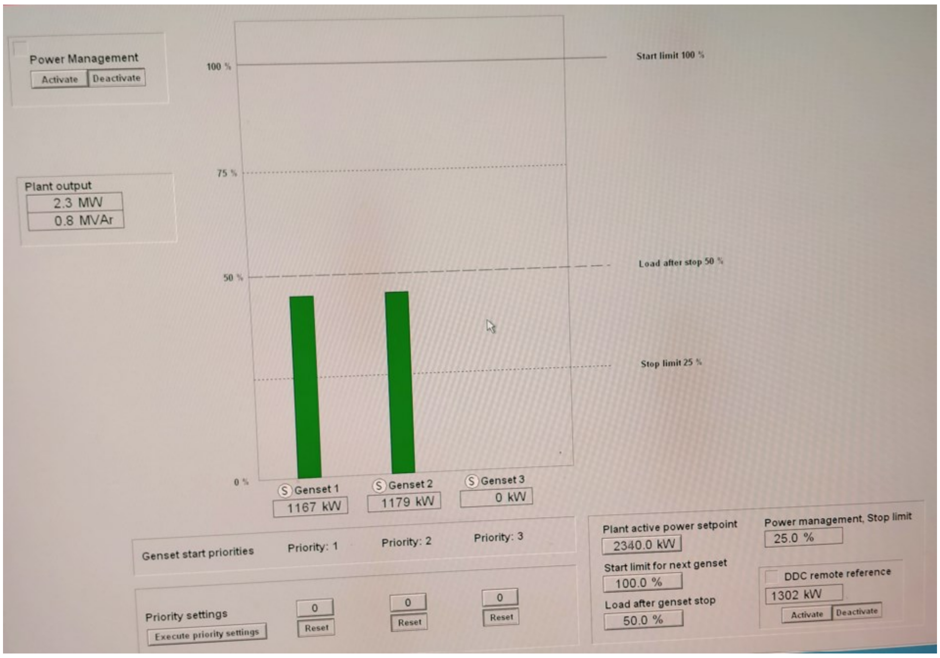
The three oil storage tanks, made of steel and with a capacity of 240 m^3, are capable of storing an available oil supply of up to 634 m^3, i.e., enough for approximately 14 days (in the case of 2 active trigenerators). Domestic water at room temperature is stored in two tanks with a capacity of 2500 m^3 each. The chilled water is stored in a tank with a capacity of 1500 m^3. The filling of this tank is done after 20:00 hours and complete before 7:00 hours, with the possibility for the operator to schedule storage at other times as well. This water is generally used on working days from 13:00 to 17:00, but can also be used at other times if required.

Fig.10 Photographic survey of two domestic water tanks (on the left and in the middle) and of chilled water tank (on the right).

Control and monitoring

The control and monitoring system of the campus are essential aspects to ensure optimal operation of the plant and to intervene in the event of anomalies. For real-time supervision of operating conditions, automation and smooth operation, the following devices are installed in the plant:

- **SCADA.** On campus is ABB's ZEE600 SCADA software, an advanced platform designed to offer high performance and optimised process management. This system features an intuitive interface, great flexibility and a modular architecture to ensure integration with different types of sensors and devices. With its advanced analytical and reporting capabilities, the ZEE600 improves efficiency, reduces downtime and supports proactive campus management.



Plant output
2.3 MW
0.8 MVAr

Genset 1: 1167 kW
Genset 2: 1179 kW
Genset 3: 0 kW

Genset start priorities: Priority: 1, Priority: 2, Priority: 3

Priority settings: 0, 0, 0

Plant active power setpoint: 2340.0 kW
Start limit for next genset: 100.0 %
Load after genset stop: 50.0 %
Power management, Stop limit: 25.0 %
DDC remote reference: 1302 kW

Fig.11 Plant control screen through SCADA

- **Microgrid controller.** The plant solution for this device involves the combination of ABB AC500 redundant PLCs and ABB OPTIMAX. AC500 PLC is responsible for field interfacing, controlling the campus assets by managing transitions to island mode or the black start of the whole grid. The PLC also communicates data to OPTIMAX and after receiving the results of calculations, adjusts setpoints and/or sends commands to the microgrid assets. OPTIMAX is thus able to provide grid optimisation in real time like:

  - the maximisation of self-consumption & grid independency;
  - the maximisation of reliability of the microgrid;
  - the minimisation of energy costs;
  - the minimisation of CO_2 emissions.

  The combination of these devices ensures high flexibility and maximisation of grid reliability, optimising production and consumption of all resources.

Protection

The campus protection system is essential to ensure the safety and reliability of the facility. These systems protect people, equipment and power lines from faults such as short circuits, overloads or power losses. Inside red cabin in the plans in Fig.7 in Chapter 4.1 are located the main device and the main protection system, which are responsible for managing the separation of the entire campus from the grid.

The main protection system provides:

- Main protection. The relay installed is ABB’s REF 615 (CEI 0-16) model, which is dedicated to the protection and control of the microgrid in accordance with specified calibrations of the Italian Standard CEI 0-16. There is also the UPS, i.e., the relevant power supply which must be guaranteed for at least one hour in case of need.

