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School of Industrial and Information Engineering

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THE IMPACT OF RENEWABLE ENERGY ON VOLTAGE STABILITY AND FAULT LEVEL IN POWER SYSTEMS

Advisor: Prof. Alberto BERIZZI

Co-advisor: Prof. Cristian BOVO

Master thesis of:

Luca VIGNALI

ID 940649

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ABSTRACT

Power systems are experiencing an important period of transition, characterized by an ever-growing need for energy together with an increasing Renewable Energy Sources (RES) penetration, which has given rise to issues never introduced before in traditional grids. One of that is voltage instability, consequent to the progressive reduction of fault level due to limited short-circuit current contribution of inverter-based generation plants, that in turn implies some troubles concerning protections, not being able to operate properly with fault currents of 1.5-2 times the nominal one.

In the described backdrop, this work of thesis aims at analysing the impact of RES on voltage stability and their influence on short-circuit power, trying to investigate possible solutions and improvements of the condition, among others RES operated at not-unitary power factor. Firstly, voltage regulation will be considered, compensation methods will be examined, and how to achieve improvements with RES in this sense will be discussed; then, short-circuit analysis will be focused, examining directly the non-linear RES behaviour under fault: an innovative short-circuit method considering their contribution will be presented, which will be exploited to perform some simulations with MATLAB in different scenarios, to verify what stated in theory and discuss a possible extension of Italian grid code.

In order to carry out these studies, the Sicilian network has been considered as testing grid, given its weakness, low load and high-RES production, shapes that have often resulted in operating issues, and hence make it the ideal context to investigate impact of RES and test different Fault Ride-Through control strategies.

In addition, taking advantage of simulation results and by consulting the point of view of important figures in the sector, the evolution of grids is overviewed, trying to outline a perspective about future power systems in accordance with the more and more imperative climate neutrality target.

ABSTRACT IN ITALIANO

Un importante cambiamento si sta concretizzando nel settore dell’energia e in particolare dei sistemi elettrici, che ha come principale peculiarità la diffusione delle Fonti di Energia Rinnovabile (FER). Ciò ha dato luogo a notevoli problematiche mai presentatesi nelle reti tradizionali: una di esse è l’instabilità di tensione dovuta al calo del livello del guasto; questo inconveniente è causato dal limitato contributo di corrente di cortocircuito delle FER connesse tramite inverter. Inoltre, in presenza di così limitate correnti e con l’aumento delle FER, insorgerebbero difficoltà di rilevamento del guasto da parte delle protezioni, il cui appropriato funzionamento non sarebbe più garantito.

In tale contesto, questo lavoro di tesi si propone di analizzare l’impatto delle FER sulla stabilità di tensione e l’influenza che tali sistemi di generazione hanno sulla potenza di cortocircuito, in modo da discutere e verificare possibili soluzioni ed ottimizzazioni, tra cui le FER operate a fattore di potenza non unitario. Inizialmente si tratterà la regolazione di tensione, si esamineranno i metodi di compensazione e si discuterà come raggiungere miglioramenti in questo senso sfruttando le FER; dunque, ci si focalizzerà sull’analisi del cortocircuito, in particolare sul comportamento non lineare delle FER sotto guasto, presentando un innovativo metodo di calcolo che tenga conto del contributo delle FER stesse. Tale procedura verrà sfruttata per effettuare alcune simulazioni MATLAB in scenari differenti, verificando nella pratica quanto analizzato e discutendo possibili estensioni del codice di rete italiano.

A tal fine, si è considerata la rete siciliana, in quanto la sua debolezza, il suo basso carico e la sua considerevole generazione di FER la rendono un perfetto scenario per valutare il loro effetto sul cortocircuito e testare varie strategie di Fault Ride-Through. Infine, tramite i risultati delle simulazioni e considerando il punto di vista di aziende importanti del settore, si definirà il futuro dell’evoluzione dei sistemi elettrici in concomitanza con i sempre più urgenti obiettivi di neutralità climatica.

INTRODUCTION

An Overview on Nowadays Italian Power System

The Italian electricity sector is experiencing a quick evolution within a wide energy transition, whose goal is the achievement of sustainability and safety of the system. The most significant elements of the new paradigm are Renewable Energy Sources (RES), which are becoming more and more important to reach the decarbonisation of the energetic system: in particular, the two common key targets are climate neutrality until 2050 and reduction of emissions up to 55% until 2030. Moreover, this will be accompanied by other innovations, such as digitalisation of the network, storage systems employment and electric vehicles integration. This is leading to a transition from the traditional "one-way" system (production, transmission, and distribution loads) to a more complex and integrated system with flows of electricity in multiple directions, high volatility, and low predictability.

For this reason, the main European Transmission System Operators, such as Terna, are redesigning strategies and investments on networks, especially taking into account the strong impact of renewables development.

In fact, the advanced electric power system of tomorrow will be characterized by power electronics, computers, large communication systems, and artificial intelligence. These new technologies will improve system availability, reliability, power quality, energy efficiency, and security, allowing a better management of the variable generation of RES and all its consequences, and also optimizing the electrical energy dispatch from the economical point of view.

Renewable Sources Issues

The high and spreading penetration of RES in power systems is leading to new issues in terms of grid handling and control. In particular, challenges can be divided in two categories, which involve the main quantities of interest in power systems: frequency and voltage. Actually, renewables cannot be totally scheduled, since they depend on natural phenomena, such as wind, solar radiation or water flows from rivers and precipitations; hence, resource availability cannot perfectly match with system requirements at all times. Therefore, the result is a variable generation, whose consequence is irregular injected active power into the grid and, consequently, variable voltage and frequency imbalances.

These issues are particularly present in photovoltaic and wind generation because hydroelectric design and production are based on natural features of territory, measurements, statistics, and long-term forecasting in order to estimate the water availability and, as a consequence, to work at constant power. Moreover, the production of these plants takes place by means of synchronous generators, such that they can be considered as “traditional power plants”.

On the contrary, photovoltaic parks and wind farms are connected to the grid through inverters, whose behaviour is completely different with respect to synchronous generators. In fact, inverter current contribution is strictly limited to protect semiconductor valves; consequently, its contribution to short-circuit is significantly reduced with respect to the synchronous machine one. Hence, inverter-based grids have low short circuit power, that means they suffer of voltage instability and little perturbations are enough to generate voltage imbalances, which can propagate at great distances.

Furthermore, renewables generation is usually carried out on medium and low voltage radial distribution grids, whose impedance is higher than high voltage meshed network, causing an additional aggravation of the condition. Given that this type of generation is intermittent and irregular by itself, as described above, the result is a weak and unstable network.

These voltage instabilities need to be compensated by means of significant employment of reactive power (voltage is much less sensitive to real power in transmission grids). Nevertheless, in the Italian network, wind and photovoltaic power plants were traditionally asked to operate at unity power factor in the past, exploiting their limited current to feed loads with active power, sharpening reactive capability issues. This is another important difference between inverter and synchronous generator, which, on the contrary, can be over-excited or under-excited in order to manage reactive power flow, exploiting its remarkable current contribution to perform both tasks. In fact, it can supply active and reactive power without particular restrictions (except for their capability curves); in other words, voltage regulation can be carried out regardless of active power flow. Therefore, in grids with high penetration of RES, a lot of compensation methods are required to control reactive power.

Moreover, power generation near loads is a total revolution with respect to traditional power system structure, where voltage followed a decreasing trend from power plants to loads; therefore, recalling what previously explained about the irregular voltage behaviour, it can happen that, especially in presence of great availability of sources (for example, in a hot sunny day), injected power is so high that overcomes power consumed by loads; consequently, loads voltage is greater than upstream power plants. This phenomenon can bring to an inversion of power flow, that is particularly problematic for radial distribution grids, which in the past were not designed for that, giving rise to protection and control issues.

The decrease of total current (due to substitution of traditional plants, especially thermal ones, with RES) can negatively affect protections and circuit breakers, which have been designed for higher current values. In particular, circuit breakers could no longer be able to detect the presence of a fault, given the limited inverter current contribution. Furthermore, protections of distribution grids are set for the maximum current; thus, a general decrease of fault level could make necessary a revolution of the protection paradigm, if fault currents cannot be kept high enough. In addition, low inverter current involves troubles not only regards fault detection, but selectivity as well.

Concerning fault, the inverter behaviour is not linear because, as previously mentioned, it strictly depends on voltage on its terminals: current is limited to protect valves, hence its short-circuit current contribution can vary in different scenarios; in addition, if voltage is too low for too much time, the breaker must be open to protect the converter and because usual “Grid Following” inverters are not able to work imposing voltage and frequency on their own. Nevertheless, in last years distributed generation power has become a great amount of the total production: therefore, separating RES from grid in case of fault could be an additional aggravation of the condition, because frequency and voltage would collapse even more disconnecting so many generators during faults. For this reason, nowadays renewables power plants are expected to remain connected during faults (Low Voltage Ride-Through), contributing to voltage regulation as well injecting or absorbing reactive power, not only during normal operation but even during faults, in order to avoid voltage to collapse and, in addition, to help fault detection with their current contribution.

In other words, no longer operating at unitary power factor, RES can mitigate perturbations due to their intermittent nature and offer services to grid during faults as well. Consequently, given their role and their increasing quantity, they can no longer be neglected in short-circuit computations.

This work of thesis aims at analysing the impact of renewable sources on the system voltage stability, evaluating their contribution to short-circuit power and fault level. Due to inverter non-linear behaviour during short-circuit, it is important to analyse how voltage regulation is carried out and how inverters are exploited to perform that, since their operative condition and control mode will affect their attitude during outages. Their behaviour to perform that regulation is established into the Grid Code by Transmission System Operator (TSO). Therefore, a new iterative method for the short-circuit computation has been used as an upgrade to the traditional linear procedure of computation based on Thévenin theorem. In order to study RES impact and their contribution during faults, Sicilian network has been chosen, since it is a perfect example of weak not-meshed grid with low load and high penetration of RES.

There are a lot of supplementary issues concerning Renewables Sources: for example, their fluctuation of injected power negatively affects system frequency. That trouble is emphasized by a further drawback with respect to synchronous generators: the absence of inertia. In fact, low inertia means less tolerance to variations of loads or, as in case of RES, of generation, implying more oscillations and frequency perturbations. Inertia stands at frequency as short-circuit power stands at voltage:

inertia is dual to short-circuit power. Nowadays, some methods to provide the so-called "synthetic inertia" and frequency control is carried out by means of inverters and power electronics. However, in this work of thesis, only issues related to voltage and reactive power are going to be analysed.

Finally, to complete the description of renewables challenges, converter currents have bad contents of harmonics; hence, concepts as power quality and Total Harmonic Distortion (THD) have become important in order to avoid voltages and currents with bad waveforms to flow into the power system.

Ultimately, it is worth adding that, concerning short-circuit analysis, this work of thesis has been developed starting from ideas and hints described in [20] of first chapter bibliography. In particular, three scenarios characterized by different inverter control modes have been reconsidered, and the idea of the algorithm reassessed. Then, all MATLAB calculation programs have been carried out ex novo, resulting in remarkable improvements regarding computation time, accuracy of results and the never failed convergence with respect to [20]. Then, further new calculation programs have been planned and used in other scenarios characterized by a different power system and different converter technologies, as will be described throughout the last chapter.

CHAPTER 1

VOLTAGE REGULATION

1.1-General Features

In power systems, voltage is one of the elements which characterize supply service quality. Considering that the main duty of the system is to supply loads and make them to work in their best efficiency condition, it is crucial that, despite all variations and perturbations, every part of the grid is supplied at its nominal voltage. Moreover, lower voltage values involve more active power losses and therefore a worse transmission quality.

The Voltage Regulation is constituted by all the operations intended to keep voltage in a small range of values with respect to the nominal one. In contrast with frequency balance, which depends on global difference between injected and absorbed power in the entire system, voltage regulation effects are mainly local, and they are principally carried out exploiting reactive power flows.

With reference to figure 1.1-1 and 1.1-2:

$$\overline{V_1} = \overline{V_2} + jX_L \cdot \bar{I}$$

since that:

$$P = v \cdot i \cdot \cos\varphi$$

$$Q = v \cdot i \cdot \sin\varphi$$

From the vectorial diagram of figure 1.1-2 it can be deduced:

$$X_L \cdot I \cdot \cos\varphi \; = \; V_1 \cdot \sin\delta$$

$$X_L \cdot I \cdot \sin\varphi = \; V_1 \cdot \cos\delta - \; V_2$$

Therefore, system power flows equations are equal to:

$$P = v \cdot i \cdot \cos\varphi = \; \frac{V_1 \cdot V_2 \cdot \sin\delta}{X_L}$$

$$Q = v \cdot i \cdot \sin\varphi = \; \frac{V_1 \cdot V_2 \cdot \cos\delta - \; {V_2}^2}{X_L}$$

Considering that in power systems the differences of phase angles δ are kept small in order to maintain the stability, it can be assumed:

$$\sin\delta \; \cong \delta \, ; \; \cos\delta \; \cong 0$$

Hence, it is clear from the procedure above how the variation of active power is directly proportional to phase shift δ, and therefore to the frequency; instead, the injected reactive power mainly depends on the voltage magnitude on load bus. Moreover, since phase-shift needs to be kept as low as possible, in order to maximize the power transmission is necessary to increase the product of voltages at the ends of the line.

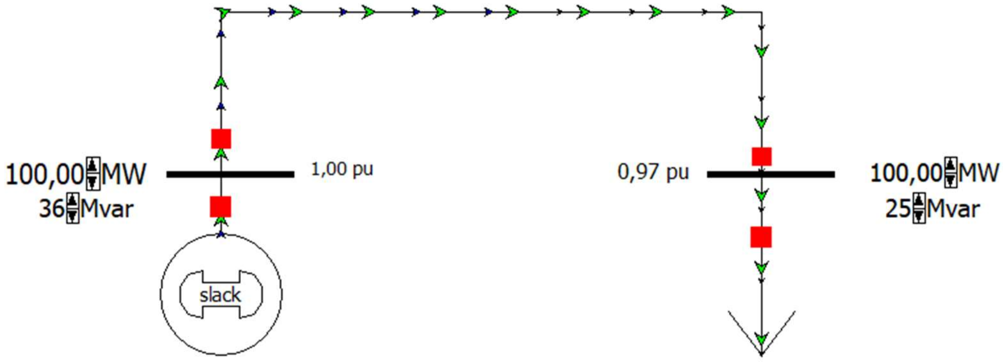


Figure 1.1-1*: PowerWorld simulation of an ideal line (no losses)*

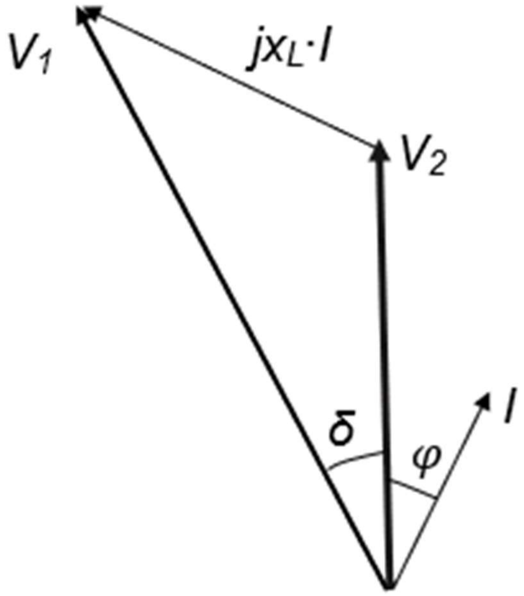


Figure 1.1-2*: vectorial diagram of the considered system*

1.2-Regulation Strategies

It is clear, as showed in the previous section, how magnitudes of system bus voltages are directly proportional to variation of reactive power, and how is crucial that they remain as high as possible (or better, as near as possible to the nominal value) in order to reduce losses and supply loads properly.

The regulation of voltage magnitude can be carried out in a few ways. The most immediate is by means of synchronous generators, which can be over or under-excited to inject or absorb reactive power, respectively. It is performed by the Automatic Voltage Regulator (AVR), which acts on the exciting current of the generator excitation system, according to limits dictated by its capability chart.

This procedure is particularly useful in context of variation of loads as it happens from day to night: during the day, a lot of loads are supplied by network and the power flowing is greater than grid characteristic power; thus, there is a prevalence of inductive component and grid absorbs reactive power, behaving as an inductor. Consequently, voltage tends to decrease, and it is necessary to compensate the reactive power over-exciting generators and keeping voltage magnitude of power plants above the nominal value.

On the contrary, during night, the grid is unloaded, hence power flowing is less than grid characteristic power and the capacitive component tends to prevail; thus, the grid behaves like a capacitor, producing reactive power. As expected, voltage tends to increase near loads, therefore synchronous generators are under-excited to absorb reactive power and to avoid voltage to extremely exceed the nominal value. This grid phenomenon is called “Ferranti effect”.

Another method to compensate for varying voltage drops and to control reactive power flow consists in exploit transformers with variable ratio installed in HV/MV stations, in order to raise the voltage of secondary side by changing the transformation ratio during high load demand or, vice versa, to decrease it. They can be of two types: On-Load Tap Changers (OLTC) and No-Load Tap Changers (NLTC). The latter configuration requires the disconnection of the transformer when tap setting has to be changed, therefore is a choice to be adopted only in case of uncommon voltage variations.

This is the reason why usually in high voltage power stations transformers are equipped with OLTC. Transformers may also be used to control phase angle and active power.

Nevertheless, the reactive power compensation by means of synchronous generators has some drawbacks: in particular, in long lines, reactive currents all along the conductors give rise to significant voltage drops and overload the system. Therefore, an efficient solution is to compensate reactive power locally, injecting it near loads, especially since reactive compensation effects are mainly local.

Consequently, reactive currents in the grid are reduced, and the efficiency of transmission improves, given that voltages on loads increase. In other words, the voltage drops all along the transmission line can be reduced.

In order to analyse this scenario, the following procedure has been considered.

With reference to figure 1.2-1 and considering the long line generic case:

$$\bar{V_1} = V_2 \cdot \cos(\beta a) + j\frac{XP}{V_2} + \frac{XQ_2}{V_2}$$

Recalling what previously mentioned about negligible phase-shifts, it can be derived:

$$V_1 - V_2 \cdot \cos(\beta a) \cong \frac{XQ_2}{V_2}$$

i.e., a voltage drop equal to:

$$\Delta V = V_1 - V_2 \cong \frac{XQ_2}{V_2} - V_2[1 - \cos(\beta a)]$$

Considering that β and a are parameters of the line itself and V_2 is assumed constant, since V_2 is the nominal voltage on load, the only control variable to modify the voltage drop along the line is Q_2. In case of short lines, the second term is equal to zero, since capacitive susceptances are negligible and $\cos(\beta a) \approx 1$, and relation between reactive power and voltage is even more evident.
This is the complete explanation which confirms what was introduced at the beginning of this chapter $(\Delta V \propto \Delta Q)$.

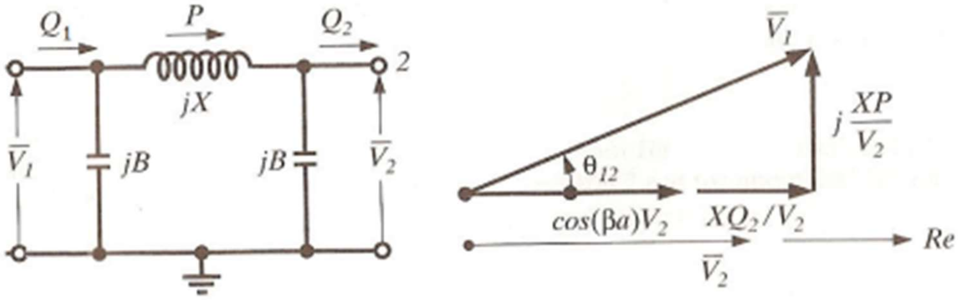


***Figure 1.2-1**: equivalent circuit of long line and corresponding phasor diagram*

Now that is clear how reactive power is totally linked with voltage drop and it plays a key role in voltage regulation of power systems, reactive compensation strategies in order to regulate the system voltage will be discussed.

1.3-Reactive Compensation Methods

In this section, reactive power compensation methods to regulate voltage are analysed. Firstly, synchronous generators and static condenser are treated; then, an overview on new technologies based on power electronics and semiconductors, such as Static Var Compensators (SVCs) and Static Synchronous Compensators (STACOMs), is provided (the principle of shunt compensation is shown in figure 1.3-1).

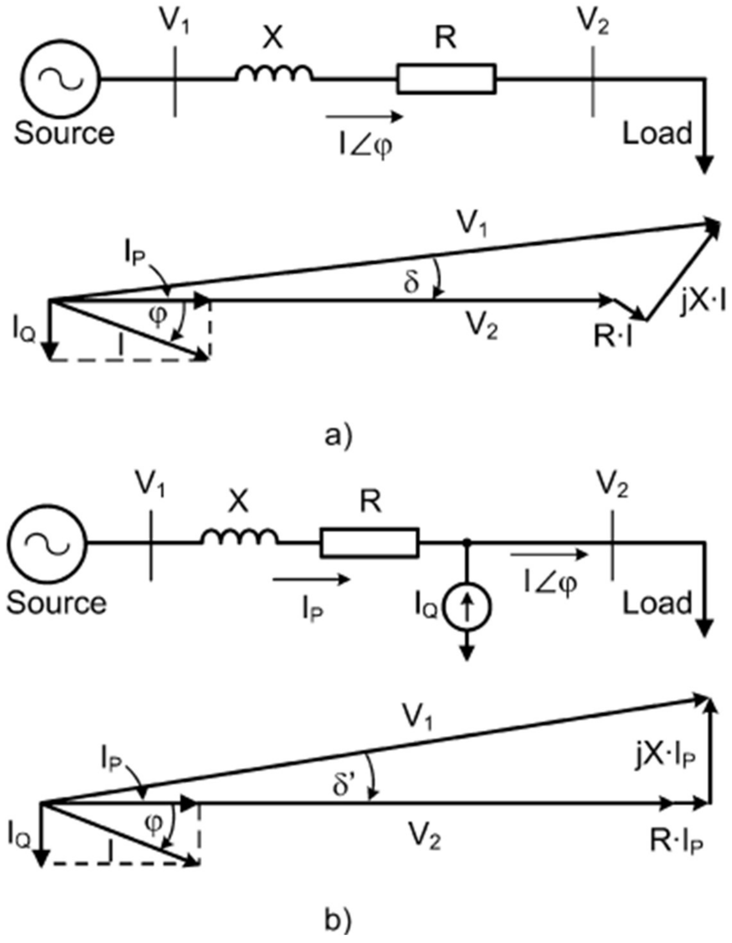


Figure 1.3-1: principle of shunt compensation in a radial ac system. (a) without reactive compensation. (b) shunt compensation with a current source

1.3.1-Synchronous Generators

Synchronous generators are the backbone of power systems. They are driven by turbines to generate power, and they can compensate reactive power at the same time. The generator excitation system keeps busbar voltage in the range of interest and controls reactive power flow: in fact, as previously mentioned, synchronous generators can inject or absorb reactive power regulating excitation current.

They are reliable machines with high overload capability, a good ability to withstand large perturbations such as faults, they can provide a continuous regulation, and their “electric strength” is also demonstrated by their high current contribution, especially during short-circuit, which is an important feature concerning voltage stability, as will be explained later.

Synchronous generator operating conditions are described by its capability curves (figure 1.3-2), which define operational areas concerning field current, armature current, active and reactive power for every framework. Current limits are mainly due to heating issues and, in case of under-excitation limit, instability as well. However, current limits are high, especially with respect to an electronic converter.

Moreover, reactive power output capabilities of SVCs and STATCOMs decrease as squared voltage and linearly with voltage, respectively. On the contrary, the high alternator overloadability allows it to significantly increase the output current for few seconds even in drastic conditions.

The result is a constant reactive injection even as voltage dramatically decreases. In this way, the voltage drop on terminals is compensated by sudden increase of voltage in direct current excitation system, remarkably increasing the stability of the machine during perturbations.

The maximum reachable voltage level is called “positive ceiling voltage”. In order to implement that strategy, the AVR response time has to be fast.

In figure 1.3-3, the equivalent circuit of synchronous generator, with related Behn-Eschenburg diagram, is shown.

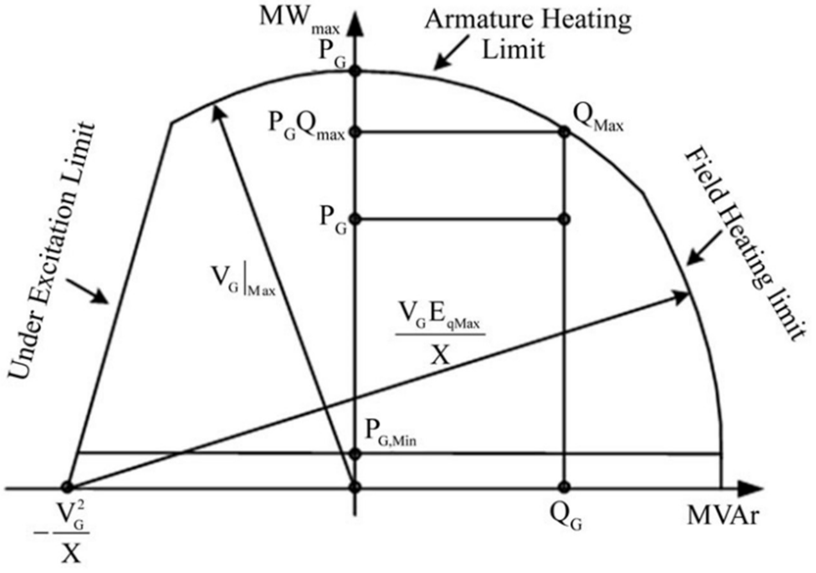


Figure 1.3-2*: synchronous generator capability curve*

Some operative conditions of interest from the practical point of view are:

- Synchronous Condenser injecting only reactive power, as known as “pure over-exciting”;
- Synchronous Condenser absorbing only reactive power, as known as “pure under-exciting”;
- Operating injecting active power only;
- Operating absorbing active power only, as known as “motor or pure pumping”.

The first two conditions are used to regulate voltage, and not only power plants alternators work accordingly, but moreover a lot of synchronous machines are used only for this purpose, working without any turbine or prime mover system.

Synchronous Condensers (SC) are strength and robust machines, but they are characterized by high costs, high time response, they require dedicated protections for their not negligible starting current, especially for their short-circuit current contribution (that in this case is a drawback), their losses are higher than those of static compensators and, moreover, they imply a lot of maintenance with respect to static compensators themselves [3]. Consequently, in last years, SC have been gradually replaced by innovative solutions based on power electronic converters, especially considering their faster controllability.

Nevertheless, not totally, and now they are regaining significance. For example, as explained in [1], Terna is reconsidering a traditional solution as SC in a modern key.

SC can help with reactive power needs, in addition being able to temporarily provide high reactive power overload, for example for voltage dip mitigation. They increase short-circuit strength with a good current contribution and they provide inertia to the system. Furthermore, SC can prevent harmonic resonances from being shifted towards lower frequencies and, coming back to their stability features, they assure better dynamic voltage recovery after severe system faults.

These are very important features, especially in presence of high penetration of RES and power electronics, just like modern grids. In fact, in Italy, the value of these devices has increased by integrating intelligently their local and remote SCADA control system, combining them with power electronics-based compensation devices as well [2]. Their comeback in vogue in power systems with high-RES penetration is described also in Terna’s Development Plan of 2021 [15].

In addition, there is a variant of SC called Adjustable Speed Synchronous Condenser, which is constituted by a doubly fed induction motor with a back-to-back converter connected to the rotor; it allows to control both reactive and active power to regulate both frequency and voltage.

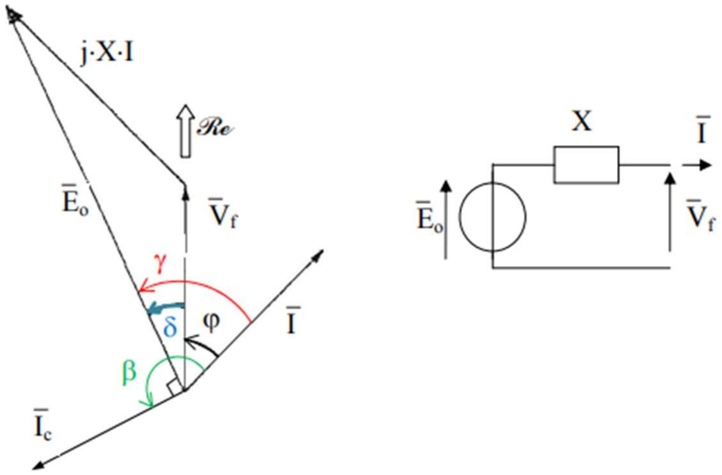


***Figure 1.3-3**: Behn-Eschenburg construction of synchronous generator with related equivalent circuit (negligible resistive voltage drop)*

1.3.2-Capacitors, Reactors and Static Var Compensators

The most common way to compensate reactive power locally is by means of capacitor batteries; especially in case of low and medium voltage grids, in order to adjust the power factor of loads and to avoid paying an over-price on energy supplied by the distributor.

Instead, reactors are used in particular cases of excessive reactive power to be absorbed: for example, in case of underwater AC lines, the proximity of the cables to the seabed make the capacity component to prevail; for that reason, it is necessary to absorb it in order to avoid over-voltages. In fact, usually long underwater lines are in DC. An example of AC underwater lines is right in the grid considered for this work of thesis, in correspondence of the connection between Sicily and Italian peninsula.

Nevertheless, in general, fixed passive components do not allow to obtain a dynamic and variable regulation; hence, they are not used specifically to regulate reactive power flow, especially in high voltage applications.

A good option to obtain the desired dynamic regulation consists in choosing compensators based on static electronic converters, such as Static Var Compensators (SVCs): they are made by capacitors and/or reactors, but they are connected to the grid by means of semiconductor valves, as for example thyristors.

According to that methodology, reactive power can be varied continuously despite the utilization of passive elements. Nevertheless, the absence of active components reduces the effect in case of low voltage regulation since the injection is proportional to the square of the grid voltage magnitude.

These converters can be of two types: Thyristors-Controlled Reactors (TCR), and Thyristor-Switched Capacitors (TSC).

TSCs are made by capacitors turned on and off by thyristors, resulting in a variable, but discontinuous, regulation (figure 1.3-4). They are usually in series of an inductance, in order to avoid resonance with the grid and to reduce inrush currents.

In this case, inrush current is already dramatically reduced with respect to fixed condensers: in fact, capacitors are connected to the network by choosing the moment in which the difference between their charging voltage and the grid one is the lowest possible. Condensers are kept charged at maximum or minimum grid voltage when are disconnected; therefore, when the connection takes place again, the transient component is about zero and, moreover, generation of harmonics is very reduced.

TCRs instead are based on reactors, which allow a continuous and smooth regulation with respect to TSCs (figure 1.3-5). Furthermore, since reactors absorb reactive power, they are usually coupled with fixed capacitor banks to inject it in case of need. In addition, reactors do not need to wait for the correct connection moment to avoid inrush current, since they do not accept sudden current peaks.

Consequently, they allow a faster regulation with respect to TSCs. Nevertheless, in order to avoid bad harmonics content injected into the grid, especially low frequency harmonics, filters are necessary. Although it is possible to keep a proportionality between reactive power and terminal voltage during normal operating conditions, at its limits TCR is equivalent to a simple capacitor or an inductor.

The result is reactive power to be a function of squared voltage, as previously introduced. Thus, voltage regulation capability is reduced if compared to voltage source-based technologies.

A configuration exploiting both advantages (continuity for TCR and wide operative range for TSC) can be chosen combining TCR and TSC. Clearly, it is a more expensive solution, but in some cases may worth.

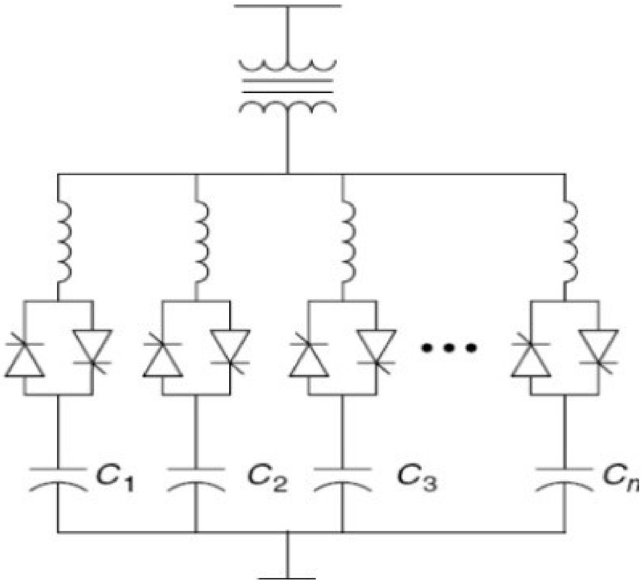


***Figure 1.3-4**: TSCs connected to the grid. Series inductances are to limit inrush currents*

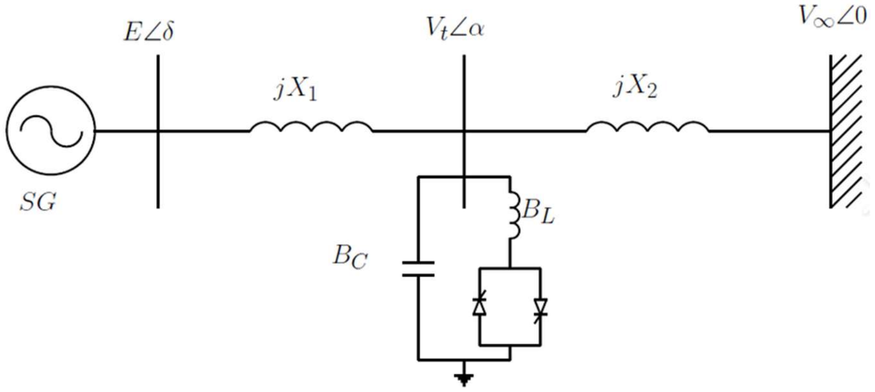


Figure 1.3-5: *TCR with fixed capacitor connected to a power system bus*

1.3.3-Static Synchronous Compensators

The improvements in semi-conductor valves and power electronics have made possible the development of high-power static converters that can be used in order to regulate voltage in power systems.

Static Synchronous Compensator (STATCOM) is an example of this technology: it is a regulating device based on voltage-source inverter and it is used to reduce voltage fluctuations supplying or absorbing reactive power.

As can be appreciated in figure 1.3-6, STATCOMs usually can be based on 2-level or 3-level voltage source inverters. They can also inject active power if equipped with an energy source on DC side. Instead, if they are only expected to compensate reactive power, a capacitor is enough. It can be charged absorbing real power from the grid.

Being electronic converters, they need filters to avoid injecting current with bad content of harmonics into the network. They can be controlled in several ways, from classic sinusoidal PWM to multi-pulse as in multi-level converters, widely used in power systems, especially in case of large amount of power, voltage, and current, as for example in HVDC (they are called Modular Multilevel Converters), in order to improve output sinusoidal waveform and reduce commutation losses.

STATCOM and inverter control drives will be explained in the next section.

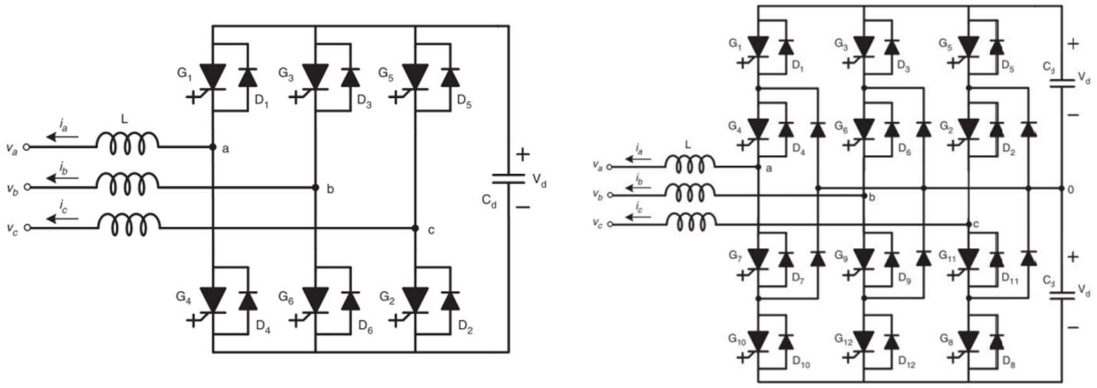


***Figure 1.3-6**: From left to right: 6-pulse VSI 2-level compensator and 3-level VSI compensator*

Since the number of passive components (reactors and capacitors) is very reduced with respect to SVCs, STATCOMs require lower capacities for the semiconductor switches; in addition, they are characterized by reduced size, space, and costs, that are the main advantages of these devices. Moreover, they are very fast and accurate in regulation, much more than methods described above.

Furthermore, they can regulate reactive injection regardless of system voltage (reactive injections of passive components are proportional to square of voltage grid). STATCOM generates a voltage waveform in phase with grid voltage one: if the first is larger in magnitude than the latter, the compensator generates reactive power; on the contrary, if it is smaller, the reactive power is absorbed.

Nevertheless, as already introduced, they linearly lose regulation capability when point of common coupling (PCC) voltage decreases too much: they cannot be overloaded in order to protect semiconductor valves, and their consequent limited current contribution does not provide a substantial contribute to the short-circuit power. In fact, in case of fault, STATCOM behaves as a controllable current source injecting its maximum current capability [2]. This is the typical inverter behaviour during faults, and it will be reconsidered later during short-circuit analysis. Thus, in case of dramatic voltage drops, STATCOM control capability is reduced.

Besides, they have not inertia, unless they are equipped with energy storage systems such as batteries or supercapacitors. In that case, inverters can provide active compensation to reduce frequency imbalances and mitigate active power perturbation, particularly emphasized in grids with high penetration of RES, delivering the so-called "synthetic inertia" and supporting the frequency regulation.

The active power can be regulated varying voltage phase shift with respect to the grid. If inverter voltage leads the grid one, STATCOM injects power into the network; on the contrary, power flows into the compensator recharging the capacitor.

Actually, STATCOMs reveal typical electronic converters issues; that is not surprising, since they are based on inverters. For these reasons, STATCOMs are often combined with other solutions to compensate voltage drops. For example, as widely explained in [2] and mentioned above, combination of STATCOMs and Synchronous Condenser is spreading in order to exploit benefits of both technologies. The connection of STATCOM and Synchronous Condenser at the same PCC is known as Hybrid Synchronous Condenser or Hybrid Synchronous Compensator (figure 1.3-7).

