IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 18 April 2023, accepted 24 May 2023, date of publication 30 May 2023, date of current version 7 June 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3281532

RESEARCH ARTICLE

Synchronous Condenser for European Grid Code Compliance: A Case Study of a PV Power Plant in Spain

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ABSTRACT The massive integration of renewable energies into the grid towards the de-carbonisation of the power system has a major impact on the stability of the grid. This has led the European Union to establish guidelines on how renewable plants should be connected to the grid, in order to continue to guarantee their operation and stability. These requirements are contained in the European Grid Code. In this code, there are requirements concerning voltage control, reactive power capacity, fault-ride-through and short-circuit current contribution capabilities of renewable power plants. These plants, in particular those powered by photovoltaic inverters, have issues of reactive power capacity, so in order to be able to connect to the grid, they usually require an oversized of the inverters or the installation of reactive power compensation elements, such as capacitor banks, static VAR compensator or synchronous condensers. Moreover, the fault-ride-through and short-circuit current contribution are difficult to fulfil as they are inverter-based generators have a low capacity to supply short-circuit current and, in some cases, they disconnect from the grid. These facts have produced large power losses and protection malfunctions in power system with high photovoltaic power penetration. This paper studies the compliance of the European Grid Code of a 500 MW photovoltaic power plant with and without a synchronous condenser. The results show that not only the use of the synchronous condenser helps for reactive power regulation but also for fault-ride-through and short-circuit current contribution.

INDEX TERMS European grid code, inverter, reactive power capability, RMS simulations, renewable energy, robustness, synchronous condenser.

NOMENCLATURE

FSM	Frequency Sensitive Mode.
HV	High Voltage.
HVDC	High Voltage Direct Current.
LFSM	Limited Frequency Sensitive Mode.
LV	Low Voltage.
MPE	Electrical Module Park.
MV	Medium Voltage.
NC RfG	Network Code on Requirements for grid connection of Generators.
POI	Point of Interface.
PPC	Power Plant Controller.
PSP	Photovoltaic Solar Plant.
PV	Photovoltaic.
SC	Synchronous Condenser.
TSO	Transmission System Operators.
WSCR	Weighted Short Circuit Ratio.

The associate editor coordinating the review of this manuscript and approving it for publication was Ragab A. El-Sehiemy.

I. INTRODUCTION

The massive integration of renewable energy in power system is not an easy task, especially photovoltaic and wind energy, as these technologies are characterized by the use of electronic converters. On one hand the behaviour of the energy sources are random. Therefore, the balance between the power generation and power demanded is more difficult than in case of traditional generation. The wind and radiation forecasts play a very important role in the power systems regulation [1], [2]. On the other hand, the presence of electronic power converters implies different behaviour as the synchronous generators in case of voltage sags, over-voltages or short-circuits. For this reason, research in the topology and control of the converters is very active research topic to reach a good integration of renewable energies in the power systems [3], [4]. Moreover, due to the high penetration of electronic power converter-based generators [5], [6], [7], [8], [9], malfunctions of the protection systems have been taken place. Some disturbances in power systems with notable presence of renewable energies have been notified with large renewable power disconnections [10]. As the electricity is a key component of the modern society, in order to keep the reliability of the power systems numerous standards and regulations have to be fulfilled to the connection of the power generation units [11], [12]. The requirements of the grid codes are related to several aspects. The first one is the reactive power control in steady state as well as in dynamic conditions in case of voltage fluctuations. Moreover, there are some requirements related to the robustness to cope with disturbances and assist to avoid a major disconnection. The generation units should accelerate the restoration of the power system after a collapse. This paper presents the use of Synchronous Condenser (SC) as a very useful tool for the compliance of the European Grid Code in case of a large PV power plant. The synchronous condenser is a well know component of the power systems. Traditionally they were used only for voltage regulation thank to the capacity of produce and absorb reactive power. However, the use of high voltage direct current (HVDC) transmission system based on thyristors converters required large among of reactive power and synchronous condenser are normally used [13]. Another application of the SC is related to the commutation failures of HVDC which produce voltage fluctuations. The use of SC helps to mitigate these fluctuations [14]. Other very important research line related to SC is the optimal location in power systems [15]. This is due to the problems that the high penetration of renewable sources are producing in weak power systems as in the case of ERCOT [16]. Not only the location is important, also the parameters of the SC are important to the correct selection [17]. The problems in the protection systems due to the electronic power converters could be mitigated thanks to the use of SC [18]. Another possible feature of the SC is the damping of the active power oscillation, for this purpose especial field current controller has been developed [19]. The control, protection and start-up systems of SC are very important to warranty the correct operation therefore this is also a significant research line [20], [21]. The SC have a great future in the integration of renewable energies for this reason new developments with superconducting machines are presented in [22].

In this paper the compliance of a 500 MW photovoltaic power plant is analyzed. For this purpose, different configurations of the PV power plant have been considered. One of the considered configurations comprises a SC. An analysis of the advantages and drawbacks of the different topologies is performed. The paper is structured as follow. Section II briefly explains the European Grid Code requirements. In the Section III the most common current solutions for the compliance of the Grid Code are presented. Section IV describes the case study, a 500 MW PV power plant. The simulations results required for the compliance of the Grid Code are presented and discussed in Section V. And finally, the main conclusions of the paper are summarized in Section VI.

TABLE 1. Classification of the different types of generation plants.

Types	Power	Voltage level
A	$P \leq 0.8\ kW$	$V \leq 110\ kV$
B	Continental Europe: $P \leq 1\ MW$	$V \leq 110\ kV$
	Great Britain: $P \leq 1\ MW$	
	Nordic: $P \leq 1.5\ MW$	
	Ireland and Northern Ireland: $P \leq 0.1\ MW$	
	Baltic: $P \leq 0.5\ MW$	
C	Continental Europe: $P \leq 50\ MW$	$V \leq 110\ kV$
	Great Britain: $P \leq 50\ MW$	
	Nordic: $P \leq 10\ MW$	
	Ireland and Northern Ireland: $P \leq 5\ MW$	
	Baltic: $P \leq 10\ MW$	
D	Continental Europe: $P \leq 75\ MW$	$V \geq 110\ kV$
	Great Britain: $P \leq 75\ MW$	
	Nordic: $P \leq 30\ MW$	
	Ireland and Northern Ireland: $P \leq 10\ MW$	
	Baltic: $P \leq 15\ MW$	

II. EUROPEAN GRID CODE

The publication of the Commission Regulation (EU) 2016/631 [11] establishing a Network Code on Requirements for grid connection of Generators (NC RfG) lays the foundations that regulate the grid codes of all the countries belonging to the european union. The NC RfG aims to guaranteeing and improving the security of the power system with a major relevance of renewable generation plants.