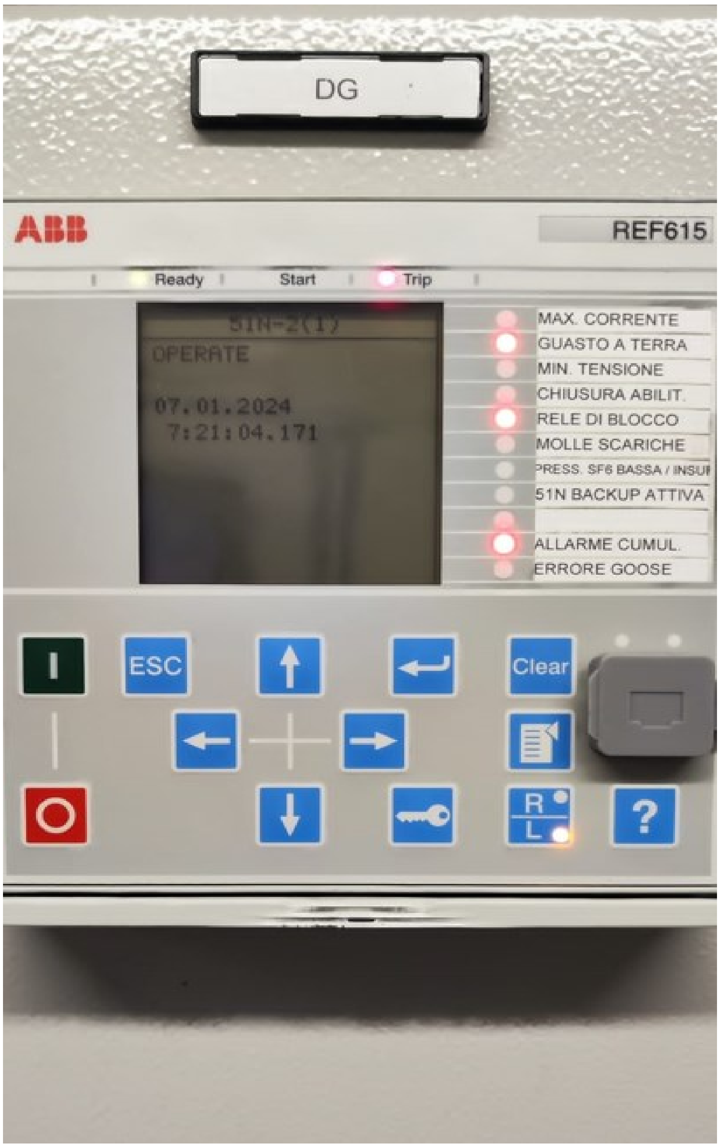


Fig.12 Photographic survey of main protection relay

- Current transformers. Three devices from ABB are installed as voltmetric and amperometric sensors, one per phase, which perform both measurements; this model is the COMBI KEVCD24AE3.

Fig.13 ABB COMBI KEVCD24AE3 photographic survey

- Homopolar transformer. As a model, ABB’s 100/1 toroidal transformer was installed, which has the purpose of detecting any leakage currents by performing the vector sum of the currents of the conductors that pass through the toroid.

Fig.14 Homopolar transformer photographic survey

As far as the main device is concerned, ABB’s medium voltage circuit breaker with minimum voltage coil, SACE HD4/A, is installed. From the switchboard where the DG is located, there are two starting lines that reach building 11 and therefore the interface protection system is characterised by the presence of two interface device, one per line. For both devices, ABB’s medium voltage circuit breaker with minimum voltage coil, model SACE HD4/R, is installed. As far as the interface protection is concern, ABB’s REF 620 (CEI 0-16) relay is installed, with its power supply guaranteed for at least 5 seconds by the UPS. As transformers there are, on each of the two lines, three phase-to-ground voltage transformers, model CGS UKM24/3, and two phase-to-phase transformers, model CGS VKM24/2/h; by means of a manual selector, the operator can decide which of the two lines to use for measurement.

Fig.15 Photographic survey of interface protection relay

About the separation of the trigeneration systems, medium voltage circuit breakers with minimum voltage coil from ABB, SACE HD4/R, are used as generator devices, while for photovoltaic generation, low voltage circuit breakers are used in the inverters. In addition, each switchgear for its trigeneration has a protection relay model ABB REF 620 (CEI 0-16) and a measuring current transformer model CGS AWR24D. All the substations of the system are connected to each other by two fibre optic ring lines to guarantee redundancy and allow the selectivity of the individual substations; communication between the substations is thus ensured with reference to the IEC 61850 standard, previously mentioned and briefly described in point 2.4.

Fig.16 Photographic survey of generator protection

The supervision operations and the related drives performed by the various components can also be carried out manually by a team of operators working on the campus daily.

4.3 Operation grid-connected and islanded operation

The campus medium-voltage plant normally works with at least one trigenerator connected in parallel to the DSO grid. The system generally works with “zero tracking” trying to keep the consumption from the grid at around 100 kW; this power can be produced by keeping two trigenerators running at the same time or by producing entirely with only one trigenerator. Should the DSO’s power supply fail or fail completely, the medium-voltage system is dimensioned to disconnect from the DSO’s grid and continue stand-alone operation, thus covering the plant’s entire energy demand with the trigenerators and the photovoltaic system. Should the medium-voltage plant go into stand-alone operation, the trigeneration plant is set up to activate the second trigenerator and connect it to the first to share the load.

Chapter 5

Analysis of contingencies and faults

Microgrids represent an important step forward for technology development, offering a sustainable, resilient, and localised solution for energy management. Despite their various advantages, however, these small energy communities present some challenges. Managing security and system stability are among the main challenges, especially with intermittent renewable energy generation facilities such as solar. Another factor that can be complex is the integration of the microgrid with the traditional grid, requiring advanced monitoring and control systems. Adequate solutions are therefore required to ensure the optimal functioning of these energy communities.

5.1 External power grid disturbances

The normal functioning of the power supply can be altered by disturbances in the grid, such as anomalies or fluctuations, affecting the quality of the power distributed to the users. Such disturbances can have detrimental results on electrical equipment, inndustrial systems and the quality of the services provided to the consumers. In the case of the campus, in fact, there are many delicate pieces of equipment that require a high quality of power supply and, in addition, there are consumers that require a constant power supply. Power failures, or voltage sag, are characterised by a lack of voltage (i.e. voltage becoming equal to zero at the interface with the public grid) for periods of more than a second and are generally caused by faults in the distribution network (such as excessive demand for electricity, thunderstorms, the presence of ice on the lines, etc.), or, following a short circuit, by the activation of the consumer's system protections. There can also be "forced outages" due to the protective devices of the supplied equipment when the voltage deviates from the preset limit values. In addition to mains drop, disturbances can be divided into semi-persistent and transient disturbances, lasting less then about a half second. Semi-persistent disturbances are: voltage fluctuations, frequency fluctuations, harmonic waveform distortions and voltage dissymetry in three-phase system. Transient disturbances are: voltage pulse, micro-interruptions or voltage dips and high-frequency disturbances (noise).