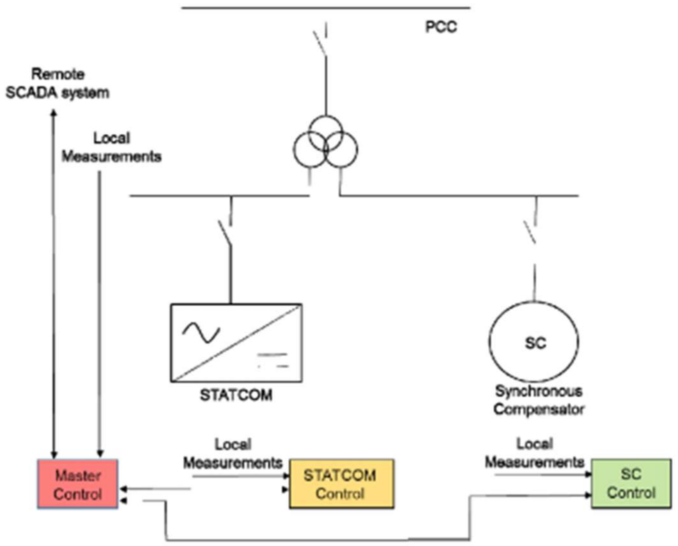


Figure 1.3-7: *simplified single-line diagram of a Hybrid Synchronous Condenser*

1.3.4-Comparison between Compensation Methods

Having regard to the above considerations, and taking into account analysis and comparison explained in [3], compensation methods based on semiconductor valves and static converters are more efficient than SC in terms of response time, control flexibility, accuracy of compensation, losses, costs, and maintenance, especially

STATCOMs: the introduction of self-commutated topologies based on IGBT and IGCT semiconductors produced a dramatic improvement in the performance of Var compensators, resulting in faster dynamic behaviour, and possibility to control more variables.

Nevertheless, SC provide support to the grid by means of inertia, harmonics, and moreover, of major interest regarding this voltage regulation analysis, providing a greater current contribution in short-circuit and a major capability of reactive control in case of voltage dips.

Therefore, it is clear how the falling fault level in power systems due to spreading penetration of RES is making more and more essential the role of synchronous machines.

In conclusion of this comparison, reactive current capabilities of different compensation methods are shown in figure 1.3-8.

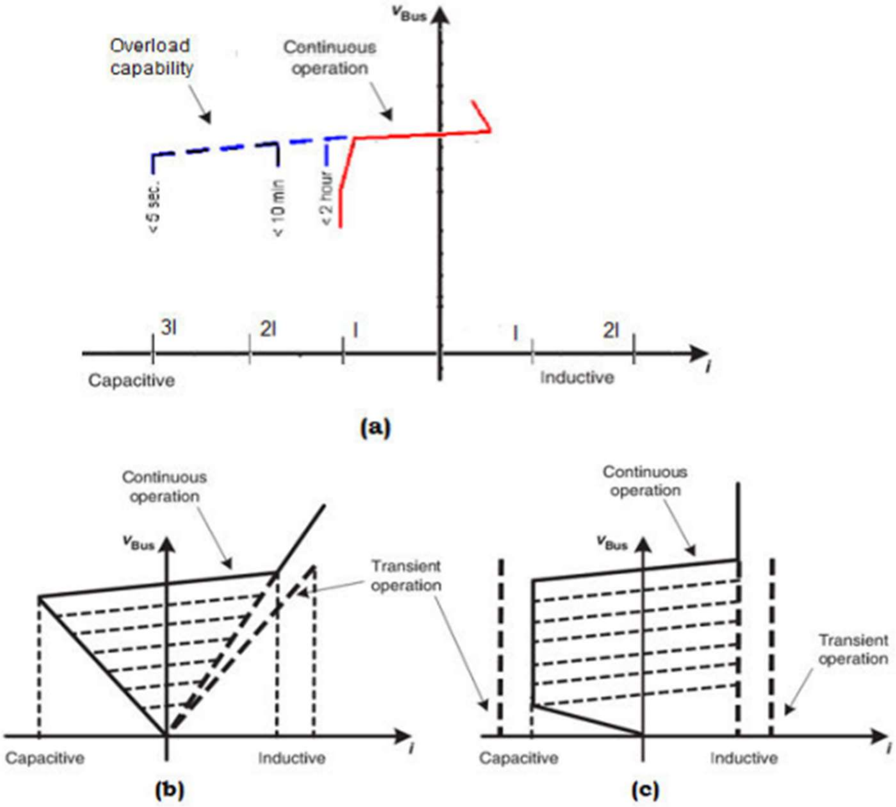


Figure 1.3-8: reactive current capabilities of (a) SC, (b) SVC, (c) STATCOM

1.4-Impact of RES on Voltage Regulation

The increase of Distributed Generation (DG) based on RES in electrical grids has been giving rise to a lot of issues concerning voltage profile and its regulation, as previously introduced.

However, great advantages of RES make them more and more necessary. Firstly, the increase of energy demand, to satisfy which it is good to exploit these energy sources, but moreover, especially in last years, the need to reduce fossil fuel use in favour of clean energy. Moreover, they promote the liberalization of electricity market. For these reasons, in order to integrate and handle RES, an upgrade in grid structure and management is imperative.

Concerning voltage regulation, the mitigation of RES flicking voltage is carried out exploiting strategies and reactive compensation methods discussed above.

An interesting analysis to show RES effects on voltage and some possible regulation and compensation strategies are shown in [4] by means of simulations on different scenarios, based on U.S. grid standards.

Simulations with and without DG demonstrate, from the practical point of view, what has been already explained in this chapter: voltage decreases both at full and light load (in second case, according to a bit higher trend) without DG (figure 1.4-1), and it rises remarkably with DG, even more dramatically in case of light load, as expected (figure 1.4-2).

Then, some attempts are carried out to regulate voltage and mitigate DG issues. The first one is based on a Voltage Regulator (VR), which is an autotransformer with many taps and a voltage sensing control unit; the tap changing is automatic and depends on control unit measurements.

VR can partially solve the high voltage DG problem bucking the voltage in correspondence of loads. Consequently, DG can produce even more with respect to the previous case without VR (figure 1.4-3).

There is a point before VR where voltage is beyond the limit, but it can be solved with another VR. Nevertheless, multiple stages of regulators are not recommended in order to avoid coordination issues.

In addition, when DG is not working, VR can increase voltage on loads improving the quality of the transmission (figure 1.4-4).

Nevertheless, VR-based method could be useful in case of constant DG, but it is not the case of RES. In fact, if DG changes its output level, switches operative conditions, or disconnects at a relatively high output level, the result is a rapid voltage variation, the so called “flicking”. In particular, if DG is disconnected abruptly, the PCC voltage suddenly drops to the pre-DG interconnection level. Since VR is not instantaneous and it is usually in bucking position while DG is working, in a similar scenario it emphasizes the voltage drop consequent to the DG disconnection.

This unusual condition holds until the reaching of a new low voltage steady state, and the VR could take several minutes to fully adequate its configuration to the new scenario, depending on the number of steps needed to move from the current buck position to the boost position required.

The resulting flicker voltage can be computed according to the following formula:

$$V_{flicker} = V_{max} - V_{min} + V_{reg}$$

where V_{max} is the maximum PCC voltage, V_{min} is voltage without DG and VR, and V_{reg} is the voltage lowered by VR. Acceptable values of voltage flicker versus its occurrence frequency are specified by IEEE Standard 519-1992.

Therefore, since VR is not a proper solution for RES, another method is applied, which is based on SVC. This compensator can support a smooth voltage profile in a lot of different conditions, thanks to its high-speed response capability to any voltage change, and is very effective to solve voltage flicker issues, as discussed previously.

Results show what explained above in theory: in case of no DG, SVC increases voltage injecting reactive power to compensate voltage drops; in case of DG, SVC absorbs reactive power, resulting in a smooth trend of voltage without any spike exceeding limits. This holds in both scenarios of light load and full load (figure 1.4-5).

In other words, SVC can solve increasing voltage trend and voltage flicker controlling reactive power in order to set the best voltage configuration in every context, from the full production of DG to its disconnection, from light load grid condition to the full load one. Moreover, this can be done almost instantaneously. Naturally, SVC has a higher cost with respect to VR.

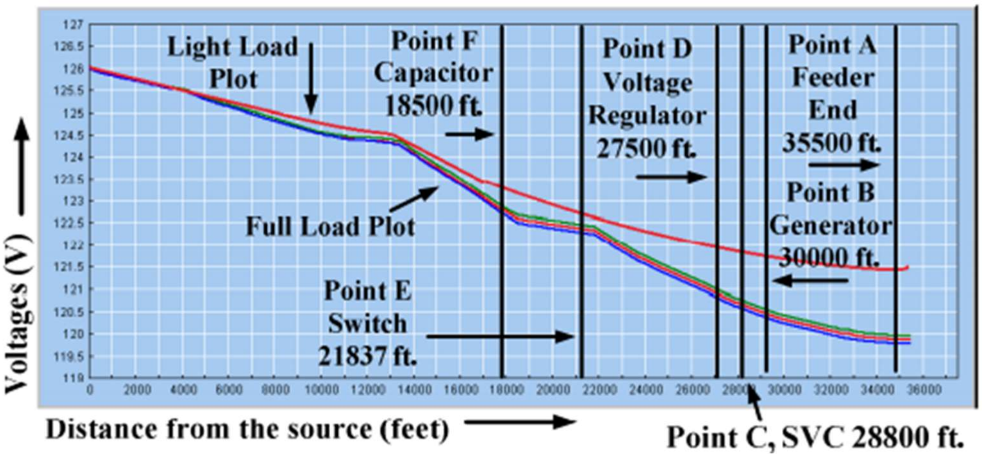


Figure 1.4-1: Voltage profile at full and light load with no DG. It follows the typical trend of traditional power systems.

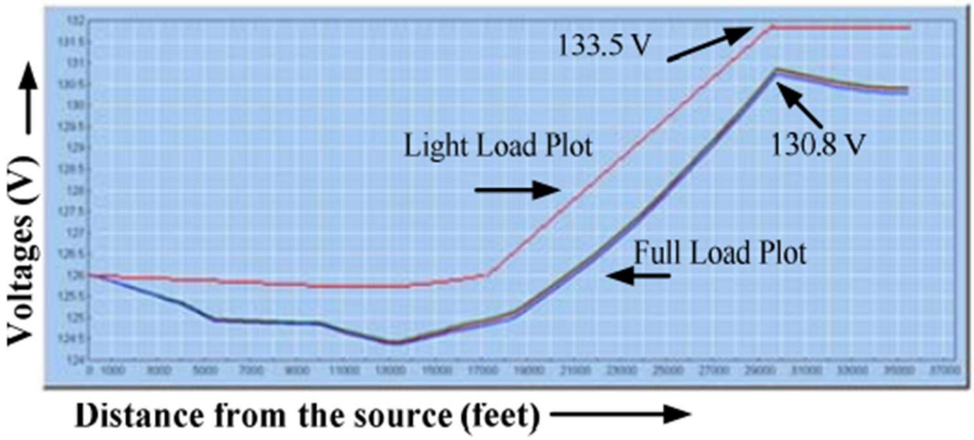


Figure 1.4-2: Voltage profile at maximum DG output, full and light load. The dramatic increase of the voltage, especially in light load condition, can be appreciated.

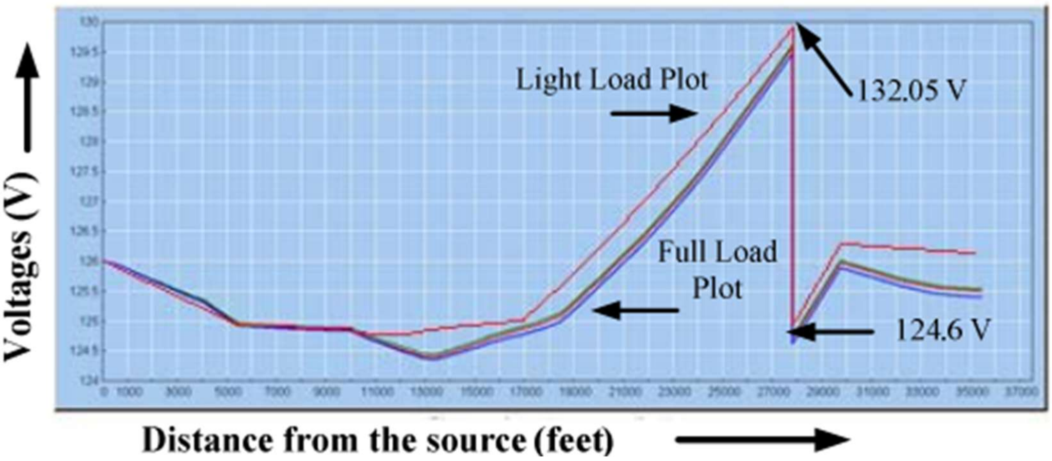


__Figure 1.4-3__: Voltage profile with VR at full and light load (with DG). The load voltage is properly regulated, but before the VR there is a huge peak totally outside of the correct range.

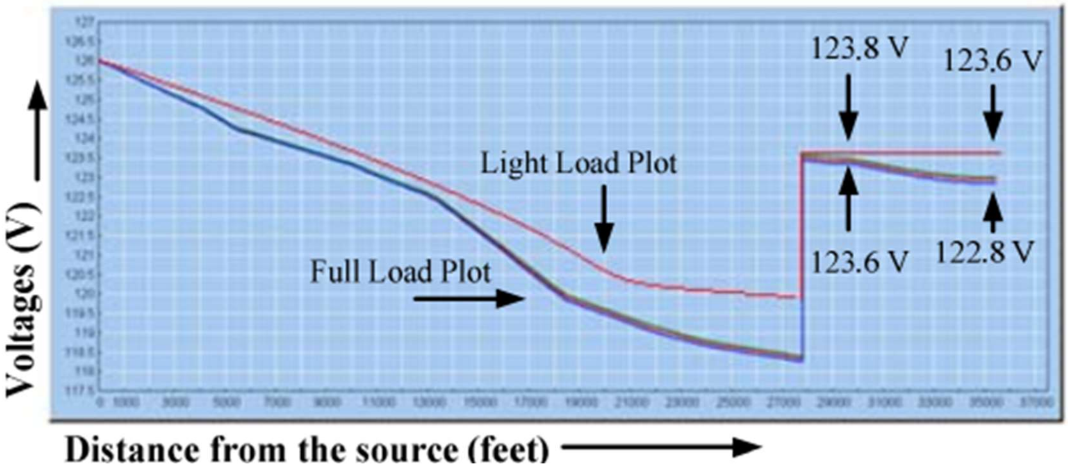


__Figure 1.4-4__: Voltage profile with VR at full and light load (no DG). There is a remarkable improvement in transmission efficiency with respect to the previous scenario without VR.

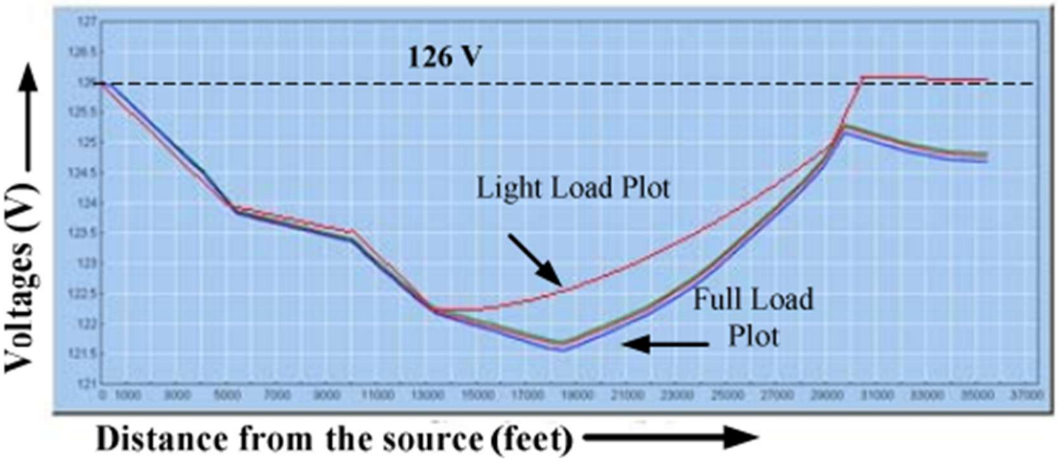


__Figure 1.4-5__: Full and light load profile at maximum DG generation, with SVC. The voltage trend is perfect in both conditions.

Another study about effects of RES integration has been made in [5], focusing on its positive aspects. In particular, it analyses the impact of 1,42 MW Photovoltaic (PV) power plant in a load variation context typical of residential area, in Brazil. A real system has been considered.

Considering that PV power plant works during the day, i.e., during the range of time of maximum load demand, it helps in voltage profile supplying loads with active power and, in this way, it allows the substation to inject less power. Consequently, line losses are reduced, and the voltage drop is significantly reduced as well; as a result, it makes a benefit on production and transmission costs. In case of excessive load demand, the compensation is carried out acting also on reactive power with fixed capacitor banks, which can help to keep voltage in correct limits and correct the power factor. Capacitor banks connection is particularly useful when PV decreases its production due to physiological reasons.

Therefore, it can be appreciated how synergy of DG and a basilar reactive compensation method as fixed capacitors can improve voltage profile and grid condition. Nevertheless, this is a PV plant whose size is proper with respect to the load (not totally since capacitors were needed in case of peak load demand). If it were a larger DG, working also in lower load condition, perhaps some of the issues seen previously could have arisen.

All described results are shown in figure 1.4-6, 1.4-7 and 1.4-8.

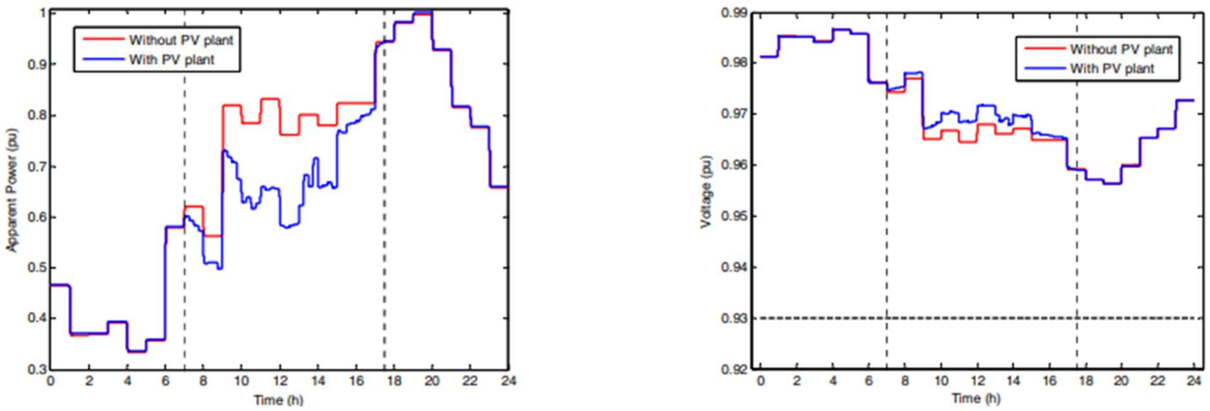


Figure 1.4-6*: from left to right, apparent power and voltage in the substation. The remarkable PV contribution in fact of apparent power injected and voltage drop can be appreciated.*

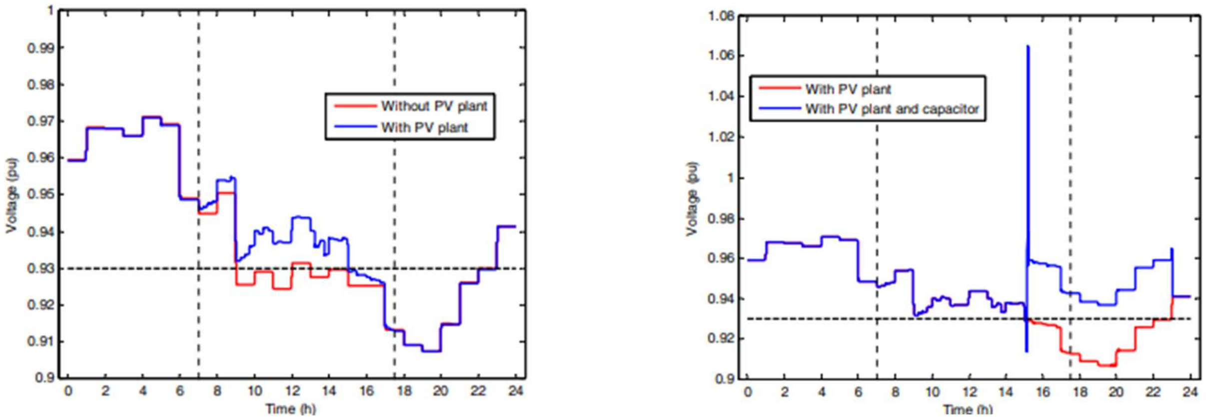


Figure 1.4-7*: from left to right, voltage at the farthest bus. It can be appreciated how capacitors help to improve voltage trend, especially when the sun goes down and PV is no longer operating. The spike on the right plot is due to the entrance in service of capacitor banks.*

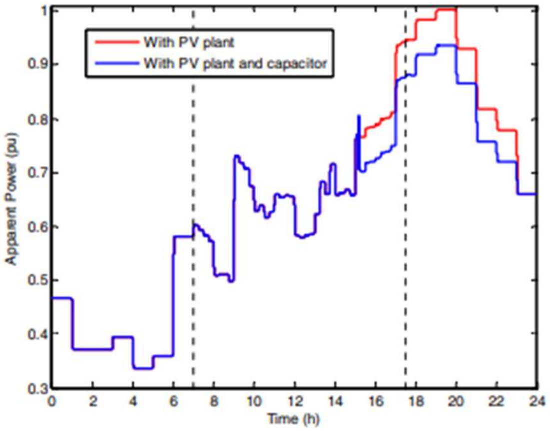


Figure 1.4-8*: the same compensation benefit of capacitors can be appreciated in the reduction of injected apparent power by substation. That is because substation supplies less reactive power, since it is provided by capacitors. The result is a lower line voltage drop and improvement of the power factor*

However, a further benefit could have been provided to voltage regulation if RES took part to reactive power compensation, in particular in case of no availability of energy (such as night, when only capacitors provide reactive power), or in general when, during the day, the voltage is changing.

This procedure, as previously anticipated and described in [6] as well, can remarkably improve the flicking voltage behaviour due to intermittent RES generation. Given the following formula:

$$\Delta V = \frac{\Delta P}{V} \cdot R - \frac{\Delta Q}{V} \cdot X$$

which describes the voltage magnitude variation due to a variable source (all parameters are in per unit); setting ΔV equal to zero, it can be derived:

$$\Delta Q = \Delta P \cdot \frac{R}{X}$$

which corresponds to the amount of reactive power necessary to cancel voltage variation caused by either variable source of power or variable load. If impedance in PCC is always known, then reactive power injection can take place in an open-loop manner. However, in practice, the PCC impedance varies with system conditions and a closed-loop voltage regulator can be used instead, in order to vary reactive power output such that voltage variation is cancelled.

Therefore, according to this formula, inverter can inject/absorb the amount of reactive power in order to keep constant PCC voltage while it is supplying real power. In case of a great solar farm, a plant level control coordinates the reactive power output of all inverters to regulate the PCC voltage in synergy.

In this way, RES can mitigate voltage magnitude variations (that they cause) providing dynamic voltage support that can improve grid voltage stability. In other words, inverters of RES power plants can behave as STATCOMs.

Not only: PV inverters are also configured to operate even when there is no real power output, i.e., exactly as a virtual STATCOM: for example, during night, the inverter absorbs active power to compensate internal losses keeping charge a DC capacitor, which allows the inverter to inject reactive power into the grid and operate as a pure reactive power source.

The benefit provided to voltage regulation is very remarkable, as can be appreciated in figure 1.4-9, and it makes the idea about the importance of RES contribution in system voltage regulation in case of high penetration of DG.

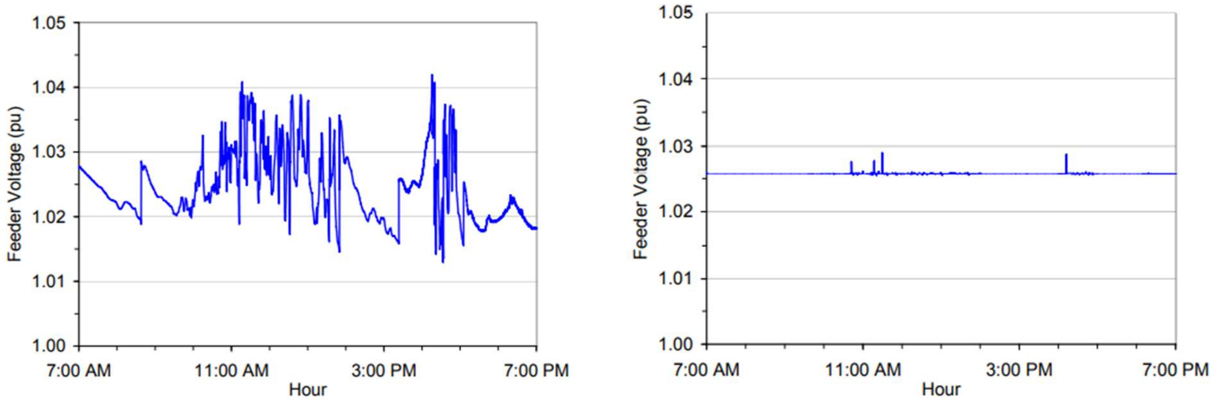


Figure 1.4-9*: from left to right, PCC voltage trend of a PV plant without voltage regulation (unitary power factor) and with voltage regulation capability*

Furthermore, this operative condition has become particularly important in case of fault. In fact, a major fault in an Extra-High Voltage (EHV) substation can potentially depress the voltage on transmission and distribution systems over a wide geographic area, causing disconnection of a lot of DG. Hence, a single fault could result in the simultaneous loss of numerous RES plants within that area and, if the grid has significant RES penetration, it can turn into a critical loss of generation resources. That condition can be further aggravated considering that grids with high penetration of RES are weak from the voltage stability point of view, due to their low short-circuit power (this RES issue has been introduced previously and will be addressed in detail in the next chapter). The result is voltage dips to propagate at great distances, and DG in a very wide area will be lost. In other words, a single fault could be enough to generate a blackout.

Therefore, it is crucial that RES remain connected injecting reactive power in order to support voltage and to facilitate the recovery. In [6], also a simulation to demonstrate the importance of this concept was performed.

A hypothetical future scenario of high PV penetration in Western US has been considered, and a series of dynamic simulations of the WECC grid were performed, varying the inverter voltage disturbance sensitivities. Results show the more the disconnection voltage threshold is high, the more the PV are disconnected, and system disturbance is aggravated, resulting, eventually, in blackout of the WECC grid (figure 1.4-10).

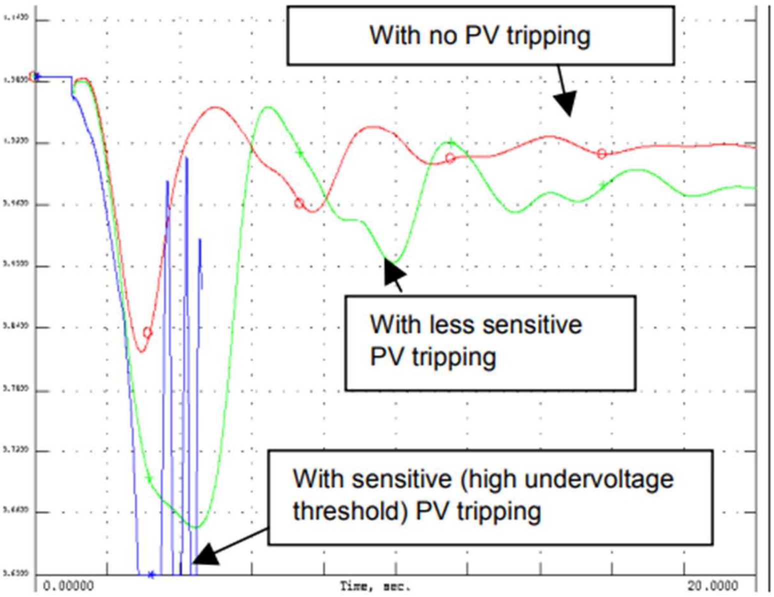


Figure 1.4-10*: Dynamic simulation of a major WECC grid disturbance with varying degrees of PV (DG) disturbance sensitivity. As can be appreciated, the best recovery condition is reached in case of no PV tripping. With high undervoltage threshold, a blackout occurs.*

Hence, these simulations demonstrate in practice what previously stated: since nowadays RES are a significant part of the global electrical energy production, they must remain connected to the grid to avoid a huge generation loss and, consequently, a blackout. Moreover, they must provide reactive power support in order to sustain voltage. These simulations were performed considering PV, but the same holds in case of wind power plants, which must be capable of riding through large and severe grid disturbances without tripping as well. These requirements are specified in grid codes, as will be shown later.

Nevertheless, inverter injected current is limited, and perhaps it would not be enough to both deliver active and reactive power in a more efficient way. Therefore, inverter behaviour depends on the context. In the case seen above, described in [5], a good configuration could be reached operating the inverter at unitary power factor and providing voltage compensation by means of capacitors. In other cases, instead, as just described, a different configuration could be a better choice.

However, in short, RES are expected to contribute to voltage regulation while they supply loads with real power. In particular situations, as faults or during night when real power cannot be produced (in case of PV), all current capabilities are exploited to inject reactive power.

Focusing on night-time, in [7] an analysis on PV behaving as STATCOM during night is carried out, exploiting the overall current capability of PV to control the voltage. In this particular scenario, the benefit of this operative condition consists in avoiding reverse power flow due to high productivity of Wind Farms.

Also in this context, the advantage of this operative condition is confirmed, since the PCC voltage is remarkably more stable, and PV-STATCOM improve fault recovery as well. In case of excessive growth of PCC voltage, PV reactive absorption keeps it on a reasonable value.

Using PV, and RES in general, as reactive compensators allows to improve grid condition and to solve their intrinsic issues. However, as mentioned above, their current contribution is limited; hence, reactive compensation methods will always be necessary. Anyway, this operative strategy will facilitate integration of more RES plants in the system without needing additional voltage-regulating devices or, in any case, saving costs, given that a lower quantity of compensators will be needed.

1.4.1-Inverter Control and Drive in RES Power Plants

The different operative modes described so far can be performed thanks to different available control strategies of inverters. Control schemes and operating condition exploited to obtain the desired regulation of RES during voltage control are described below.

Inverter control drives are usually based on Park’s transformation. Before analysing how a PV-STATCOM works, general control drives of inverter performed to regulate power flow will be discussed.

The grid equivalent circuit interfaced with the inverter is quite similar to the circuit of an AC machine (figure 1.4-11), except frequency and voltage which, in this case, are constant. The inverter three-phase output voltages are in phase with and coupled to the corresponding AC grid voltage (in real case, there is a relatively small filter reactance, which here is not represented).

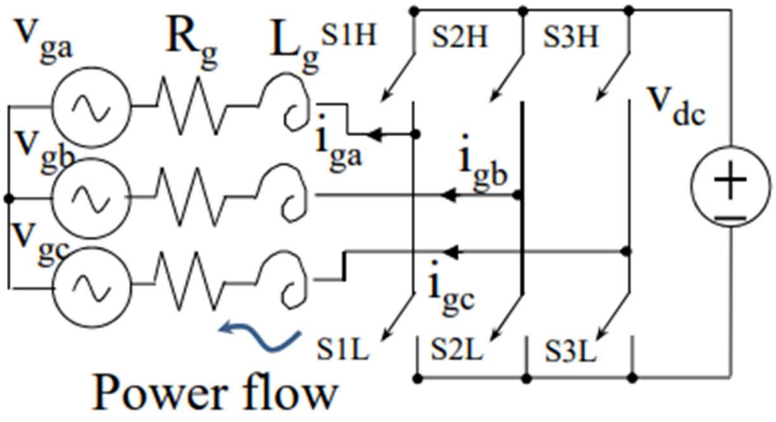


***Figure 1.4-11**: equivalent circuit of inverter interfaced with the grid*

The Park's space phasor formula is applied to grid voltage v_g in stationary frame (α-β axis, figure 1.4-12).

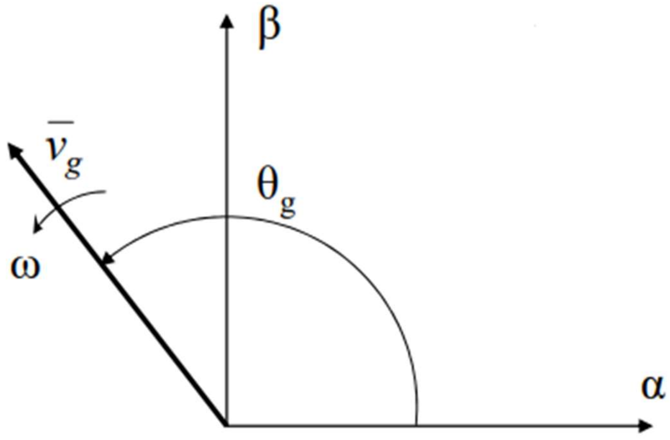


***Figure 1.4-12**: voltage grid in a stationary frame*

For "phase a", the result is:

$$v_{ga} = V_{ph\,MAX} \cos\theta_g$$

and, in general, space phasor of three-phase voltages is equal to:

$$\overline{v_g} = V_g e^{j\theta_g}$$

where V_g is rms line-to-line voltage and θ_g the space phasor angle with respect to α-axis.

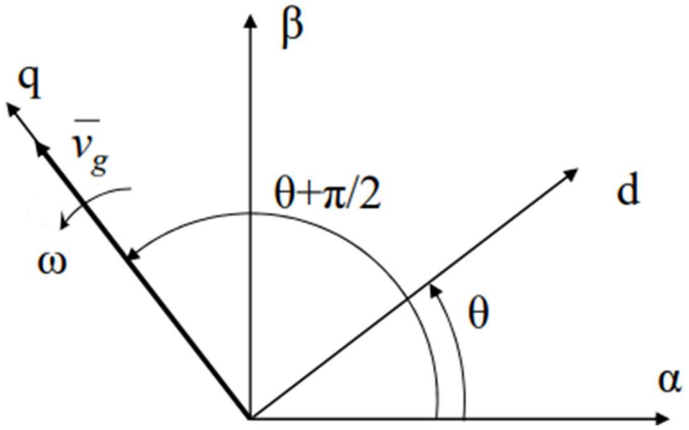


***Figure 1.4-13**: d-q axis reference*

Then, considering d-q reference frame fixed with grid voltage (imaginary axis q aligned with grid voltage space phasor, figure 1.4-13), the space phasor of inverter voltage is defined, according to the following equation and the equivalent circuit of figure 1.4-11:

$$\overline{v_i} = R_g\overline{i_g} + L_g p\overline{i_g} + j\dot{\theta}L_g\overline{i_g} + \overline{v_g}$$

where “g-subscript” means “grid”.

Therefore, isolating d-q axis components:

$$v_{id} = R_g i_{gd} + L_g p\, i_{gd} - \dot{\theta}L_g i_{gq}$$

$$v_{iq} = R_g i_{gq} + L_g p i_{gq} + \dot{\theta}L_g i_{gd} + v_g$$

Thus, active and reactive power fed into the grid can be derived*:

$$P_g = Re\left(\overline{v_g}\underline{i_g}\right) = v_g i_{gq}$$

$$Q_g = Im\left(\overline{v_g}\underline{i_g}\right) = v_g i_{gd}$$

Now, a steady state condition is considered, where grid voltage is constant in amplitude and frequency. All quantities are constant with respect to the reference frame (therefore, derivatives are equal to zero). Moreover, considering that:

$$\overline{v_g} = V_g e^{j\omega t}\ ;\ \dot{\theta} = \omega$$

where ω is the grid frequency, equations become:

$$v_{id} = R_g i_{gd} - \omega L_g i_{gq}$$

$$v_{iq} = R_g i_{gq} + \omega L_g i_{gd} + V_g$$

Finally, different operative conditions of the inverter can be represented. If d-axis current component is set equal to zero, inverter exchanges only real power with the grid; power flow depends on the sign of the current (figure 1.4-14).

---

*Power control depends on chosen convention. If voltage were fixed with d-axis, links of powers with current components would be reversed: real power would be dependent on d-axis current and reactive on q-axis one (reversed in sign). The choice of voltage coincident with q-axis is typical of United States

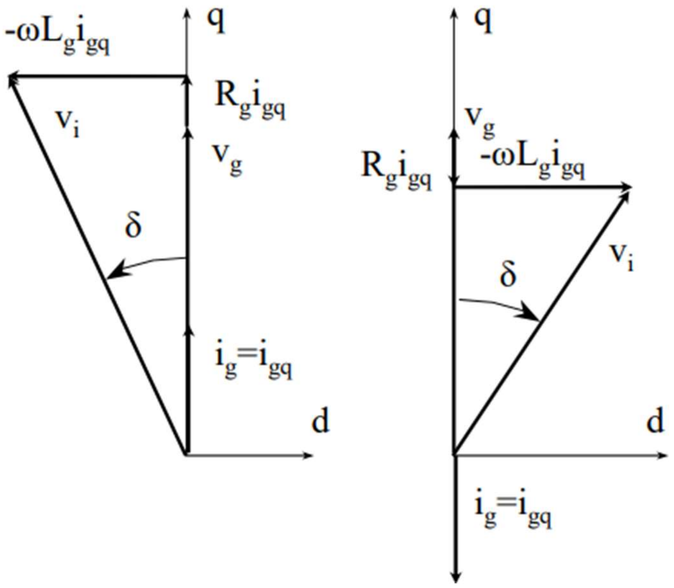


Figure1.4-14: *from left to right, inverter injecting real power into the grid; inverter absorbing real power from the grid*

On the contrary, settling q-axis current component equal to zero, inverter exchanges only reactive power with the grid, behaving as a STATCOM (figure 1.4-15).

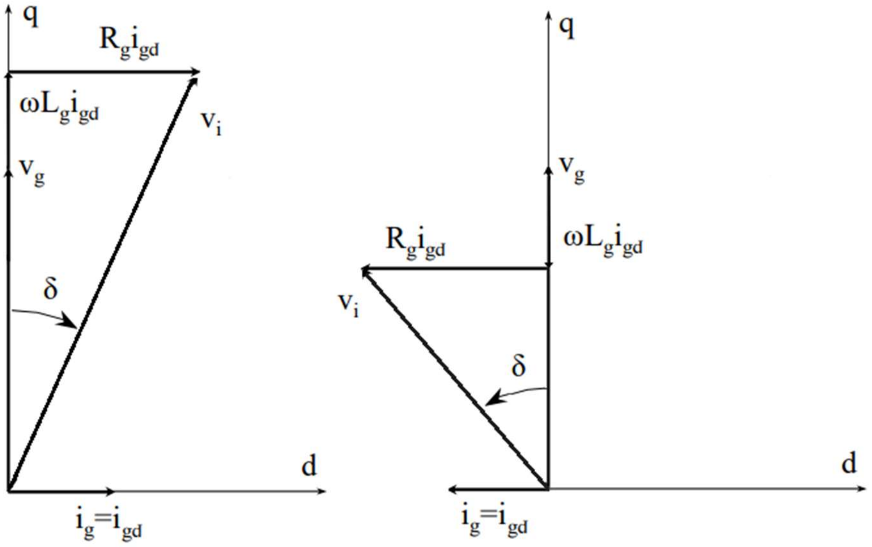


Figure 1.4-15: *STATCOM operating condition; from left to right: inverter injecting reactive power into the grid as a capacitor; inverter absorbing reactive power behaving as an inductor.*

Setting both d-q currents different from zero, both active and reactive power can be regulated (figure 1.4-16). For example, reactive power can be managed in order to regulate voltage and real power can be absorbed to charge DC-bus capacitor.