Based on this European network code, the different countries have had to publish their own national network codes, with the requirements that new renewable or non-renewable generation plants that desire or intend to connect to the network must comply.

The requirements that are exposed in the european grid code are based on a proportional approach according to the system relevance of the generators. For small generation plants are basic requirement with the objective to ensure system stability. With higher capacity systems the grid code requirements are more demanding in order to maintain system stability and operation. In the case of a retrofit, the regulations will be applied if it is technically justifiable.

The generation plants are classified in four categories, depending on the synchronous area, theirs rated power and the grid voltage level. (See Table 1).

The type of generator implies that the plant must meet different requirements described below:

- Type A: generators shall meet stable operation over extended frequency range with limited automated response and minimal system operator control required.

TABLE 2. General requirements adressed by the NC RfG.

System aspect	A	B	C D
Frequency stability	X	X	X
Voltage stability		X	X
General system management		X	X
Robustness		X	X

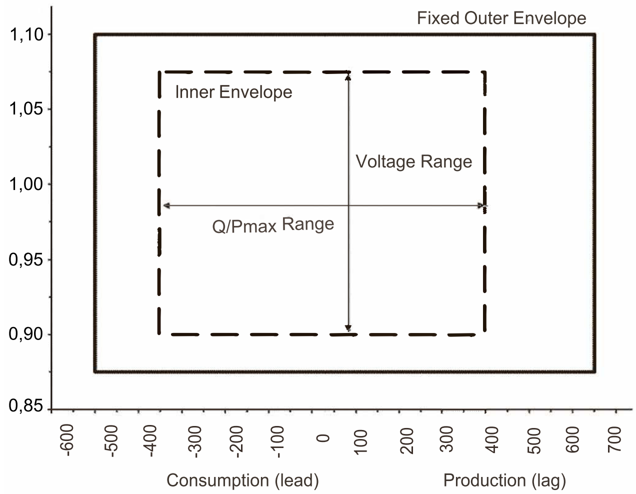

FIGURE 1. Example of UQ profile.

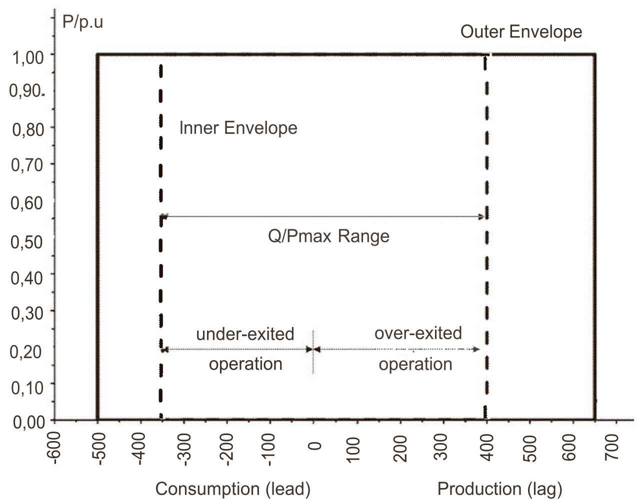

FIGURE 2. Example of PQ profile.

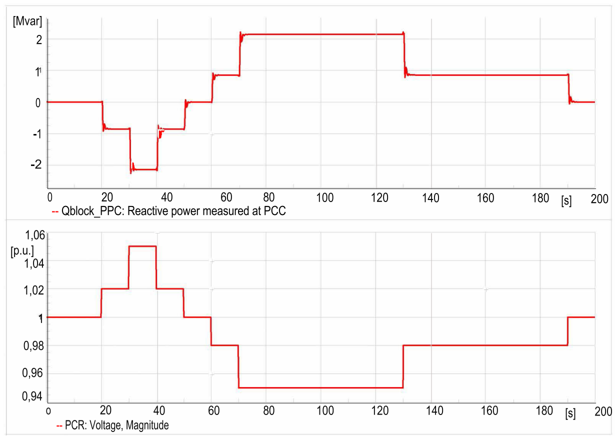

FIGURE 3. Voltage control response profile with a slope of 7% required for the case analysed.

- Type B: generators provide higher resilience to operational events, appropriate dynamic response and basic system operator control.
- Type C: generators shall provide a stable and highly controllable (real time) dynamic response to provide balancing services to ensure security of supply. The requirements cover all operational network conditions and detailed specification of the functions, controls and information exchange to use these capabilities. They must ensure a fast and safe response of the plant in real time to system events.
- Type D: requirements cover a wide area of control and range of operation. They ensure specific needs for high voltage networks and their operation and stability over wide areas, allowing the use of ancillary services from generation Europe wide.

Table 2 gives a summary of the requirements for each type of generation plant.

Within the requirements there are both static and dynamic that power generation plants must meet, as described below:

- Static requirements:
  - Reactive Power Capability: the power generation plant must produce or absorb more reactive power than the requirements that specify the relevant system operator in coordination with the relevant TSO. The profile of these requirements take a shape as shown in the Fig.1 and Fig. 2.
- Dynamic requirements:
  - Reactive Power Control by:
    * Voltage Control: with a slope with a value between 2 to 7% the power plant must be able of contributing to voltage control at the grid connection point exchanging reactive power with the network with a setpoint voltage between the values of 0.95 to 1.05 pu. Fig.3 shows an example of this requirement:
    * Reactive Power Control: the renewable power plant shall be capable of setting the reactive power setpoint anywhere in the reactive power range indicated in the static requirement of Reactive Power Capability, controlling the reactive power at the connection point to an accuracy within plus or minus 5 Mvar or plus or minus 5 % (whichever is smaller) of the full reactive power. The response and set-up time for each country's requirements must be met.
    * Power Factor Control: the renewable power plant must be able of controlling the power factor at the connection point within the required reactive power range, the static requirement of Reactive Power Capability. The relevant system operator shall specify the target power factor value, its tolerance and the period of time to achieve the

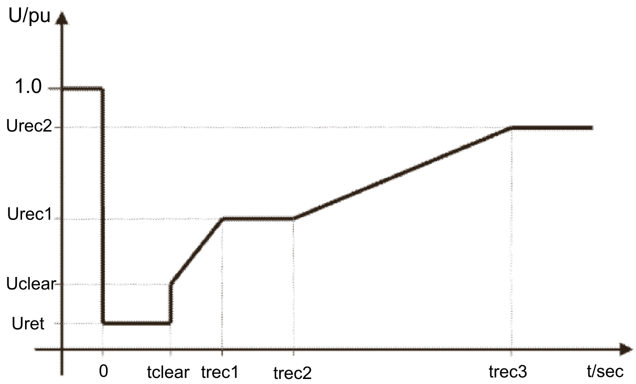

FIGURE 4. Fault-ride-through profile of a power-generating module.

target power factor following a sudden change of active power output. This is the least demanding reactive power control requirement.