Microinterruptions

Reductions in mains voltage with an amplitude of 90 % of the nominal value down to 0 volts, with a duration ranging from 10 to 500 milliseconds. They are generated by transient phenomena such as the rapid automatic opening and reclosing of circuit breakers on high-voltage network (380000 V). They can also be caused by short circuits on the mains upstream of the consumer, before the protective device are tripped.

Voltage pulses

Transient variatons in mains voltage whose amplitude can be as high as 800 V, lasting from less than a microsecond to over 500 millseconds. They can be caused by automatic grid switching manoeuvers, by the sudden disconnection of inductive loads such as large electric motors, or, less frequently but with disastrous effects, by lightning on overhead distribution lines.

Voltage variatons (overvoltage and undervoltage)

Variatons of more than 10% of the nominal value that generally depend on variaton in the demand and supply of electricity. Although this kind of disturbance does not have a very rapid evolution, since it basically depends on the voltage drop/rise along distribution lines, it may have an impact over the correct operation of the microgrid devices and, possibly, cause the tripping of interface protections. Voltage fluctuations are quite frequent and are caused by the switching on or off of the loads of other consumers that are supplied by the same portion of electric grid.

Waveform harmonic distortions

Power absorption, or injection, by non-linear loads and generators in the grid having a non-sinusoidal waveform may cause the presence of harmonic content in the public grid's voltage, which is one of the most frequent disturbances. Example could be an impulse draw from a load or the DC/AC conversion operated by inverters in the case of static generators, both of which may result in a non-sinusoidal voltage waveform at the grid bus. Such harmonics are particularly harmful to electric motors, transformers and degrade insulation.

High frequency noise

Very frequent disturbances especially in the industrial environment that can be caused by the brushes of an asynchronous motor or the arc of an electric welder. Electromagnetic interference with high-frequency radio trasmitters, induction on overhead lines by lightning strikes in the circumstances, and poor quality UPSs could be further causes of disturbance.

5.2 Control and lightening of loads following a fault

Under certain operating conditions of the microgrid, either at the discretion of the operator or when only one of the trigenerators is active, it may happen that there is a substantial draw of energy from the grid. If, during this operation conditions, the plant was disconnected from the grid and become isolated, the only active generator would not be able to cover the entire energy demand of the campus, thus causing the generator to go off at minimum frequency after a few seconds as the prime mover is unable to increase the generated power quickly, sending the entire plant into blackout. For this specific operating situation, a PLC is foreseen to relieve the loads of the MV plant in the event of the above-mentioned conditions occurring. This logic is not activated in the event of an island occurring when the plant was supplied by the grid and two active cogenerators in parallel. The PLC must be able to remove the load that the generator cannot handle instantaneously as quickly as possible and return it in steps that the generator can support without tripping. The PLC must not, however, remove too much load from the running generator, which would trip by maximum frequency, leading to a campus blackout. If the single generator is unable to take over the entire load by itself, the second generator is started up in parallel with the first and once the available power is detected, the PLC proceeds to repower the remaining transformers. The same load-relief logic is applied if an island operation condition with both cogenerators in operation is changed to an island operation condition with only one cogenerator

active. This solution could occur, for example, following the opening of the MV switch of one of the two active generators due to an electrical or mechanical fault.
Through the specific SCADA interface, the ABB PLC allows the following parameters to be set:

- **“Logic selector” - Enable/Disable**: this parameter prevents the PLC from sending commands to the MV system when operators want to prevent this from happening;

- **“Wait for trafo insertion”**: is the time that elapses between the insertion of one transformer and the next, in order to allow the generator to stabilise after load insertion;

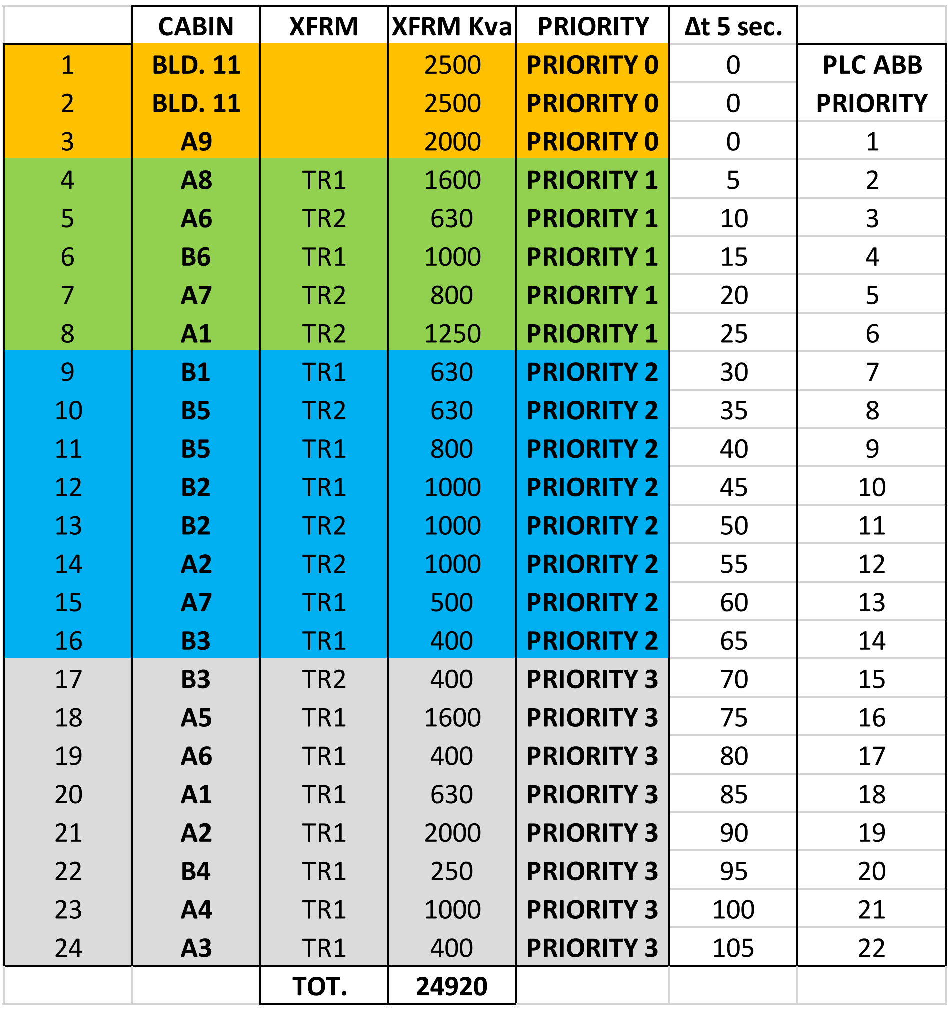
- **“Wait for trafo disconnection”**: is the time that the PLC waits before analysing the result of the load relieving;