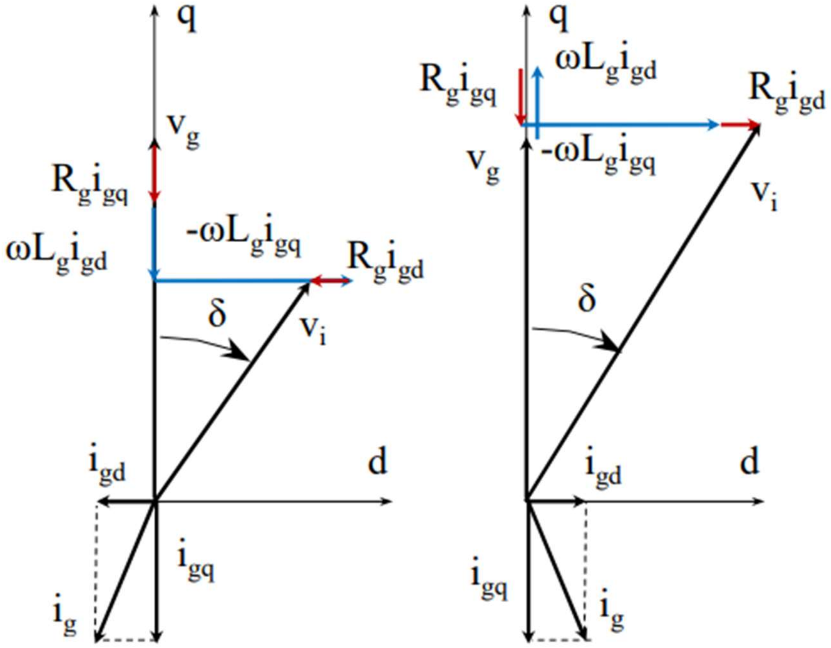


***Figure 1.4-16**: from left to right, inverter absorbing and injecting reactive power; in both cases real power is absorbed.*

Therefore, controlling the two components of current space phasor is possible to drive powers totally decoupled. That is the great advantage of Park's transformation

According to equations and procedure explained above, the complete control block scheme of the inverter is represented below (figure 1.4-17). Basing on power values of reference, d-q axis reference components of voltage are derived in the control unit. The control is performed in closed loop and output currents are measured and converted with Park's space phasor (blocks called "T" in function of θ angle) in order to being used in control unit as input for Proportional-Integral (PI) controllers ("R"-blocks), subtracted from reference values.

Scheme passages, as mentioned above, are referred to equations described above, and "u" indicates the voltage drop on resistance and inductance.

Voltage reference values are sent to PWM modulator to drive the inverter. On the right, grid model is showed to have the two current components as output. Grid model is based on LaPlace equations and, again, currents are measured in Park's components; sending measured values to the control unit, it is necessary to perform the conversion again.

Phase and magnitude of grid voltage are measured by a Phase-Locked-Loop (PLL) based control, for the purpose of maintaining synchronization with the grid and performing Park's transformation at fixed voltage with respect to the chosen reference axis.

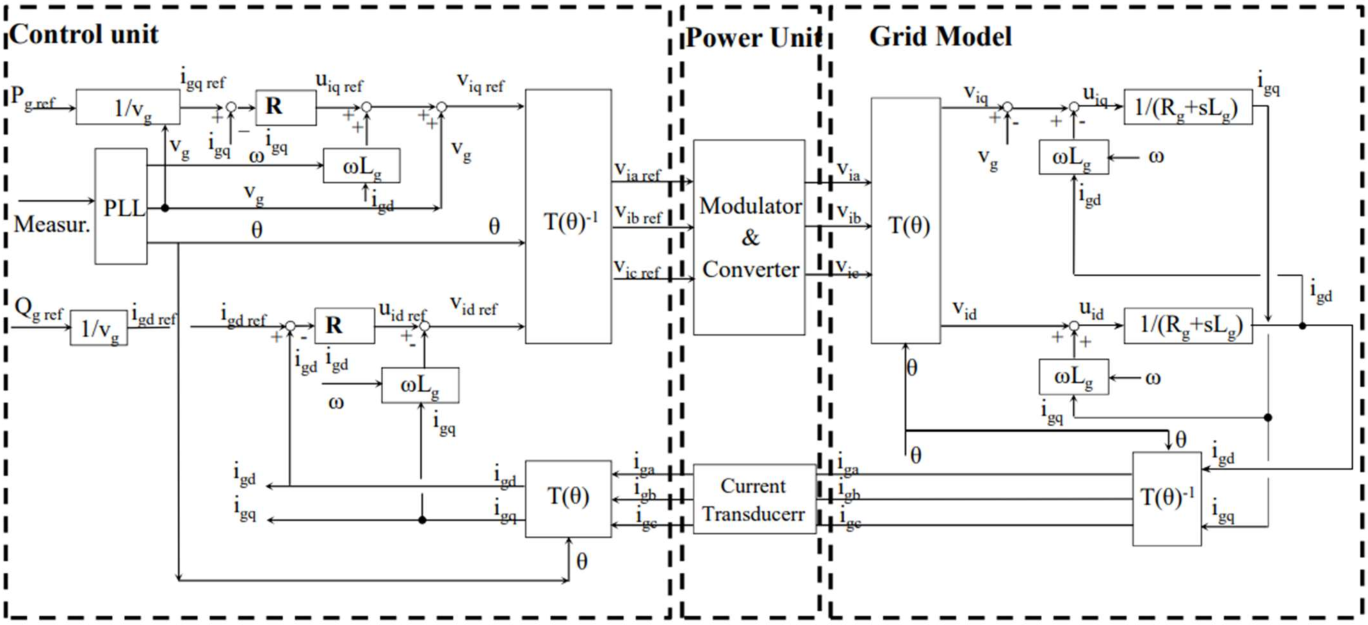


__Figure 1.4-17__: complete control block scheme of the inverter

Hereinafter, the PV-STATCOM working will be analysed in detail [9]. A general grid-connected PV system is driven by two control loops. The inner loop is a pulse width modulation (PWM), which regulates output currents of the inverter, in order to meet the requirements of waveform and phase (as represented in control scheme above). The outer loop determines the output power of the inverter according to the Maximum Power Point (MPP) of PV panels (in the control scheme, the reference value of power is directly sent to the control unit and this loop is not shown).

In general, the two loops are realized in two stages: the first is carried out by a DC/DC converter with Maximum Power Point Tracking (MPPT) control, the second, naturally, is based on the inverter. Nevertheless, since two stages may result in more power losses with respect to a single-stage conversion, both loops are realized at once in a single-stage grid-connected PV systems. According to this configuration, only one power conversion stage is needed, simplifying the system topology.

This single-stage PV generation system delivers active power produced by the PV array and, at the same time, it compensates harmonic currents, to avoid injection of waveforms with bad harmonic contents, and reactive power, for voltage regulation (figure 1.4-18, [8]).

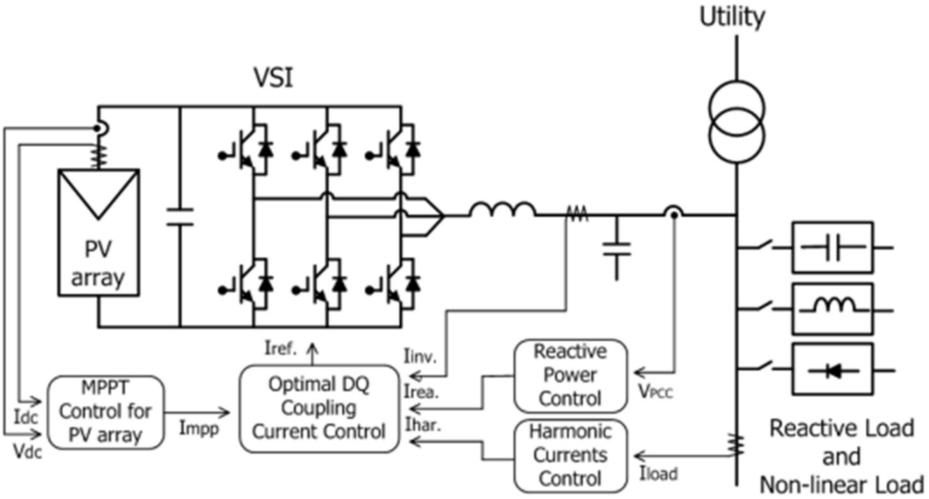


Figure 1.4-18: *single-stage grid-connected PV generation system*

The inverter detection variables are the DC bus voltage V_{DC}, the PCC line-voltage V_{PCC}, the inverter current I_{inv} and the load current I_{load}. The real power conversion with MPPT, the compensation of harmonic currents and regulation of reactive power are all integrated into the electrical drive, and detection variable are necessary to perform it.

The proposed system (figure 1.4-18) has three current references: the current reference I_{MPP} of the PV output power control, the current references I_{har} of active filter function, and the current reference I_{rea} for the reactive control. The compensation current is generated continuously basing on the detection variables.

In general, two kinds of control strategies exist for extracting current (or voltage) harmonic component from the corresponding distorted current (or voltage). The first is based on Fourier Analysis in the frequency domain, the latter, called the "P-Q Theory," is based on the instantaneous power theory in a three-phase circuit. Both are based on Park’s space phasor transformation.

In this procedure, as for the analysis at the beginning of this section, the general direct-quadrature Park’s transformation will be used. With d-q transformation, the positive-sequence component, the negative-sequence component, and the harmonic component become DC values, which is another quality of this approach.

The load d-q current components can be derived according to the well-known expression of Park’s transformation (figure 1.4-19):

$$\begin{bmatrix} i_{load\_d} \\ i_{load\_q} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta - \frac{4}{3}\pi) \\ -\sin\theta & -\sin(\theta - \frac{2}{3}\pi) & -\sin(\theta - \frac{4}{3}\pi) \end{bmatrix} \begin{bmatrix} i_{load\_a} \\ i_{load\_b} \\ i_{load\_c} \end{bmatrix}$$

The d-q components are filtered with Low Pass Filter (LPF), resulting in d-axis positive sequence component of load harmonic current i_{d_lpf}, and q-axis positive sequence component of load harmonic current i_{q_lpf}.

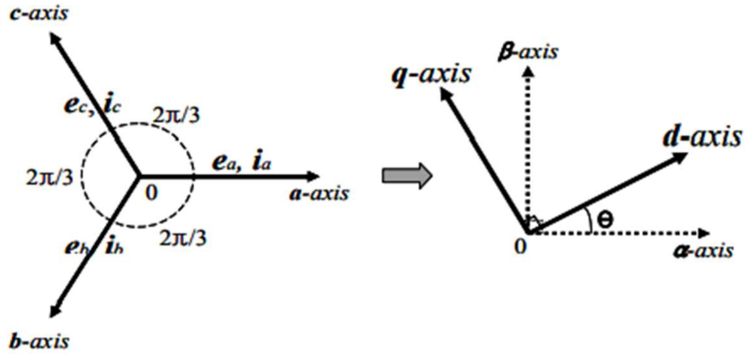


Figure 1.4-19: Park transformation of three-phase components in d-q ones; α-β axis are orthogonal coordinates converted from three-phase coordinates, d-q coordinate components are obtained shifting α-β coordinate system

As mentioned, fundamental frequencies of load currents have been transformed into DC components. Consequently, differences between d-q axis components of load currents and DC components are sent as input to PI controllers, and d-q axis components of harmonic current references are obtained, as follow (figure 1.4-20, [8]):

$$i_{har\_d\_ref} = i_{load\_d} - i_{d\_lpf}$$

$$i_{ha\ \_q\_ref} = i_{load\_q} - i_{q\_lpf}$$

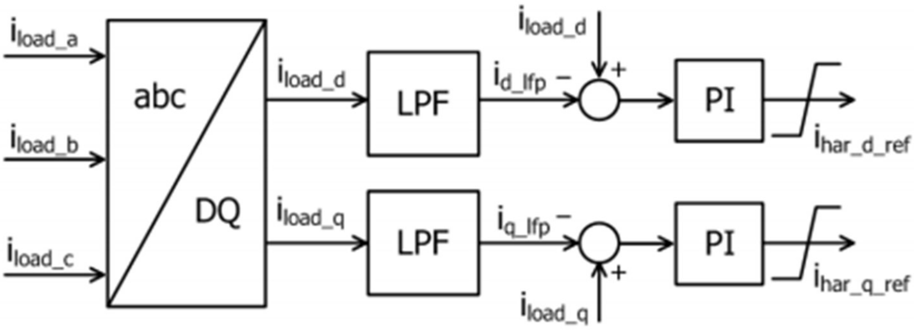


Figure 1.4-20: *control block diagram of the active filter function*

Afterwards, coming to voltage regulation, as previously explained, if inverter output voltage is higher than the grid one, it delivers reactive power; vice versa, it absorbs it. Phase voltages at PCC are detected and converted by means of Park's transformation; then, the difference between q-axis component and the reference one, as input for a PI controller, allows to derive the d-axis current reference, which, as demonstrated previously, control the reactive power (figure 1.4-21, [8]).

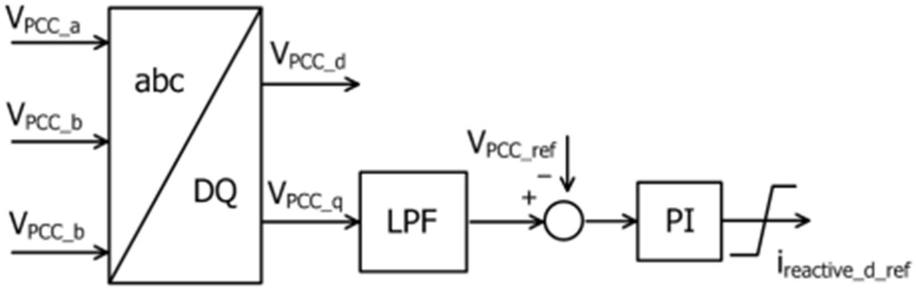


Figure 1.4-21: *control block diagram of reactive power drive*

Now, all the elements of interest for the control block diagram of PV-STATCOM system have been obtained. The overall reference currents are derived by means of reference currents found above to compensate reactive power and harmonics.

The sum of q-axis component of harmonic current and q-axis reference current of MPPT (which sets the real power operating condition) is equal to the total q-axis reference of inverter output current:

$$i_{q\_ref} = i_{har\_q\_ref} + i_{power\_q}$$

The sum of d-axis component of harmonic current and d-axis current reference of reactive power compensation is equal to the total d-axis reference of inverter output current:

$$i_{d\_ref} = i_{har\_d\_ref} + i_{reactive\_d\_ref}$$

Therefore, direct and quadrature axis voltage are finally obtained, and PWM reference voltages of PV-STATCOM system are computed by their Park's transformation inverse, according to the usual equation:

$$\begin{bmatrix} v_{ref\_a} \\ v_{ref\_b} \\ v_{ref\_c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta - \frac{2}{3}\pi) & -\sin(\theta - \frac{2}{3}\pi) \\ \cos(\theta - \frac{4}{3}\pi) & -\sin(\theta - \frac{4}{3}\pi) \end{bmatrix} \begin{bmatrix} V_{d\_ref} \\ V_{q\_ref} \end{bmatrix}$$

Thus, summarizing, q-axis current component controls inverter active power, keeping into account real power reference value, which is regulated by MPPT control loop based on measurements of V_{DC} and i_{DC}, and harmonic compensation. Instead, d-axis current component controls inverter reactive power, keeping into account reactive power reference value, which is based on detected V_{PCC} values and depends on the desired operative condition, i.e., if V_{PCC} has to be increased or decreased; moreover, it keeps into account harmonic compensation as well.

The resulting d-q axis voltages are anti-transformed and PWM will use them with the aim of driving the inverter according to the desired conditions (figure 1.4-22, [8]).

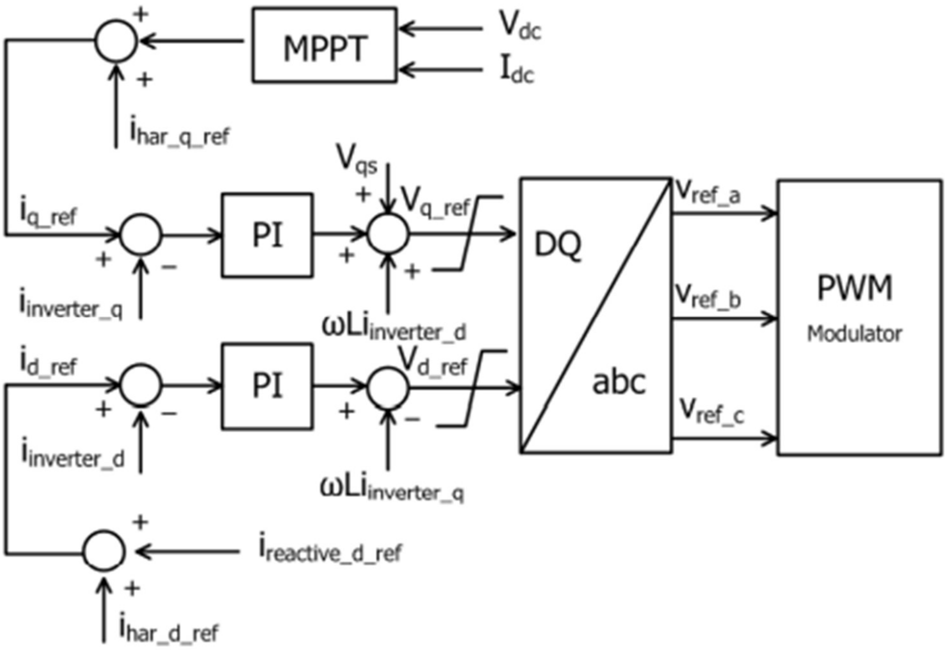


***Figure 1.4-22**: control block diagram for PV-STATCOM system.*

As can be appreciated, the difference between this control scheme and the general one showed in the initial analysis lies mainly in the presence of the purpose of compensating harmonics: the reference current which allows to achieve this result is summed to both d-q reference current, in order to obtain the final current components.

An interesting resume of the logic behind inverter drive can be found in [7]; it has been reported below, for completeness. In this control block scheme, the two loops with PI controllers are showed in a more synthetic way, allowing a global view of the inverter electrical drive (figure 1.4-23).

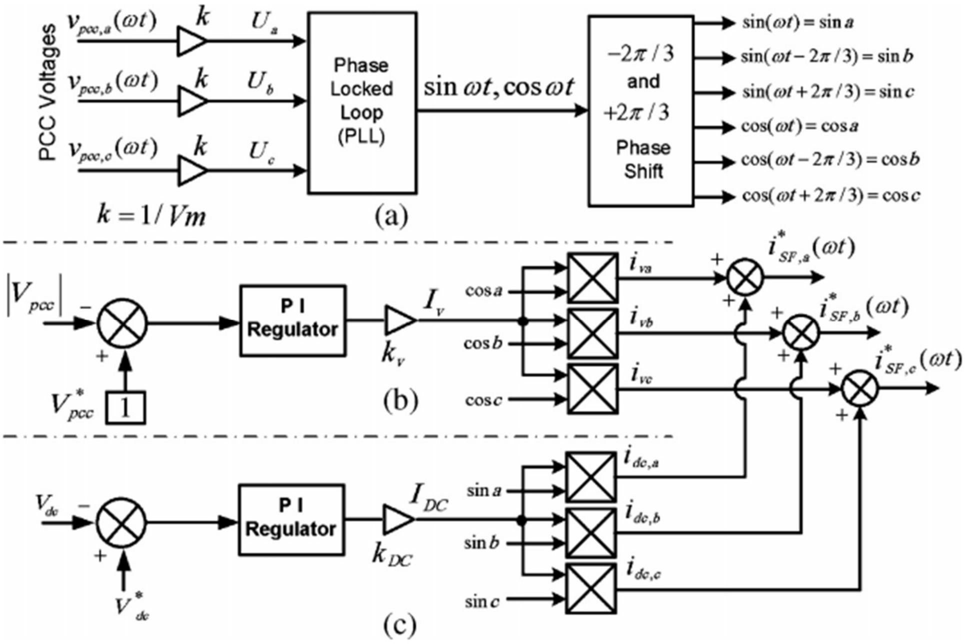


***Figure 1.4-23**: synthetic resume of inverter electrical drive*

On the top, PLL based control approach for maintaining the synchronization with PCC voltage is represented. Just below, there is the first loop, regulating the PCC voltage managing reactive power. Finally, on the bottom, there is the second loop, which maintains constant the DC bus voltage across the capacitor.

Finally, in conclusion of this analysis and to integrate these concepts of RES control, an overview on PV and Wind Systems architectures is provided [9].

In a typical wind generation system, (figure 1.4-24), a variable speed wind turbine is coupled to the shaft of an AC machine (induction or synchronous) through a speedup gear. The variable voltage-variable frequency power is converted to constant voltage and constant frequency by two-sided PWM converter system before being injected into the grid through a step-up transformer. In particular, the machine-side converter regulates the torque, allowing the shaft speed to vary and adapting to the maximum efficiency in providing the power, while the grid side converter controls the DC bus voltage and the reactive power. Currents on both AC sides are sinusoidal and at programmable power factor. The machine flux can be controlled by its reactive current.

The control system, as shown in figure, measures wind speed and controls the generator speed in order to optimize the power generation (improving the aerodynamic efficiency of turbine regulating blades and varying the angular speed).

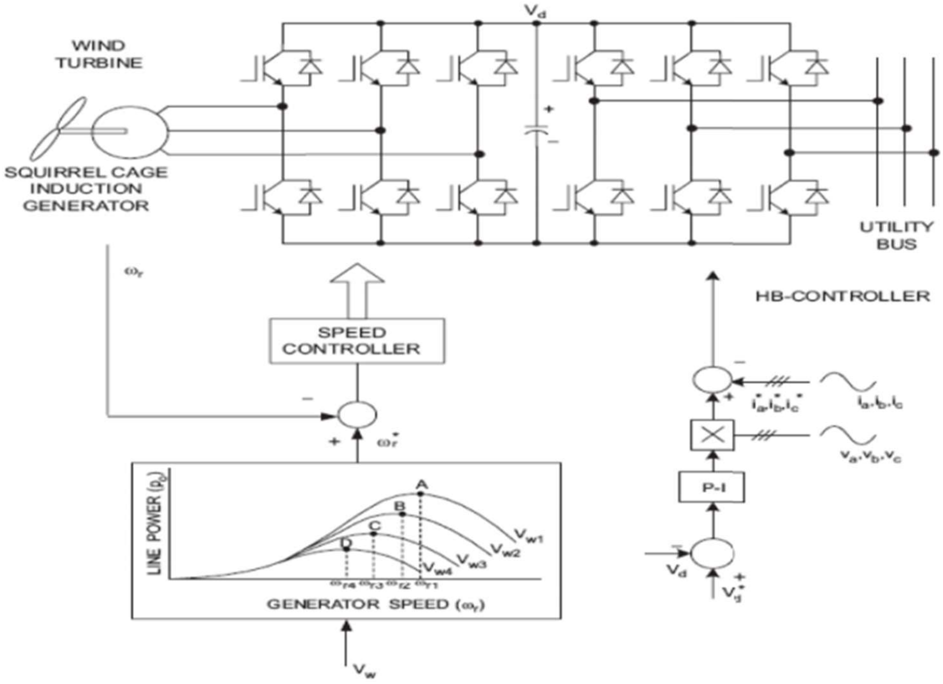


Figure 1.4-24: *Wind Energy System based on Induction Generator*

Otherwise, at any wind speed, the maximum power point can be searched by MPPT technique, as in PV (in figure 1.4-24, on the bottom right). The line-side converter controls the DC bus voltage by programming the line current in phase with the phase voltage. It is possible to control both active and reactive power by means of the line-side converter, according to the methodology explained above in this section. One disadvantage of a Wind Generation Systems with respect to PV consists in the more sporadic availability of power, which depends on the wind speed. Consequently, a back-up power source or bulk energy storage is suggested.

In case of PV systems, as already shown analysing the inverter control drive, a typical configuration can be appreciated in figure 1.4-25: PV array is connected to DC-DC converter with the aim of boosting the DC voltage; moreover, the converter controls the maximum power output of the array by MPPT search algorithm, as indicated in the figure.

Afterwards, voltage is converted to AC by means of PWM inverter. Multiple units are coupled by transformers at the interface with the network.

The advantages of PV systems lie in their stillness, safeness, high reliability, and little need of maintenance. However, PV power is dependent on the availability of sunlight and requires energy storage or back-up power, like Wind Energy Systems.

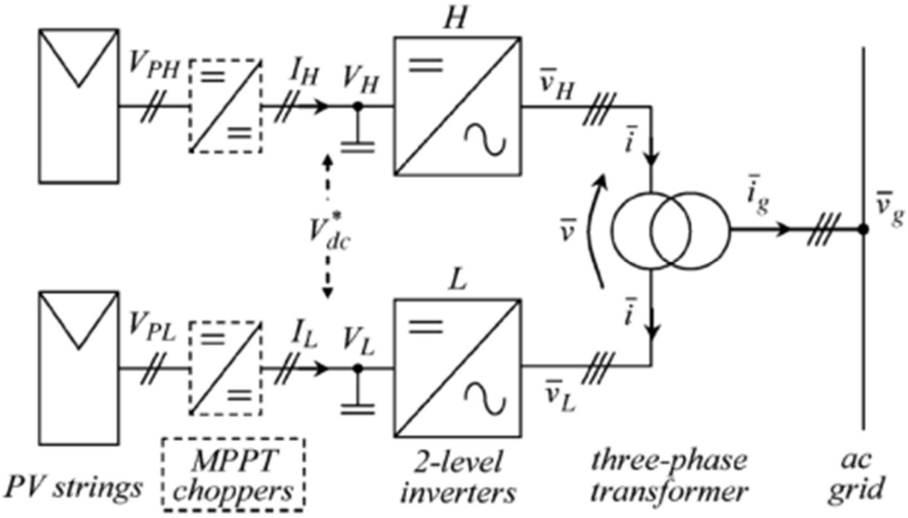


Figure 1.4-25: PV generation system

Reconsidering what previously introduced about power management strategies, as demonstrated in this analysis, thanks to Park's Transformation, active and reactive are decoupled. The only constraint lies in current capability of the inverter:

$$\sqrt{{I_d}^2 + {I_q}^2} = |I_{MAX}|$$

As mentioned, maximum current of the inverter is limited in order to preserve semiconductor valves. Therefore, to provide reactive power support constantly, in PV systems the capacitor DC voltage is kept constant during night absorbing active power from the grid (as in STATCOMs); instead, throughout the day, it is bounded to the MPPT, which adapts V_{DC} with the operating condition determined by insulation and temperature, to obtain the maximum available power.

Exceptions can happen during particular situations, for example faults: since grid codes require, as will be discussed later on, that in case of short-circuit the inverter must provide reactive power supporting the voltage (Fault Ride-Through), current capabilities could be totally exploited with the aim of providing reactive power to the grid.

Lastly, it is important to specify that Wind System considered above is not the only existent type of Wind Turbine (WT). There are four types of WT (figure 1.4-26), and the model considered above is Type 4, which can behave as STATCOMs, being its power conversion totally based on power electronics, thus there is not much more to add about it.

Type 3 is called Doubly-Fed Induction Generator (DFIG), since it is based on an induction generator whose rotor is driven by a converter sized for about 30% of the total power, while stator is directly connected to the grid. Its control is performed by a grid-side converter, which regulates the DC bus voltage, keeping it constant, and the power factor to the grid, and a rotor-side converter, which controls torque and power exchanged with the grid modulating the rotor current.

In particular, the latter converter controls the slip of the machine varying its own voltage, controlling active and reactive power according to the desired operating conditions; in other words, it compensates the difference between mechanical speed and synchronous one injecting a rotor current at variable frequency. In this way, the induction machine can operate as a generator not only in super-synchronous mode, but in sub-synchronous one as well. Stator power is always from stator to the grid, while the rotor one flows from rotor to the grid in super-synchronous mode and vice versa in sub-synchronous one.

This technique allows a wide range of control and a decoupled management of active and reactive power. Moreover, the controllability of reactive power allows to adopt DFIG in weak systems, avoiding large voltage perturbations due to high induction machine in-rush currents, as in case of Type 1 and 2. In fact, in the Sicilian grid, considered for this work of thesis, all WTs are DFIG.

Coming back to DFIG controls, direct-axis current component allows to vary the angular speed and the torque of WT, i.e., regulating active power, while the quadrature one the power factor, i.e., controlling reactive power. In other words, as shown in figure

1.4-27, DFIG can be associated to synchronous generator, making it possible to control both powers decoupled even more accurately, easily, and quickly by means of its “excitation current”. In fact, they can be represented by the same equivalent circuit.

Nevertheless, magnitude of DFIG current contribution is remarkably lower with respect to the alternator due to the nature of converters, as discussed previously, showing also in this smart generation technology the shapes of the main trouble on which this work is focused, i.e., the reduction of fault level in power systems.

On the contrary, Type 1 and Type 2 (Squirrel Cage Induction Generator and Wound Rotor Induction Generator respectively), are based on induction generators, and they are not driven by power converters. Therefore, they always absorb reactive power, resulting in total lack of voltage regulation with respect to the other two types (actually, Type 2 can be dissipative regulated inserting in series of the rotor a resistance). Thus, they need capacitor banks to work at a reasonable power factor, and more expensive devices, such as SVCs or STATCOMs, to control reactive power for voltage regulation, as induction machines themselves are useless from this point of view.

In conclusion, control schemes of type 3 and 4 WT are shown figure 1.4-28 and 1.4-29.

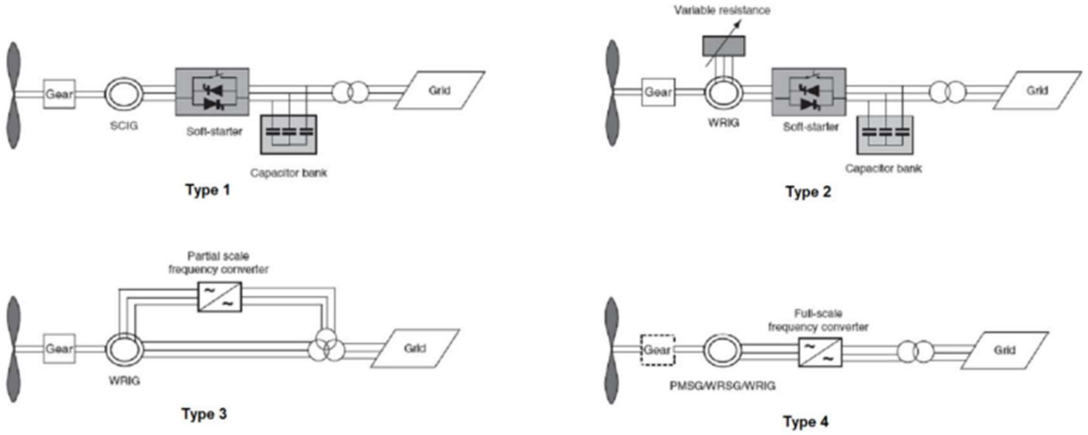


***Figure 1.4-26**: the four types of WT drive trains*

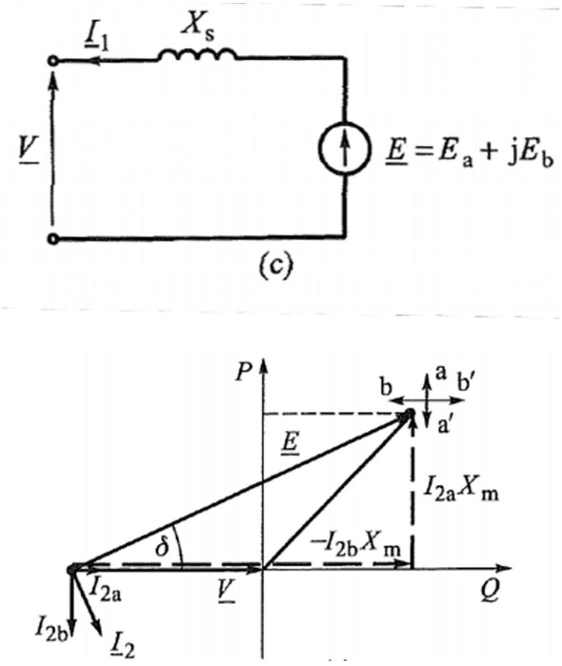


***Figure 1.4-27**: capability control and equivalent circuit of DFIG. I_{2a} and I_{2b} control active and reactive power, respectively*

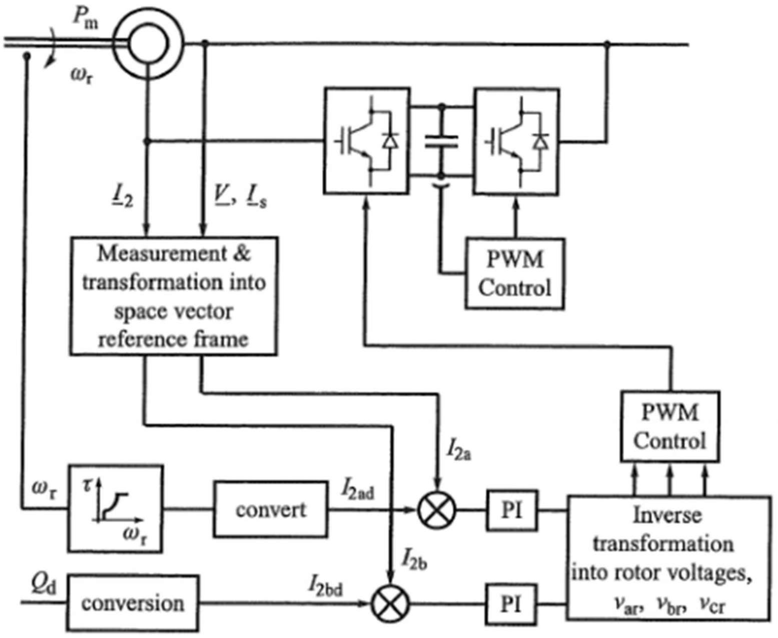


***Figure 1.4-28**: control scheme of DFIG; once active power, based on optimal operative condition, and reactive power depending on grid needs, are known, correspondent rotor currents can be computed, driving PWM inverter control*

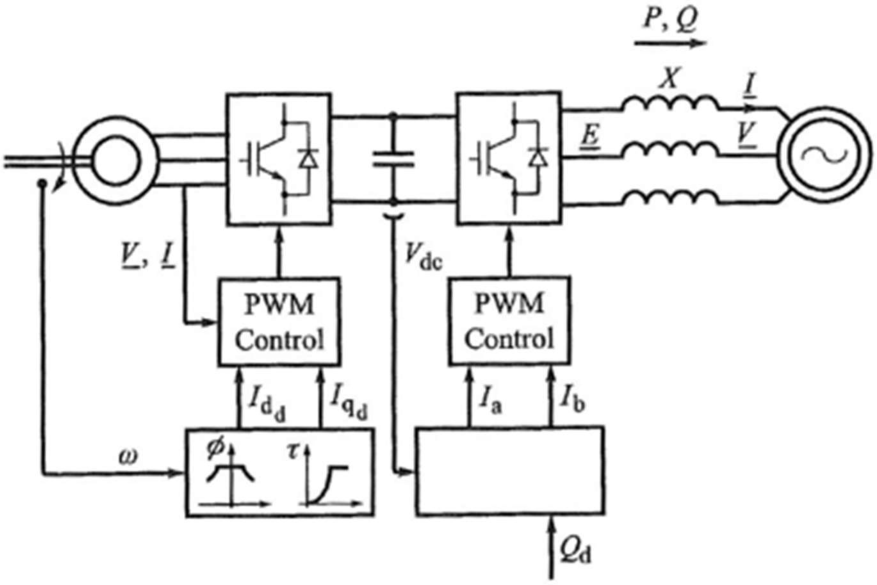


***Figure 1.4-29**: control scheme of Full-Converter WT. Active and reactive power reference values are chosen as for DFIG; for the rest, it is controlled as explained above in this section, being WT interfaced with the grid through a frequency converter only*

1.4.2-Additional Considerations

In conclusion of this section, some considerations have to be made, since actually there are other possible compensation methods, and other strategies that allow to exploit RES to provide benefits to voltage regulation. For example, the series reactive compensation. Both shunt and series compensation strategies are used in order to change the natural electrical shapes of the power system, but shunt compensation modifies equivalent impedance of the load (if installed near loads), while series compensation varies transmission or distribution system parameters. The first are more popular, though the second allow to reach even better results, despite their higher cost and complexity.

In both cases, the reactive power flows can be controlled. They can be based on passive components or electronic converters. In case of passive components, for example, a capacitor in series of the line can change the equivalent reactance seen by the system; in order to obtain a continuous regulation, also in this context, thyristors can be used, and they are called Thyristor Controlled Series Compensators (TCSCs).

Instead, the basic function of electronic converter series compensator is injecting voltage in series with the line irrespective of the line current. In this way, controlling the angular position of supplied voltage with respect to the current, reactive compensation can be obtained, in order to balance voltage drops all along the line. In case the converter is equipped with an energy source, the same can be performed providing active power compensation to mitigate resistive voltage drops. As result, resistive and reactive components of series line impedance can be compensated at the same time, increasing reactance to resistance ratio, and therefore increasing steady state transfer limit of the line [3].

Inverter-based series compensator are called Static Synchronous Series Compensators (SSSCs) and they are the series device dual to STATCOMs.

In general, as defined by IEEE, a power system based on power electronics and other static equipment (both series and shunt) that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability is called Flexible AC Transmission System, or FACTS [10].

Inverters of RES can be exploited to operate according to this strategy. However, these compensation methods are mainly addressed to improve transmission capability of the system, and they are aimed at regulating voltage in order to increase active power flow. Furthermore, series compensation, as explained above, is not widespread due to its more complicated technologies and higher costs. In other words, these techniques are quite beyond the scope of this analysis, i.e., investigate the impact of RES on fault level. Therefore, they will not be investigated in detail.

Nevertheless, for completeness concerning innovative RES operative conditions, a few papers are mentioned. In case of interest and for further information, please refer to the following documents.

An explanation about SSSC is provided in [10], and in general about all reactive compensation methods in [3].

In [11], an analysis on the possible connection in series of RES was performed, showing the remarkable positive improvements concerning active and reactive power transmitted on the line. RES connections with the grid can be changed in order to operate as normal real power sources or as STATCOMs, i.e., connecting RES in parallel, or instead connecting them in series with the aim of compensating voltage drops varying series parameters of the system, operating inverters as SSSCs.

Other interesting studies and simulations about this topic were performed in [12]; in particular, a PV system is operated in order to provide reactive power support for voltage regulation and load compensation, dynamic active and reactive power support in multiple line at the same time, to improve power flow management, and to perform an optimal utilization of PV inverters, especially during night.

1.5-Terna Requirements

In conclusion of this chapter, requirements of Terna, the Italian TSO, for RES voltage regulation in the Italian network will be discussed. Rules and provisions about PV and WT concerning voltage regulation are exposed in [13] and [14]. Both types of DG must remain connected to the grid in every operative condition according to the following PCC voltage constraint:

$$85\%\,V_n \leq \; V_n \; \leq 115\%\,V_n$$

Moreover, as widely described so far, RES must join voltage regulation controlling reactive power flow injected into the grid. Therefore, required capabilities by Terna are described in following charts (figures 1.5-1, 1.5-2, 1.5-4 and 1.5-5).