- Robustness: fault-ride-through capabilities. This requirement requires generation plants to have the ability to withstand a voltage dip for a certain time and to have the ability to remain connected to the grid. It also requires an injection of reactive current to the fault. The required current injection will depend on the country where the power plant is connected, with a minimum value that guarantees system stability during a fault. Fig 4 shows a Fault-ride-through profile example pertaining to the European Grid Code.
- Frequency stability: this requirement will be applied to all generators under the NC RfG, independently of their capacity. According to the NC, Article 13.1(b)"a power-generating module shall be capable of staying connected to the network and operate at rates of change of frequency up to a value specified by the relevant TSO, unless disconnection was triggered by rate-of-change-of-frequency-type loss of mains protection. The relevant system operator, in coordination with the relevant TSO, shall specify this Rate-Of-Change-Of-Frequency-type loss of mains protection [11], [23].

III. STATE OF ART

In this section the most common current solutions for the compliance of the European Grid Code for large size PV power plants are presented [15].

- PV INVERTER OVERSIZED.
  This solution allows to increase the reactive power capability of the PV power plants. It is an economical solution with a suitable dynamic response of the inverters. In this solution the dynamic response depends on significantly the control system installed of the inverter.
  The main drawback of this solution is that the inverters do not supply large short-circuit current during a fault. Moreover, there are numerous cases of large PV disconnection due to a short-circuit. On one hand because the protection of the power systems need short-circuit current in order see the faults and operate correctly. And on the other hand, because the inverters need a minimum voltage for the control of the semiconductors switching.
- STATIC VAR COMPENSATOR SVCs.
  This solution increases the reactive power capability of the PV power plant and allows it to comply with the static requirements of the European grid code. The control system in these facilities is very complex and expensive. However, the dynamic behaviour of the SVCs is very fast. The main drawback of this solution is that does not improve the short-circuit current supply by the power plant.
- SYNCHRONOUS CONDENSERS.
  The initial investment of installing a synchronous condenser is greater than the other solutions, but its installation is much more beneficial to the power plant. The main advantages are:
  - Increase the reactive power capability to comply with the static requirement of the European Grid Code.
  - Increase the renewable power plant response to short circuit events, increasing the WSCR at the POI terminal. In this case is very important to highlight that the synchronous machine contribute to the short-circuit current regardless its control system, and the response is instantaneous.
  - The large-scale introduction of renewable parks into the power system has led to an increasingly less robust grid in terms of short-circuit protection. This is why many grid operators now require a minimum WSCR at each system node to be able to connect renewable power plants, in order to reach a grid solution that allows the massive entry of renewable generation parks without damaging the robustness of the system.
  - Inertia. With this solution is possible to increase the inertia of the power system. In some cases flywheels have been coupled to the SC, in this way the frequency variations in case of renewable energy oscillations are damped.

There are two drawbacks, on one hand the SC required a minimum energy to operate and on the other hand and starting system is required.

IV. CASE STUDY

The main objective of the study is to compare the influence and relevance of the use of synchronous condensers in order to help the compliance of the grid code. Among all the possible systems, the compensator has been chosen since it is the only system that significantly improves the fault-ride-through and the short-circuit current contribution. For this purpose, two identical photovoltaic power plants will be compared, one of them includes a synchronous condenser.

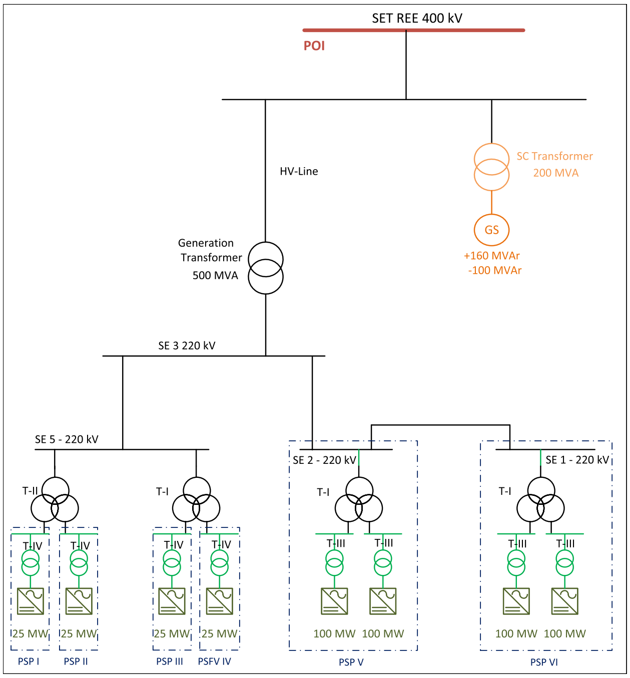

FIGURE 5. Diagram of the photovoltaic solar power plant (500 MW).

The synchronous condenser allows to meet the static requirement of reactive power capability of the Spanish grid code. Moreover, the influence of the condenser on the dynamic requirements demanded will also be analyzed.

In this section, the PV power plant considered as case study are described. Afterward the simulation model is presented.

A. PV POWER PLANT DESCRIPTION

There are two case studies:

- Photovoltaic Solar Power Plant (500 MW).
- Photovoltaic Solar Power Plant (500 MW) with a Synchronous Condenser of 160 Mvar.

The photovoltaic plant in both cases is 500 MW, which makes it a type D plant according to the European grid code.

The photovoltaic power plant is connected to the 400 kV grid through one power transformer. The PV are grouped in 2.4 MW inverters equipped with three-winding transformers. The output voltage of the inverter transformer is 30 kV. There are two 220/30 kV switchgears. There are 208 central inverters in the power plant.

Fig. 5 shows a simplified single line diagram of the photovolatic solar power plant.