- **“Power threshold trafo insertion for a trigenerator”**: A default power threshold parameter is set. When the output threshold of the individual generator is below this threshold, the PLC considers that the generator is able to accept new loads and it is therefore possible to insert other transformers. When the individual generator production threshold is above this threshold, the PLC considers that the generator is not able to accept new loads and therefore does not insert further transformers;

- **“Power threshold trafo detachment for a trigenerator”**: A power threshold parameter is set. When the current output threshold is below this threshold, the PLC considers that the generator is able to support the current load and therefore does not add or remove loads. When the current production threshold is below this threshold, the PLC considers that the generator cannot support the current load and therefore proceeds to disconnect the excess transformers;

- **"Maximum acceptable power step from a trigenerator"**: A default value parameter of maximum acceptable power step from a trigenerator is set. This parameter is necessary for choosing the number of transformers to be disconnected;

- **"Transformer's priority and enabling"**: Allows the load disconnection logic to be disabled for each individual transformer, in this way the PLC does not send open/close commands to that utility, but continues to monitor and read its electricity consumption. To ensure that they are never disconnected under any condition, the transformers with the most important utilities on campus should be disabled. Each enabled transformer is associated with a priority value from 1 to 50 (1=most important load), thus allowing the PLC to be told which transformers to open first in case of need, and which to reattach more quickly. The table priority assignment to the different loads can be seen below. The cabin nomenclature refers to Fig. 7 chapter 4.1 (CAD plan) and a "trafo insertion wait" time of five seconds has been assumed.



	CABIN	XFRM	XFRM Kva	PRIORITY	Δt 5 sec.	
1	**BLD. 11**		2500	**PRIORITY 0**	0	**PLC ABB**
2	**BLD. 11**		2500	**PRIORITY 0**	0	**PRIORITY**
3	**A9**		2000	**PRIORITY 0**	0	1
4	**A8**	TR1	1600	**PRIORITY 1**	5	2
5	**A6**	TR2	630	**PRIORITY 1**	10	3
6	**B6**	TR1	1000	**PRIORITY 1**	15	4
7	**A7**	TR2	800	**PRIORITY 1**	20	5
8	**A1**	TR2	1250	**PRIORITY 1**	25	6
9	**B1**	TR1	630	**PRIORITY 2**	30	7
10	**B5**	TR2	630	**PRIORITY 2**	35	8
11	**B5**	TR1	800	**PRIORITY 2**	40	9
12	**B2**	TR1	1000	**PRIORITY 2**	45	10
13	**B2**	TR2	1000	**PRIORITY 2**	50	11
14	**A2**	TR2	1000	**PRIORITY 2**	55	12
15	**A7**	TR1	500	**PRIORITY 2**	60	13
16	**B3**	TR1	400	**PRIORITY 2**	65	14
17	**B3**	TR2	400	**PRIORITY 3**	70	15
18	**A5**	TR1	1600	**PRIORITY 3**	75	16
19	**A6**	TR1	400	**PRIORITY 3**	80	17
20	**A1**	TR1	630	**PRIORITY 3**	85	18
21	**A2**	TR1	2000	**PRIORITY 3**	90	19
22	**B4**	TR1	250	**PRIORITY 3**	95	20
23	**A4**	TR1	1000	**PRIORITY 3**	100	21
24	**A3**	TR1	400	**PRIORITY 3**	105	22
		TOT.	**24920**			

Tab.4 Table representing the distribution of loads and priority assigned to them.

Load shedding algorithm

When the campus goes into island mode with only one generator active, the PLC must decide how many and which transformer to disconnect according to the priorities assigned and the current state of the MV system, so as to remove the load that the generator would not be able to handle instantaneously. In fact, the PLC constantly detects the power that the microgrid is constantly drawing from the grid, power that the generator is not and cannot instantaneously supply at this instant. As soon as the plant goes off-line and has only one active trigenerator, the

PLC calculates the “power reserve” of the only active generator:

“Power reserve” = Parameter “power threshold trafo separation for one generator” – “power currently delivered by the generator”

This value indicates show much power the running generator is currently able to generate. When the “power reserve” parameter is higher than the “maximum power acceptable from a generator” parameter, the unit is able to accept the set load increment step, and the power to be detached is then calculated as follows:

“Power to be disconnected” = power currently drawn by the DSO – “maximum acceptable power step from a trigenerator”

When the “power reserve” parameter is lower than the “maximum acceptable power step from a generator” parameter, the unit is unable to accept the set load increment step as it is already at full load and the power to be detached is therefore calculated as follow:

“Power to be disconnected” = power currently drawn by the DSO – “power reserve available to the trigenerator”

At this point, the PLC is able to determine how many loads to disconnect so as not to send the generator into crisis and, using the load priority list, starts to disconnect the transformers from the grid (starting with the least priority), adding up the load share of each transformer until the amount of power it has decided to disconnect is reached. When this PLC algorithm ends, the trigenerator is delivering a little more power than it was delivering before it went into isolation, ensuring that it does not experience too high a frequency fluctuation; the next step is characterised by the load modulation algorithm, which is dedicated to reactivating the transformers in a timed way.