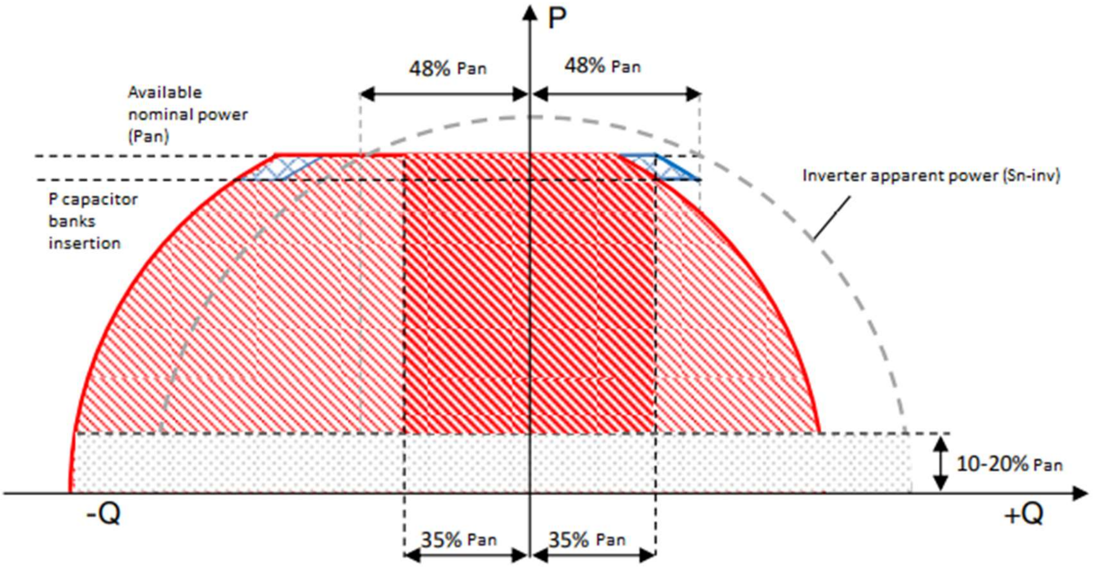


Figure 1.5-1: *P/Q capability chart of PV according to Terna Grid Code at nominal voltage*

Power plants are expected to provide a continuous regulation within the minimum dark red area, which correspond to real power higher than 10-20% of the available nominal power (Pan) and is defined by capability limits in under-excitation and over-excitation. Regarding under-excitation, the limit must be equal to 35% Pan for every real power value and for every type of DG. Instead, concerning over-excitation, the limit can change from 35% Pan to a minimum value of 20% Pan in WT, and from 35% Pan to a minimum of 30% Pan in PV.

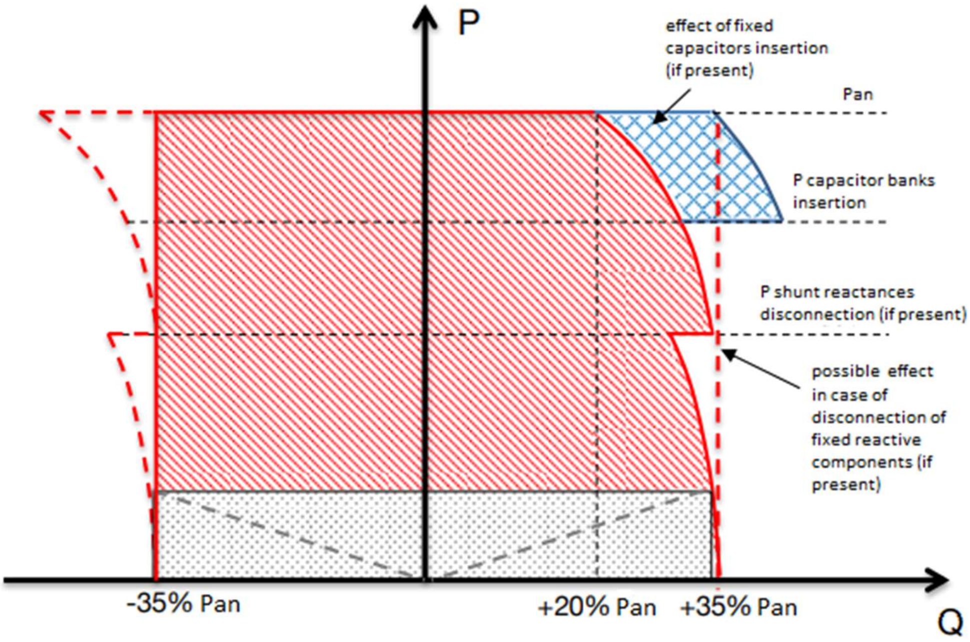


Figure 1.5-2*: P/Q capability chart of WT according to Terna Grid Code at nominal voltage*

Concerning the grey area on the bottom, i.e., in case of real power lower than 10-20%, two possible operating conditions are expected: in case it is possible to inject reactive power at null real power, maximum capability limit must be 35% again (both injected/absorbed); if not, reactive power must be gradually decreased until zero, in case of no real power injected.

The reason of this operating constraint is to avoid abrupt step variations of reactive power in case the plant stops. In this case, exact shapes of capability constraints are not provided. Insertion of eventually capacitor banks is allowed above certain thresholds of real power and voltage.

Reactive power injection (or absorption) must be performed according to a characteristic curve $Q = f(\Delta V)$ (figure 1.5-3). The amount of power depends on the gap between reference value and the measured one. The reference value is indicated by Terna and must be included into the range:

$$95\%\, V_n \leq V_{ref} \leq 105\%\, V_n$$

A further requirement expects PV and WT to provide 90% of the requested reactive power within 2 seconds and 100% within 5 seconds.

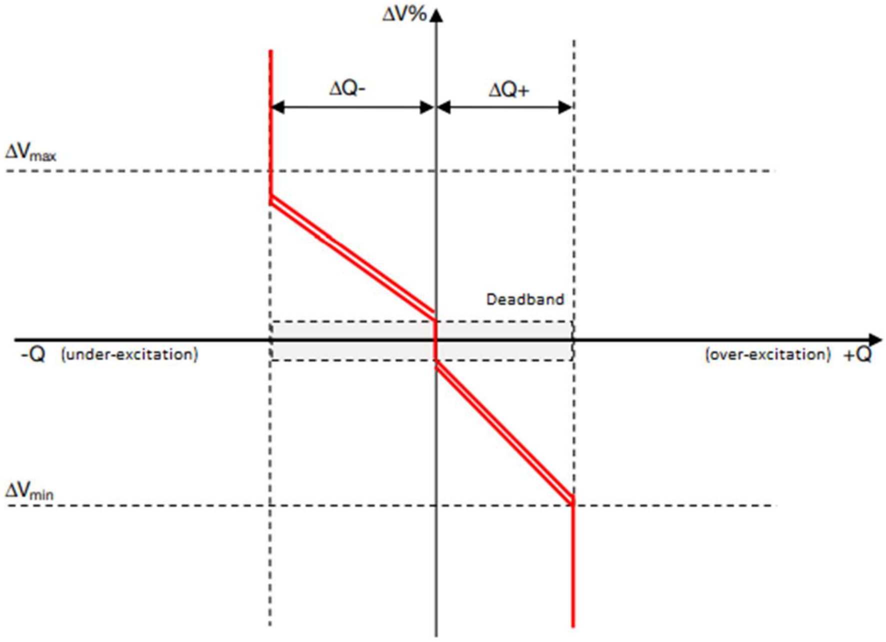


***Figure 1.5-3**: characteristic curve of voltage regulation $Q = f(\Delta V)$. Maximum reactive variations are equal to 35% of the nominal active power*

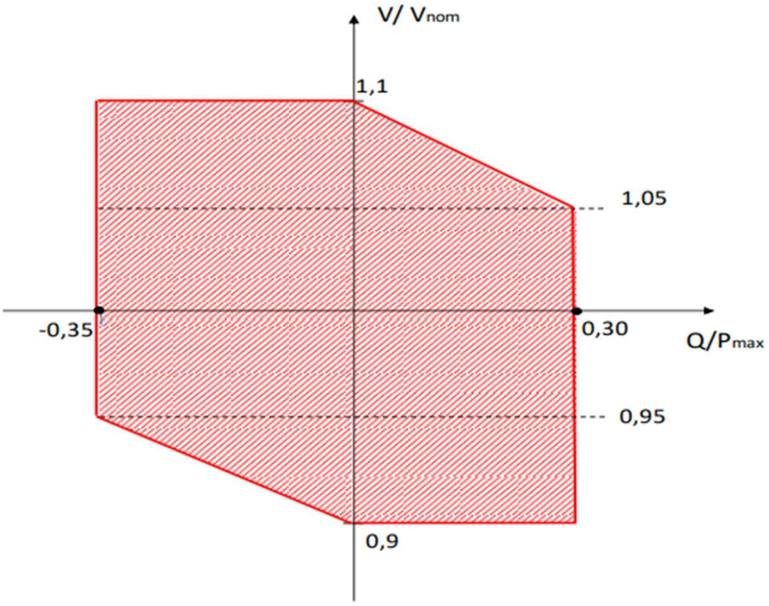


***Figure 1.5-4**: V/Q capability chart of PV according to Terna Grid Code*

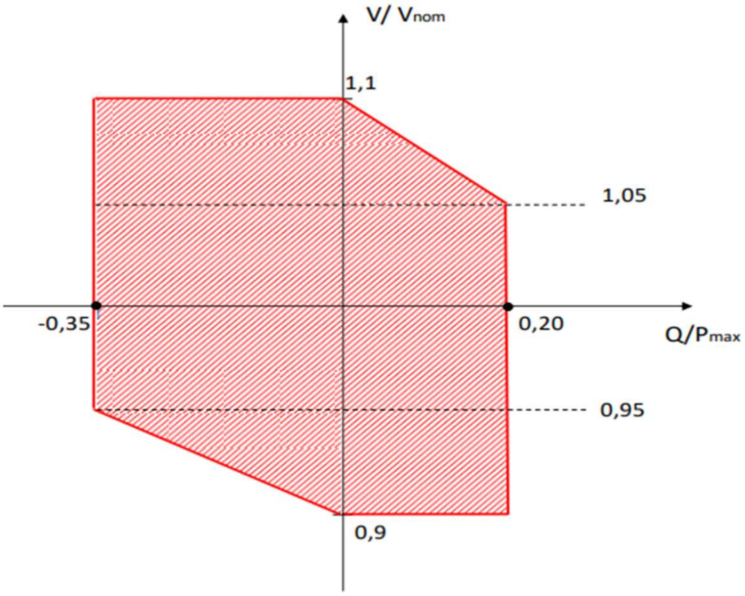


***Figure 1.5-5**: V/Q capability chart of WT according to Terna Grid Code*

BIBLIOGRAPHY

[1] E.M. Carlini, S. Neri, A. Marietti, A. Boriello, L. Barison, L. Campisano, *Integration of synchronous compensator in Terna's remote control and remote operation system*, AEIT International Annual Conference (AEIT), 2019

[2] A. Stiger, R.A. Rivas, M. Halnonen, *Synchronous Condensers Contribution to Inertia and Short Circuit Current in Cooperation with STATCOM,* IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), 2019

[3] J. Dixon, L. Morán, J. Rodríguez, R. Domke, *Reactive Power Compensation Technologies: State-of-the-Art Review,* Proceeding of the IEEE, 2005

[4] M.Vaziri, M. Afzal, M. Zarghami, A. Yazdani, S. Vadhva, F. Tavatli, *Voltage Impacts of DG on Distribution Grid with Voltage Regulators and SVCs,* IEEE Green Technologies Conference (GreenTech), 2013

[5] J. H. de Oliveira, J. P. R. Gomes, W. D. C. Boaventura, V. F. Mendes, *Impact of Integrating a Photovoltaic Power Plant in a Distribution Feeder,* 17th International Conference on Harmonics and Quality of Power (ICHQP), 2016

[6] R. A. Walling, K. Clark*, Grid Support Functions Implemented in Utility-Scale PV Systems,* IEEE PES T&D, 2010

[7] R.K. Varma, V. Khadkikar, R. Seethapathy, *Night-time Application of PV Solar Farm as STATCOM to Regulate Grid Voltage,* IEEE Transactions on Energy Conversion, 2009

[8] H. Seo, G. Kim, S. Jang, S. Kim, S. Park, M. Park, I. Yu, *Harmonics and Reactive Power Compensation Method by Grid-Connected Photovoltaic Generation System,* International Conference on Electrical Machines and Systems, 2009

[9] B.K. Bose*, Power Electronics, Smart Grid, and Renewable Energy Systems,* Proceedings of the IEEE, 2017

[10] P. Nagar, S.C. Mittal, *Reactive power compensation by Static Synchronous Series Compensator*, International Conference on Micro-Electronics and Telecommunication Engineering (ICMETE), 2016

[11] H. Vallecha, Shivam, *Smart Utilization of Solar and Wind Power Farm Inverters as SSSC in Grid Connected Renewable Energy System,* IEEE 6th International Conference on Power Systems (ICPS), 2016

[12] V. Khadkikar, J. L. Kirtley, *Interline Photovoltaic (I-PV) Power System –- A Novel Concept of Power Flow Control and Managemen*t, IEEE Power and Energy Society General Meeting, 2011

[13] Attachment A68 of Terna's Grid Code, *CENTRALI FOTOVOLTAICHE-Condizioni generali di connessione alle reti AT, sistemi di protezione, regolazione e controllo,* 2019

[14] Attachment A17 of Terna’s Grid Code, *CENTRALI EOLICHE-Condizioni generali di connessione alle reti AT, sistemi di protezione, regolazione e controllo, 2019*

[15] Terna’s Development Plan, 2021, available on Terna’s website: https://www.terna.it

[16] R. Marconato, *Sistemi Elettrici di Potenza*, 3^{RD} reprint, ed. CEI, 1988

[17] H. Saadat, *Power System Analysis*, ed. McGraw-Hill, 1999

[18] R. Marin, M. Valtorta, *Trasmissione ed Interconnessione*, ed. CEDAM, 1973

[19] F. Iliceto, *Impianti Elettrici*, ed. Patron, 1984

[20] D. Polinelli, *Preliminary study on Voltage Regulation in presence of high RES penetration*, Tesi di Laurea, Politecnico di Milano, A.A. 2012-2013

[21] L. Nivelleau, J.Poyhonen, *How Statcom can solve dynamic grid problems*, General Electric, 2020, https://youtu.be/uJKBTKYQBrk

CHAPTER 2

SHORT-CIRCUIT ANALYSIS

The analysis of short-circuit and faults is a procedure of the utmost importance to be performed in power systems. It is essential to set protections and define breaking capacity of circuit breakers, to organise strategies of selectivity with the aim of guarantee the security of the system and the continuity of service as more as possible.

Moreover, it can be particularly useful to evaluate strength of a system from the voltage stability point of view. In fact, as introduced in last chapters, short-circuit power is a measure to evaluate how the system, or a specifical bus, are sensitive to voltage perturbations.

Since short-circuit power depends on fault current magnitude, in case of grid based on RES this quantity is dramatically reduced due to inverter limited contributions. However, supporting synchronous generators, RES injections can improve the total amount of fault current and increase the short-circuit power of system buses, as will be demonstrated later on.

Therefore, summarizing, the involvement of RES in voltage regulation during faults by means of reactive current injections can avoid the voltage to collapse and, moreover, increase short-circuit power, enhancing the stability of bus voltages with respect to perturbations, i.e., making the system stronger.

Thus, considering these positive effects and the great amount of RES in nowadays power systems, they can no longer be neglected during short-circuit computations.

Nevertheless, RES inverter-based behaviour is not linear like for traditional generators. Therefore, in order to analyse their impact on fault level, a different computation method will be used in order to include RES current in the procedure, updating the traditional and convenient one based on Thévenin equivalent.

2.1-Short-Circuit Power

The short-circuit power, or short-circuit capability, is the most common measure of system strength. It is defined as the product of rated bus voltage magnitude and fault current.

Assuming the network purely reactive, as usual in transmission power systems where resistive component is negligible, the short-circuit power S_{sc} of a generic bus represents the amount of reactive power to drain at that bus in order to bring its voltage to zero. Therefore, naturally, the higher the short-circuit power is, the lower is the voltage variation due to any operational change, including large perturbations.

Recalling formula seen in the last chapter in per-unit values and referring to a generic bus “k”, it can be derived:

$$\Delta\dot{V}_k = \dot{R}_k\dot{P}_k + \dot{X}_k\dot{Q}_k$$

$$\Delta\dot{V}_k \cong \dot{X}_k\Delta\dot{Q}_k$$

Hence:

$$\Delta\dot{V}_{k\,\%} \cong 100\frac{X_k}{{V_{kn}}^2}\Delta Q_k$$

Therefore:

$$\Delta\dot{V}_{k\,\%} \cong 100\frac{\Delta Q_k}{S_{sc\,k}} = \Delta\dot{Q}_{k\,\%}$$

where: $S_{sc\,k} = \frac{{V_{kn}}^2}{X_k}$; X_k represents the equivalent reactance seen by k-bus.

This result shows the inverse relationship between voltage variation in per-unit value and short-circuit power: if the considered bus, or in general the electric system is strong, i.e., S_{sc} is high, a variation in reactive power does not affect the voltage remarkably. On the contrary, in a weak grid, a variation in reactive power involves a great variation of voltage.

Moreover, as introduced above, S_{sc} is equal to the product of rated bus voltage magnitude and fault current:

$$S_{sc} = \sqrt{3}V_{sn}I_{sc} \text{ (MVA)}$$

In fact, $I_{sc} = \frac{V_n}{X}$ (in per-unit), which shows the link between this short-circuit power formula and the previous one (where X is the equivalent reactance seen by the fault).

Therefore, these results demonstrate that buses with high values of rated voltage and high short-circuit current are the strongest concerning voltage stability. In addition, a lower value of impedance involves a higher value of current, since a greater number of branches connected in parallel results in a lower impedance. In fact, the strongest buses in a power system are in High Voltage (HV) and Extra-High Voltage (EHV) meshed grids.

These considerations clarify the reason why large intermittent loads, such as arc furnaces, rolling mills or railway supply systems, need to be connected to high short-circuit power buses, in order to avoid dramatical voltage variations on the other load buses. The same holds for variable and intermittent generation, as in case of RES.

Nevertheless, as explained in previous chapters, RES are usually connected to distribution grids with lower short-circuit power and radial topology. From here, the emphasis of issues related to voltage stability in case of high penetration of RES.

In any case, the mitigation of voltage variations is performed by means of reactive power management and compensation strategies explained in last chapter.

Additional properties of great importance linked to these observations find application in faults: in particular, since short-circuits involve large voltage sags, the greater is the short-circuit power of a bus, the less it suffers faults on other buses. Consequently, the greatest voltage variations occur in case of fault on the bus characterized by the highest short-circuit power. In other words, according to their short circuit power, network buses can be divided in strong and weak buses.

The extreme ideal case is a scenario where reactance is equal to zero. In that occurrence, short-circuit power tends to infinite, defining the so-called infinite power bus. It represents the condition in which a bus voltage remains constant whatever happens, from load variations to faults (figure 2.1-1).

In practice, this scenario can be compared to the connection of a power plant to the transmission grid. In fact, the contribution to the short-circuit power due to all grid branches in parallel and all generators of the system is huge with respect to the plant one: the result is that first can be considered infinite compared to the latter, resulting in almost insensitivity of the grid to any perturbation in the power plant; this is the so-called infinite power network.

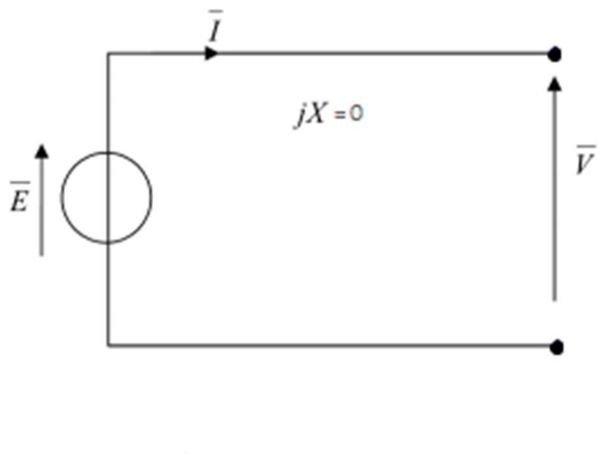


Figure 2.1-1*: an infinite power source: for any load, terminal voltage remains equal to the generator one since the impedance voltage drop is null.*

Now that the meaning and the utility of short-circuit power have been analysed, the impact of RES on fault level will be discussed accordingly.

2.2-Impact of RES on Fault Level

The impact of RES on power system fault level has been previously introduced discussing about voltage regulation and RES issues. Hereinafter, the effect of spreading penetration of RES on the system stability will be studied in detail.

In general, as already studied in section above concerning short-circuit power, the power system strength regarding voltage can be defined from the following aspects, which define the entity of fault level:

- Impedance;
- Pre-fault voltage;
- Short-circuit current.

In Italy, 80% of PV plants are located on Medium Voltage (MV) and Low Voltage (LV) grids, where the impedance is high and, in addition, resistive component is not negligible. Moreover, in the future, penetration of RES is going to increase more and more, since the National Strategic Plan of November 10th, 2017, launched the ambitious challenge of phasing-out thermal power plants based on fossil fuel and increase the RES electrical energy more than 55% by 2030 of gross final consumption. Just to get an idea, in 2017 RES installed power was about 9,7 GW for WT and 19,7 GW for PV, while thermal power plants were reduced more than 12 GW in 5 years. In 2030, installed power is expected to reach about 16,2 GW and 46,6 GW for WT and PV, respectively [1].

According to the last update of Terna’s development plan (available on its website) presented in 2021, RES generation must increase from 117,7 TWh of 2019 to 186,8 TWh, i.e., increasing RES capacity of 40 GW. In addition, national targets require coal-based generation plants phase-out by 2025.

This strategy involves a lot of issues since, as already discussed, grids with a lot of inverter-based RES generation are weak due to their low short-circuit power, which derives from bad values of three parameters listed above: high impedance of radial distribution grids, lower voltage with respect to EHV and HV transmission systems, and a very small short-circuit current contribution due to thermal reasons, in order to protect inverter valves.

The phasing-out of thermal power plants, which supply the majority of base annual load, will cause a huge need of energy and an even greater worsening of fault level, since synchronous generators of those plants will be put out of service.

Consequently, power system must improve its capability to withstand perturbations and react to unplanned events quickly, in order to avoid risk of cascading effects and voltage collapses, since a weak grid involves a wide-ranging impact on voltage stability; actually, a single fault could be enough to cause voltage dips to propagate within an area of hundreds of kilometres.

In order to understand the impact of this phenomenon on the grid and the effects of the new prospected scenario, an analysis has been performed in [2], observing short-circuit impact from the two main different points of view that characterize it: intensity and extension.

A three-phase short-circuit has been simulated in three different parts of Italy, considering grid scenarios of 2008, 2017 and 2030. In all three cases, it is possible to observe a general reduction of fault voltage level in 220 - 400 kV grid, that can reduce more than 20% in 2030 compared to 2008. The extension is surprising, as can be appreciated in figure 2.2-1. In fact, in southern part of Italy, a single fault affects the overall grid of the considered region: in Sardinia, the whole island suffers from a single short-circuit. The reason of the major northern grid stability is due to the fact that is interconnected with other European countries, which means having more generators and a more meshed topology. The entity of perturbation can be realized figuring out that EHV meshed transmission network has been considered, where short-circuit power is the highest in electrical systems. In view of this consideration, even the intensity and the extension of voltage dip in Veneto appears as a serious deal.

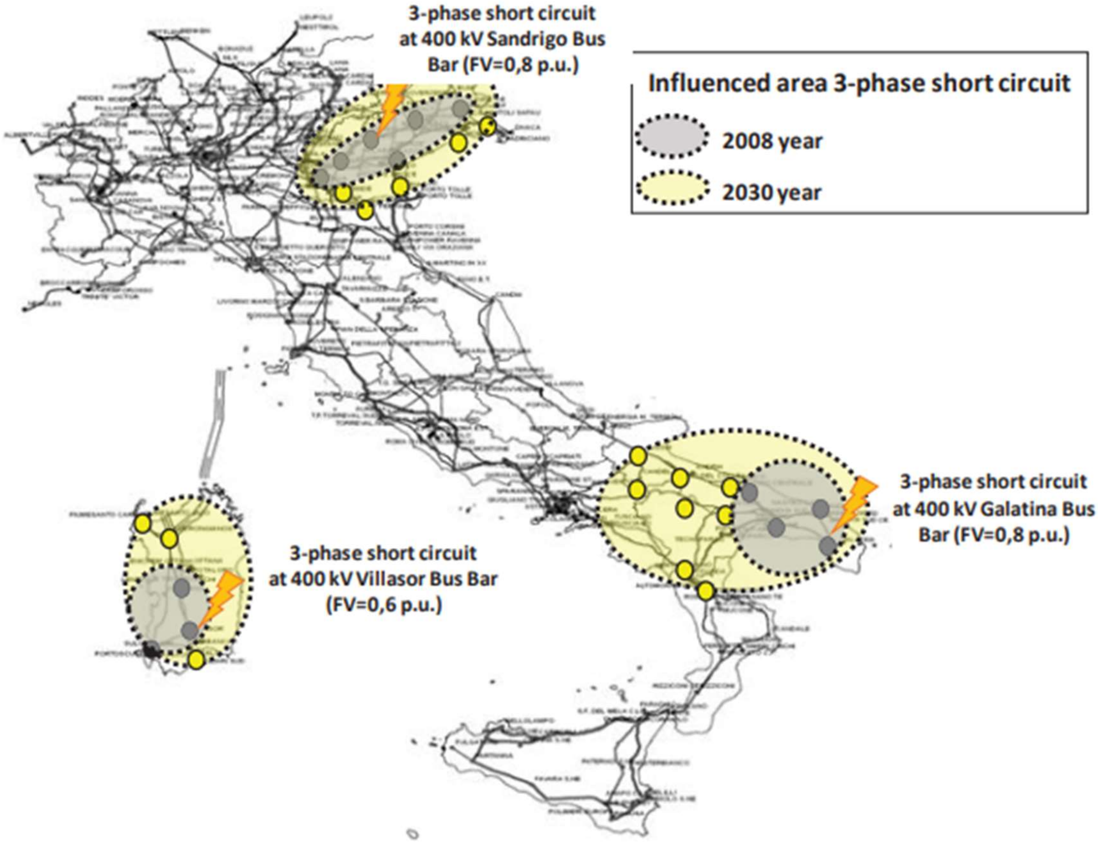


Figure 2.2-1*: spatial impact of considered fault scenarios where voltage decreases up to 60% in Sardinia, and up to 80% on the peninsula. FV means Fault Voltage level*

Furthermore, seeking to achieve improvements concerning RES impact, an analysis during faults has been carried out in [2] and [3].

In [2], what already discussed in last chapter has been demonstrated, i.e., the best voltage profile during faults is achieved if RES join voltage regulation injecting reactive power. In other words, synchronous generators regulate voltage during normal conditions while during faults their significant current contribution guarantee a high fault level; instead, RES need to regulate reactive power both in normal conditions and under fault, in order to mitigate issues derived from their limited short-circuit current.

In addition, RES benefit has been observed also from a probabilistic point of view: in fact, according to obtained results, RES injecting reactive power can also reduce the probability of severe voltage sags happening. In fact, as shown in figure 2.2-2, the difference with respect to the case of RES disconnection and RES supplying only real power is almost negligible.

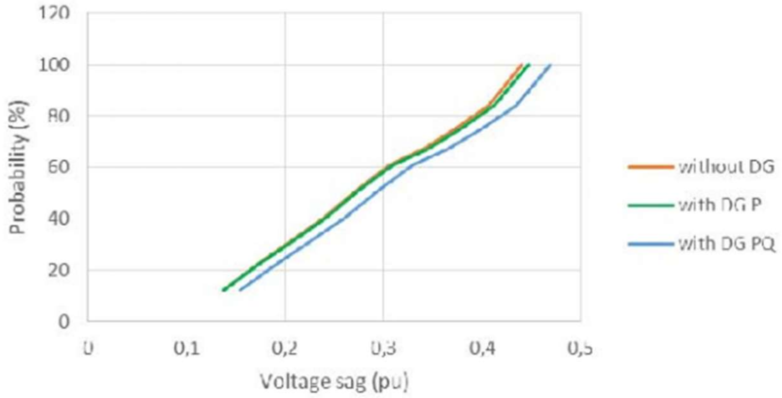
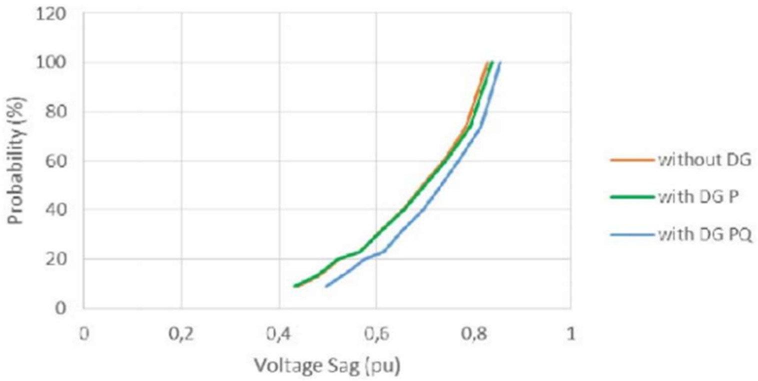


Figure 2.2-2: *cumulative probability curves of phase-A voltage considering fault in the closest point with respect to DG (on top), and in the farthest point (on bottom). Naturally, in case of fault near DG, the voltage drop is more critical.*



This result is not surprising, since, as demonstrated, voltage is more sensitive to reactive power, whose injection creates a remarkable benefit for the most locally. Anyway, it constitutes another confirm about the importance of this strategy.

Moreover in [3], a practical demonstration related to RES penetration influence on short-circuit current has been performed in nowadays grids, i.e., with the actual fault level and the present grids conditions (with the actual number of synchronous generators). As expected, in the short-term RES contributions increase fault currents, rising the fault level of the grid. Actually, the aim of that paper is to discuss about negative effect of RES on protections. Concerning the analysis carried out so far, the fault level rise is a benefit from the voltage stability point of view, and it is a confirmation about the fact that penetration of RES in nowadays grids increase short-circuit power (of course, if RES remain in service during faults). Nevertheless, as already introduced previously, this is not a realistic assumption since RES penetration implies reduction of synchronous generators. Therefore, the fault level is destined to reduce remarkably, and protections will be affected by the opposite issue: short-circuit currents quite similar to nominal ones, faults difficult to detect and selectivity problematic to be performed.

In conclusion, as previously mentioned discussing about Synchronous Condensers, the increasing of RES makes synchronous machines role more and more important to guarantee a reasonable grid fault level (especially due to thermal power plants reduction in the long term), as well as the contribution of RES to voltage regulation, exploiting all reactive compensation methods and strategies discussed above. A smart cooperation of synchronous generators, compensators and RES is fundamental to improve grid condition during faults, keeping voltage profile adequate and avoiding dramatic events that could threaten the proper functioning of power systems.

At this point, the behaviour of all types of RES generators during short-circuit will be discussed and analysed, in order to introduce a study on the Italian grid.

2.3-Short-Circuit Contribution of Generators

In this section, the behaviour of different generation technologies is going to be analysed in detail. In particular, given its paramount importance concerning fault level, and being the main factor of influence in regard to the change taking place in power system voltage stability, short-circuit current contribution of synchronous generator and inverter-based RES generators will be compared.

This section is particularly relevant to discuss how to model and represent different generators in short-circuit analysis.

2.3.1-Synchronous Generator

As discussed in last chapter, the short-circuit current contribution of synchronous generator is very remarkable, and it is formed by two components:

- a sinusoidal component at nominal frequency;
- a unidirectional decaying component (called “DC-component”).

Moreover, the sinusoidal component is equal for all three phases, and it is characterized by a variable amplitude due to three states constituted by different reactance values: sub-transient, transient and steady-state. This is since, at early times of transient, only the rotor damper windings are affected by short-circuit; then, once they have reached the steady state, the transient state takes place and regards the excitation field; finally, the steady state is reached, whose current could be even lower than the nominal one.

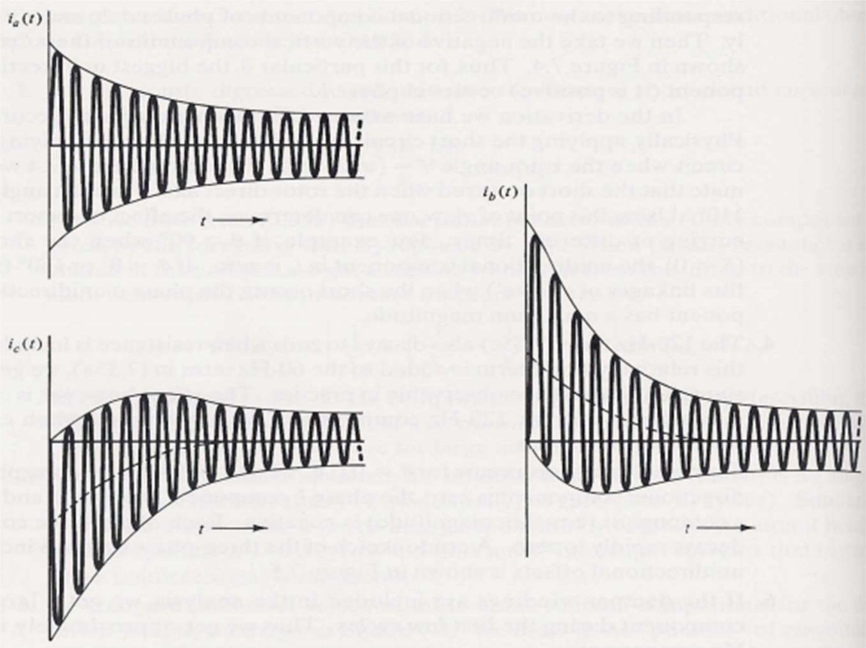


Figure 2.3-1*: short-circuit currents on three phases of synchronous generator*

The first state of fault, the sub-transient one, is of paramount interest, since its reactance is the lowest one and consequently it presents the highest value of short-circuit current (this is due to the fact that, in the first instants of transient, the overall flux linked with the stator is mainly leakage in air, resulting in very low reactance); thus, despite the dynamic nature of the phenomenon, short-circuit analysis can be assumed as steady-state procedure, referring to sub-transient state only, in order to size protections for maximum current values.

In addition, it is expected that protections themselves isolate the fault before other two states are reached, limiting the fault duration as more as possible to avoid dramatic consequences on system components, such as thermal damages, electrodynamical forces, and power flow variations that can compromise stability (in fact, short-circuit is a great perturbation of the system).

Furthermore, synchronous generators can lose synchronism and reach the runaway speed.

Concerning unidirectional components, they are different in each phase and tend exponentially to zero according to their own time constants; consequently, the highest short-circuit current value occurs in first instants of transient in the phase which presents the highest unidirectional component. This component causes the offset of the current delaying the crossing zero instant, making the interruption more difficult.

This negative behaviour is the more present the more inductive are the circuit shapes. Thus, since EHV-HV power systems resistance is negligible, and synchronous generators show high inductive behaviour, especially during short-circuit as explained above (there is only sub-transient reactance whose value is very low indeed), it is evident how tricky could be the interruption of short-circuit at generator’s terminals.

It is worth noting that excitation system of synchronous generator strongly affects short-circuit current, because, due to the reduction of voltage terminals, it increases excitation voltage and in turns excitation currents, resulting in a very slow decay of sub-transient current component (figure 2.3-2).

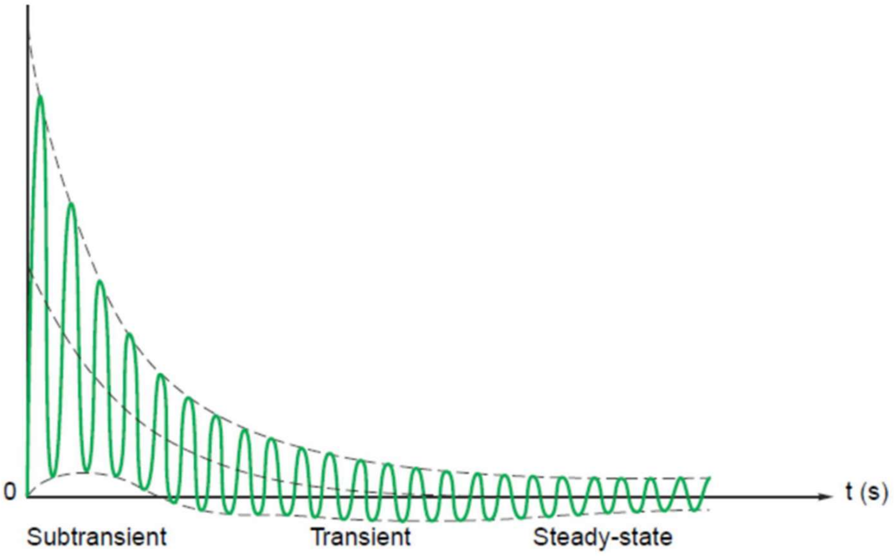
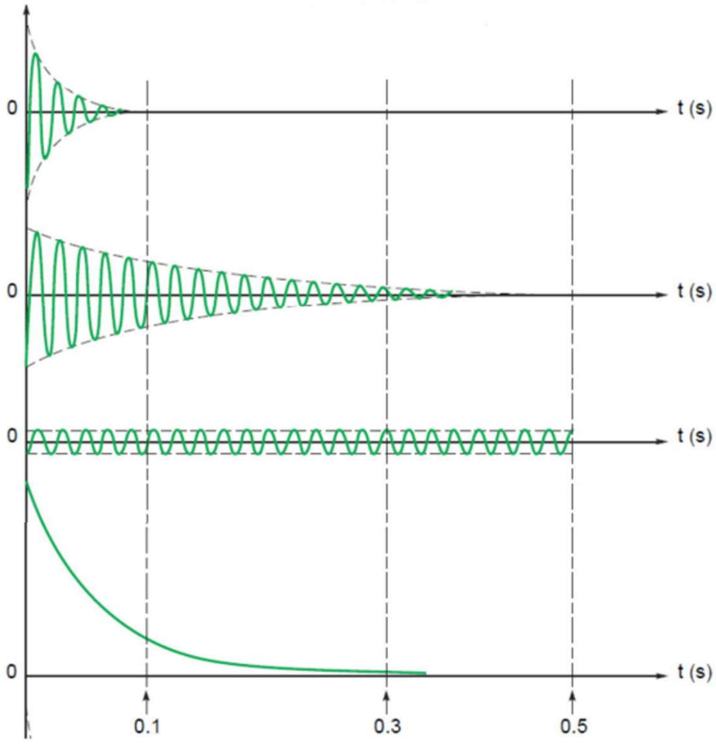


***Figure 2.3-2**: short-circuit current and its components. On top: overall short-circuit current (the unidirectional component is dashed); on bottom: from top to bottom, sub-transient, transient, synchronous, and unidirectional components*



As mentioned above, faults are dynamic transient phenomena, but considering only the worst case (sub-transient) a steady-state analysis can be adopted being on safe side, while in general the overall short-circuit current of a balanced three-phase fault at generator terminals can be described by the following equation:

$$i_{(t)} = \sqrt{2}E_d\left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{-\frac{t}{T'_d}} + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{-\frac{t}{T''_d}}\right] sin(\omega t + \alpha)$$

where T'_d and T''_d are transient and sub-transient time constants, respectively. The sub-transient fault current is equal to:

$$i_{(0)} = \frac{E_d}{X''_d} = I''$$

Regarding the aforementioned "sub-transient steady-state", synchronous generators can be consequently modelled as constant voltage source in series of their sub-transient reactance, neglecting armature resistances, saliency, and saturation, as in figure 2.3-3. The constant voltage is a reasonable assumption since excitation circuit does not change in first instants of fault.