Table 3 shows a summary with the main characteristics of the power plant. It is important to clarify that is a normal practice to determine the capacity of the generation transformer just taking into consideration the active power of the PV power plant, that's due to the transformer load will be cyclic in the case of a photovoltaic power plant, so the lifetime of the transformer will not be affected by short periods of overload when it is necessary to deliver or absorb reactive power.

TABLE 3. Main characteristics of the photovoltaic solar power plant.

P_{max}	500 MW
Voltage at POI	400 kV
Technology	Photovoltaic Solar Power Plant

TABLE 4. Main power system characteristics.

Rated Voltage	400 kV
Maximum Voltage	420 kV
Short-circuit capacity	13891 MVA
X/R ratio	15.3

TABLE 5. Main technical characteristics of the inverters.

Technology	Central Inverter
Nominal Power	2.4 MWn
Output Voltage	0.66 kV
Rated Voltage	[0.85 ; 1.1] p.u.
Short Circuit Contribution	1.2 p.u.

TABLE 6. Main technical characteristics of the main transformers.

Characteristics	Generation Transformer	SC Transformer
Rated Power	500 MVA	200 MVA
Rated Voltage	400±10x1%/220 kV	400±10x1%/18 kV
Zcc (%)	13	11
Load losses	250 kW	95 kW
No load losses	100 kW	42 kW

TABLE 7. Main technical characteristics of the HV/MV transformers.

Characteristics	T-I	T-II
Rated Power	220/110/110 MVA	80/40/40 MVA
Rated Voltage	230±10x1%/30/30 kV	400±10x1%/220 kV
Zcc (%) HV-MV	6.25%(@110 MVA)	5.5%(@40 MVA)
Zcc (%) HV-LV	6.25%(@110 MVA)	5.5%(@40 MVA)
Zcc (%) MV-LV	6.25%(@110 MVA)	7.5%(@40 MVA)
Load losses HV-MV	200 kW	100 kW
Load losses HV-LV	200 kW	100 kW
Load losses MV-LV	0 kW	0 kW
No load losses	80 kW	42 kW

B. PV POWER PLANT SIMULATION MODEL

The power plant is modeled by the use of DIgSILENT 2021 software.

The data of the model of the main components of the analyzed system is described below:

1) Power System: The power system is modelled as a voltage source with a serial impedance. Table 4 shows the main ratings of the power system.

2) PV Arrays:

The power plant is made up of a 208 central inverters. Table 5 shows a summary of the main technical characteristics of the inverters.

3) Transformers:

There are four different types of transformers in the photovoltaic solar power plant. Its characteristics are summarized in Tables 6, 7 and 8.

4) PPCs inverter:

The behaviour of the inverter in terms of active and reactive power is controlled by a PPC (Power Plant Controller).

TABLE 8. Main technical characteristics of the MV/LV transformers.

Characteristics	T-III	T-IV
Rated Power	110 MVA	40 MVA
Rated Voltage	30±2x2.5%/0.66 kV	30±2x2.5%/0.66 kV
Zcc (%)	12.5	10
Load losses	200 kW	100 kW
No load losses	40 kW	20 kW

TABLE 9. Main technical characteristics of the inverters PPC.

Active Power Control Modes	FSM
	LFSM - Overfrequency
	LFSM - Underfrequency
	Control Active Power at POI
	Control Active Power at Terminals
Reactive Power Control Modes	Voltage Control
	Control Reactive Power at POI
	Control Reactive Power at Terminals
	Power Factor Control

TABLE 10. Synchronous condenser ratings.

Excitation System	Static
Nominal Power	160 MVA
Rated Reactive Power	$[-100\ ;+160]$ Mvar
Rated Voltage	$18 \pm 5\%$ kV
Rated Speed	3000 rpm
X_d	0.271 p.u.
X_d'	0.341 p.u.
X_d"	0.249 p.u.

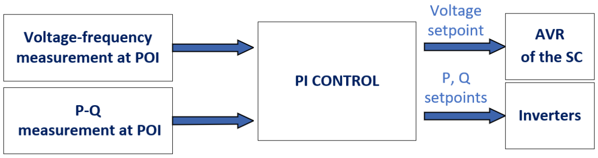

FIGURE 6. Block Diagram of power plant controller.

Table 9 summarizes the main technical characteristics of the PPC.

5) Synchronous Condenser:

The synchronous condenser chosen to support the power plant to comply with the grid code is a synchronous generator of 160 Mvar (is analyzed only in the second case of study,). Table 10 summarizes the main technical characteristics of the SC.

6) Power Plant Controller:

The setpoint of the inverters are generated by the Power Plant Controller as shown in Fig. 6. As it can be seen the PPC has a main PI control block, in which, given the measurements of active power, voltage, frequency and reactive power (all measured at POI), the operating setpoints for the inverters (active power and reactive power) and the voltage setpoint for the AVR of the synchronous condenser are generated.

7) AVR Operational Modes:

The automatic voltage regulator AVR is in charge of regulation the excitation current of the SC. In this way is possible to produce or absorb reactive power. The AVRs can operate at different regulation modes in steady state conditions. It is a normal practice to have four as summarized in the Table 11. The voltage control mode regulates the terminal voltage of the SC. The reactive power or power factor modes make

TABLE 11. Main technical characteristics of the synchronous condensers PPC.

Reactive Power Control Modes	Voltage Control
	Control Reactive Power at POI
	Control Reactive Power at Terminals
	Power Factor Control

the machine to have a reactive power to fulfil with reactive power or power factor required, with the machine in the voltage operational range (usually UN $\pm 10\%$). And finally the control of reactive power at POI has a similar operation but the regulator compares the setpoint and the reactive power at the POI. Additionally in case of short-circuit the voltage in terminal of the SC decreases below the voltage operational range and the AVR increases the excitation current to supply short-circuit fault current.

The model use for the AVR of the synchronous condenser is a DIgSILENT library model, IEEE Type AC7C.

All the simulations required to accomplish the European Grid Code have been performed. However, only the most representative simulations where the SC has an important role are presented in the paper.