Load modulation algorithm

At this point, the PLC has to re-power as many loads as possible with the available trigenerators; to do this, it consults the load priority list and reactivates them starting with the most prioritised with a time interval between one and other set with the "wait for trafo insertion" parameter (for example five seconds). The shutdown of each transformer only takes place once the PLC has checked that the power supplied by the trigenerators is below the parameter "power threshold trafo insertion for a trigenerator": each time loads are inserted, the trigenerator proceeds independently to gradually increase its output. If the value "trafo insertion power for a trigenerator" is exceeded, the PLC no longer inserts any transformers so as to block the power increase. This value is set considering a safety margin such as to allow the trigenerator to accept any increase in the load of the transformers already inserted, without thus exceeding its maximum available power. Depending on the operating conditions of the system, it may happen that when the parameter "trafo insertion power for a trigenerator" is reached, not all the loads have been reactivated; in this case, the PLC waits for a second trigenerator to be inserted so that the last loads are also re-powered using the logic illustrated above. If the second trigenerator is started up cold, it is able to produce less power than the nominal power. For this reason, it is set in the PLC that the trigenerator that has just been switched on is able to deliver 50% of the power for one minute after shutdown; this time, verified by motorists, is necessary to allow the system to warm up without putting the system into crisis. During this period, therefore, the PLC considers a power equal to 1.5 times that of the trigenerator to be available; if the threshold is reached by the load before the two minutes have elapsed, the system stops inserting loads. Once two minutes have passed, the system resumes inserting any missing loads up to the available power both generators. Once all loads on the campus have been re-powered, the system remains in island status until the grid status of the DSO allows it to return in parallel with the grid. With two active trigenerators, the Wartsila system distributes the load equally 50/50 between the two groups. If the power delivered by the group of active trigenerators exceeds the threshold "trafo disconnection power for one generator", the PLC proceeds by disconnecting the excess loads using the same procedure as above, both in terms of priority and quantity of loads to be disconnected. If, under these operating conditions, one of the two trigenerators is disconnected from the MV grid due to an electrical or mechanical fault, the PLC proceeds to disconnect the loads in the same way as for disconnection from the grid, but calculating the power of the loads to be disconnected using the power that the trigenerator was delivering before the fault. In this situation, the PLC will therefore disconnect about half of the loads and then reconnect all the loads in a timed sequence until the active generator reaches the "trafo insertion for one trigenerator" power; should the third trigenerator started up and be connected to the MV network, the PLC, after detecting twice the available power, will proceed to insert the remaining loads in the same procedure as described above. When the grid problem is resolved and the grid becomes available again, the operators activate the grid-parallel re-entry procedure on the Wartsila system. Once the PLC has detected the return in parallel of the MV system with the grid, it proceeds with the reclosing of any still open loads that had previously been disconnected by the PLC. At this point the PLC goes back to monitoring the microgrid and prepares to intervene in the event that the plant returns to island operation.

PRIORITA'			POTENZA
ABILITATO	ON	OFF	36 KVA
DISABILITATO	ON	OFF	0 KVA
ABILITATO	ON	OFF	0 KVA
ABILITATO	ON	OFF	103 KVA
ABILITATO	ON	OFF	54 KVA
ABILITATO	ON	OFF	18 KVA
ABILITATO	ON	OFF	0 KVA
DISABILITATO	ON	OFF	0 KVA
ABILITATO	ON	OFF	42 KVA
ABILITATO	ON	OFF	23 KVA
ABILITATO	ON	OFF	143 KVA
DISABILITATO	ON	OFF	0 KVA
ABILITATO	ON	OFF	26 KVA
ABILITATO	ON	OFF	186 KVA
ABILITATO	ON	OFF	355 KVA
ABILITATO	ON	OFF	218 KVA
ABILITATO	ON	OFF	34 KVA
DISABILITATO	ON	OFF	0 KVA
ABILITATO	ON	OFF	159 KVA
DISABILITATO	ON	OFF	0 KVA
ABILITATO	ON	OFF	409 KVA
DISABILITATO	ON	OFF	0 KVA
ABILITATO	ON	OFF	48 KVA
ABILITATO	ON	OFF	74 KVA
ABILITATO	ON	OFF	80 KVA
ABILITATO	ON	OFF	104 KVA
ABILITATO	ON	OFF	211 KVA
DISABILITATO	ON	OFF	0 KVA
DISABILITATO	ON	OFF	131 KVA
DISABILITATO	ON	OFF	471 KVA
DISABILITATO	ON	OFF	66 KVA

Fig.17 Photographic survey of the PLC during load modulation phase

The modulation of loads is fundamental in order to be able to respect all the technical and regulatory constraints that may arise. A first constraint that must be complied with, is the CEI 0-16 standard, which sets the maximum value of simultaneous energisation equal to 3x2000 kVA; a second constraints is for technical reasons, since if all the loads were to be reconnected at the same time, 24920 kVA would be absorbed and this would be a very important threshold for the trigenerator. This technical constraint is important and is related to the energisation of the transformers and the inrush current that characterises it. Energisation refers to the gradual feeding of the transformer up to the rated voltage and load, in this case following a voluntary disconnection. During this action, inrush current occurs, i.e., the absorption of a high current during the first energisation. It is proportional to the current flowing in the primary winding and is generated by the sudden change of magnetic flux in the transformer core. During the first energisation, a large current must flow through the primary winding in order to create magnetic flux, and precautions must be taken to manage this. The inrush current, which can be many times higher than the rated current, increases as the transformer size increases. Inrush can therefore trigger protection devices or even overload the power system or connected equipment. Protection devices are in fact designed to detect and intervene in the event that abnormal current levels are detected in order to protect the system from damage. In fact, it could happen that in the presence of a high inrush current, a false tripping of the protection systems occurs, unnecessarily interrupting the power supply. To cope with this effect, the three-phase inrush detector function has been implemented in the protection devices, which does not intervene during the energising time (which must be set appropriately) in the presence of high currents. The activation of all loads is also modulated to prevent the general protection device from tripping due to inrush currents and overloading the power source. In fact, the initial surge of inrush current could overload the power sources supplying energy to the system (trigenerators and any other transformers), resulting in voltage instability, increased losses and decreased efficiency of the generators themselves.