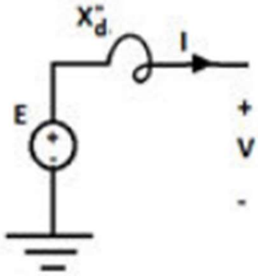


Figure 2.3-3: *synchronous generator model for short-circuit analysis*

2.3.2-Induction Generator

Given the increase of RES penetration in power systems, the use of induction generators is spreading, especially concerning WTs. In addition, they can be found in hydropower plants due to some advantages with respect to synchronous generators: they are cheaper, simpler, and are ideal for automatized power stations since they do not need of turbine speed control and synchronization. Nevertheless, they always need reactive grid support to work, and can only produce active power, i.e., they are useless regarding voltage regulation; therefore, they are only used in small plants not strategical from the power system point of view.

Back to their use in WTs power plants, their short-circuit current contribution is going to be discussed and compared [4]: regarding “traditional” induction generator, it has some common shapes with the alternator’s one, being characterized by a unidirectional component as well (that is not surprising, since induction machines functioning itself is strictly based on inductive phenomena).

However, in this case, the sinusoidal component decays exponentially and reaches its zero-crossing in the steady-state (figure 2.3-4, [4]): in fact, there is not any excitation circuit to sustain it, hence the final current is null; in addition, damping windings are not present, thus sub-transient state is absent.

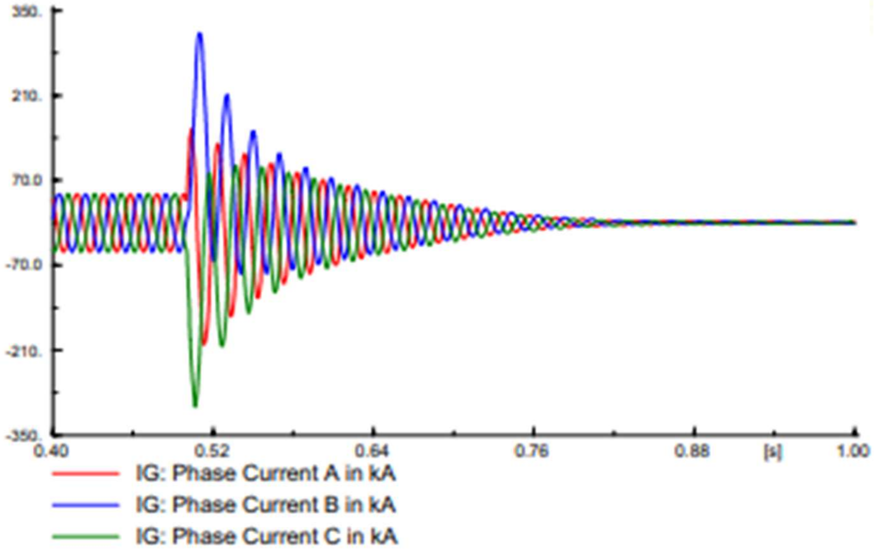


Figure 2.3-4: *short-circuit currents of induction generator*

Despite everything, also in induction generators the voltage can be assumed constant in first instances of fault, because the flux does not vary immediately. In fact, they can be modelled as constant voltage source in series of the locked rotor reactance, just like for induction motors. The reason of that is because rotor accelerates during fault since, as for synchronous generators, the imbalance between mechanical moving power and electrical resistive one is stored into the rotor as kinetic energy; as a result, slip increases, and rotor resistance becomes negligible. Consequently, the equivalent circuit corresponds to the locked-rotor one.

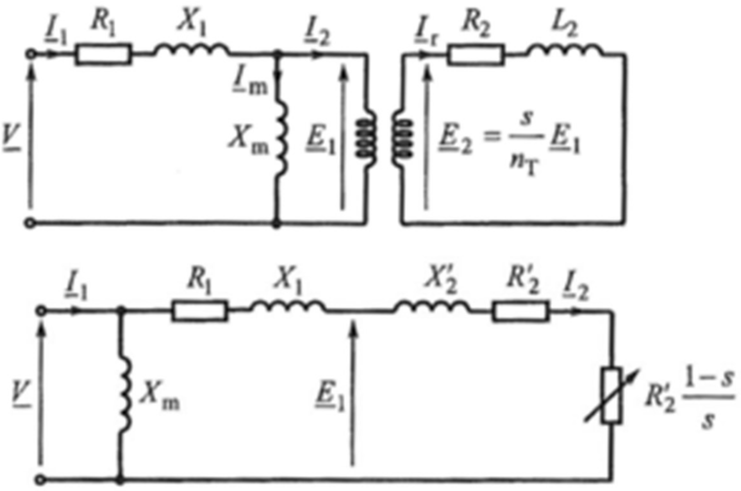


Figure 2.3-5*: equivalent circuit of induction machine and its simplification with mechanical shaft power term highlighted*

In case of Squirrel Cage Induction Generators (SCIG), used in WT Type 1, there is not much more to add; in case of Wound Rotor Induction Generators (WRIG), used in WT Type 2, the same statements hold, with an additional resistance in series of the others in the rotor circuit, which allows to control the rotor current.

The result of this dissipative regulation can be appreciated looking at variations of mechanical characteristic of the machine, as in figure 2.3-6, while the correspondent equivalent circuit of induction machine is shown in figure 2.3-5.

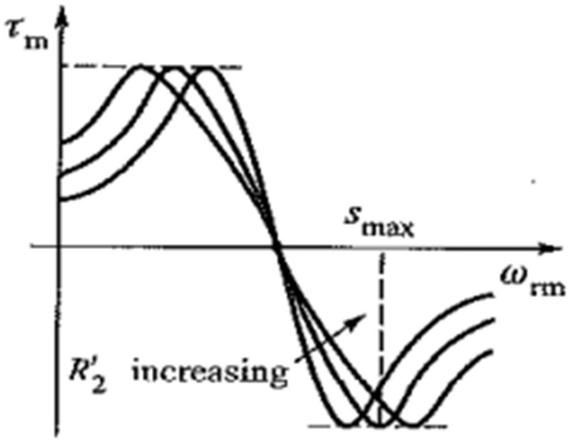


Figure 2.3-6: effect of rotor resistance variation on characteristic curve of induction machine; note that, despite the maximum torque remains the same, the starting torque can be regulated

2.3.3-Doubly-Fed Induction Generator (DFIG)

The DFIG presents some differences with respect to the just described induction generator [4] [5] [6], since its rotor is interfaced with the grid by means of a frequency converter to carry out the accurate regulations described in last chapter.

In general, DFIG behaviour under fault depends on its terminal voltage, and its current is made by the contribution of the natural electromagnetic response of the generator to the perturbation (the stator is directly connected to the grid) and the converter one, whose aim is controlling active and reactive power to match with grid codes requirements during faults (Fault Ride-Through).

Due to the direct connection with the grid, transient disturbance is transmitted to the stator, and naturally due to their electromagnetic relation is transmitted to the rotor. For this reason, to protect power electronic converter from overcurrent, there is always a so-called crowbar protection, which consists in a resistance inserted in the rotor, in case current reaches a threshold value as consequence of excessive voltage drop; accordingly, the converter is bypassed, thus rotor control capabilities are lost, and generator starts to behave as “normal” induction generator.

In fact, as can be appreciated from figure 2.3-7 [4], DFIG short-circuit current with crowbar protection is quite similar to induction generator one.

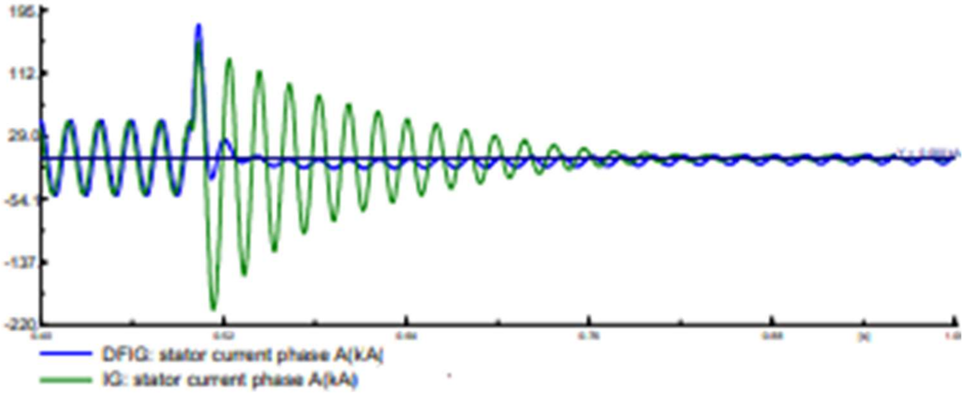


***Figure 2.3-7**: comparison between short-circuit currents of crowbarred DFIG and induction generator*

The main difference consists in a more rapid decaying of DFIG AC component, due to the smaller rotor time constant. That is consequence of crowbar resistance (in figure 2.3-8 [5], behaviour according to different crowbar resistance is represented).

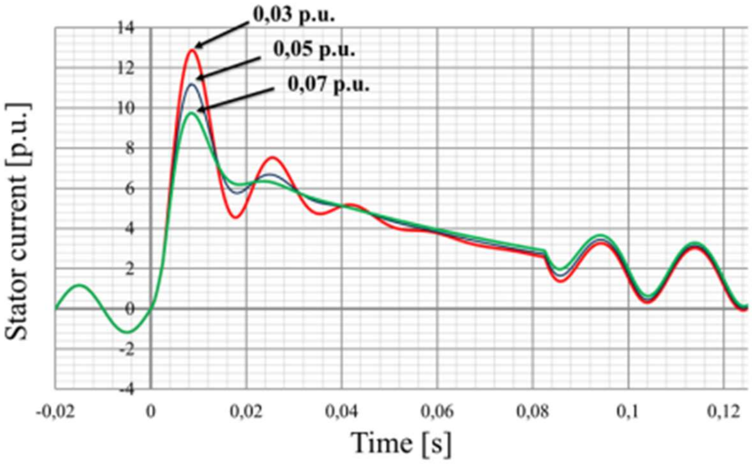


***Figure 2.3-8**: DFIG stator current for different crowbar resistance*

Regarding DFIG behaviour in case of crowbar not triggered, rotor converter controls of active and reactive power are not lost and contribute to the resulting short-circuit current. In fact, it can be appreciated from figure that current shows the following characteristics: at the beginning, the current bursts, then decreases, and increases again, subsequently at flux decreasing and control system effect.

Firstly, stator flux decades, implying a decreasing current; then, when the rotor controller detects that active and reactive power outputs are decreasing, the reference rotor current increases in order to increase in turn power output. Accordingly, stator current increases to get a new stable state, avoiding reaching zero in case protections are not tripped.

Comparing figure 2.3-4 and 2.3-9 [4], it can be noted how, at first instants as well as over (except at steady state obviously since induction generator’s currents go to zero), fault current of DFIG is remarkably lower. In particular, fault steady state currents of DFIG are slightly greater than its pre-fault currents. That is naturally due to current limits of power electronic converter, thus recalling what previously discussed about current contribution magnitude of DFIG and power converters in general.

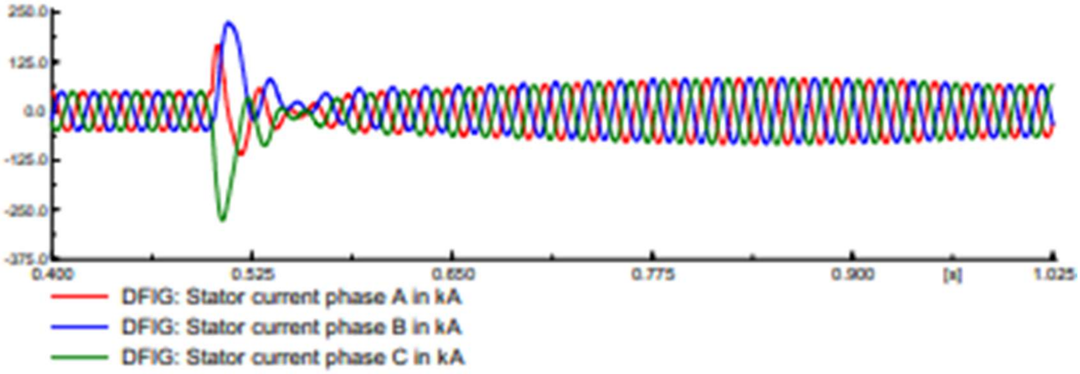


***Figure 2.3-9**: short-circuit currents of DFIG*

At this point, having regard to the two operating modes of DFIG under fault, it is useful to understand when one takes place rather than the other.

As introduced above, it depends on terminal voltage. In particular, if voltage drop is relatively moderate, the current transient has small duration and lower magnitude with respect to induction generator, as seen above; in particular, DFIG can continue to inject reactive power to sustain voltage during the fault.

In case of a more extensive voltage drop, typically from 0.4 to 0.2 per-unit, DC-side voltage increases due to active power imbalance between WT blades and grid (actually another crowbar tripping threshold is 1.2 per-unit of DC overvoltage), since converter regulates and limits injection; as a result, to keep voltage and current values away from dangerous thresholds for the converter, crowbar resistance is inserted, blocking rotor-side converter to protect it, but losing the regulation.

Coming to the model of DFIG in short-circuit analysis, in case of crowbar not connected it is well represented by the converter control response, while if the crowbar is inserted, as described, the generator behaves as an induction generator, more precisely as a WRIG (given the supplementary resistance on the rotor), thus it can be modelled as crowbar resistance in series of locked rotor reactance and constant voltage source.

2.3.4-Full-Scale Converter WT and PV

Lastly, Type 4 WT and Photovoltaic (PV) behaviours under fault are discussed [6]. They can be analysed together, since both are interfaced with the grid by means of a full-scale frequency converter, i.e., sized for all generator power flows (differently from DFIG where converter is sized for about 30% of the overall power).

Since all is controlled by the converter, it is evident how these generation technologies are less affected by electromagnetic and electromechanic phenomena during faults, and the resulting current is strictly dependent on converter shapes and its control mode. In particular, since power electronic converters are limited in current, as discussed previously and in the last chapter, if voltage at terminals are high enough the generator works according to the desired operative mode, regulating both powers; in case of excessive voltage drop, the converter limits current to 1.1-3 per-unit, typically 1.5, to protect itself and semiconductor valves.

Regarding Type 4 WT, the consequent imbalance of power between blades and grid makes the shaft to accelerate, in case of storing it as kinetic energy, or DC-side voltage to increase, if stored as electrostatic energy. This latter consequence can be limited oversizing converters or components (such as the capacitor) or inserting resistances on DC-side.

The same holds for PV power plants, except obviously for the imbalance stored as kinetic energy.

In conclusion of this discussion, it is evident how the more accurate model to describe behaviour under fault of Full-Scale Converters-based generation plants consists in a voltage controlled current source, which implies a not linear current contribution, differently with respect to synchronous and induction generators. These shapes strongly affect not only voltage stability due to limited current contribution, as already described, but also the impact of RES on short-circuit and its analysis, as will be shown later. Short-circuit currents of FSC WT and PV are shown in figure 2.3-10.

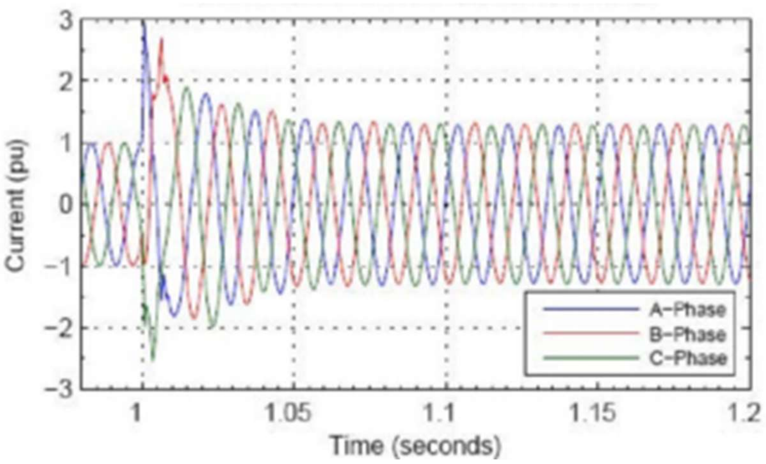
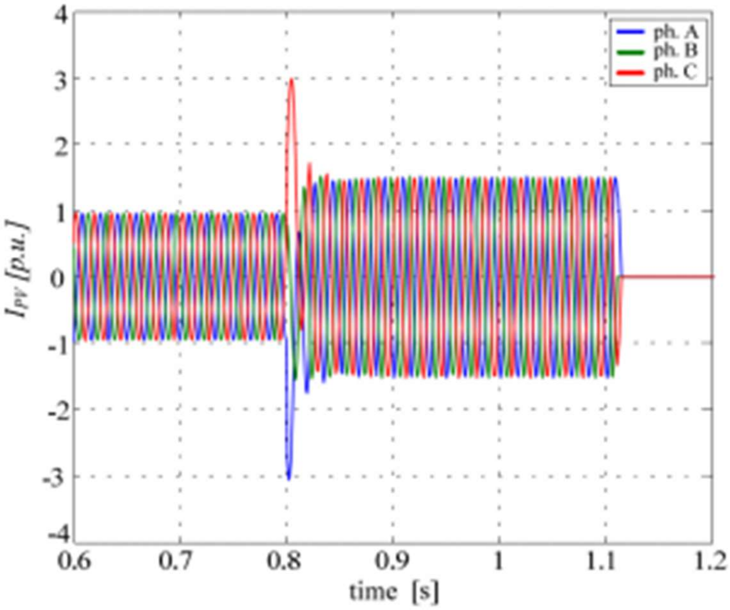


***Figure 2.3-10**: short-circuit currents of FSC WT (on top) and of PV (on bottom). As can be appreciated, in both cases the converter limits current magnitude to protect valves within about two cycles. The resulting fault current is slightly higher than the pre-fault one*



2.3.5-Additional Considerations

In general, Wind Farms are constituted by several WTs connected with the system. Therefore, in order to model correctly the plant in the short-circuit analysis, some considerations have to be discussed.

In case of Type 1 and 2 WTs, the equivalent circuit is defined connecting generators, cables, and transformers according to real plant topology, computing the Thévenin equivalent of the plant seen by the system.

Instead, concerning Type 3 and 4 WTs (figure 2.3-11 and 2.3-12), some assumptions must be made. Considering all WTs of the same type, with similar parameters and working under the same wind conditions and considering that all turbines participate to the voltage regulation at point of common coupling by means of a controller, all power outputs can be reasonable considered in phase and summed together. Otherwise, the real topology of the plant and the wind distribution must be known, in order to determine every turbine contribution and derive the Thévenin equivalent model seen by the system by means of the circuit theory.

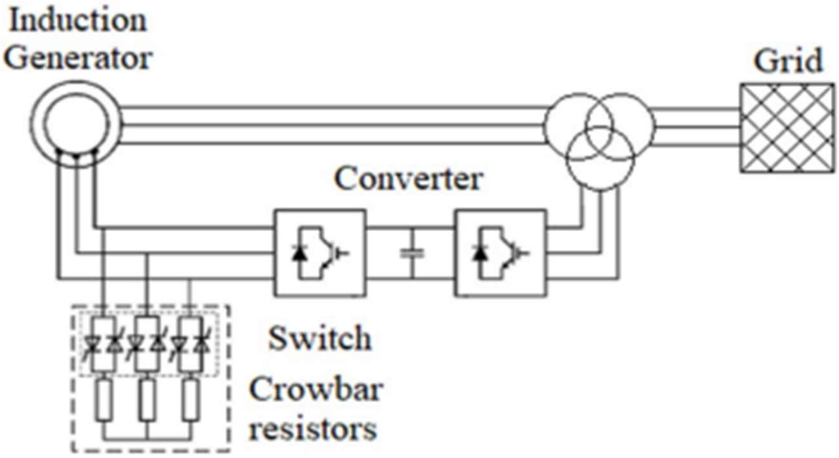


Figure 2.3-11: DFIG; on the bottom left, crowbar resistors with semiconductor valves can be noted

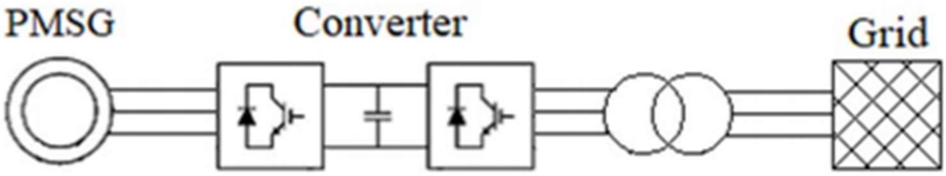


Figure 2.3-12*: Permanent Magnets Synchronous Generator (PMSG) with Full-Scale Converter*

2.4- Fault Ride-Through Requirements of Terna

Now that the physical behaviour of different generators under fault has been discussed, RES fault requirements of Terna are going to be analysed. They are explained in the grid code, in attachments A68 [7] and A17 [8] regards PV and WT, respectively.

Voltage Ride-Through curve is reported below in figure 2.4-1 and consists in a time dependent disconnection based on voltage magnitude at RES generator terminals. Low Voltage Ride-Through (LVRT) requirements are focused, in order to carry out the short-circuit analysis.

As already explained in the last chapter, voltage between 85% and 115% is considered normal operation, therefore disconnection is never allowed within this range.

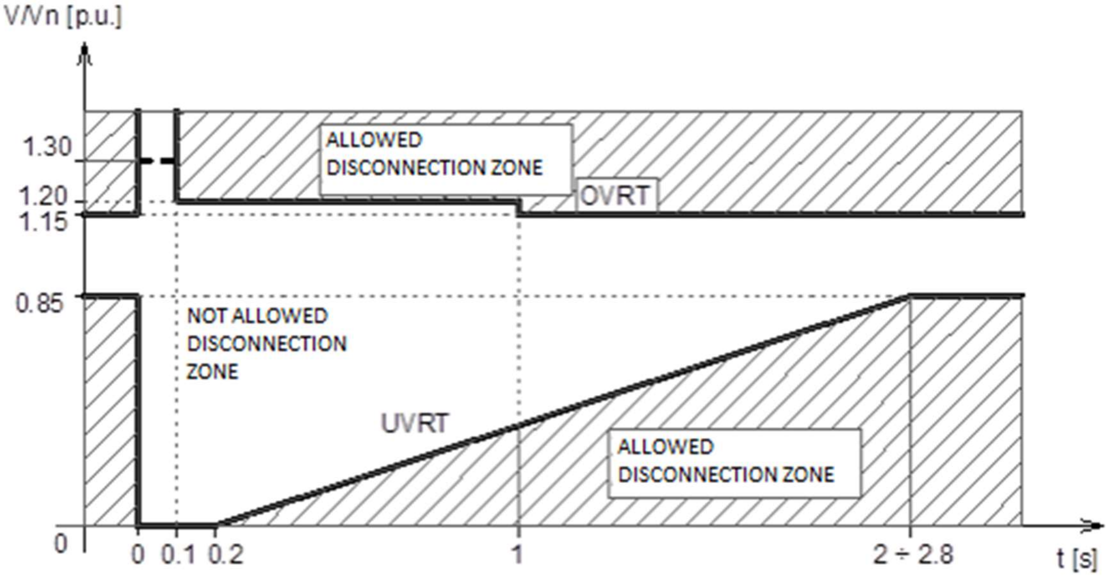


***Figure 2.4-1**: LVRT characteristic curve at RES connection point (both WT and PV)*

LVRT requirements are the same for PV and WT; in particular, the ability to withstand the total cancellation of voltage for 200 ms is required. The final point of LVRT characteristic depends on PCC nominal voltage: 2 s in 132/150 kV grids (HV), 2,8 s in 220 kV ones (EHV). Within the not allowed disconnection area, nowadays strict specifications concerning active and reactive power dispatch are not required.

Nevertheless, as explained in [9], the large majority of WTs in the Sicilian network, whose scenario will be considered for the short-circuit analysis, is not equipped for LVRT, and typically disconnect for terminal voltage lower than 0.4 per-unit.

2.5-Short-Circuit Computation

The short-circuit computation procedure used to be performed considering synchronous generators only. As discussed in last section, their short-circuit behaviour is linear, i.e., they can be represented as a constant voltage source in series of their sub-transient reactance. Consequently, this shape allows to apply the Thévenin theorem, evaluating the faulted state as a superposition of the pre-fault grid and the Thévenin equivalent.

In next sections, this traditional short-circuit procedure will be recalled and, afterwards, updated with an innovative computation method which takes into account RES contribution despite their non-linear behaviour under fault.

2.5.1-Traditional Short-Circuit Analysis

Since the aim of this work is to assess the network strength concerning voltage stability, short-circuit analysis is carried out considering solid three-phase fault, in order to achieve the short-circuit power of buses. Hence, the grid can be modelled considering positive sequence only.

According to the superposition method, the fault is represented by two equal and opposite voltage sources, each with a magnitude equal to the pre-fault voltage in the faulted point. Then, since the circuit is linear, it can be decomposed in two different circuits, which are the pre-fault state and the so-called Thévenin state.

The pre-fault state is constituted, as the name implies, by the normal operating condition of the grid before that the fault takes place, and it is determined by a power flow; the Thévenin one is formed by the dead network and one voltage source equal to the opposite of the pre-fault one.

Focusing on the application of this procedure in large systems, the grid is modelled and described by its admittance matrix Y_{bus} , whose bus terminals are connected to generators and loads: generators model has been already discussed, while loads can be treated in two ways: in general, most loads do not contribute to short-circuit, hence they are usually neglected; otherwise, they can be assumed as constant impedances obtained by absorbed powers of loads.

By means of the substitution theorem, every bus voltage is represented as a constant voltage source; in case of fault, the two voltage sources with opposite polarity are connected in series to the faulted bus. Generator’s voltages are the same as the pre-fault state, since in sub-transient state flux remains constant and consequently the excitation voltage does not change.

Thus, the pre-fault network is made by the bus admittance matrix Y_{bus}, sub-transient reactances of synchronous generators X_d'', and, if included, loads model as shunt constant impedances (figure 2.5-1).

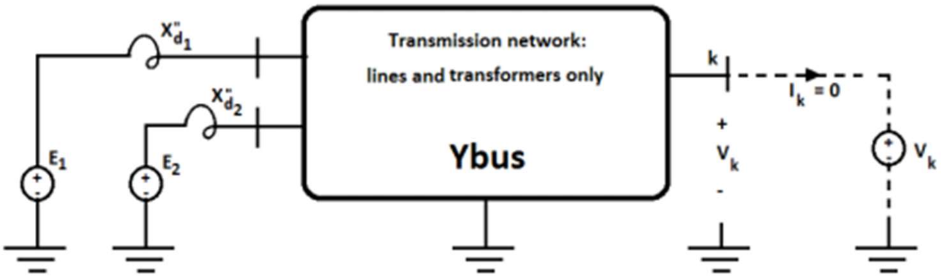


***Figure 2.5-1**: Grid model in normal operating condition: nominal voltage at bus k is modelled as constant voltage source and exiting current is equal to zero*

All admittances form the so-called short-circuit admittance matrix Y_{sc}, which is the same in both states. In Thévenin state, which represents the perturbation of the fault, all voltage sources are short-circuited except for the negative one connected to the faulted bus.

All these concepts are shown in figure 2.5-2: in the Thévenin state, the short-circuit current is derived considering it exiting from the node (since voltage source is negative). In the pre-fault state, faulted bus current is equal to zero and its voltage is imposed by the constant voltage source equal to the nominal pre-fault voltage.

Now it is clear that variables of interest during fault can be obtained superimposing the two states. For example, faulted bus voltage is equal to zero, as expected since the fault is solid three-phase, and the two voltage sources are equal and opposite.

Consequently, short-circuit computation is reduced to a preliminary power flow superimposed to the Thévenin equivalent circuit.

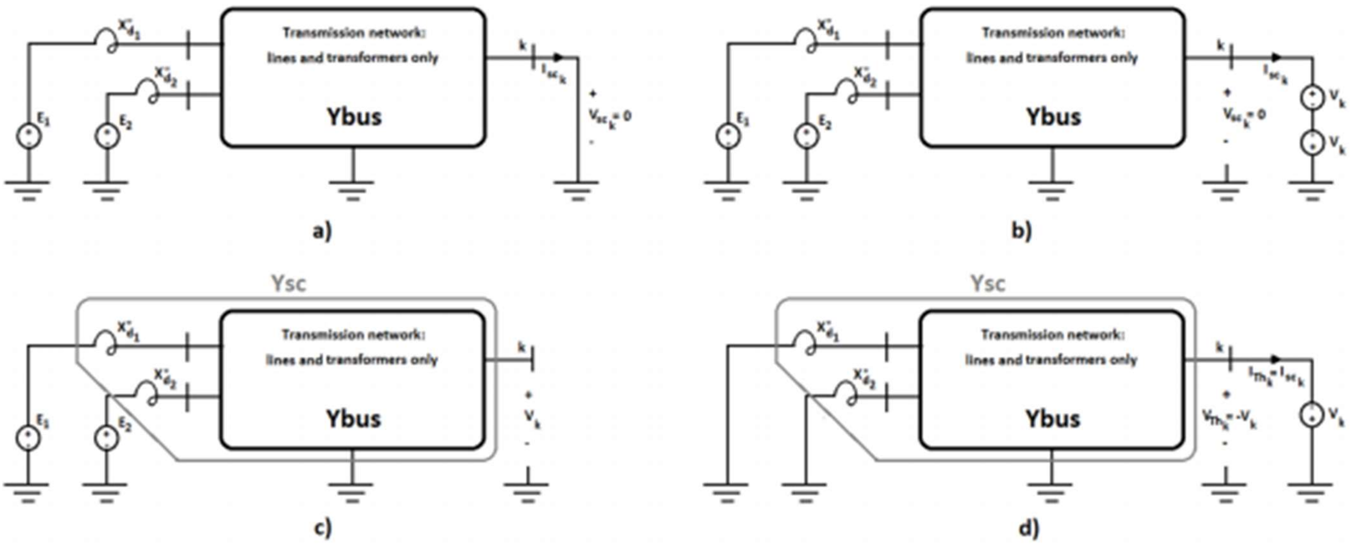


Figure 2.5-2*: Grid models under short-circuit: a) overall model of the faulted grid; b) overall model shown as superposition of pre-fault and Thévenin state; c) pre-fault state; d) Thévenin state.*

Now that the procedure and its theoretical foundation have been discussed, the mathematical computation is explained. Firstly, the short-circuit current is derived, which is present only in the Thévenin state; therefore, it can be stated:

$$E_{Th} = Z_{sc} \cdot I_{Th}$$

where E_{Th} is voltage under Thévenin state, Z_{sc} is the impedance short-circuit matrix derived inverting the admittance one (easier and faster to obtain), and I_{Th} is the currents vector under the Thévenin state. All variables are phasors.

Thus, expressing instead the equation in matrix format, i.e., explicating all values for every bus of the system and assuming this latter formed by n buses and the k-buses as the faulted one, as in figure 2.5-1 and 2.5-2:

$$\begin{bmatrix} E_{Th(1)} \\ \vdots \\ \vdots \\ E_{Th(k)} \\ \vdots \\ \vdots \\ E_{Th(n)} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1k} & \cdots & Z_{1n} \\ Z_{21} & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{k1} & \cdots & \cdots & Z_{kk} & \cdots & Z_{kn} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nk} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ -I_{sc(k)} \\ \vdots \\ \vdots \\ 0 \end{bmatrix}$$

therefore:

$$E_{Th_{(k)}} = -Z_{sc_{(k,k)}} \cdot I_{sc_{(k)}}$$

Since, as explained above, Thévenin voltage of faulted bus is equal and opposite to the pre-fault one, the short-circuit current can be achieved in function of the pre-fault voltage as follows:

$$I_{sc_{(k)}} = \frac{E_{pre_{(k)}}}{Z_{sc_{(k,k)}}}$$

According to these conclusions, all bus voltages can be obtained superimposing the two states:

$$V_{fault} = E_{pre} + E_{Th}$$

where Thévenin voltages can be optimized from a computing implementation point of view, since currents vector is composed by all zero elements except the short-circuit current at k-bus:

$$E_{Th} = col_k\,(Z_{sc}) \cdot I_{Th_{(k)}}$$

Hence, expressing all for completeness:

$$\begin{bmatrix} V_{fault_{(1)}} \\ \vdots \\ \vdots \\ V_{fault_{(k)}} \\ \vdots \\ \vdots \\ V_{fault_{(n)}} \end{bmatrix} = \begin{bmatrix} E_{pre_{(1)}} \\ \vdots \\ \vdots \\ E_{pre_{(k)}} \\ \vdots \\ \vdots \\ E_{pre_{(n)}} \end{bmatrix} + \begin{bmatrix} E_{Th_{(1)}} \\ \vdots \\ \vdots \\ E_{Th_{(k)}} \\ \vdots \\ \vdots \\ E_{Th_{(n)}} \end{bmatrix} = \begin{bmatrix} E_{pre_{(1)}} \\ \vdots \\ \vdots \\ E_{pre_{(k)}} \\ \vdots \\ \vdots \\ E_{pre_{(n)}} \end{bmatrix} + \begin{bmatrix} Z_{1k} \\ \vdots \\ \vdots \\ Z_{kk} \\ \vdots \\ \vdots \\ Z_{nk} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ -I_{sc_{(k)}} \\ \vdots \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} E_{pre_{(1)}} - \frac{Z_{1k}}{Z_{kk}} E_{pre_{(k)}} \\ \vdots \\ \vdots \\ E_{pre_{(k)}} - \frac{Z_{kk}}{Z_{kk}} E_{pre_{(k)}} = 0 \\ \vdots \\ \vdots \\ E_{pre_{(n)}} - \frac{Z_{nk}}{Z_{kk}} E_{pre_{(k)}} \end{bmatrix}$$

Once all post-fault voltages are known, it is easy to achieve any other variable of interest, such as current contributions.

Finally, the main quantity of interest from network strength point of view can be computed: according to the following formula, the short-circuit power of the k-bus is equal to the product of its pre-fault voltage and short-circuit current magnitudes:

$$S_{sc_{(k)}} = \left|E_{pre_{(k)}}\right| \cdot \left|I_{sc_{(k)}}\right|$$

2.5.2-Innovative Short-Circuit Analysis

As mentioned above, inverter-based RES were not included in short-circuit computation being their contribution negligible; nevertheless, with a more and more relevant RES production they cannot be no longer excluded. The main feature of synchronous generators that allows to exploit the superposition principle in the Thévenin method is their linearity; this is not the case of inverters, whose behaviour and current contribution is bonded to the voltage at their terminals.

Therefore, another strategy is needed to consider contribution to the short-circuit of type 3 and 4 WTs and PV (for type 1 and 2, the model of constant voltage source in series of a reactance is still appropriate).

As discussed previously, inverter behaviour is comparable to a voltage controlled current source, whose current injection depends on their control strategy and on terminal voltage. But voltages are the unknowns of analysis; in other words, to model inverters in short-circuit computation and determine current and voltages, voltages themselves must be known, i.e., it is a non-linear problem. This concept allows to guess the background of the innovative procedure of short-circuit computation.

In fact, as shown in [10] and [11], the procedure is based on an iterative approach; according to these guidelines, the computation method has been developed and it is going to be discussed hereinafter, to be used and tested in different scenarios based on the Sicilian grid.

The key concept is to consider inverters current as function of pre-fault supplied power and voltage magnitude during short-circuit, modelling the inverter as a variable equivalent impedance draining the opposite of the injected current during the fault; then, iterating until the convergence of the current injected is reached, achieve the final Thévenin profile.

Furthermore, before starting, some assumptions concerning inverter control mode must be made. Current magnitudes and entities of direct and quadrature currents, as several times demonstrated, depend strictly on pre-fault operative condition and control strategy. Nevertheless, as widely described in [6], this information is considered property of the manufacturer and not publicly available, not even to the TSO; most of times, only available information is maximum and minimum limits of injected current magnitudes.

Thereby, in order to test the iterative short-circuit computation, it has been assumed inverter controllers match with grid code, and in particular not only the Terna’s grid code, but also the German’s one has been taken into account [12] [13], following hints of the above-mentioned papers.

In fact, unlike Terna, whose grid code does not specify particular requirements of LVRT concerning power injection, the German one requires RES to contribute to voltage support by means of reactive power injection also during the fault itself and consequently specifies the amount of injected active and reactive current magnitudes, making it ideal to test the algorithm of the iterative method. In addition, since the voltage support is the main aim of German grid code (in fact, supplied active power during faults is subject to reactive current injection and could even be lower than the nominal one, if the maximum overcurrent limit is reached), it is particularly interesting to consider it in order to appreciate and study advantages of RES voltage regulation analysed in last chapter during fault as well. Moreover, as already discussed in last sections and chapters, the inverter regulation is very fast (in particular, in German grid code, reactive injection is required within 20 ms), thus it is reasonable to consider inverter already controlled under the sub-transient state.

Keeping these concepts in mind, LVRT German code requirements are resumed according to the following steps, referring to figure 2.5-3 (it is resumed also in figure 2.5-4):

- within the so-called “dead band”, defined by voltage variations lower than 0.1 pu, the inverter continues to inject pre-fault complex power;
- in case of greater voltage variations at PCC, the converter injects into the grid a quadrature current variation ΔI_q equal to two times the voltage variation in pu, which is added to the pre-fault injected reactive current, if present;
- reactive injection has the priority over the active one, hence real power by means of active current I_d is supplied only in case the overall current is lower than the maximum accepted overcurrent, exploiting the residual current capability.

In addition, ΔI_q must not be higher than 1 per-unit, and the maximum inverter current has been assumed equal to 1.5 times the nominal one in any case; concerning DFIG, their behaviour has been considered in accordance with these shapes up to crowbar threshold: beyond that, they start to behave as induction generators.