- Static Simulation:
  - Reactive Power Capability. In this static simulation, a secondary control is defined so that the inverters can give the nominal power of the power plant in the POI. This secondary control is a DIgSILENT proprietary object which allows to regulate the active power at the connection point in static simulations.
- Dynamic Simulations:
  - Reactive Power Control:
    In these dynamic simulations, the PPC of the photovoltaic central inverters keep the 0.8 of the nominal power of the plant in the POI, as it is required by the European grid code.
    Three control modes are required for reactive power:
    * Voltage Control.
    * Reactive Power Control.
    * Power Factor Control.
  - Robustness: To evaluate this requirement, two simulations are carried out. From the results, it is calculated the WSCR of the POI, and the short circuit contribution of the power plant. The simulations are:
    * Fault Ride Through.
    * Short Circuit Fault.

To evaluate these benefits, simulations have been carried out regarding the different requirements of the european network code purchased by two differents power plants:

- Photovoltaic Solar Power Plant of 500 MW.
- Photovoltaic Solar Power Plant of 500 MW and a Synchronous Condenser of 160 Mvar.

The simulations carried out to evaluate the presence of the synchronous compensator in support of compliance with the European network code are evaluated according to Spanish regulations in order to establish specific tests.

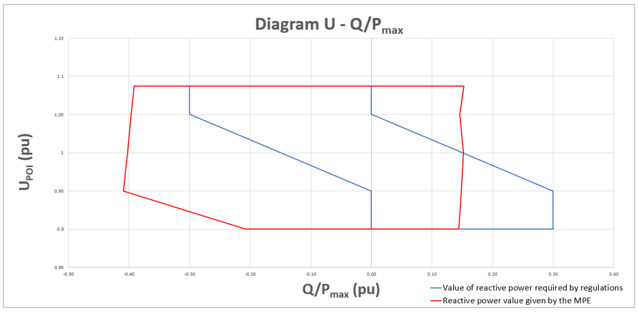

FIGURE 7. Reactive power capability. Diagram U-Q without SC.

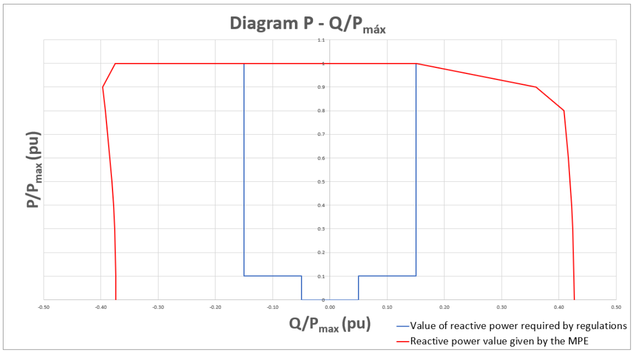

FIGURE 8. Reactive power capability. Diagram P-Q without SC.

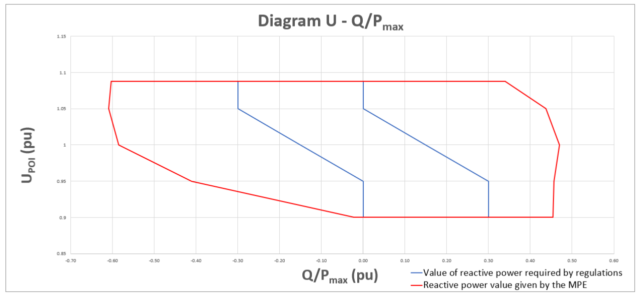

FIGURE 9. Reactive power capability. Diagram U-Q with SC.

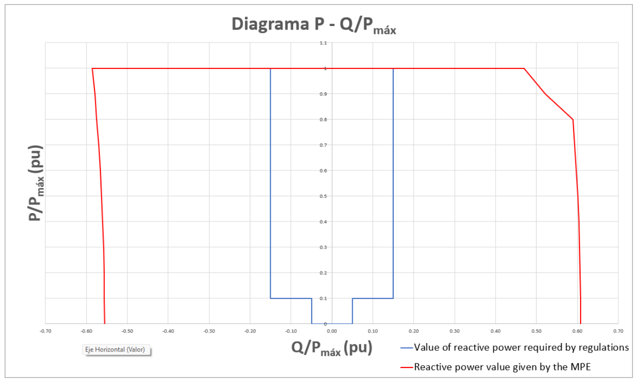

FIGURE 10. Reactive power capability. Diagram P-Q with SC.

V. SIMULATIONS AND RESULTS

The simulations have been carried out according to the conditions that are described in the Spanish Grid Code [12].

The Spanish grid code is based on the European grid code described above, and includes all the requirements described in the latter. What differentiates them, is that being the European Grid Code very general, the Spanish Grid Code has already been revised and approved by the TSO in Spain, setting more demanding times and values for the requirements outlined in the European Grid Code.

A. REACTIVE POWER CAPABILITY

Fig.7 and Fig.8 shows the results of the evaluation of this requirement in the POI for the power plant without SC.

The Fig.7 shows the requirement of the Grid Code for eactive power production or consumption as function of the voltage. It can be clearly seen than the capacity of the plant can not produce reactive power in case of voltages below 1 pu.

In the Fig.8 it represented the reactive versus active power curve of the power plant. In blue the requirements of the grid code and in Red the curve of the power plant. This curve is evaluate with 1 per unit voltage at POI.

In Fig.7 and Fig.8, the curve of the requirement is represented in blue and the curve of the reactive power capability of the power plant in red. Looking at these curves, it can be seen that since the red curve remains inside the blue one in the reactive power capacity zone (Fig.7), the park will need to add some additional element that allows it to deliver the required reactive power.

Fig.9 and Fig.10 shows the results of the evaluation of this requirement in the POI for the power plant with the inclusion of a synchronous condenser.

With the addition of the above-mentioned synchronous condenser, the farm now meets the 5.7 requirement of high margin reactive power capacity, allowing the plant design to be optimized for production. In the case where a synchronous condenser is not installed, the power plant does not meet the required reactive power requirement, so it cannot be connected to the grid. Possible solutions to this problem are the installation of large capacitor bank, or the addition of a larger number of inverters, which requires a lot of space.

B. REACTIVE POWER CONTROL

This test is divided into three different simulations. This is due to the fact that the generator units of a power plant must have different modes of control of reactive power, and in this test evaluate how fast and well operate under these control modes.

1) REACTIVE POWER CONTROL

In these simulations, the voltage at the POI is set to its rated value of 1 p.u. and the value of the PPC reactive setpoint is modified to the values described in the Spanish regulation requirement [12].