5.3 Logic selectivity for internal microgrid faults

There are numerous electrical components within the campus, including solar panels, switching devices, electricity distributions system, etc.. Should facts occur in these components, such as failures due to short circuits, overloads, physical damage or control system malfunctions, this could lead to a system-wide power failure. Thanks to logical selectivity, in the case of internal campus failures, it is possible to limit the power outage to only the area affected by the fault, thus improving reliability and efficiency, reducing downtime and limiting system-wide damage.
The logic selectivity system (SSL) operates by monitoring the current and is based on the transfer of information, via a hard link (pilot line), between the protection systems. Through this hard link, the unit affected by fault immediately transmits a logic hold pulse to the upstream unit. Since the protection equipement located immediately upstream of the fault has not received a hold signal, it remains free to operate.
This selectivity system has the advantage to reduce the tripping times and all protection equipement located upstream a fault are able to see that, thanks to the redundancy of the system. This system, by connecting all protection units via a pilot line, also enjoys high reliability. The choice of

protection systems falls to directional protection systems, which operate according to the current and its directional of flow. Directional protection systems intervene if the current exceeds a set threshold and at the same time, it flows in a direction other than the set direction.
There are different types of directional protection, those of interest to the campus are:

- **Phase current directional protection;** When a fault occurs in a sources or lines operating in parallel with other sources and lines, there is the risk of a total failure of the distribution. This is due to the fact that the same fault current flows in all these elements and changes direction in the fault element. Directional protection is therefore used to quickly detect the fault element and to isolate by interrupting its supply.

- **Earth fault current directional protection;** if the transformers supplying the grid, which are connected with the neutral to earth, were to experience an earth fault, a residual current would circulate between all sources. In this case, the source subject to fault will have a residual current operating in the opposite direction from the others. The earth fault directional protection use this principle to identy the faulty element. Measuring the phase shift between the "residual current" and "residual voltage" vectors is possible to determine the direction. These device can also be used for systems with long cables to detect a faulty start in networks with high capacitive currents. In this case, the residual current, of the healty starts flows in the same direction, while in the faulty start it flows in the opposite direction, thus allowing the directional protection to intervene.

5.4 Remote interruption of generator (teledistacco)

In recent years, distributed generation has changed the world of power generation and significantly increased generation from renewable sources. However, generation from non-programmable renewable sources could lead to the creation of temporary situations of vulnerability in the operation of the primary electricity system. Such situations could be due to temporary critical situations in the operation of the electricity grid caused by reduced regulation capacity, or control issues, as generation is distributed across several generators connected to distribution network. Under special operating conditions, such as periods of high irradiation and low energy consumption, it may be necessary to limit distributed generation's supply to contain its contribution to the voltage magnitude rise in the public grid. In order to ensure a correct composition of the generation park, a special procedure for the disconnection of distributed generation is adopted, which is called RIGEDI (Reduction of Distributed Generation). This plan was created to ensure the security of the national electricity grid and its smooth operation without being affected by the criticality of distributed generation. This procedure refers to the resolution by Italian energy authority AEEGSI 344/2012/R/eel of 2 August 2012, which approves Annex A72 to Terna's grid code, and deals with the provisions regarding the disconnection of wind and photovoltaic generators connected to the Medium Voltage (MV) grid. Terna, in order to guarantee the security pf the National Electricity System, uses the reduction of distributed generation deal with possible critical situations that could compromise the continuity and quality of the electricity supply service. The plan involves producers owing renewable energy generation plants connected to the medium-voltage grid such as the analysed campus, distributors, and Terna. If there is excess production from distributed generation on the electricity grid, Terna, in order to avoid grid congestion and grid collapse, orders distributors to disconnect the generation plant connected to the grid according to the plan established in RIGEDI. Remote disconnection therefore means the remote disconnection of plants producing energy from solar photovoltaic or wind power sources with a capacity of at least 100 kWp connected to the Medium Voltage grid from the distribution network.

The remote disconnection must allow the distributor to perform the following actions for each individual installation:

- Send the opening command, associating the date and time of disconnection and the date and time of restoration to the producer concerned;
- Acquire the opening confirmation, so as to have a confirmation of the successful opening operation;
- Send the reset command, so that the producer can resume service;
- Acquire diagnostic signals, so as to verify the correct functioning of the connection on the telecommunications network and if there are any anomalies on the telecommunications system;
- Acquire, associate or estimate an analogue measurement of the power the system produces.

As previously mentioned, the system installed on the campus is therefore one of the cases subject to remote disconnection. Should these situations arise, it is therefore necessary to guarantee the power supply of all loads on the campus using energy from the grid and the trigenerators.

Chapter 6

Optimization of the network management

6.1 Plant optimization

A Battery Energy Storage (BESS) is being installed on the campus as; a solution to further increase the energy efficiency of the microgrid and ensure greater resilience to power grid outages. Thanks to these batteries, it will be possible to store excess electricity produced during periods of low demand and release it when needed, further reducing dependency on the grid and optimising energy consumption. Should the electricity from the grid fail, the BESS will be able to provide backup power, thus helping to keep the main campus services and infrastructure running. In conjunction with the BESS, a hot water storage tank is also being installed. This will make it possible to store the hot water produced by recovering excess heat from the trigenerators during periods of lower demand and make it available when needed.