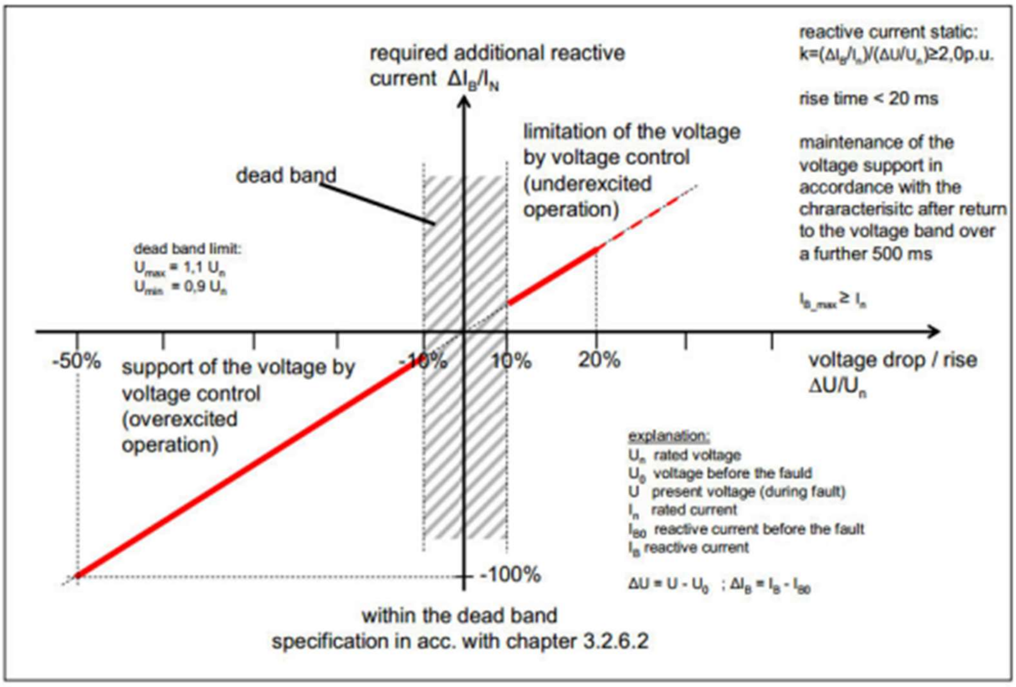


***Figure 2.5-3**: German grid code reactive injection requirement*

Therefore, at this point, the mathematical deployment of the algorithm is going to be discussed in detail. At first, a traditional short-circuit computation is carried out, i.e., neglecting inverters; it is worth noting that neglecting converters means to model them as infinite impedances in Thévenin state (being inverters current generators), linearizing at every step. This first procedure allows to achieve a reasonable initial setpoint for the iterative process.

Then, once short-circuit voltages V_{sc} have been obtained, they are used to compute the variable equivalent shunt admittances of inverters y_{inv}, as follows:

$$y_{inv} = \frac{I_{inv}}{V_{sc}}$$

Inverter currents I_{inv} employed in the formula are obtained according to the chosen control mode, whose shapes are defined by LVRT requirements of the grid code. The equivalent admittances are added to the short-circuit bus admittance matrix Y_{sc}, each one on its correspondent generator position on the diagonal (being generators shunt connected); for example, if the converter is connected to n-bus, its admittance is added to (n,n) matrix position. Afterwards, the new matrix, $Y_{sc}{}'$, is used to perform another short-circuit computation, resulting in another voltage profile $V_{sc}{}'$, which is used in turn to calculate inverter currents:

$$I_{inv}{}' = y_{inv} \cdot V_{sc}{}'$$

Finally, if active and reactive mismatches between obtained currents and the previous ones are below the chosen tolerance level, i.e., $I_{inv}{}' - I_{inv}$ < ε, it means that short-circuit voltages of the two iterations are the same, i.e., the convergence of currents has been reached and the final short-circuit voltage profile has been achieved. Otherwise, the procedure must be repeated from the equivalent admittances, this time using as input the just obtained fault voltage (the same for inverter currents, which have to be derived in accordance with the new voltage profile). The overall algorithm is resumed in the flowchart shown in figure 2.5-4.

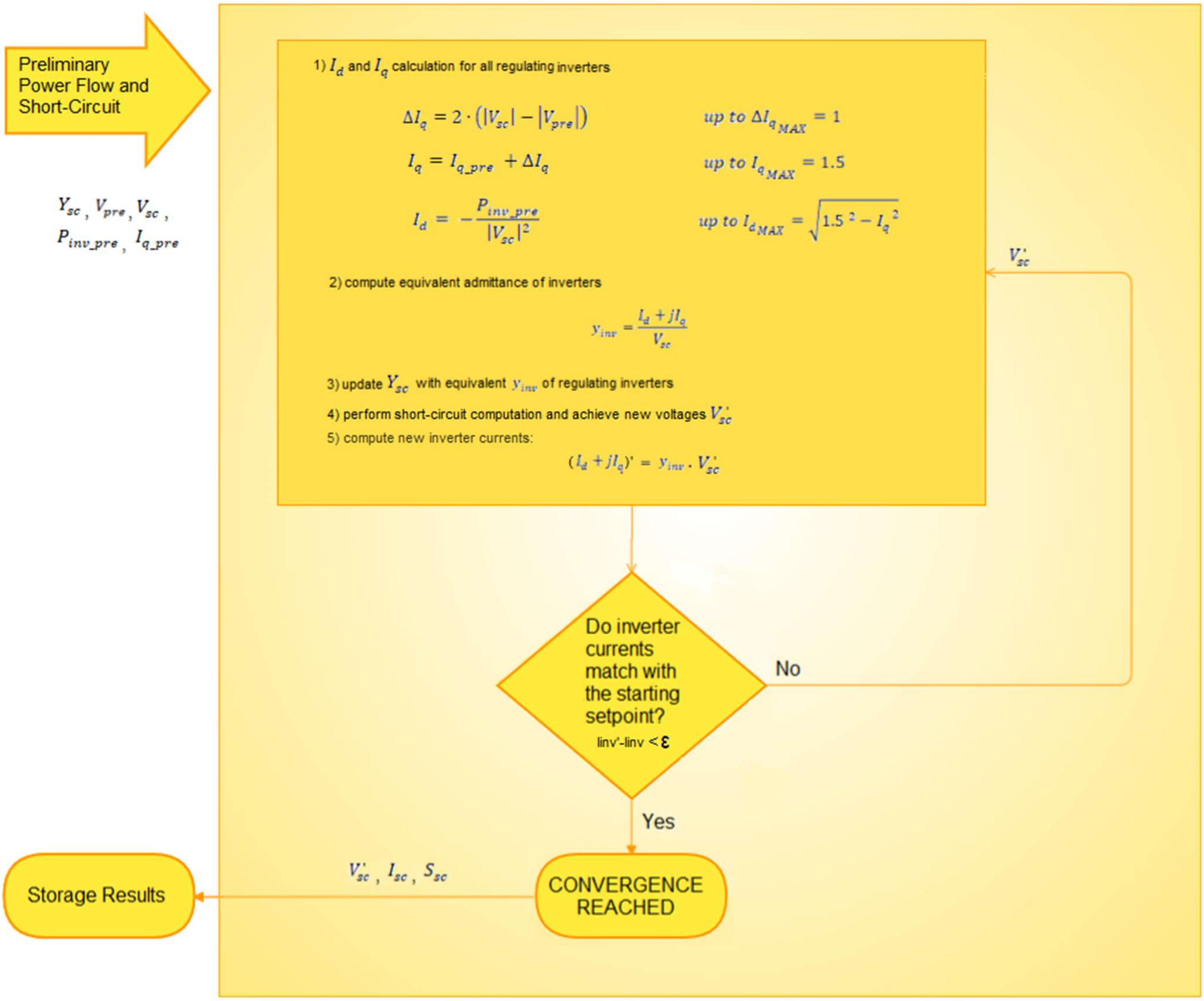


Figure 2.5-4: *Iterative short-circuit analysis including inverters (inverter currents are determined according to German code)*

Now that the iterative short-circuit analysis has been presented, some enhancements have been introduced, some of them dedicated to the Sicilian scenario. Being Sicilian WTs mainly DFIG, the crowbar protection has been implemented. Once the convergence is reached, all terminal voltages of current controlled RES are checked; if any voltage is lower than crowbar intervention threshold, the correspondent RES generator is moved from current controlled RES to the crowbarred one.

In addition, RES disconnection has been implemented as well and treated according to the same strategy: if any voltage, in both current controlled RES and crowbarred WTs, is lower than disconnection threshold, related generator is moved from its list to the disconnected RES one.

If some changes in RES lists take place, the solution is not the physical one, hence the short-circuit procedure must be performed from the beginning using the updated generators lists.

Concerning models of crowbarred and disconnected RES, they have been represented according to the following shapes: crowbarred WTs are modelled as constant impedances added to Y_{sc}, i.e., they are excluded from iterative procedure and their impedance is added to the bus admittance matrix at the beginning of computation; instead, regarding disconnection, it is a bit more complex.

Since, as shown above, inverter currents are equal to the product between equivalent admittances and short-circuit voltages, computation would converge if equivalent admittances of disconnected generators were equal to zero. However, despite its mathematical correctness, it is a wrong solution from physical point of view. This is because modelling disconnected RES current equal to zero in the Thévenin state means to achieve an overall current equal to the pre-fault one, when pre-fault and Thévenin states are superimposed. Thus, it is clear that disconnection must be modelled imposing an equivalent admittance in the Thévenin state draining the opposite of the inverter pre-fault current: consequently, superimposing the two states, the final current will be zero (or lower than the tolerance), representing the disconnection correctly.

Therefore, in order to determine the correct value of the admittance, another iterative loop is implemented within the Thévenin state computation (figure 2.5-5).

It is worth emphasizing that non-linear behaviour of inverters requires to evaluate their currents iteratively but, once they are obtained, RES can be treated as external ideal sources (as synchronous generators) connected to a linear circuit/grid; consequently, the key concept on which short-circuit analysis is based, the superposition principle, can be adopted correctly.

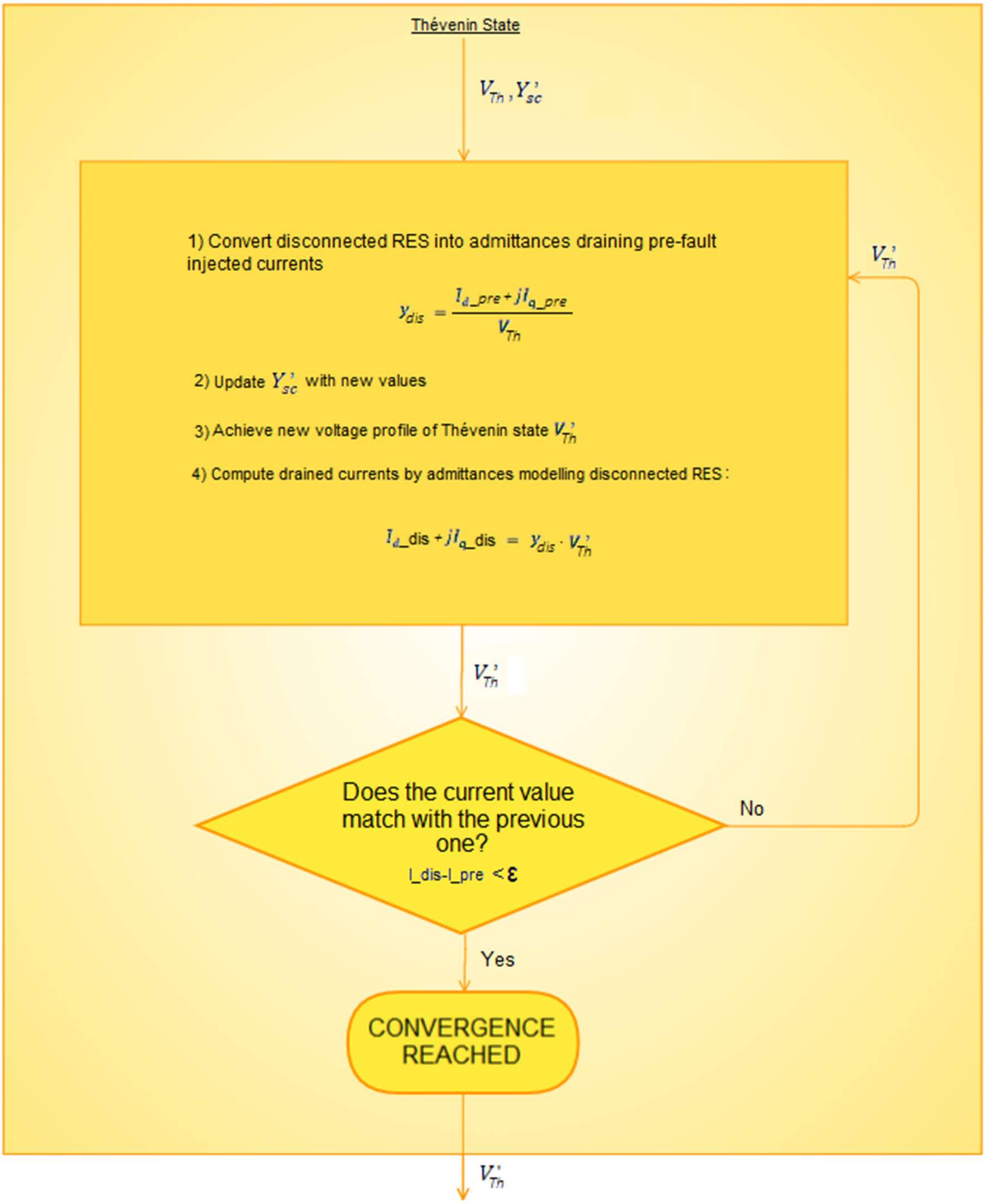


Figure 2.5-5: Iterative loop under the Thévenin state to model disconnected RES

Finally, when convergence is reached and modifications in RES lists no longer take place, the short-circuit analysis is completed and obtained voltages and currents can be stored and used to compute short-circuit power of considered faulted bus.

Two additional issues need to be clarified: in case of direct connection of any RES generator to a faulted bus, they are suddenly moved to disconnected list and excluded from iterative procedure, in accordance with their physical behaviour. Moreover, with the increase of RES penetration, reaching the convergence could result tough, being the analysis based on Gauss iterative method; hence, in the considered scenario of this work of thesis, the Sicilian grid, being composed by 181 RES over 261 power plants, iterations have been limited to 15 with a tolerance threshold equal to 5e-4 per-unit, both on active and reactive components of currents. If convergence has not been reached, iterative computations have been decelerated adding 25 more iterations performed using at each one the mean of the actual short-circuit voltage value and the one determined in the previous iteration, according to the following formula (where “n” means the n-iteration):

$$V_{sc_{(n)}} = \frac{V_{sc_{(n)}} + V_{sc_{(n-1)}}}{2}$$

The complete flowchart of the algorithm, considering crowbar and disconnection as well, is reported in figure 2.5-6.

Ultimately, as additional consideration, it is worth mentioning that another paper has been considered [14], in which a different approach is proposed. In particular, the method described therein is meant for the software PSS/e and keep the inverter model as current source, in accordance with the Norton theorem. The main difference with respect to the procedure adopted in this work of thesis consists in adding a resonant admittance for fault current computation to cancel out the impact of equivalent admittance for fault current computation; as a result, the iterative computation can be avoided. Nevertheless, as can be deduced from the paper, this procedure is mainly meant to overcome some limitations of PSS/e: for example, among others, this software does not include the current limiting functionality for steady state short-circuit analysis of inverters. Consequently, it has been decided to keep on using iterative approach, given that it is a computation method perfect to implement in MATLAB, it presents very good performances, as will be shown in next chapter, and it is flexible: in fact, different specifications of grid codes can be easily implemented, allowing to perform a lot of simulations to test different Fault Ride-Through strategies, which is one of the main purposes of this work of thesis.

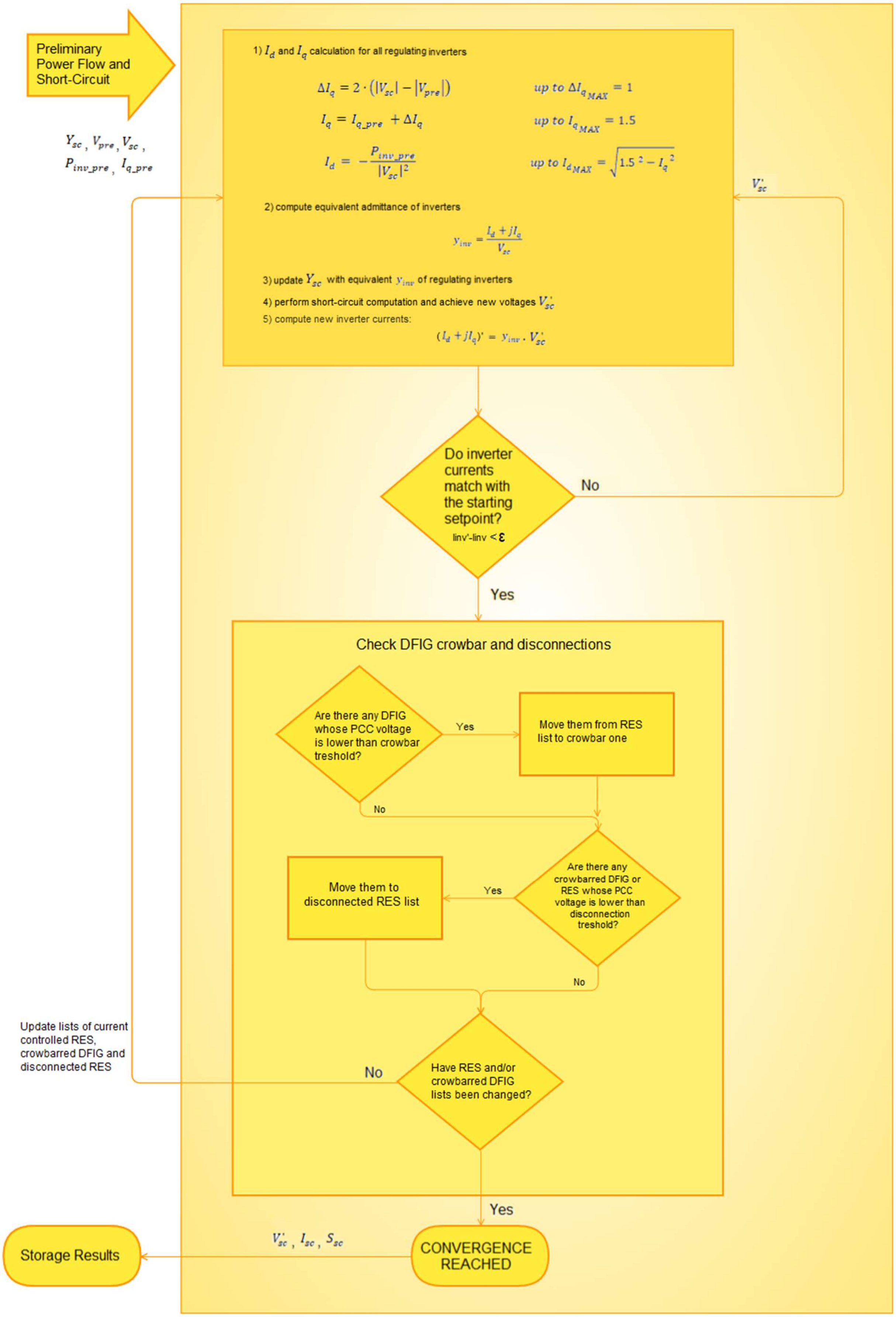


Figure 2.5-6*: Overall short-circuit algorithm taking into account RES disconnection and DFIG crowbar*

BIBLIOGRAPHY

[1] A. Berizzi, C. Bovo, D. Polinelli, L. Caciolli, A. Proietti, L. Michi, E.M. Carlini, P. Capurso, *The effects of new 2030 scenario: reduction of short-circuit power and widening of voltage dips*, AEIT International Annual Conference, 2018

[2] J. P. R. Gomes, W. C. Boaventura, E. N. Cardoso, B. M. Lopes, *Impact of integrating a solar power plant in a distribution feeder considering short circuit events,* IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), 2015

[3] A. Z. Adnan, M. E. Yusoff, H. Hashim, *Analysis on the Impact of Renewable Energy to Power System Fault Level,* Indonesian Journal of Electrical Engineering and Computer Science, 2018

[4] X. Li, T. Zheng, Y. Chi, W. Whang, *Short circuit current characteristic of Wind Generators,* Asia-Pacific Power and Energy Engineering Conference, 2009

[5] N. Leonov, G. C. Cho, A. Poluektov, *Short-Circuit Currents from Wind Turbine Generators Study in Laboratory Workshop,* V International Conference on Information Technologies in Engineering Education, 2020

[6] R. A. Walling, E. Gursoy, B. English, *Current Contribution from Type 3 and Type 4 Wind Turbine Generators during Faults,* IEEE/PES Transmission and Distribution Conference and Exposition (T&D), 2012

[7] Attachment A68 of Terna's Grid Code, *CENTRALI FOTOVOLTAICHE-Condizioni generali di connessione alle reti AT, sistemi di protezione, regolazione e controllo,* 2019

[8] Attachment A17 of Terna's Grid Code, *CENTRALI EOLICHE-Condizioni generali di connessione alle reti AT, sistemi di protezione, regolazione e controllo,* 2019

[9] D. Polinelli, *Preliminary study on Voltage Regulation in presence of high RES penetration*, Tesi di Laurea, Politecnico di Milano, A.A. 2012-2013

[10] Ö. Göksu, R. Teodorescu, B. Bak-Jensen, F. Iov, P. C. Kjær, *An Iterative Approach for Symmetrical and Asymmetrical Short-Circuit Calculations with Converter-Based Connected Renewable Energy Sources. Application to Wind Power,* IEEE Power and Energy Society General Meeting, 2012

[11] H. Margossian, J. Sachau, G. Deconinck, *Short Circuit Calculation in Networks with a High Share of Inverter Based Distributed Generation,* IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2014

[12] E.On Netz GmbH, *Grid Code for high and extra high voltage*, 2006

[13] VDE, *VDE-AR-N 4120, New German Transmission Code for onshore connections at 110 kV (or above)*, 2017

[14] L. Sigrist, J. Renedo, F. M. Echavarren, F. P. Thoden, L.Rouco, *Modeling of steady state fault current contribution of inverter-connected generation in PSS/e,* IEEE, 2021

[15] R. Marconato, *Sistemi Elettrici di Potenza*, 3^{RD} reprint, ed.CEI, 1988

[16] F. M. Gatta, *Impianti Elettrici,* 1^{st} edition, ed. Esculapio, 2014

[17] R. Marin, M. Valtorta, *Trasmissione ed Interconnessione*, ed. CEDAM, 1973

[18] F. Iliceto, *Impianti Elettrici*, ed. Patron, 1984

CHAPTER 3

SIMULATIONS ON THE SICILIAN POWER SYSTEM

The iterative short-circuit method will be performed and tested in this chapter. In order to achieve that, the Sicilian network has been considered, given its combination of weakness from voltage stability point of view and high penetration of RES, shapes that make it the ideal scenario to implement and test innovative tools and methods of RES management.

This method allows to avoid resorting to complex dynamic time-domain simulations, keeping the superposition principle valid and using phasors also in case of non-linear RES generators, saving computation time as well.

Its potentialities will be studied according to different scenarios of the considered grid, getting at the same time a powerful tool to pursue the study of RES impact on voltage stability and fault level.

3.1-Comparison between Short-Circuit Methods

Firstly, given the higher computational effort with respect to the traditional short-circuit analysis, a comparison between results achieved with traditional and innovative methods has been made. In particular, the current grid scenario has been considered, i.e., inverters operating according to Terna’s grid code requirements.

As shown in figure 3.1-1, representing the percent error committed neglecting RES, i.e., considering them as infinite impedances in the Thévenin state, the error between short-circuit powers of the 56 EHV buses of the system achieved with traditional and iterative methods cannot be neglected. In fact, its mean is equal to about 3%, which is too high to justify the aforementioned approximation and making necessary the use of a computation tool including inverters contribution. Furthermore, the ever-growing RES penetration validates even more the importance of adopting the iterative method, in order to compute correctly short-circuit currents.

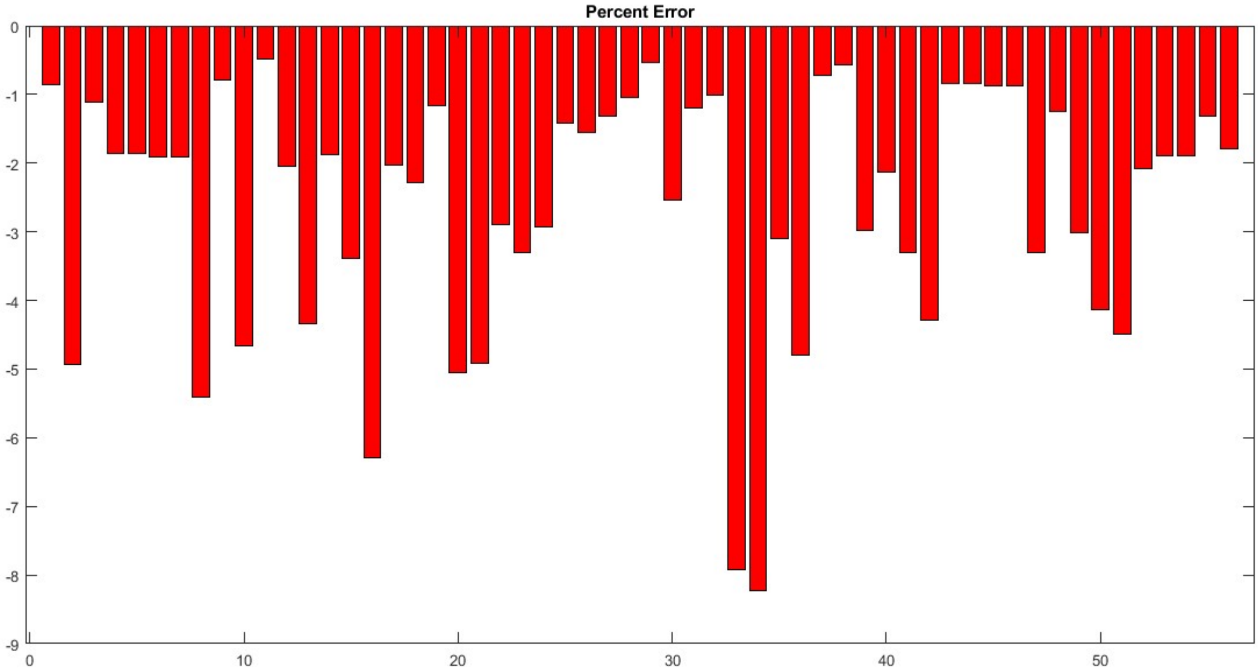


Figure 3.1-1*: short-circuit powers errors in percent of the 56 EHV buses if inverters are neglected*

Concerning the considered scenario, characterized by 181 RES over 261 power plants, according to Terna's requirements [1] [2] discussed in last chapter, HV RES must remain connected for every voltage value (except if fault is at their terminals), both PVs and WTs; regarding the latter, being all Type 3 WTs (DFIG), crowbar protection threshold has been assumed equal to 0.4 per-unit. Crowbarred DFIG are converted into WRIG whose transient admittance equal to 0.02+j 0.02 per-unit.

Since Terna's grid code does not specify any particular requirement concerning power injections during faults, as discussed in last chapter, all HV RES have been assumed injecting their pre-fault complex power until the maximum current limit of inverters, equal to 1.5 In, is reached; if that happens, the power is reduced at constant power factor keeping the current equal to the maximum acceptable one.

MV RES have been treated according to [3], i.e., they must remain connected for every value of voltage (except if fault is at their terminals), hence they have been represented as constant power injections. In other words, their behaviour is the same as HV RES.

Concerning computation time, with a personal computer characterized by an Intel® Core™ i7-6500U CPU and 12 GB of RAM, the simulation took just over 30 minutes, never failing the convergence.

3.2-Short-Circuit Analysis in Different Scenarios

Once effectiveness and potential of the iterative short-circuit method have been tested and confirmed, it has been used to perform analysis on Sicilian network, in order to study the impact of RES.

Initially, according to power system data provided by Terna, different inverter control modes have been tested, comparing, as foretold in last chapter, different LVRT strategies, from Terna's grid code to German one, in order to evaluate some possible improvements concerning the Italian grid code.

Afterwards, two more experimental scenarios have been considered, in order to predict eventual developments of the grid and investigate future fault level of the power system, as will be explained later.

3.2.1-Impact of RES Control on Fault Level

The impact of RES control on short-circuit power will be analysed in this section. In particular, three different scenarios have been considered.

1. The first scenario, as already introduced previously, is based on the present situation of Sicilian power system. HV RES are controlled according to Terna's A68 [1] and A17 [2] attachments, never disconnecting for every voltage value, assuming to inject pre-fault complex power, and keeping the current less or equal to its maximum acceptable value (1.5 In), adapting supplied power accordingly under the same power factor. DFIG crowbar protection is triggered if voltage is lower than 0.4 pu, losing control capability of the converter and making the generator to act like a WRIG. MV RES, according to CEI 0-16 [3], are treated in the same way: they are never allowed to disconnect, and they keep on injecting pre-fault complex power.
2. The second scenario can be defined as a hybrid, since first scenario's shapes are kept, with the only difference that HV RES supplies are controlled according to German grid code [4] [5], as described in last chapter. Recalling that, RES inverters are expected to inject and control reactive current to sustain voltage during the fault. The reactive injection is defined as the sum of pre-fault reactive current and the reactive current increment during the fault, which must be equal to twice the voltage dip, in per-unit. In case the resulting current is lower than the maximum current capability of inverter, the remaining capacity can be exploited to inject active power. The submission of active power role with respect to reactive one in the advanced German grid code can already give the idea of how much this control strategy during fault is crucial to avoid critical voltage drops, especially in presence of high-RES penetration. Therefore, summarizing, this scenario represents a trade-off between the actual Italian power system shapes and the more advanced German ones, resulting in a solution surely easier to implement with respect to put in place a total revolution of existing power plants to increment their Fault Ride-Through capabilities.
3. The third scenario is an even more advanced context, characterized by the extension of German requirements to all HV RES; hence, in contrast to scenario 2, DFIG crowbar protection is not allowed, and reactive control capability must be kept in any case. Also in this scenario, MV RES are controlled according to CEI 0-16.

It is worth repeating that, given that no specifications are defined both in Terna's grid code and CEI 0-16 concerning RES power supply under fault, the injection of pre-fault complex power is the best choice to approximate physical behaviour of RES during short-circuit.

Moreover, it was considered interesting to analyse Italian grid evolution in last decade [6], to observe direction in which improvements have been oriented; therefore, a further scenario has been considered, denominated 1.1, which corresponds to Terna's grid code of 2010. The difference with respect to the present grid code lies in WTs disconnection: in fact, a decade ago, WTs were allowed to disconnect in case of PCC voltage magnitude lower or equal to 0.2 Vn. All shapes of described scenarios are resumed in figure 3.2-1.

	Scenario 1 Terna 2021	**Scenario 1.1 Terna 2010**	**Scenario 2 Hybrid**	**Scenario 3 E.On-VDE**
HV RES control	Pre-fault power	Pre-fault power	Reactive injection	Reactive injection
HV DFIG crowbar	0.4 Vn	0.4 Vn	0.4 Vn	—
HV WT disconnection	—	0.2 Vn	—	—
MV RES control	Pre-fault power	Pre-fault power	Pre-fault power	Pre-fault power
MV DFIG crowbar	—	—	—	—
MV WT disconnection	—	—	—	—

Figure 3.2-1: *Summary table of different scenarios considered*

Moving to simulation results, EHV short-circuit powers in per-unit values are represented in figure 3.2.2. As can be appreciated, the more RES participation during fault increases, the higher the fault level, even on transmission system. In fact, reactive current injections remarkably increase short-circuit powers, showing all benefits that an improvement of Italian grid code in that direction would imply, especially considering the future perspective of RES penetration growth at the expense of fault level.

Since, as can be noted, the difference between second and third scenarios is negligible, an improvement limited to the hybrid scenario would be enough to obtain a significant benefit to voltage stability. In addition, a higher fault level would prevent (or, at least, reduce) troubles related to protections discussed previously.

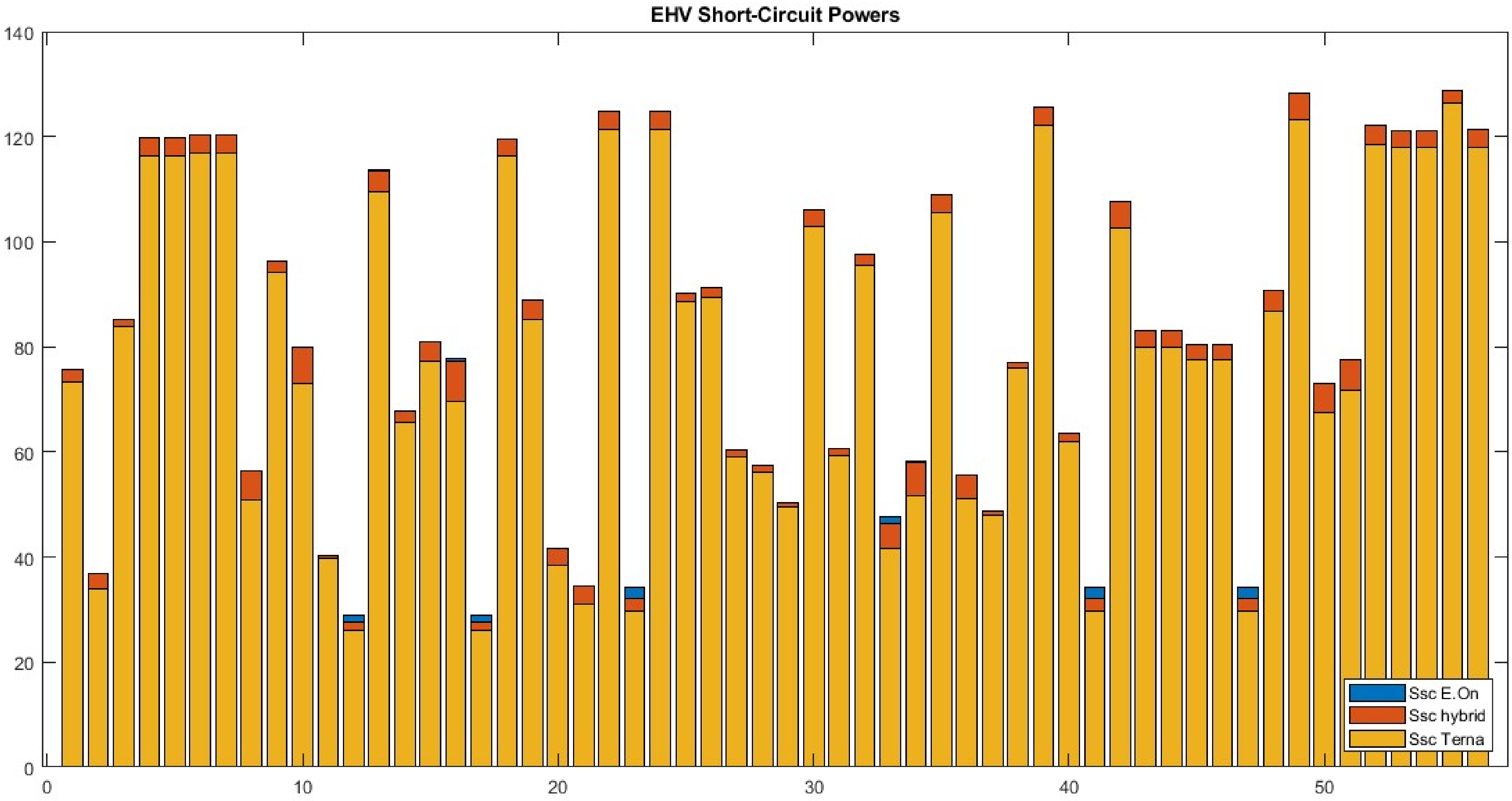


***Figure 3.2-2**: EHV buses short-circuit powers of Sicilian power system in per-unit, according to three different RES control mode scenarios*

Regarding scenario 1.1, as shown in figure 3.2-3, no remarkable improvement has been reached foreclosing the disconnection to WTs as well (the same has been detected implementing disconnection requirement of 2010 to the hybrid scenario; it is not reported to avoid redundancies, since also in that case nothing changes). Actually, few increments are present, but they are infinitesimal and not even noticeable by chart, as shown in figure.

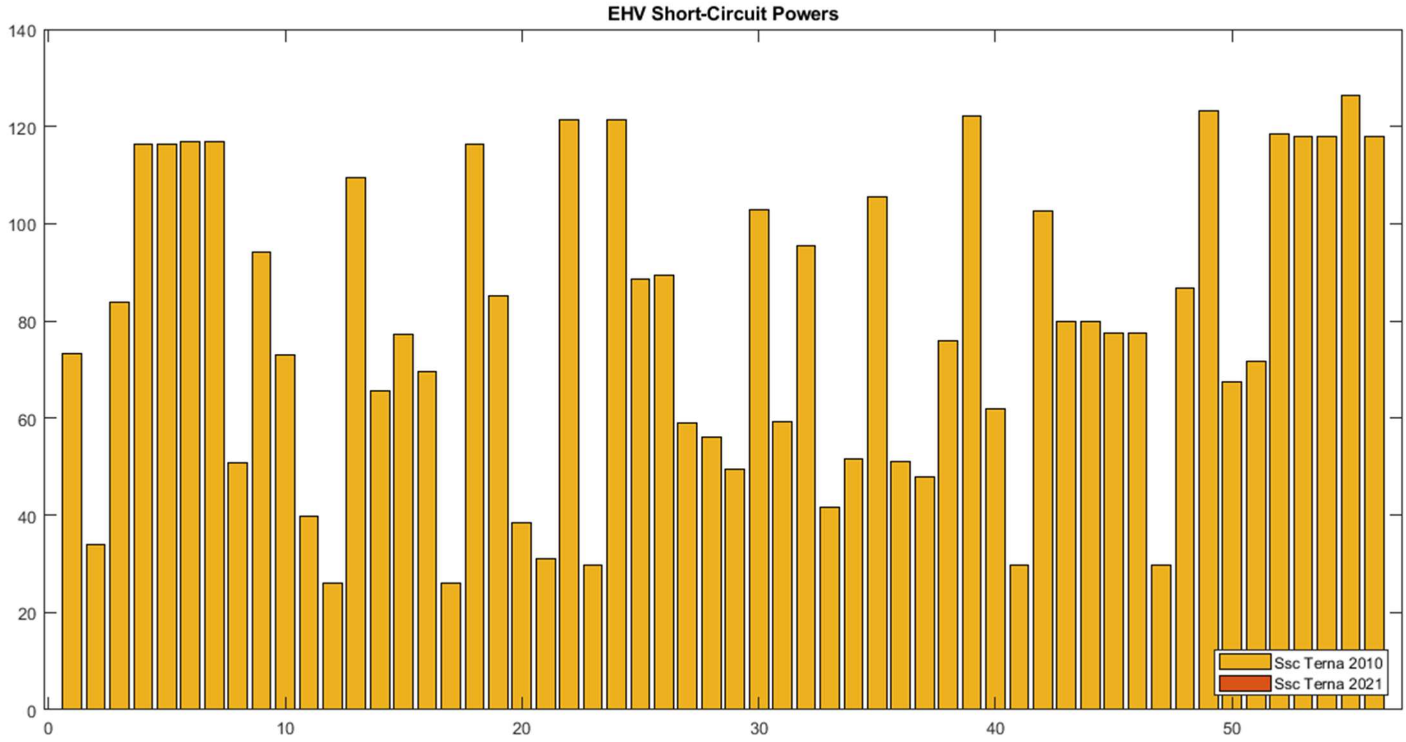


Figure 3.2-3*: Comparison between EHV short-circuit powers in Sicilian grid of 2010 and 2021 (in per-unit)*

In conclusion of these results, it can be affirmed that, as already discussed in this work of thesis, avoiding RES to disconnect provides a benefit to short-circuit power thanks to their current contribution, and allows to avoid unacceptable generation losses, given the not negligible amount of active power supplied by RES nowadays; but, as demonstrated, the most significant benefit can be obtained if RES inject reactive power during faults, resulting in a significant increase of short-circuit power and, consequently, improving voltage stability condition. Considering the future perspective of continuous reduction of fault level with the growth of RES penetration, this control strategy could really be an essential enhancement to be implemented in Italian grid code.