Fig. 11 and Fig.12 show the response of the power plant without and with SC to the reactive power POI changes. The red line represents the global response of the power plant at the POI, blue line shows the reactive power contribution of the SC and green line represents the contribution of the photovoltaic solar power plant. As can be seen, it is not

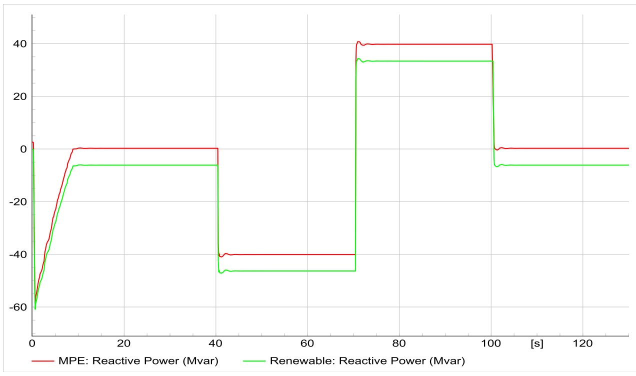

FIGURE 11. Reactive power control response profile without SC.

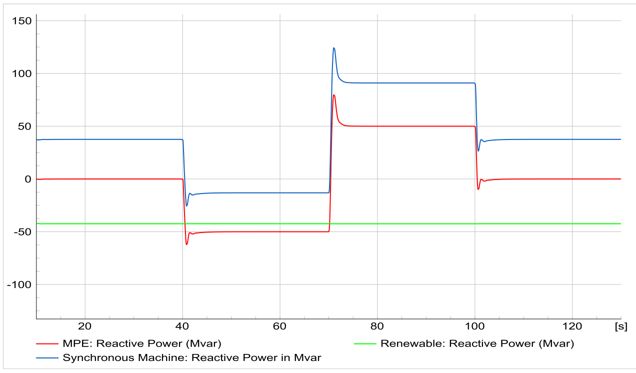

FIGURE 12. Reactive power control response profile with SC.

TABLE 12. Results without SC of the 5.8 Reactive power control requirement.

Q setpoint (%)	Q (Mvar)	Q required (Mvar)	t_1	t_{1max}
-10 %	-50	-50 ± 7.5%	0.43 s	60 s
0 %	0	0 ± 7.5%	0.47 s	60 s
10 %	50	50 ± 7.5%	0.5 s	60 s

TABLE 13. Results with SC of the 5.8 reactive power control requirement.

Q setpoint (%)	Q (Mvar)	Q required (Mvar)	t_1	t_{1max}
-10 %	-50	-50 ± 7.5%	0.55 s	60 s
0 %	0	0 ± 7.5%	0.64 s	60 s
10 %	50	50 ± 7.5%	0.48 s	60 s

necessary that the inverters provide reactive power to meet the requirement.

Tables 12 and 13 show the settling times and the reactive power value reached at each instant for each power plant configuration. The settling time is defined as the time it takes for the signal to reach 95% of the expected value (t_1). t_{1max} is the maximum allowed settling time, Q setpoint is the setpoint of reactive power defined on the requirement, and Q (Mvar) and Q required (Mvar) are the reactive power reached and required respectively.

2) VOLTAGE CONTROL

In this requirement, the voltage at the POI is modify with the goal to evaluate the response and the establishment time of the power plant and if the reactive response reaches the value

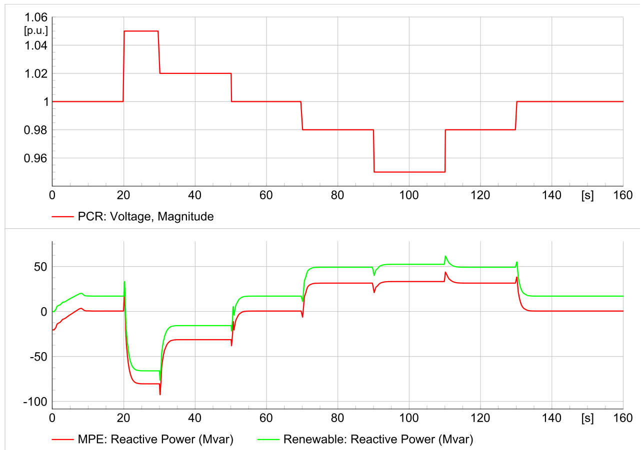

FIGURE 13. Voltage control response profile with a droop of 7% without SC.

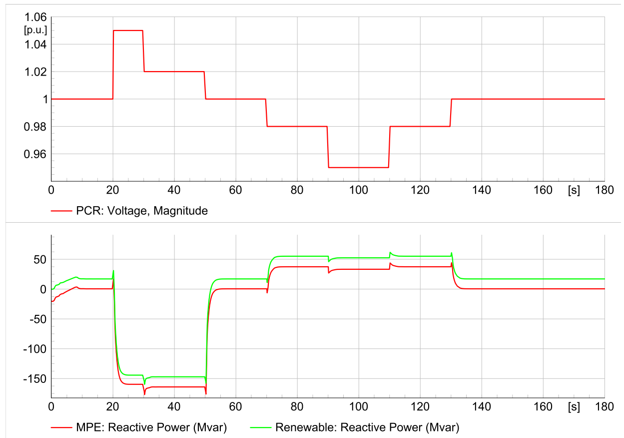

FIGURE 14. Voltage control response profile with a droop of 2% without SC.

indicated in the regulations. To implement this test, a voltage setpoint of one is set on the PPC at the POI and the voltage on the POI is varied with a variable ideal voltage source.

In this simulation, a final reactive power value is accepted within a range of 1.5% of the expected response. In addition, to reach the final value in each voltage step, the plant must be able to modify its response to a value of 90% of it in one second (t_1: response time) and stabilize around the final value of the same in less than 5 seconds (t_2: settling time). This values are defined in the Spanish Grid Code [12].

In the upper part of the Figures 13, 14, 15 and 16, the voltage variations in the POI of the requirement are represented. In the lower part it is shown the response of the power plant to the voltage control requirement in the POI for two levels of droop, the 2 and the 7%.