BESS

The BESS can switch from the "Grid Following" operating mode when connected to the grid as a power generator, to the "Grid Forming" stand-alone operating mode as a voltage generator. The BESS, by means of remote voltage measurements connected upstream of the DDIs on the incoming line side of the distribution grid, can recognise the grid status. If grid availability is detected, the load busbar is energised and the BESS is in "Ready" mode. Once energised, the BESS increases voltage and connects to the load bus, thus starting its parallel operation with the grid following. The BESS is now available for charging or discharging batteries. Using SCADA and the opening commands to the relays of the DDIs, it is possible to intentionally isolate the system when it is known that there will be a schedule grid outage. In such a case, the BESS instantaneously switches from "Grid Following" to "Grid Forming", thus controlling the voltage and frequency of the bus (protected bus). If the grid outage occurs in an unplanned mode, thanks to the continuous monitoring of the line, the system ensures that the BESS switches instantaneously (or with a possible pre-set delay so as to allow for possible grid self-closing) to the "Grid Forming" operating mode. In the event of a grid-side fault, the BESS can be programmed with timed opening curves of the DDIs so as not to feed the fault and ensure that the current flows to the loads and not to the grid. When the load bus is isolated from the grid, the BESS monitors its voltage and frequency. If the voltage measured upstream of the DDIs again confirms to the specifications defined by the grid code or by the user, the BESS increases the voltage and frequency busbar to match the corresponding grid values, initiating synchronisation. When grid-system alignment is achieved, the DDIs are closed by consensus signals and the BESS return to grid-following mode of operation as a current generator. The transition takes place without interrupting the supply of the load bus, which is now supplied by both the BESS and the grid.

The BESS being installed on the campus has a capacity of 3 MW of power and 4.5 MWh of energy, which will allow it to store and return a significant amount of energy to support load demands and increase the energy efficiency of the microgrid. The size of the BESS was chosen based on the loads that require continuous feeding; referring to the priorities assigned to each load (as in Table 4), it was therefore possible to detect a total priority power of 1 MW. The previously mentioned size was therefore chosen assuming that the campus, operating on an island mode, can power these loads with BESS alone for at least 4 hours. In any case, the use of trigenerators and the PV system in parallel with the BESS is envisaged on campus in the event of prolonged island operation. This installation makes it possible to cope with peak demand, improve grid stability and encourage the exploitation of renewable energy sources. The battery that will be installed are NMC/G, or Nickel Manganese Cobalt/Graphene; an advanced technology that combines the high energy density of NMC batteries with the improved characteristics that graphene provides. These batteries are ideal for high-capacity applications, such as the BESS that will be installed in the campus, as they offer extended life cycles, high efficiency and optimal performance even under intensive use.

Domestic hot water storage tank

A domestic hot water storage tank is being installed on the campus to increase the energy efficiency of the system and reduce its consumption. The new tank, with a capacity of 900 m^3, will ensure continuous availability and optimise the use of thermal energy in a sustainable way. Once installed, the storage system will be set to be supplied when the return water temperature beings to rise above 74°C and there is no demand for hot water produced by the recovery of exhaust gases and the cooling jacket of the trigenerators. When the hot water storage tank is not hot and the temperature of the exhaust manifold of the trigeneration recovery heat exchangers tends to excess 91°C, the hot water flow will be diverted to the storage system before the diverters to the radiators and the exhaust gas by-pass are activated. Once the tank reaches set-point, the controls will divert the excess heat to atmosphere.

When the temperature of the exhaust manifold of the trigenerator heat recovery exchangers falls below the set-point of 91°C and the storage tank is hot, the control system will supplement the hot water flow before the boilers are used for hot water. Thanks to the hot water storage tank, it is therefore possible to improve energy management and efficiency, and to reduce the share of excess heat that would otherwise be lost to the atmosphere, thus also leading to a further return in economics term.

6.2 O&M (Operation and maintenance)

To ensure system efficiency and safety, while minimising the risk of system failure and interruption, preventive maintenance of campus components is essential. Organising maintenance in structured way, including regular inspections, preventive actions and timely corrective actions, is essential to optimise the performance of the system and extend its life. The following are required on campus: preventive maintenance of the trigenerators, corrective maintenance to the monitoring and control systems, the direct control system (DDC), the supervisory control and data acquisition system (SCADA), electrical distribution system, power generation, communication infrastructure, lightening system.

Engines, generators and all auxiliary components are subject to preventive maintenance to ensure their efficient operation. Full routine maintenance of these components is carried out every 4000 hours of operation by specialised and qualified O&M (Operations and Maintenance) certified personal using O&M certified materials.

Employees are subject to training:

- On operation. Motor operation including knowledge of normal operating conditions with system parameters as well as any malfunctions or fault conditions of the system.
- On maintenance. Training on performance of maintenance operations at intermediate levels in multiples of 4000 hours, including spare parts and labour.

Maintenance for each trigenerator includes following components: dual-fuel (gas/diesel) engine, alternator, collector, the collector interface, the engine coupling, alternator and flywheel, all engine auxiliary and all electrical and hydraulic connections, and the control and supervision system. Finally, unscheduled maintenance related to "counter-parallel" is carried out on campus: on campus, in order to enable the automatic connection of the trigenerators to the main power grid, it is necessary to integrate the trigenerator control system with software and hardware to enable synchronism between the main medium-voltage switchgear and the main supply lines from the POD power substation. In addition to all maintenance-related operations, semi-annual environmental reports must be provided on the quantities of fuel used and quantities of waste produced to meet the environmental targets set by the campus.