3.2.2-Fault Level in a 100% RES Power System

Given the prospected increase of RES penetration and in view of what demonstrated in last section, some additional simulations have been performed to get an idea about the entity of RES future impact on power systems. Therefore, a hypothetical Sicilian 100% RES scenario has been implemented.

Naturally, to model a scenario like that, some assumptions must be made:

- All Sicilian traditional generation plants, both on HV and MV grids, have been substituted with RES, except for Calabrian Rizziconi power plant since it has been considered as slack bus (see appendix for Sicilian grid model).
- In order to keep grid shapes and not overturn casually all load data, all generators have been assumed capable to supply the same quantity of active and reactive powers as synchronous generators they substituted.
- New RES power plants maximum current values have been set according to ones of comparable already existing RES generators.

Obviously these assumptions are approximations, but it can be interesting in any case to get an idea about hypothetical future condition of the grid basing on actual available data. The reasons behind the just described assumptions are described hereinafter.

Regarding the choice to keep Rizziconi thermal power plant, it is important to stress that slack bus does not represent Rizziconi power station only: in fact, it has been modelled also taking into account the power exchanged with the rest of the Italian power system (in all charts, it is the second-to-last EHV bus, which is exactly the one with highest short-circuit power: about 12 GVA; see appendix for details regarding Sicilian network). In addition, physically, keeping few CCGT power plants can represent a reasonable perspective, since it could be meaningful to assume a future cooperation between RES and CCGT, as will be discussed in next section, especially in a weak grid context like the one considered. Hence, given that slack bus model should not be changed, it is assumed acceptable to keep at least one traditional power plant, especially if it is the one located on the most powerful bus. Last, but not least, it is important to remark that all considered inverters are “Grid Following”, i.e., they are synchronized with grid voltage by PLL to control current output and inject power into the system, as discussed in chapter 1. Therefore, given their dependence on grid voltage, an independent voltage source is needed; thus, in a hypothetical 100% RES Sicilian grid scenario, Rizziconi’s synchronous generators, and even more the connection with power system of the Italian Peninsula, are fundamental.

Concerning the second hypothesis, it is a strong assumption, but it can be acceptable according to two reasons: first, to overturn grid data removing loads without criterion would not make sense, also from a physical point of view since there is no future reason to reduce loads. Secondly, it can be assumed that in general RES power stations will increase their power with respect to nowadays, for instance thanks to more powerful technologies, as ones that are being developed in these years. For example, as reported by CNBC [7], the Chinese MingYang Smart Energy has presented a new prototype of WT, called MySE 16.0-242, which, among other broken records, can produce 16 MW, the most powerful WT existing so far. This is an example of how WT technology is evolving. Nevertheless, in future, since loads will not decrease and, on the contrary, energy demand is more and more increasing, a lot of technologies will be implemented (and they are already being implemented, as widely discussed in chapter 1) to cooperate with RES supplying active and reactive powers, such as storage systems, compensation methods and others. Anyway, according to present available grid data, this assumption has been necessary.

Coming to the last presumption, no particular motivations are needed, since changing data of new inverters according to ones of similar already existing RES is a logical approach.

In order to complete the description of the considered backdrop, coming to RES control mode, the most advanced of previously described scenarios, the third one, has been chosen, i.e., the German grid code: in fact, in a 100 % RES power system, it is reasonable to assume a control strategy focused on voltage sustainment during faults, given the prospected low fault level. Moreover, as described above, all RES are already supplying reactive power during normal condition as well, since they substituted traditional power plants.

At this point, moving to simulation results, they are shown in figure 3.2-4. The collapse of fault level is dramatic, in particular considering that represented powers are related to the most powerful buses of the system (EHV).

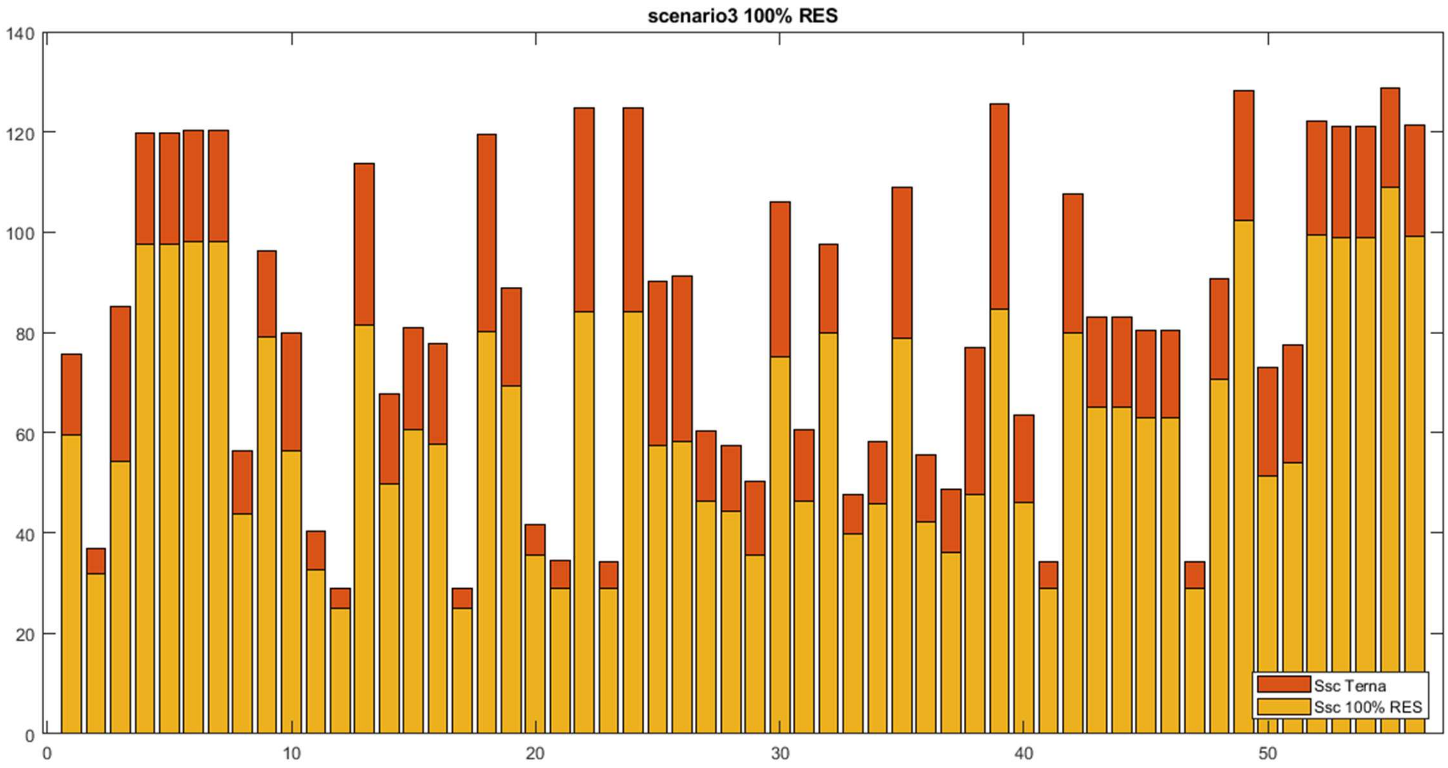


Figure 3.2-4: *Comparison between nowadays Sicilian power system and the hypothetical future 100% RES one (in per-unit). In both cases, RES are controlled according to German grid code*

Furthermore, it is important to emphasize that scenario 3 has been considered, whose control mode follows German requirements, i.e., RES injecting reactive power in any voltage condition; in addition, according to taken assumptions and as just reminded, RES was already supplying reactive power before the fault, since they have been assumed capable to supply loads with reactive power as well (thus, a great amount of VAr). Hence, it can be affirmed that results shown are optimistic, since they are related to an almost optimal backdrop; in a more realistic context, consisting in integration of a massive number of compensators capable to supply all reactive power that RES cannot provide, the effect would probably not be better than simulation output.

In order to detect a possible enhancement, an even more hypothetical scenario has been implemented, where German requirements are extended to all RES of the system, both HV and MV. Results can be appreciated in figure 3.2-5. Obviously, by increasing reactive injection, the condition improves, and not a little.

Therefore, summarizing, these results allow to get an idea not only about the collapse that fault level would experience in case of 100% RES penetration, but how RES reactive injections can contribute substantially to improve the condition.

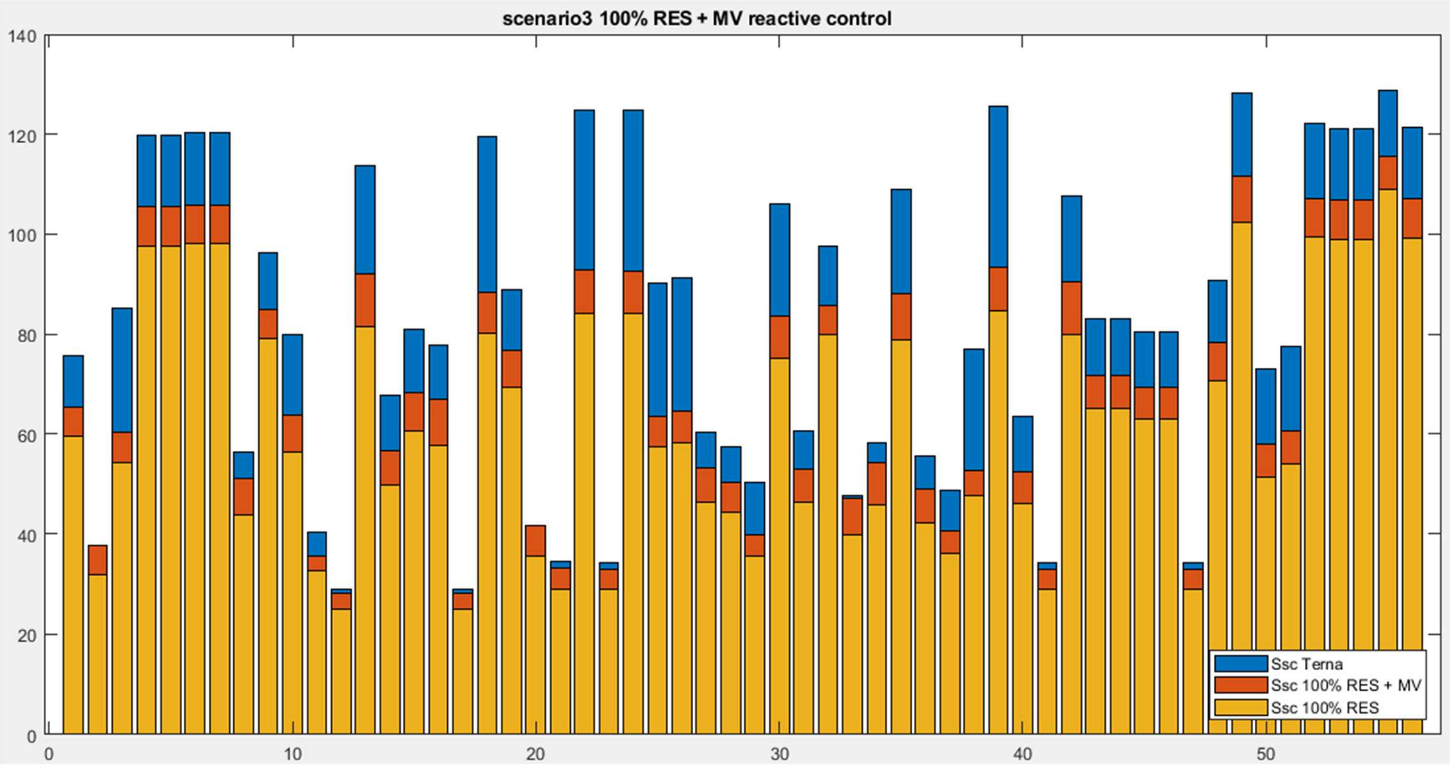


Figure 3.2-5: *Comparison between nowadays Sicilian power system, the hypothetical future 100% RES one with German code extended to HV RES, and both HV and MV RES, respectively (in per-unit)*

3.2.3-An Overview on Future Power Systems Evolution

In a 100% RES scenario, compensation methods described in chapter 1 can help to inject reactive current and regulate voltage, not only in normal operation but during faults as well, although delegating all voltage regulation to compensators would mean a huge number of these devices (since voltage, being unstable due to low fault level, would require a lot of reactive compensation), hence a lot of costs, obtaining a regulation system not directly linked with generation units. Thus, if RES penetration is intended to increase up to this level, substituting almost all synchronous generators (which regulate voltage themselves), also RES shall start to be used as their "predecessors", notably during faults given the just demonstrated benefit that this strategy allows to achieve.

Nevertheless, since inverter current contribution is limited for supplying both requested active and reactive powers, compensation methods will probably always be needed, and probably synchronous machines as well (also for a more stable system, given that compensators themselves, except Synchronous Condensers, are based on power electronics, thus resulting the same problematics concerning decadence of fault level). In fact, given their significant contribution to short-circuit power, Synchronous Condensers are returning to be increasingly used, as discussed in chapter 1, and exposed in Terna's Development Plan of 2021 [13]; in addition, thermal power plants are not being totally replaced: natural gas is seen as a good resource for the transition from actual grid condition to the future one.

According to Enel [8], RES penetration is proceeding too slowly, hence gas-based power plants are necessary, thanks to their flexibility, to fill the gap due to intermittent RES production avoiding the system to collapse, and to accelerate the transition from present grid condition to a zero-carbon emission system, in order to achieve international targets concerning environmental impact.

Moreover, gas turbine is a relatively new technology, which presents a wide range of improvement: in fact, General Electric Company is very focused on that and, as discussed on a few of published papers available on their website [9], such as in [10], they are accomplishing significant achievements in developing this technology. Gas turbines, combined with steam turbines in CCGT power plants, allow to improve remarkably the efficiency, and thanks to their flexibility and rapidity they can match very well with intermittent RES production, also limiting greenhouse gas emission. Furthermore, in [11], General Electric claims that combination of RES and gas power can accelerate the reduction of emissions keeping the system reliable and safe, while in parallel technologies development for low or near zero-carbon power generation continues. Besides, how nowadays batteries cannot compensate for long RES gaps is discussed, remarking even more gas power benefit and the still high cost of batteries themselves, too high with respect to gas-based energy. It is also stressed that gas power involves less than half of CO_2 coal generation, and that there is an ongoing pathway to decarbonize existing and future gas turbine power stations using hydrogen as fuel.

These concepts are strengthened by looking, for example, at what has been happening in California in recent times, as summed up by Forbes in [12].

The CCGT power plant of Rizziconi has been kept in 100% RES Sicilian network model also according to these reasons and taking into account the perspective of two aforementioned giants of the sector.

Coming back to this work of thesis analysis, what described above acquires even more importance bearing in mind what discussed and demonstrated about decline of fault level. A cooperation between RES, compensation methods and CCGT synchronous generators could be a good trade-off in order to keep the system stable and short-circuit power reasonably high (in favour of both voltage stability and protections), to match with load needs, and to reach environmental targets that are becoming more and more imperative.

However, despite what just stated, a 100% RES future grid is not unrealistic. Gas power could help the transition in short-medium term, as claimed by General Electric, but in a bit more distant future some new technologies and improvements may help to realize that.

According to Terna’s Development Plan of 2021 [13], a lot of interventions and improvements are planned regarding Italy and in particular Sicilian network: among others, the enhancement of grid meshing, from new regional power lines to the inter-regional submarine HVDC “Tyrrhenian Link”. Among all benefits that these new transmission lines will bring, the one of major interest in this analysis is the enhancement of short-circuit power due to the increased meshing of the grid. This will allow a better management of RES and will facilitate their penetration, improving fault level and voltage stability conditions.

Moreover, in Terna's Plan, a new project, the so-called "Massive Integration of Power Electronic Devices" (MIGRATE), is mentioned and introduced: it consists in development of innovative solutions in view of a massive RES penetration, up to a 100% RES scenario, and it has been joined by a few of European TSO. Hence, it can be deduced that, in long term, the road to a 100% RES grid has begun to be mapped out.

In accordance with this perspective, especially concerning the black start, some new converter technologies are mentioned, in particular converters capable to emulating synchronous machines behaviour. It is precisely these devices that will be discussed in next section, in order to investigate their impact on fault level in the considered 100% RES scenario.

3.2.4-Grid Forming Inverters in Power Systems

As discussed and demonstrated so far, high-RES penetration in power systems involves the decadence of short-circuit power, which in turn implies that voltage drops are deeper and propagate over long distances, as shown in chapter 2. This can result in a great number of inverter-based generators that are disconnected due to their inability to operate without a reasonable voltage sustainment by the grid. In fact, traditional "Grid Following" inverters, as investigated in chapter 1, are controlled by PLL, which keep the synchronism with grid voltage to drive current and inject power into the network. Hence, they need sufficient system strength to operate in a stable manner. Considering the significant amount of power produced by RES nowadays, a single fault in a weak system could mean a generation loss such as to cause a blackout. As demonstrated, Grid Following inverters controlled to sustain voltage during faults can improve the condition (if can remain connected) but, in addition, the vision of a future 100% RES system presents another issue in this sense: besides low fault level, inverters would no longer have synchronous generators imposing their voltage waveform. In other words, black start would result impractical.

These challenges have given rise to the development of Grid Forming Inverters (GFI). The idea behind their conception is to emulate desirable characteristic of synchronous machines as close as possible using inverters. In order to investigate and try to predict their effect regarding fault level, their working principle will be briefly discussed in this section [14] [15] [16], to model them in considered Sicilian scenarios. A lot of studies and analysis are carried out within these papers concerning GFI and what benefits they can bring into power systems, but they will not be investigated since they exceed the scope of this work of thesis; thus, relevance has been given to info related to fault level and how to model GFI in short-circuit analysis (a first idea about that is already shown in figure 3.2-6).

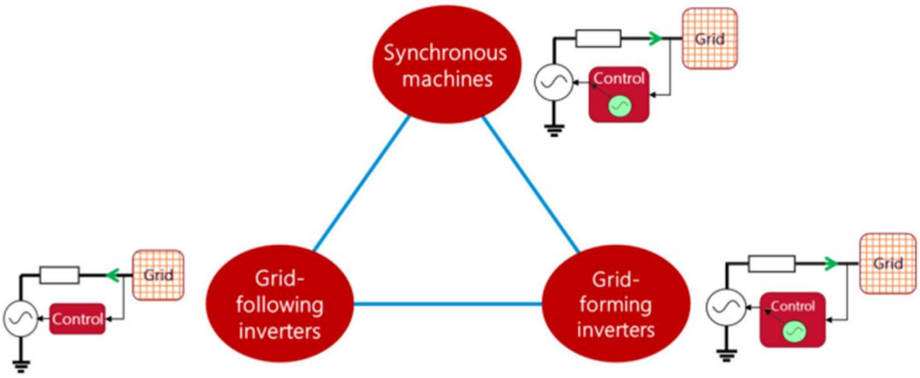


Figure 3.2-6: *Classification of generation technologies from a system strength perspective. The direction of green arrow indicates whether system strength is provided, actively supporting the power system, or the correct operation is dependent by the network*

As widely discussed in all these papers, GFI do not rely on PLL and can generate their own voltage waveform, including during faults. The evolution of these converters in last times has resulted in the so-called “Virtual Synchronous Machine”, which is a GFI with dynamic behaviour of synchronous generator capable, among other items, to impose voltage and frequency generating them on its own, provide services such as synthetic inertia, voltage regulation, black start, operate in island, even emulate rotor flux dynamic. In addition, it can ride through and keep synchronism during faults, and it can support the system strength significantly, which are benefits of major interest regarding this analysis.

Being an independent voltage source, the injected current is a consequence of the load (or fault) rather being imposed according to voltage at converter terminals. In figure 3.2-7, different inverter technologies are shown.

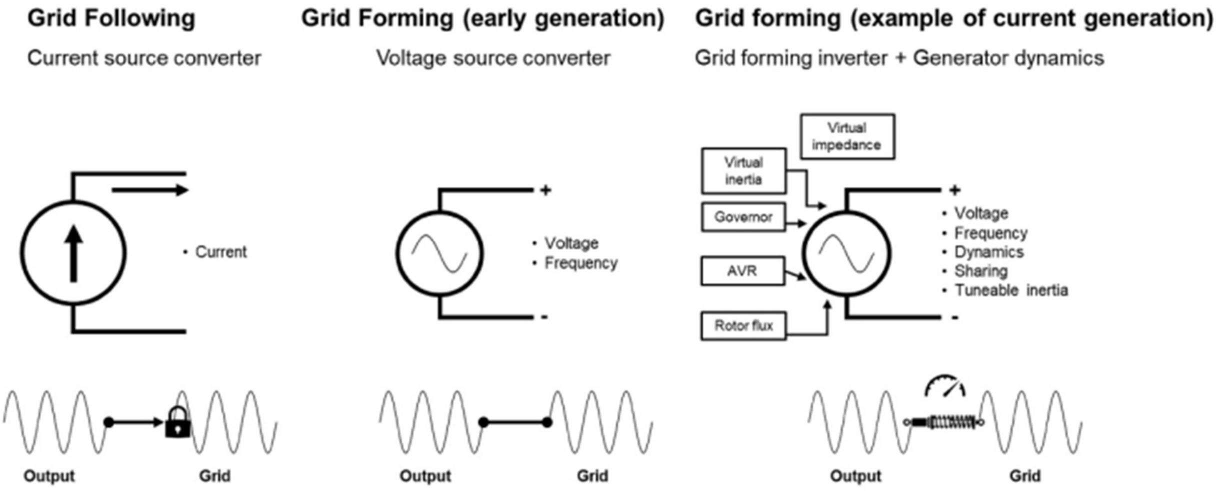


Figure 3.2-7: Grid Following and Grid Forming inverter types

The aforementioned shapes allow GFI to operate in low fault level systems and independently with respect to synchronous machines, being helpful to provide voltage support in weak grids, contributing to the strength of power system, and enabling black start as well. An example of black start carried out by GFI-based RES can be found in [17]: Scottish Power Renewables has achieved what is believed to be a global first using an onshore Wind Farm to re-energize part of the power system by using this new inverter technology.

Coming back to short-circuit analysis, the model to represent GFI, as should be evident from what stated so far, is similar to synchronous machine one; in fact, as explained in particular in [15], GFI behave as a Thévenin voltage source in series of an impedance: the voltage source is controlled in frequency and magnitude, the impedance can be emulated.

Nevertheless, not totally. In fact, as further specified in the considered paper, at the same time, GFI must protect themselves by limiting currents according to their overcurrent capacity. That is not surprising, since GFI are still power electronics-based converters, hence troubles related to protect valves from overcurrent remain.

Therefore, summarizing, the converter responds to a voltage variation with large fast current as a voltage source behind an impedance, whereby exceeding extreme current limit is forbidden by modifying voltage angle and magnitude. If current limitation is necessary during perturbations, there are two possible strategies available: either switch over to current control during the fault to limit the current or implement some current clipping features. However, it is explained in the paper that this is an unsolved issue for power industry, and in particular how current should be prioritised in case of overcurrent limit are reached, i.e., if current should be proportionally scaled or active or reactive power should be prioritised.

According to these hints, the GFI model has been set as follows:

- GFI are modelled as constant voltage source in series of their sub-transient reactance.
- If GFI exceed their overcurrent limit, they are switched to current controlled mode, i.e., they are converted into Grid Following Inverters.
- Concerning current priority if GFI are switched to current control mode, given the aim of this work of thesis and the nature of prospected problem about fault level reduction, reactive injection has been priorities, implementing the German grid code requirements (the third scenario), in order to sustain voltage and persist in providing benefit to fault level even if GFI are switched to current control mode.
- GFI disconnection is not intended, given that they must behave as synchronous generators and provide contribution to short-circuit power, unless they are switched to current control mode: in that case, since they start behaving as Grid Following, they are disconnected only if fault is located at their terminals. Disconnection is modelled according to procedure described in last chapter.

Consequently, the new designed short-circuit method results to be a hybrid of traditional and innovative approaches: in fact, both RES and synchronous generators are treated in the same way, i.e., modelled as voltage source in series of sub-transient reactance $x_d{}''$; hence, $x_d{}''$ are added to Y_{sc} and Thévenin profile is achieved. Afterwards, once fault voltages are computed, RES currents are checked: if any of

GFI-based RES current exceeds the limit of its converter, generator lists are updated and correspondent GFI are moved to current controlled RES.

Therefore, since the achieved solution is not correct, the procedure is restarted from the beginning adding to short-circuit admittance matrix only reactances of GFI and synchronous generators; current controlled RES equivalent admittances are obtained iteratively as shown in last chapter. Concerning disconnection, as mentioned above, it is acceptable only for current controlled RES connected to faulted buses. In all other cases, current controlled RES must respect German grid code requirements injecting reactive current to sustain voltage. The overall algorithm of GFI short-circuit method is resumed in figure 3.2-8.

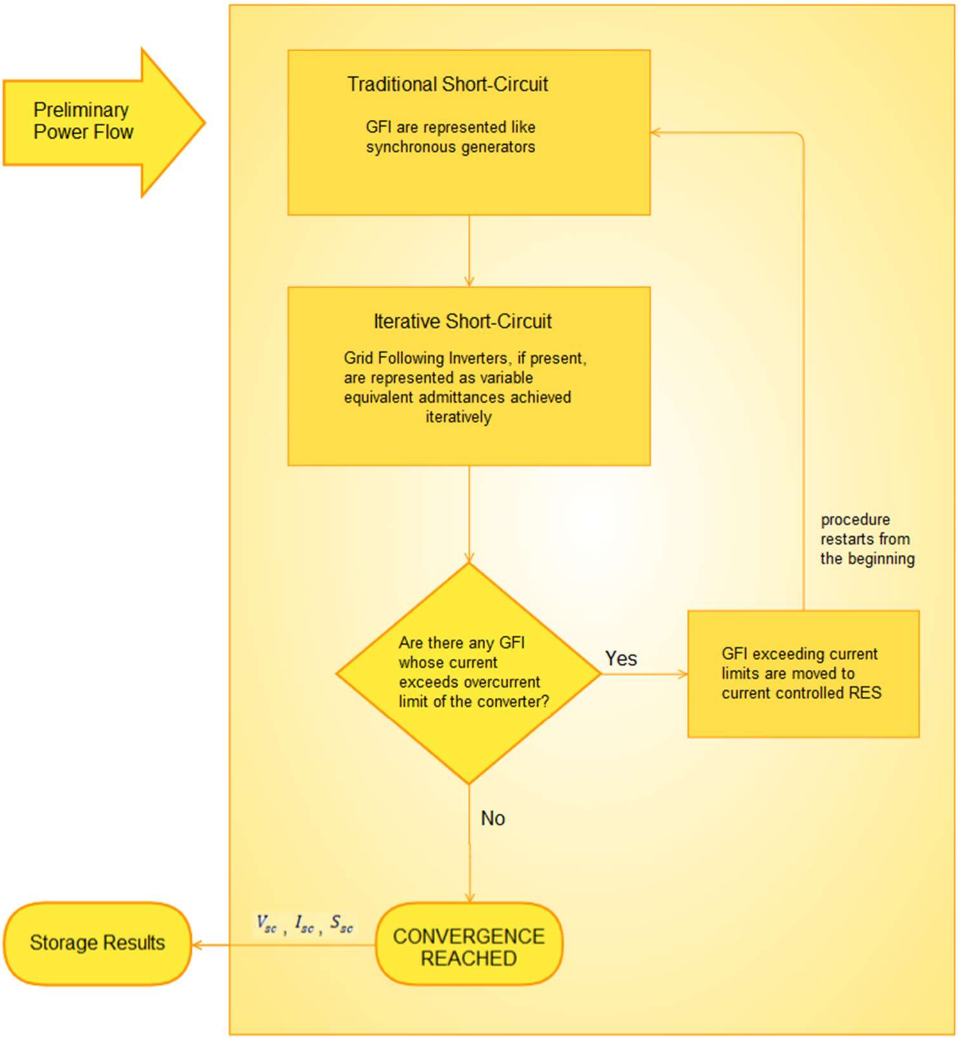


***Figure 3.2-8**: Algorithm of short-circuit analysis with GFI-based RES*

Despite being conceptually easy, this algorithm is not so fast to compute. In particular, it presents a drawback. As RES increases, the convergence is more difficult to reach. In present-day scenario, convergence can be reached after one repetition without any issue. Nevertheless, in 100% RES scenario (with 260 RES), there are few buses in which voltage profile after repetition involves that a couple more generators overcome their current limit. In some cases, one more repetition is enough, in some others it goes on to happen. Hence, a few of attempts have been performed, and given the infinitesimal mismatch between results after one repetition and ones at convergence reached, it has been decided to limit repetitions to only one with good approximation, in order to keep a reasonable computation time, and because complexity of calculation program would not be worth it, seen the negligible difference.

Coming to the Sicilian grid scenario, it is worth recalling that 100% RES network has been obtained changing all synchronous generators data, according to criterion previously explained, except also in this case Rizziconi slack bus. In this context, there is no physical need of a generation technology which imposes voltage since grid forming can perform it by themselves. Nevertheless, Rizziconi CCGT power plant has been kept also in this case for three reasons. Firstly, as already said, slack bus has been modelled in order to represent also power exchanged with the rest of Italian power system, thereby it does not make sense to substitute it; secondly, as already explained, since slack bus model should not be changed, it is acceptable also for reasons previously mentioned to keep its CCGT power plant; lastly, it is logical to compare short-circuit power results according to the same backdrop, in order to draw reasonable conclusions comparing GFI simulations with previous Grid Following-based ones.

Moreover, it is worth remarking that considered data of maximum current limits are those available of actual Grid Following Inverters. Nonetheless, in this way, also inverters in different scenarios are directly comparable, resulting in opportunity to draw a comparison on equal terms between two different control modes (Grid Following and Grid Forming), highlighting their strengths and weaknesses.

Therefore, also in this case, despite these necessary approximations (especially given the novelty of GFI technology), the analysis allows to get an idea about GFI contribution to short-circuit power.

Keeping these concepts in mind, results of simulations are going to be shown and discussed hereinafter.

In figure 3.2-9, EHV buses short-circuit powers of 100% RES scenario with Grid Forming and Grid Following converters are compared. As can be appreciated, GFI improve fault level condition of the power system in almost all buses. In some buses, no improvement has been reached, probably because, in case overcurrent limits are reached, converters start to behave as current controlled converters, as in scenarios previously analysed.

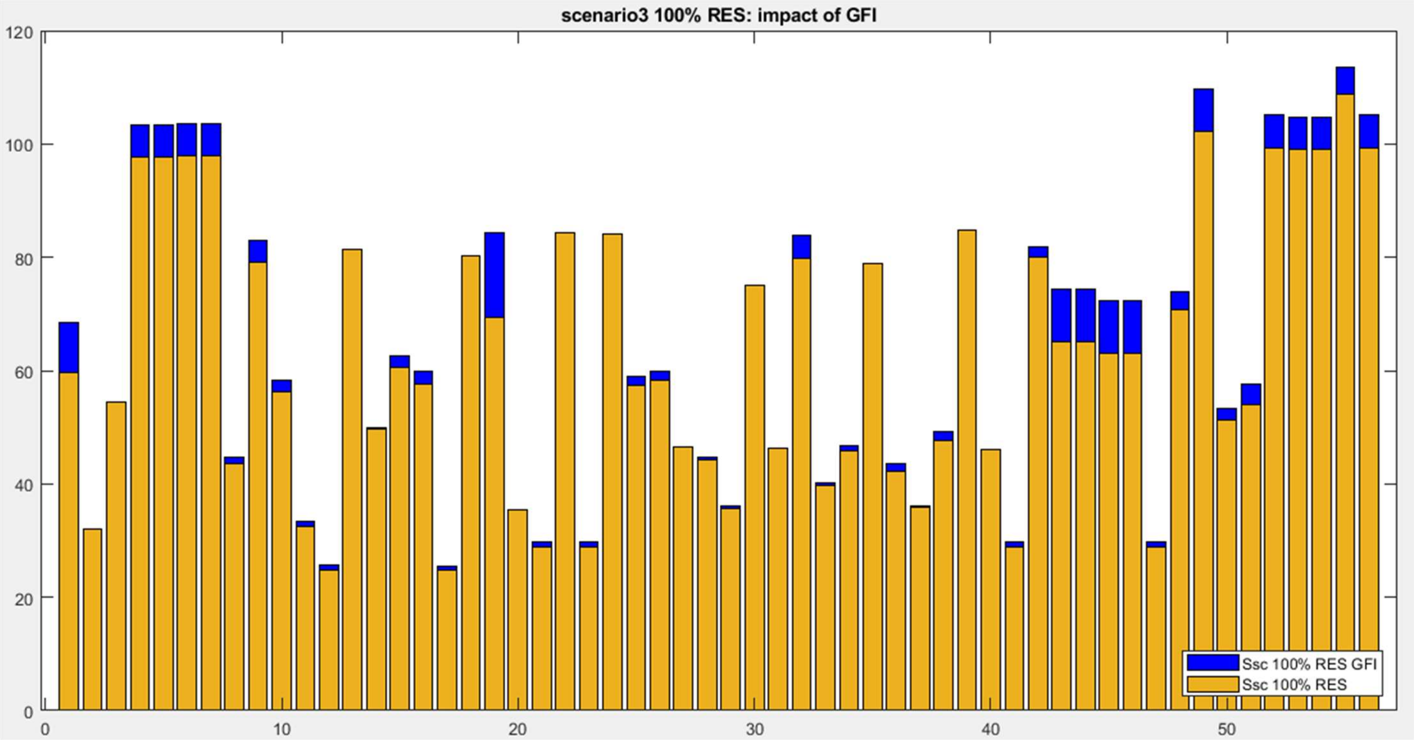


Figure 3.2-9*: EHV buses short-circuit powers in 100% RES scenario with RES based on Grid Following and Grid Forming, respectively (in per-unit)*

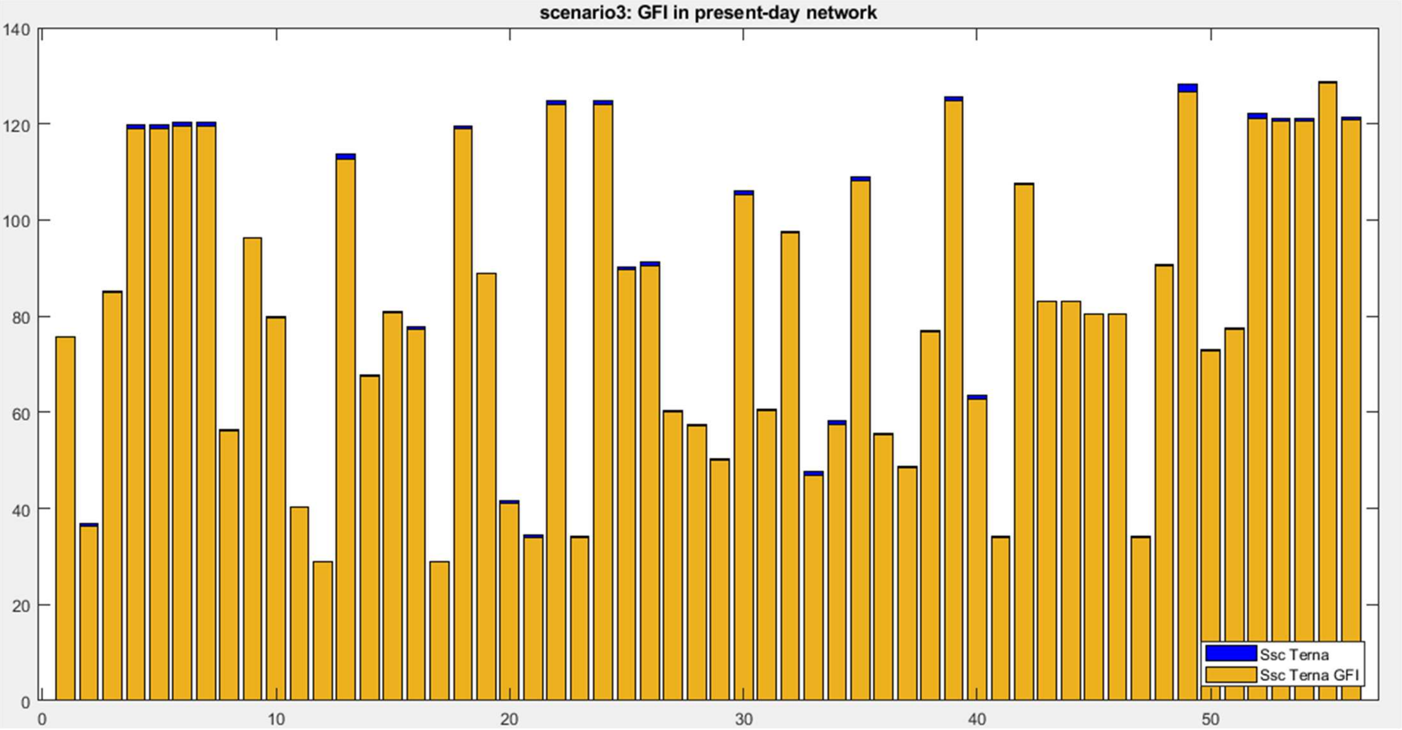


***Figure 3.2-10**: EHV buses short-circuit powers in present-day network scenario with RES based on Grid Following and Grid Forming, respectively (in per-unit)*

The same cannot be appreciated concerning simulation in present-day network (figure 3.2-10). In fact, short-circuit powers are almost the same, besides GFI scenario presents results slightly lower than standard system with Grid Following converters.

Despite the reduction is infinitesimal, that is quite surprising. Nevertheless, it can be physically motivated recalling what has been discussed and studied in a very recent paper, where a new perspective based on a duality principle between Grid Forming and Grid Following Inverters is presented [18].

In fact, after a study concerning inverter control structures and operations, it is demonstrated that GFI working is unstable in strong grids while Grid Following one is stable, and vice versa; i.e., grid strength plays an important role in inverter stability also in GFI technology. In order to clarify this concept, a summary of what demonstrated in the document is recalled, considering what needed for this analysis and not investigating in detail what exceeds the scope of this work.

Since Grid Forming and Grid Following can be defined as voltage forming and voltage following, respectively, it can be affirmed (and demonstrated studying and focusing on their control theory, as carried out in the paper) that they can be defined also as current following and current forming, respectively. In other words, a GFI can be considered as voltage forming current following converter. Moving on, according to this definition, it is demonstrated that reducing grid equivalent impedance for GFI and grid equivalent admittance for Grid Following results in unstable working. Concerning Grid Following is logical: since its PLL relies on voltage (voltage following), if terminal voltage is unstable, the operative condition will be unstable in turn; but also in case of GFI (or current following), for reason dependent on its control drive, it holds the same but from the current point of view. Thus, as known, a traditional inverter is vulnerable in weak grids with low admittance (high impedance), i.e., in presence of low fault level, while, and that is the news, GFI are vulnerable in low impedance (high admittance), i.e., in presence of strong grids with high short-circuit power.

The “circuital reasons” can be found thinking about the fact that network can be compared to a voltage source rather than a current one (in fact, all short-circuit theory is based on Thévenin theorem and all buses and generators are modelled according to that). By the way, the same dual representation can be carried out with Norton theorem. Consequently, thinking about the two equivalent circuits, an ideal voltage source is obtained if impedance is zero, and an ideal current one if admittance is zero, respectively.