Results without SC:

Results with SC:

Figures 15 and 16 show the response of the synchronous compensator in blue, the inverters in green and in red the global response of the power plant. Analyzing this simulation, it is seen that the synchronous compensator is capable of helping to fulfill the voltage control requirement, with rapid response times to voltage variations in the network. The times

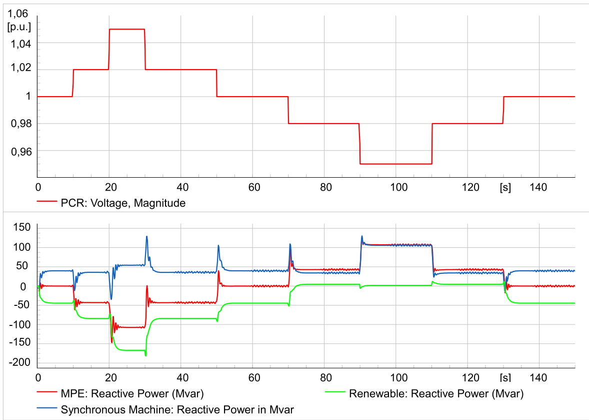

FIGURE 15. Voltage Control Response Profile with a droop of 7% with SC.

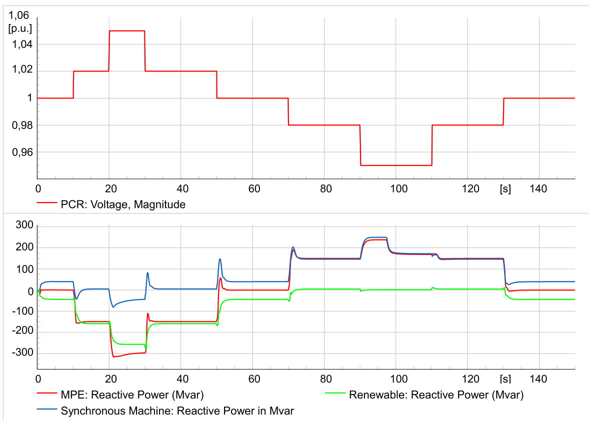

FIGURE 16. Voltage control response profile with a droop of 2% with SC.

TABLE 14. Results of the 5.8 voltage control 7% requirement without SC by spanish grid code.

U_{PCR}	Q (Mvar)	Q required (Mvar)	t_1	t_{1max}	t_2	t_{2max}
1.00	0	0	-	-	-	-
1.02	-43	-150 ± 1.5%	4.02 s	1 s	6.34 s	5 s
1.05	-107	-375* ± 1.5%	2.23 s	1 s	4.23	5 s
1.02	-43	-150 ± 1.5%	2.2 s	1 s	4.87 s	5 s
1.00	0	0 ± 1.5%	1.2 s	1 s	4.35	5 s
0.98	43	150 ± 1.5%	1.23 s	N/A	2.55	60 s
0.95	107	375* ± 1.5%	1.11 s	N/A	2.89	60 s
0.98	43	150 ± 1.5%	0.98 s	N/A	3.21	60 s
1.00	0	0 ± 1.5%	3.7 s	N/A	5.4	60 s

and the reactive power value reached and required by the standard for each level of static are shown in the Tables 14 and 15, without SC and in Tables 16 and 17, with SC.

*Note: this evaluation points can saturated, so its no relevant to reach the reactive power value described on the regulation.

When analyzing the data of the tables 15 and 14, it can be observed that without a synchronous condenser, some settling times are not fulfilled, so that, in case it is decided not to use a synchronous condenser, in order to fulfill the requirement, it would be necessary to think about changing the power plant controller for one that would allow a greater speed in sending the settling time to the inverters.

TABLE 15. Results of the 5.8 voltage control 2% requirement without SC by spanish Grid Code.

U_{PCR}	Q (Mvar)	Q required (Mvar)	t_1	t_{1max}	t_2	t_{2max}
1.00	0	0	-	-	-	-
1.02	-150	-150 ± 1.5%	3.84 s	1 s	5.87 s	5 s
1.05	-300	-375* ± 1.5%	1.89 s	1 s	4.01	5 s
1.02	-150	-150 ± 1.5%	2.34 s	1 s	4.35 s	5 s
1.00	0	0 ± 1.5%	1.07 s	1 s	4.64	5 s
0.98	150	150 ± 1.5%	0.99 s	N/A	1.86	60 s
0.95	180	375* ± 1.5%	1.15 s	N/A	1.97	60 s
0.98	150	150 ± 1.5%	0.87 s	N/A	2.1	60 s
1.00	0	0 ± 1.5%	3.23 s	N/A	3.6	60 s

TABLE 16. Results of the 5.8 voltage control 7% requirement with SC by spanish grid code.

U_{PCR}	Q (Mvar)	Q required (Mvar)	t_1	t_{1max}	t_2	t_{2max}
1.00	0	0	-	-	-	-
1.02	-43	-43 ± 1.5%	0.68 s	1 s	4.72 s	5 s
1.05	-107	-107 ± 1.5%	0.69 s	1 s	4.70 s	5 s
1.02	-43	-43 ± 1.5%	0.65 s	1 s	4.74 s	5 s
1.00	0	0 ± 1.5%	0.65 s	1 s	4.71 s	5 s
0.98	43	43 ± 1.5%	0.68 s	1 s	4.68 s	5 s
0.95	107	107 ± 1.5%	0.67 s	N/A	4.74 s	60 s
0.98	43	43 ± 1.5%	0.69 s	N/A	4.68 s	60 s
1.00	0	0 ± 1.5%	0.71 s	1 s	4.77 s	5 s

TABLE 17. Results of the 5.8 voltage control 2% requirement with SC by spanish grid code.

U_{PCR}	Q (Mvar)	Q required (Mvar)	t_1	t_{1max}	t_2	t_{2max}
1.00	0	0	-	-	-	-
1.02	-150	-150 ± 1.5%	0.6 s	1 s	3.79 s	5 s
1.05	-300	-375* ± 1.5%	0.65 s	1 s	4.17 s	5 s
1.02	-150	-150 ± 1.5%	0.68 s	1 s	4.23 s	5 s
1.00	0	0 ± 1.5%	0.65 s	1 s	4.61 s	5 s
0.98	150	150 ± 1.5%	0.68 s	N/A	4.36 s	60 s
0.95	180	375* ± 1.5%	0.63 s	N/A	4.46 s	60 s
0.98	150	150 ± 1.5%	0.67 s	N/A	4.62 s	60 s
1.00	0	0 ± 1.5%	0.66 s	N/A	2.42 s	60 s

*Note: this evaluation points can saturated, so its no relevant to reach the reactive power value described on the regulation.

This problem could not be solved by modifying the setting of the plant controller, because varying the PI controller parameters would improve the response for the 2% steady state simulation but would lead to non-compliance with the 7% steady state response. Then, either a faster response than the inverters is installed, or a plant controller that allows a much faster control has to be changed.