Conclusion

This thesis analysed microgrid technology, an innovative energy system that represents a key solution to meet the challenges of the transition to a more sustainable and resilient energy model. In the first part, the main components of a microgrid were analysed, such as the energy generation and storage systems, control, monitoring and protection devices, dealing with the benefits, such as reliability and reduction losses, but also with the disadvantages, related to complex management and initial costs. Some of its main applications were also examined, ranging from industrial to residential and academic sector. In the second part, a specific practical application of a microgrid was analysed, a campus located in the province of Vicenza powered by a trigeneration system and a photovoltaic plant. By describing the structure of the system, it was possible to understand how the different energy sources can work together efficiently to meet the energy needs of the campus. It was also analysed how the microgrid is able to handle situations of grid failure or instability, guaranteeing the continuity of power supply to loads even in isolate mode. Finally, to optimise the performance of the microgrid, two installation improvements were analysed: a battery energy storage system (BESS) and the installation of a hot water storage tank. Thanks to these two improvements, it will be possible to further improve energy management, reducing production fluctuations and improving the overall efficiency of the system.

In conclusion, microgrids are confirmed as highly promising technology for local energy management, ensuring sustainability, efficiency and resilience. The proposed campus improvements and high-performance microgrid management systems could also foster an increasing penetration of these technologies, contributing to energy transition and decarbonisation goals.

Bibliography

1. Robert Liam Dohn (2011). The business case for microgrids. *The new face of energy modernization,* Siemens.
2. The distributed energy transformation. GE Power. (June 2018).
3. Siemens microgrid-infographic-en-final. Siemens.
4. Cogenerazione e Trigenerazione. CPL Concordia Group.
5. S. Ghettini (2023). OPTIMAX Microgrid Controller. ABB Digital Solutions.
6. (January 2009). Criteri di protezione delle reti elettriche di media tensione. *Guida Tecnica ABB,* ABB.
7. (October 2009). Utenti attivi secondo norma CEI 0-16. *Guida Tecnica ABB,* ABB.
8. (April 2009). Soluzioni per l'adeguamento alla norma CEI 0-16. ABB.
9. (March 2023). Regola tecnica di riferimento per la connessione di Utenti attivi e passivi alle reti AT ed MT delle imprese distributrici di energia elettrica. *Norma Italiana CEI 0-16.*
10. Ing. Gabriele Carrescia, Ing. Marco Carrescia (n. 3, March 2022). Guida all'applicazione delle norme nel settore elettrico. *Tutto Normel.*
11. Andrè Sastre (May 1996). Protection of industrial and commercial MV networks. *Cahriers technique n. 174,* Merlin Gerin, Group Schneider Electric.
12. Design documents provided by the consumers on the analysed installation.

Sitography

1. Schneider Electric: https://www.se.com/it/it/work/solutions/microgrids/#:~:text=Una%20microgrid%20%C3%A8%20una%20rete,utilizzarla%20quando%20%C3%A8%20pi%C3%B9%20necessaria
2. Enel: https://www.enelx.com/it/it/faq/cos-e-una-microgrid
3. Linkedin: https://www.linkedin.com/pulse/microgrids-environmental-social-costs-importance-olatunji--gq2ce
4. NREL: https://www.nrel.gov/research/learning.html
5. Enel Green Power: https://www.enelgreenpower.com/it/learning-hub/energie-rinnovabili/impianti-storage
6. Svizzera Energia: https://www.svizzeraenergia.ch/programmi/segui-la-corrente/ricarica-bidirezionale/
7. SIELCO Sistemi: https://www.sielcosistemi.com/it/cosa-%C3%A8-scada.html
8. eSolare: https://esolare.it/cosa-e-un-inverter-come-funziona/
9. News Energia: https://newsenergia.com/certificazione-spi-delibera-786-prove-in-campo-cassetta-rele-0322.html

10. ABB:
    https://new.abb.com/low-voltage/it/soluzioni/selettivita/definizioni-principali/tecniche-di-selettivita#:~:text=Questo%20tipo%20di%20selettivit%C3%A0%20si,a%20diversi%20valori%20di%20corrente
11. BIT Stream:
    https://bitstream.pl/it/news/introduzione-alla-norma-iec-61850-informazioni-sintetiche-sullo-standard-e-sui-suoi-requisiti/
12. Energy Pool:
    https://www.energy-pool.eu/en/what-is-a-microgrid/
13. Reads Alibaba:
    https://reads.alibaba.com/it/everything-you-need-to-know-about-microgrid-off-grid-applications/
14. Wartsila:
    https://www.wartsila.com/docs/default-source/energy-docs/technology-products/product-leaflets/wartsila-34df.pdf?sfvrsn=add2a345_19
15. Industrial Marine Power:
    https://www.industrialmarinepower.com/w%C3%A4rtsil%C3%A4-34df-main-technical-data-wartsila-6l34df-9l34df-16v34df-20v34df---/
16. Maddox:
    https://www.maddox.com/resources/articles/how-to-manage-transformer-inrush-current#:~:text=is%20Inrush%20Current%3F-,Inrush%20current%20is%20the%20high%20current%20that%20a%20transformer%20draws,primary%20winding%20of%20the%20transformer

17. Online-UPS: https://www.online-ups.it/wp-content/documenti/Articoli%20tecnici/disturbi-sulla-rete-elettrica-ed-effetti-sugli-apparati-informatici.pdf
18. E-distribuzione: https://www.e-distribuzione.it/Azienda/Rete/riduzione-generazione-distribuita.html
19. Schneider Electric: https://www.studiecd.dk/cahiers_techniques/Protection_of_industrial_and_tertiary_MV_networks.pdf
20. DigiKey: https://www.digikey.it/it/articles/using-electrification-more-efficient-sustainable-power-grids-part-1
21. Flyfine Battery: https://flyfinebattery.com/microgrid-system-solution/
22. Fortress Power: https://www.fortresspower.com/microgrids-help-community-reach-energy-goals/
23. Voronoi: https://www.voronoiapp.com/energy/Battery-Costs-Have-Fallen-by-More-Than-90-Since-2010-1165

Ai miei genitori,
A mio fratello Nicholas,
A mia sorella Noemi.

Voi che ci avete sempre creduto,
forse anche più di me,
spero di rendervi orgogliosi ogni giorno come oggi.

Some people STOP because it's hard.
Some people START because it's hard.