According to what stated so far, the notion of grid strength can be reformulated. As discussed all along this work of thesis, a strong grid is characterized by high short-circuit power, resulting in a stable voltage profile; extremizing that, an infinite power grid presents a constant voltage profile, given that its impedance is null and its Thévenin equivalent results to be an ideal voltage source (as discussed in chapter 2). All these concepts can find their dual in the opposite scenario, i.e., a grid strong from the current point of view: a null admittance in the Norton equivalent results to be an ideal current source.

Consequently, in line with what just stated, the grid strength concept can be extended and split into voltage strength and, dually, current strength. As introduced above, a strong current network is the ideal scenario for GFI, while on the opposite the ideal operative condition for Grid Following can be reached in a strong voltage network.

A summary of what explained can be appreciated in figure 3.2-11.

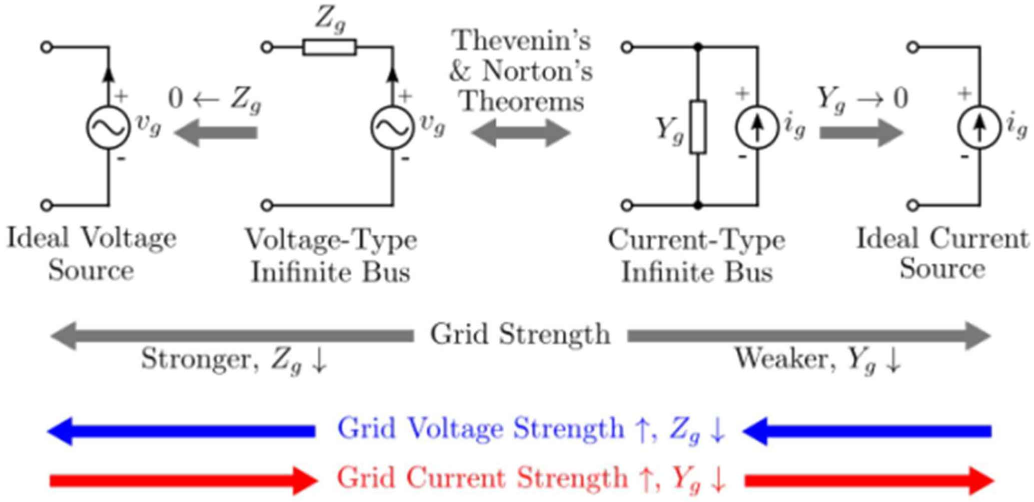


***Figure 3.2-11**: Duality of grid strength*

Thus, in conclusion, the interface with a high fault level is perfect for a Grid Following, since voltage is almost constant; on the contrary, a weak grid is a good scenario for GFI, since in the same way the current is almost constant.

In light of these considerations, simulation results can be explained. In 100% RES network, GFI can provide a benefit in term of short-circuit power, resulting in a significant improvement of the condition; in some cases, no particular changes with respect to the same scenario with traditional inverters are achieved due to converters current limit that, if reached, results in a switch to current control drive (as Grid Following) to limit the current, i.e., behaving as inverters in base scenario. On the contrary, substituting traditional inverters with GFI in nowadays power system implies a slight decrease of fault level because it is a meshed network, which is not the perfect scenario for GFI. Surely, the condition is only slightly worse because there are synchronous generators and connection with Italian peninsula, whose contributions are predominant with respect to RES and sustain fault level. Besides, Sicilian grid is a weak system with relatively high impedance: in fact, traditional power plants are not many, and there is only one connection with the peninsula. Hence, it is not the worst condition for GFI. Summarizing, grid shapes are not so strong to result in the worst condition for GFI, but at the same time they operate worse than Grid Following, from these the decrease of fault level. Despite that, the decrease is not significant since synchronous generators allow to preserve the present fault level with their remarkable contribution.

Therefore, simulation results confirm what stated in [18]. From this analysis it can be deduced that the best strategy can be exploit both converter technologies, GFI in microgrids, or in networks characterized by high impedance, remarkably low fault level, and providing the system with black start capability, while Grid Following in opposite environments, i.e., in meshed transmission grids, or with synchronous generators.

In accordance with that, another simulation has been performed, in order to compare in nowadays Sicilian power system, the impact of GFI and the effect of a massive voltage regulation during faults, as the one carried out by the already considered scenario in which all RES, both HV and MV, are controlled according to German grid code. Results are shown in figure 3.2-12.

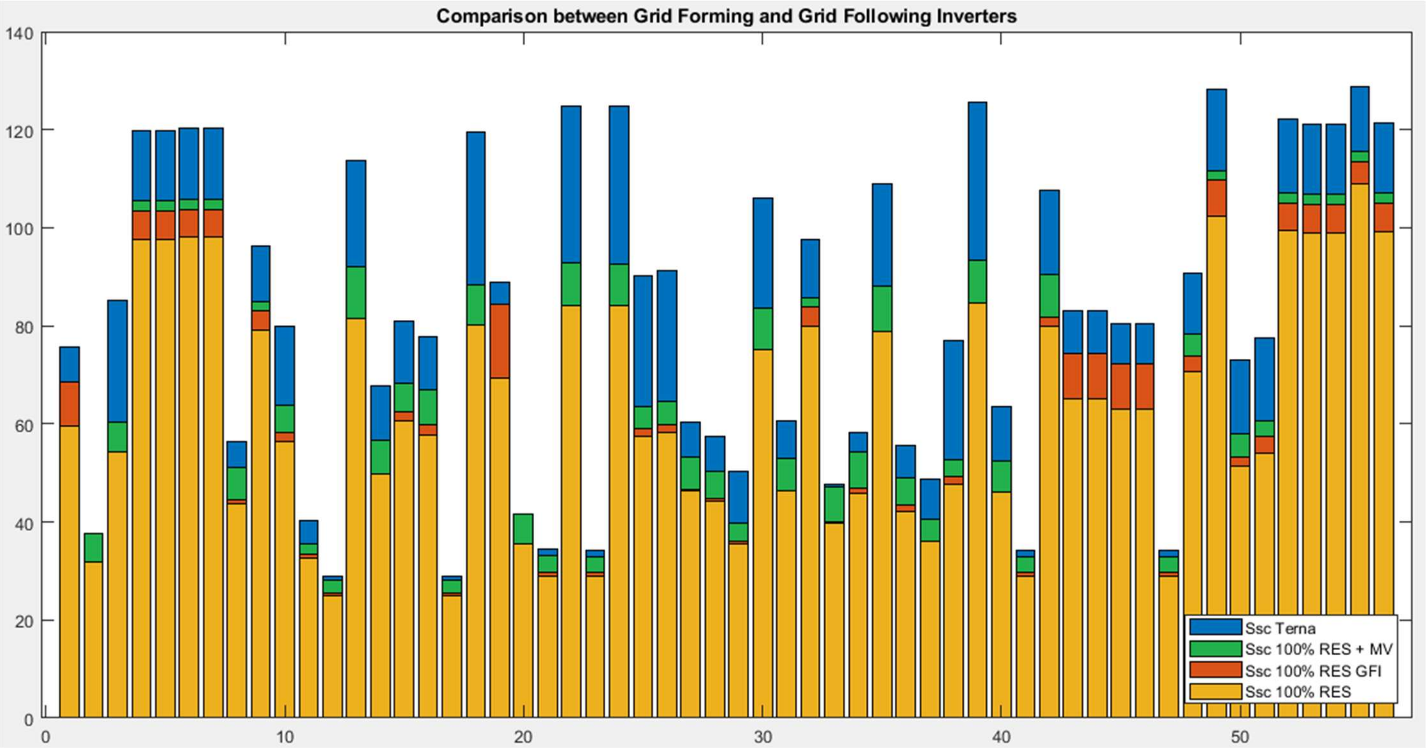


***Figure 3.2-12**: EHV buses short-circuit powers in per-unit in 100% RES scenario according to different inverter control strategies compared with fault level of nowadays grid (Grid Following meet German requirements)*

As show in chart, the best enhancement of short-circuit powers is reached extending German code requirements to all traditional inverters, both HV and MV. This confirms the better contribution of Grid Following with respect to GFI in low impedance meshed transmission systems (in this network, there is also slack bus synchronous generator), and validates what just stated above, regarding a smart combination of two inverter types. Furthermore, it highlights even more the importance of reactive current injection to improve fault level and voltage stability under fault, fully exploiting the potential of inverters.

All performed simulations have shown, as lowest common denominator, how beneficial would be for the Italian power system to update Italian grid code in this sense, especially in view of future expansion of RES penetration and considering the inherent weakness of networks in the south of the country, where in addition the largest concentration of intermittent RES is located.

BIBLIOGRAPHY

[1] Attachment A68 of Terna’s Grid Code, *CENTRALI FOTOVOLTAICHE-Condizioni generali di connessione alle reti AT, sistemi di protezione, regolazione e controllo,* 2019

[2] Attachment A17 of Terna’s Grid Code, *CENTRALI EOLICHE-Condizioni generali di connessione alle reti AT, sistemi di protezione, regolazione e controllo,* 2019

[3] CEI 0-16, *Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company,* 2019

[4] E.On Netz GmbH, *Grid Code for high and extra high voltage*, 2006

[5] VDE, *VDE-AR-N 4120, New German Transmission Code for onshore connections at 110 kV (or above)*, 2017

[6] D. Polinelli, *Preliminary study on Voltage Regulation in presence of high RES penetration*, Tesi di Laurea, Politecnico di Milano, A.A. 2012-2013

[7] Anamr Frangoul, *Chinese firm announces giant 264-meter-tall offshore wind turbine*, CNBC, Aug 23, 2021, https://www.cnbc.com/2021/08/23/chinese-firm-announces-giant-264-meter-tall-offshore-wind-turbine.html

[8] Nicola Pini, *Enel allenta la spinta sul gas naturale ma i nuovi impianti sono necessari,* Avvenire, Aug 15, 2021:
https://www-avvenire-it.cdn.ampproject.org/c/s/www.avvenire.it/amp/economia/pagine/enel-allenta-la-spinta-sul-gas-naturale-ma-i-nuovi-impianti-sono-necessari

[9] General Electric website: https://www.ge.com/

[10] General Electric, *HA Gas Turbine-Validation of the HA Gas Turbine Platform*, 2017:
https://www.ge.com/content/dam/gepower-pgdp/global/en_US/documents/product/gas%20turbines/White%20Paper/gea32162-ha-gas-turbine-validation-of-the-ha-gas-turbine-platform.pdf

[11] General Electric, *Renewables and Gas Power can rapidly change the trajectory on climate change*, 2021:
https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/future-of-energy/ge-future-of-energy-white-paper.pdf

[12] Michael Shellenberger, *Why California’s Climate Policies Are Causing Electricity Blackouts,* Forbes, Aug 15, 2020:
https://www.forbes.com/sites/michaelshellenberger/2020/08/15/why-californias-climate-policies-are-causing-electricity-black-outs/?sh=5ca9131b1591

[13] Terna’s Development Plan, 2021, available on Terna’s website: https://www.terna.it

[14] B. Badrzadeh, Z. Emin, S. Goyal, S. Grogan, A. Haddadi, A. Halley, A. Louis, T. Lund, J. Matevosyan, T. Morton, D. Premm, S. Sproul, *System Strength*, published in “Towards System

Strength” by CIGRE Science&Engineering, Innovation in the Power Systems Industry, volume n° 20, February 2021

[15] P.Christensen, G. K. Andersen, M. Seidel, S. Bolik, S. Engelken, T. Knueppel, A. Krontiris, K. Wuerflinger, T. Bülo, J. Jahn, M. Ndreko, S. Salehi, I. Theologitis, B. Weise, H. Urdal, A. E. Alvarez, A. J. Roscoe, J. Fortmann, *High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters*, Technical Report, ENTSO-E, 2020

[16] Y. Lin, J.H.Eto, B. B. Johnson, J. D. Flicker, R. H. Lasseter, H. N. Villegas Pico, G. Seo, B. J. Pierre, A. Ellis, *Research Roadmap on Grid-Forming Inverters*, NREL, 2020

[17] Scottish Power Renewables, *Dersalloch Windfarm-Virtual Synchronous Machine,* 2020, https://www.youtube.com/watch?v=S2NJCbPg-9I

[18] Y. Li, Y. Gu, T. C. Green, *Rethinking Grid-Forming and Grid-Following Inverters: A Duality Theory*, IEEE, Jun 24, 2021

CONCLUSIONS

The integration of RES in power systems has given rise to great opportunities and has opened new horizons concerning exploitation of energy sources that could help the sustainable development of humanity. Nevertheless, this new scenario has presented a lot of issues, that made necessary a reformulation of network paradigm and a new conception of its management strategies.

Within this work of thesis, RES problematics related to voltage and fault level have been considered and analysed to research solutions and improvements that can be helpful for transition towards a decarbonized, safe, and reliable system.

Concerning voltage regulation, compensation methods have been examined, observing that in this condition, despite STATCOMs advantages, Synchronous Condensers are regaining significant importance to guarantee a reasonable fault level. In addition, exploiting RES to regulate voltage can provide remarkable benefits in this sense, mitigating oscillations due to their intermittent nature, keeping voltage within acceptable range in a low short-circuit power grid scenario, and allowing to save costs of compensators.

Regarding short-circuit analysis, potential and effectiveness of a particular short-circuit method taking into account inverter-based RES contribution have been demonstrated, notably the possibility to keep on using Thévenin superposition principle even though the non-linear inverter behaviour. Then, the iterative method has been used to carry out simulations on Sicilian power system and investigate influence of several Fault Ride-Through strategies on short-circuit power. Furthermore, a hypothetical 100% RES scenario has been implemented, to get an idea about the entity of fault level reduction in a similar backdrop.

All simulation results have shown significant benefits of RES reactive injections during faults, in order to sustain voltage and avoid voltage collapses that, in a low fault level grid, would spread over great distance. Thus, the extension of Italian grid code has been assessed as important in this sense, especially in view of the growth of RES penetration, even more present in weak southern area of the country.

Moreover, new Grid Forming Inverter technology has been discussed, and the iterative method has been adapted to include their behaviour and evaluate their peculiarities concerning short-circuit. In particular, their capability to provide considerable support to the system strength has been demonstrated to be better in high impedance systems, proving that, in a meshed network, better improvements can be accomplished exploiting a massive reactive compensation strategy by traditional Grid Following Inverters. This result validates even more the importance of this control strategy, and leads to conclude that, in future grids, a combination of these two types of inverters will be the best game plan to implement: Grid Forming in high-impedance radial systems and to provide black start capability, and Grid Following in meshed transmission systems.

Finally, the evolution of the grid has been considered according to influential companies' points of view, such as Terna, Enel and General Electric: it is concluded that gas power can help to speed up reduction of emissions and reach national targets of 2025, 2030 and 2050. Furthermore, in short-medium term and while development of technology for a zero-carbon power generation (including Grid Forming implementation) are proceeding, CCGT power plants can allow to keep a reasonable fault level and at the same time guarantee the coverage of energy gaps when RES production decreases.

A smart cooperation of synchronous machines (both CCGT and Synchronous Condensers), compensators and RES injecting reactive power (both in normal operating conditions and under fault) can be a good trade-off to keep the system stable and short-circuit power reasonably high during the transition towards a completely decarbonised power system.

APPENDIX

THE SICILIAN POWER SYSTEM

A.1-Introduction

This appendix presents in detail the Sicilian network used as testing grid in simulations, describing procedures and assumptions taken to adapt and convert data provided by Terna into a proper model for the calculator.

Since Terna's data were provided to Politecnico di Milano in the past and conversion was carried out earlier at this work of thesis, the information related to that have been found in [6] of last chapter bibliography, therefore all following explanations refer to it.

In addition to its high-RES penetration and weakness, which make it the ideal scenario to test and analyse impact of RES on power systems, the Sicilian Network can be easily distinguished from the Italian system thanks to its unique connection with it, simplifying its representation and implementation.

In order to achieve that, the grid model has been extended until the power station of Rizziconi, Calabria, which has been assumed as slack bus. Consequently, 7 Calabrian power stations have been added to the system model, connected to Sicily by the double tern 380 kV link Sorgente-Rizziconi and the cable Bolano-Paradiso. The lower voltage networks have been modelled as constant loads connected to those buses.

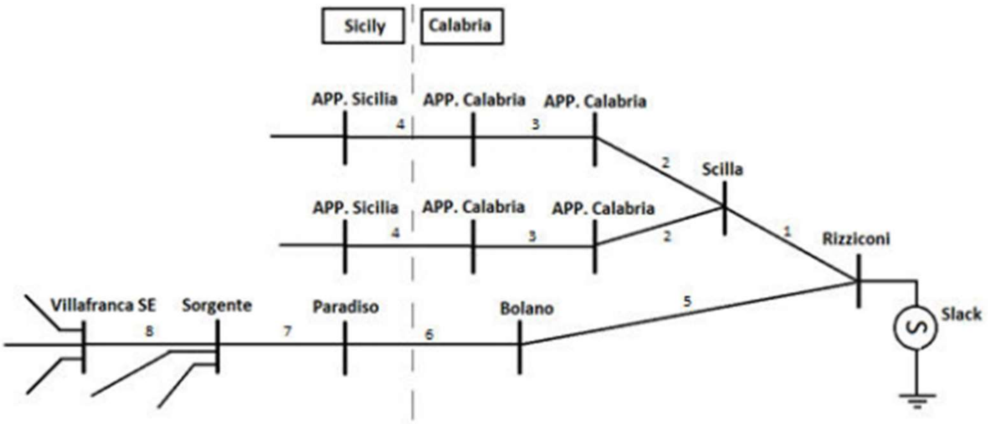
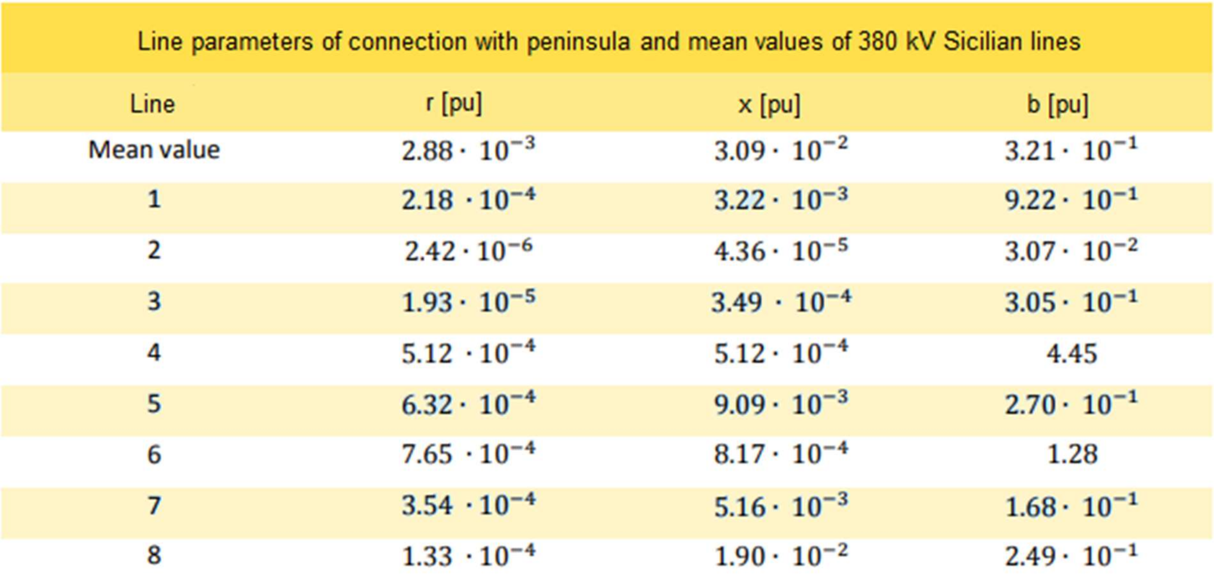


***Figure A.1-1**: Representation of Sicilian power system with slack bus including peninsular grid*



Line parameters of connection with peninsula and mean values of 380 kV Sicilian lines			
Line	r [pu]	x [pu]	b [pu]
Mean value	$2.88 \cdot 10^{-3}$	$3.09 \cdot 10^{-2}$	$3.21 \cdot 10^{-1}$
1	$2.18 \cdot 10^{-4}$	$3.22 \cdot 10^{-3}$	$9.22 \cdot 10^{-1}$
2	$2.42 \cdot 10^{-6}$	$4.36 \cdot 10^{-5}$	$3.07 \cdot 10^{-2}$
3	$1.93 \cdot 10^{-5}$	$3.49 \cdot 10^{-4}$	$3.05 \cdot 10^{-1}$
4	$5.12 \cdot 10^{-4}$	$5.12 \cdot 10^{-4}$	4.45
5	$6.32 \cdot 10^{-4}$	$9.09 \cdot 10^{-3}$	$2.70 \cdot 10^{-1}$
6	$7.65 \cdot 10^{-4}$	$8.17 \cdot 10^{-4}$	1.28
7	$3.54 \cdot 10^{-4}$	$5.16 \cdot 10^{-3}$	$1.68 \cdot 10^{-1}$
8	$1.33 \cdot 10^{-4}$	$1.90 \cdot 10^{-2}$	$2.49 \cdot 10^{-1}$

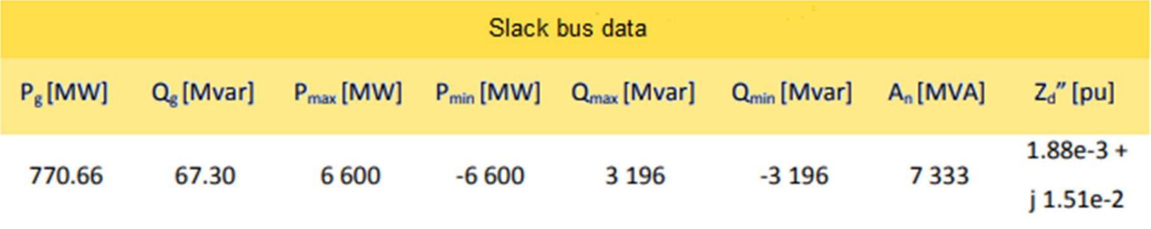
***Figure A.1-2**: parameters of lines of the connection with the Italian system. In addition, mean values of parameters related to 380 kV power lines present in Sicilian network are reported (numbers are related to figure A.1-1)*

The complete model of the connection between Sicily and Italian peninsula is showed in figure A.1-1, and all line parameters of branches are listed in figure A.1-2, with in addition the mean values of 380 kV power lines present in the Sicilian grid.

The overall system is composed by:

- 539 buses:
  - 17 PV
  - 515 PQ
  - 6 fictitious buses caused by three windings transformers
  - 1 slack bus located in Rizziconi power station
- 664 lines
- 162 two-winding transformers
- 6 three-winding transformers
- 468 generators (plus the equivalent of peninsular grid connected to slack)

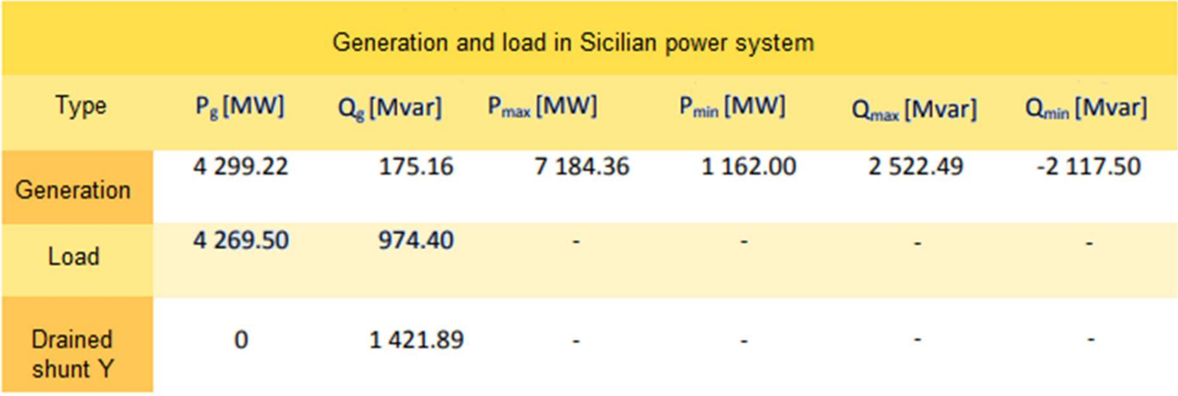
Regarding the slack bus model, an equivalent generator has been connected to Rizziconi power station to consider power exchanged with the peninsula: slack active and reactive power have been set as the sum of power flows of all connections between Rizziconi and the rest of the grid, while the capability limits have been chosen according to line current ratings with a transmission power factor of 0.9. For what concerns short-circuit analysis, the continental grid sub-transient impedance seen from slack bus has been achieved as sub-transient impedance of the equivalent generator, as resumed in figure A.1-3.



Slack bus data							
P_g [MW]	Q_g [Mvar]	P_{max} [MW]	P_{min} [MW]	Q_{max} [Mvar]	Q_{min} [Mvar]	A_n [MVA]	Z_d'' [pu]
770.66	67.30	6 600	-6 600	3 196	-3 196	7 333	1.88e-3 + j 1.51e-2

***Figure A.1-3**: parameters of slack bus equivalent generator considering the peninsular grid as well*

The overall Sicilian load and generation is summarized in figure A.1-4, including slack bus as well (except in maximum and minimum power values); mismatch between powers indicates system losses, which are equal to 29.72 MW and -2.221GVAr. The high value of reactive power generated by transmission system is due to submarine connection between Sicily and Calabria. All reactive power generated by submarine cables is compensated by three shunt inductor banks connected to power stations of Villafranca, Scilla and Rizziconi; their drained power is listed as “Drained shunt Y” in table A.1-4. Furthermore, the reactive production could be due to low network loading in the considered backdrop.

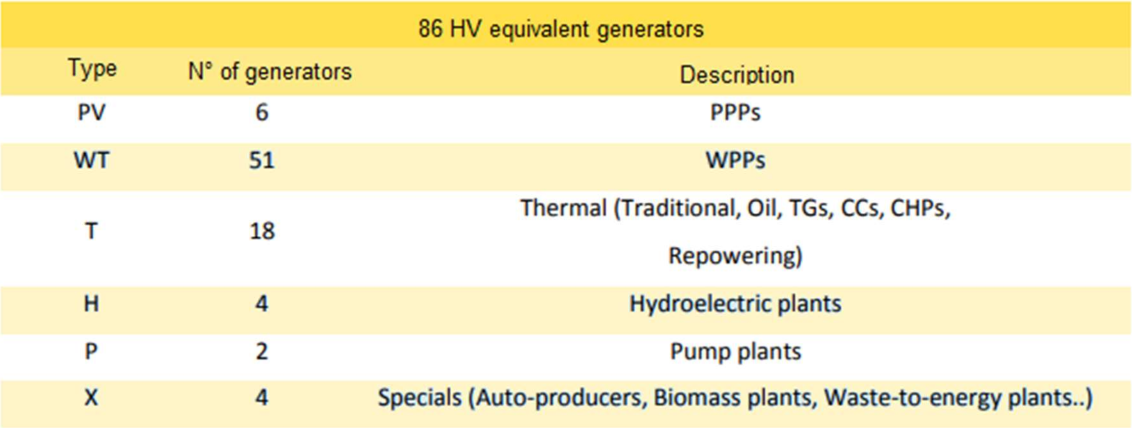


Generation and load in Sicilian power system						
Type	P_g [MW]	Q_g [Mvar]	P_{max} [MW]	P_{min} [MW]	Q_{max} [Mvar]	Q_{min} [Mvar]
Generation	4 299.22	175.16	7 184.36	1 162.00	2 522.49	-2 117.50
Load	4 269.50	974.40	-	-	-	-
Drained shunt Y	0	1 421.89	-	-	-	-

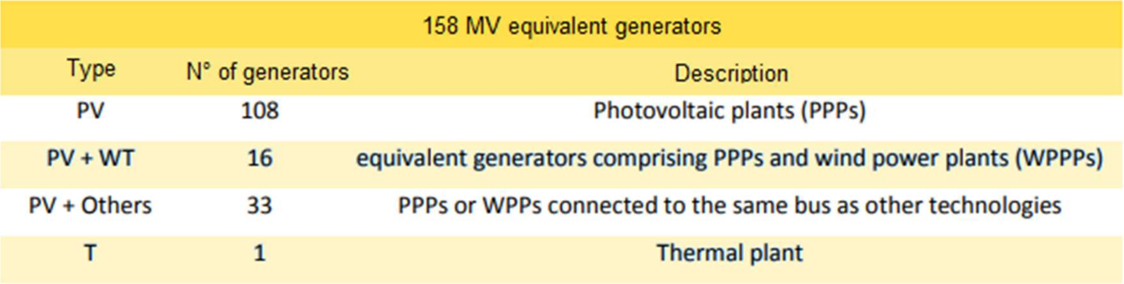
Figure A.1-4: summary of total load and generation in Sicilian network

A.2-Generators

All generators connected to the same bus have been converted into an equivalent model, resulting in 261 generators, of which 244 in service (figures A.2-1 and A.2-2).

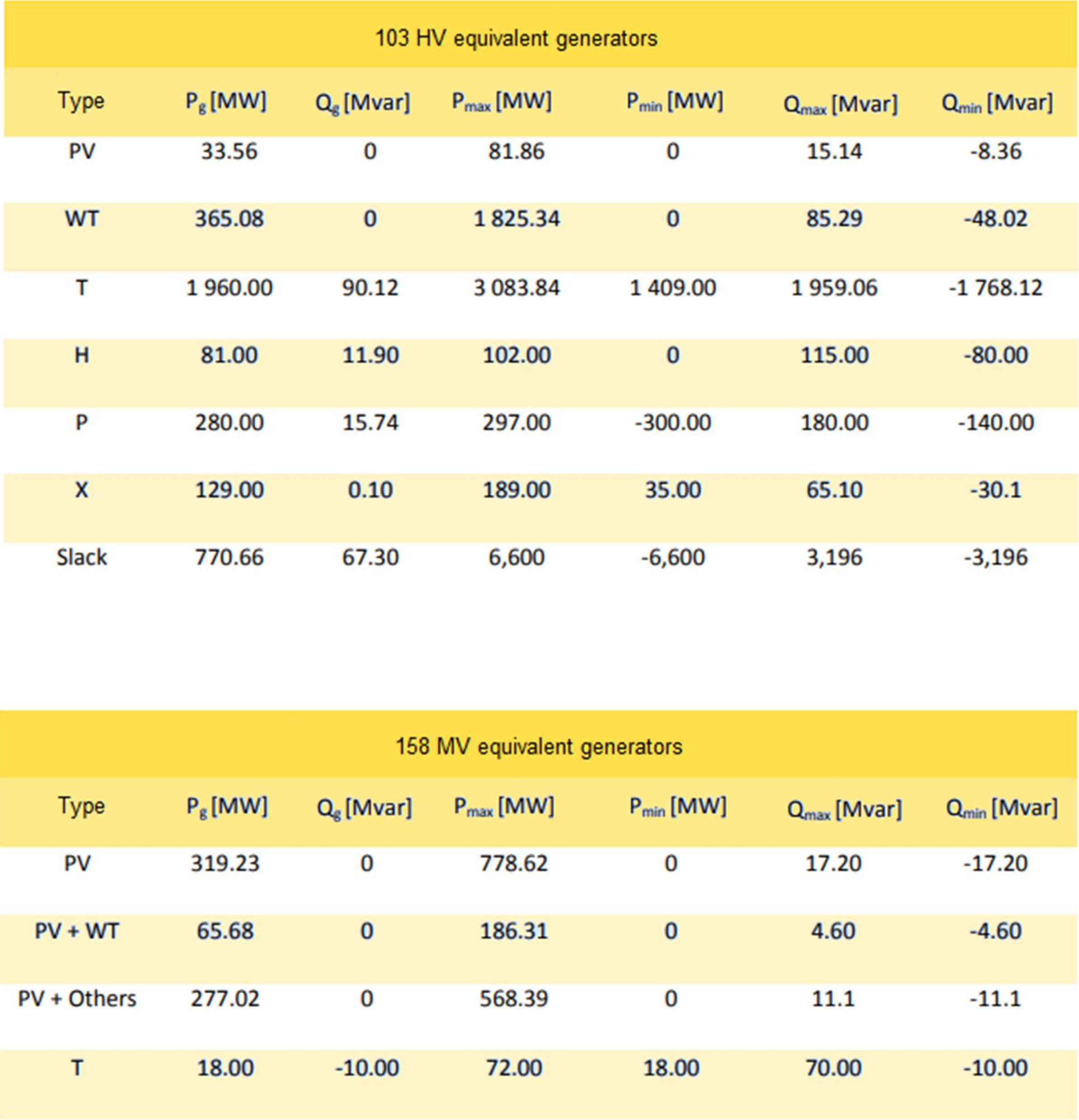


86 HV equivalent generators		
Type	N° of generators	Description
PV	6	PPPs
WT	51	WPPs
T	18	Thermal (Traditional, Oil, TGs, CCs, CHPs, Repowering)
H	4	Hydroelectric plants
P	2	Pump plants
X	4	Specials (Auto-producers, Biomass plants, Waste-to-energy plants..)



158 MV equivalent generators		
Type	N° of generators	Description
PV	108	Photovoltaic plants (PPPs)
PV + WT	16	equivalent generators comprising PPPs and wind power plants (WPPPs)
PV + Others	33	PPPs or WPPs connected to the same bus as other technologies
T	1	Thermal plant

***Figure A.2-1**: summary of generators after grouping excluding the out of service ones*



103 HV equivalent generators						
Type	P_g [MW]	Q_g [Mvar]	P_{max} [MW]	P_{min} [MW]	Q_{max} [Mvar]	Q_{min} [Mvar]
PV	33.56	0	81.86	0	15.14	-8.36
WT	365.08	0	1 825.34	0	85.29	-48.02
T	1 960.00	90.12	3 083.84	1 409.00	1 959.06	-1 768.12
H	81.00	11.90	102.00	0	115.00	-80.00
P	280.00	15.74	297.00	-300.00	180.00	-140.00
X	129.00	0.10	189.00	35.00	65.10	-30.1
Slack	770.66	67.30	6,600	-6,600	3,196	-3,196

158 MV equivalent generators						
Type	P_g [MW]	Q_g [Mvar]	P_{max} [MW]	P_{min} [MW]	Q_{max} [Mvar]	Q_{min} [Mvar]
PV	319.23	0	778.62	0	17.20	-17.20
PV + WT	65.68	0	186.31	0	4.60	-4.60
PV + Others	277.02	0	568.39	0	11.1	-11.1
T	18.00	-10.00	72.00	18.00	70.00	-10.00

***Figure A.2-2**: Production and capability of all generators*

Obviously, only in service power stations have been considered while grouping (i.e., both powers other than zero), and all powers have been added up. The same has been carried out also for capability limits instead of considering the lowest one, since committed generators cannot be turned off, hence the ratio between lowest values of active and reactive power supplied by equivalent generator must be higher than the sum of ratio between lowest values of active and reactive power over all generators, to ensure that active and reactive capability limits are respected for every single generator.

Concerning short-circuit analysis, the parameter of interest of synchronous generators is sub-transient reactance, while for inverter-based power plants it is the maximum current supplied by the converter. In case of more than one synchronous generator connected to the same bus, the equivalent generator is characterized by the parallel of sub-transient reactances (excluding out of service generators). Regarding inverter-based power plants, if more than one inverter is connected to the same bus, their maximum current capabilities are simply summed together, as if all current contributions were in phase. Finally, if different generation technologies are connected to the same bus, as for the 33 equivalent generators listed as “PV + Others” (figures A.2-1 and A.2-2), converter current contributions are summed up in phase and synchronous generator sub-transient reactances are put in parallel.

A.3-Lines and transformers

The π model, neglecting shunt conductance, has been considered for both power lines and two-winding transformers, in order to obtain a simple formulation of bus admittance matrix of the system. This choice results in splitting shunt susceptance (which represents the line capacitance or the transformer magnetizing inductance) into two equal components connected to the terminals, as in figure A.3-1: on the right, the ideal transformer shown represents tap-changer transformer off nominal turn ratios, defined as follows:

$$k = \frac{\frac{V_{T1}}{V_{T2}}}{\frac{V_{n_{bus1}}}{V_{n_{bus2}}}}$$

where in denominator there is the ratio between bus nominal voltages of both sides, and in numerator the off-nominal ratio. The same holds true in case bus nominal voltage ratio differs from the transformer nameplate one.

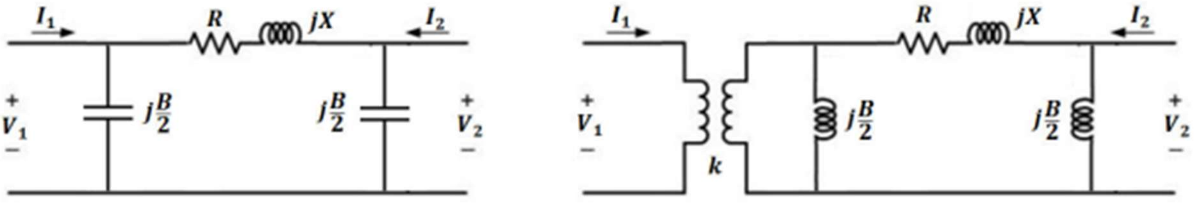


Figure A.3-1: On the left, the equivalent circuit of a power line; on the right, the one of two-winding transformer

For what concerns three-winding transformers (figure A.3-2), the model is based on the insertion of a fictitious bus that is used as common ending of three two-winding transformers modelling one branch of the machine each. Two distinctions must be discussed: firstly, being in reality a single transformer, shunt susceptances representing the magnetizing inductance are present only on the first branch; secondly, all parameters obtained from the on load and short-circuit proves can assume opposite sign with respect to the typical model of two-winding transformer. Lastly, if the fictitious bus nominal voltage is set equal to voltage of bus 1, the ideal transformer on the first branch has unitary turn ratio, thus it can be neglected, as on the right in figure A.3-1.

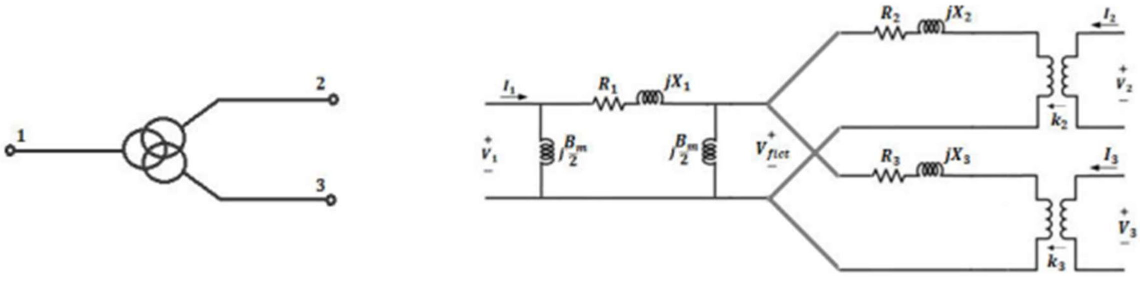


Figure A.3-2: On the left, the three-winding transformer pattern; on the right, its equivalent circuit