C. ROBUSTNESS

The robustness requirement requires the plant to remain connected during a voltage dip of 0.5 seconds, and also takes into account the level of current that can be supplied by the power plant under these conditions. When a voltage dip occurs, the power plant starts to inject reactive power into the POI, the more the power plant can provide, the more the power plant will help to recover from the voltage dip and therefore the more stable the system will be. So, for grid operators, this is a very important requirement in order to maintain grid stability.

Next, we will show the results of the simulations for the robustness requirement for the power plant with and

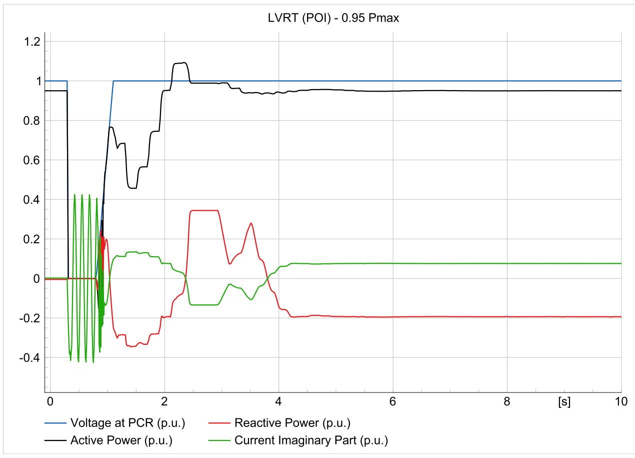

FIGURE 17. Recovery of the active power without SC.

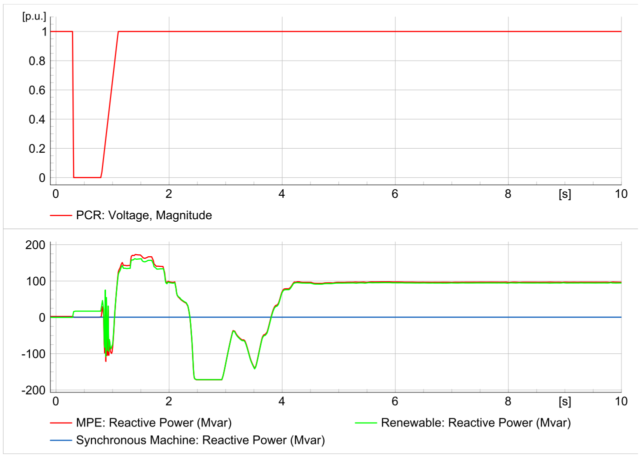

FIGURE 18. Voltage dip without SC.

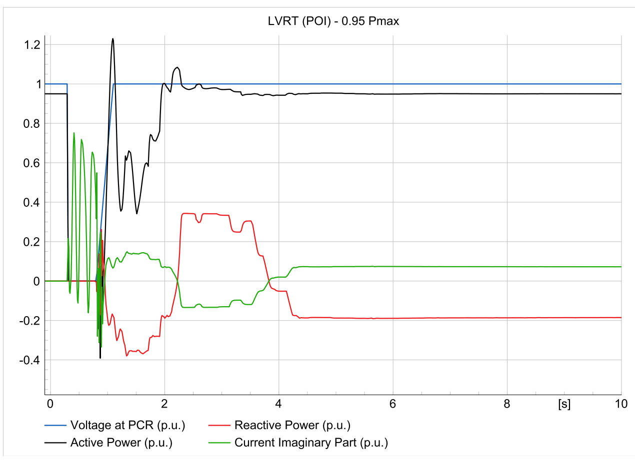

FIGURE 19. Recovery of the active power with SC.

without synchronous condenser. Figures 17, 18, 19, and 20 show the results of this requirement, without and with SC. Figures 17 and 19 show the recovery of the active power, since when a voltage dip occurs, the active power drops to zero, and when the voltage recovers, it is very important for the stability of the network and the installation that the active power recovers as fast as possible.

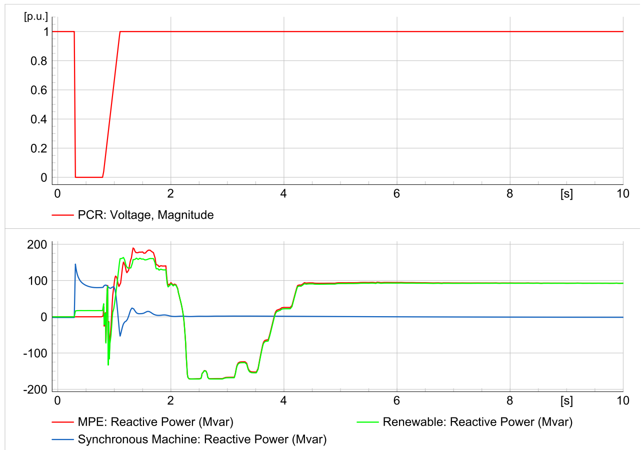

FIGURE 20. Voltage dip with SC.

Figures 18 and 20 show two graphs, the upper one shows the voltage gap that has been performed (red color). The lower graphic shows the reactive power injected at each instant of the simulation, in blue appears the reactive power delivered by the synchronous condenser, in green the one provided by the inverters and in red the total reactive power injected by of the MPE.

As can be seen by analyzing the previous graphs, the reactive power contribution is higher in the case of a synchronous condenser, as well as the recovery of the active power occurs faster in the case of a synchronous condenser. That is to say, for the stability of the network, as shown by these simulations, the installation or reconversion of generators in synchronous condensers is a great benefit.

VI. CONCLUSION

Due to the large installations of renewable power plants based on non-conventional synchronous generation that are expected in the coming years, the presence of synchronous condensers will be of vital importance to maintain the stability of the power systems, whether they are directly manufactured machines with this function, or generators that have undergone a retrofit.

In fact, the results obtained allow us to conclude that the presence of a synchronous compensator is very relevant for the stability of the network, since in the event of a voltage dip they allow a faster recovery of the active power of the photovoltaic power plant, as well as a better response to the dip, since they inject a large amount of reactive power to the fault.

In addition, it clearly helps to comply with the reactive power requirements of the new grid codes, mainly to comply with the reactive power capacity requirement and the voltage control requirement.

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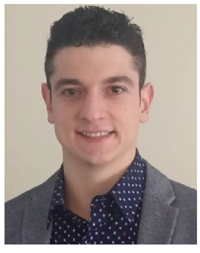

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