Centralized Synchronous Controller Based on Load Angle Regulation for Photovoltaic Power Plants

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Abstract—The integration of renewable energies based on photovoltaic power plants (PVPPs) is increasing exponentially fast. In consequence, stability problems associated with the lack of inertia are becoming a serious concern. Transmission and distribution system operators are demanding more requirements in PV plants to provide grid functionalities in terms of frequency and voltage support. Therefore, power converters based on virtual synchronous controllers have been proposed to emulate the dynamic behavior of synchronous generators. Control strategies such as the synchronous power controller have been proposed for PV applications to fulfill this requirement. However, most of these control strategies are integrated locally as an add-on firmware embedded in each converter, providing the demanded support in their connection point. For PVPPs, the inherent synchronous characteristic is expected at the connection point with the electrical grid, which is not always the connection point of each power converter; thus, unexpected power support levels can be obtained. The aggregation of several power converters operating in a coordinated synchronous action would solve this issue, due to the fact that they can provide voltage and frequency support in a specific point. In this article, a centralized control strategy based on a synchronous central architecture is proposed. The control strategy emulates an aggregated synchronous control to regulate a PVPP as a coordinated system. The simulation and experimental results validate the effectiveness of the control proposed.

Index Terms—Grid stability, photovoltaic power plants (PVPPs), synchronous power control.

I. INTRODUCTION

THE proportion of conventional fossil fuels in the energy mix from power plants is decreasing worldwide due to the evolution of renewable energy systems, which provide the

best levelized cost of energy (LCOE) indexes [1] as well as a sustainable solution for CO₂ emission reduction [2]. Without considering hydropower plants, which provide a significant contribution to green energy production worldwide, renewable power generation systems such as photovoltaic (PV) or wind power plants are typically connected to the electrical network through power electronics converters, whose purpose is to decouple the generation sources from the main electrical grid and enable the capability of controlling the interchange of active and reactive power [3].

Currently, PV or wind power plants can reach power installation levels compared to coal or nuclear power plants. This is the case of many PV farms, whose layouts are normally based on central configurations, where several inverters are connected in parallel to handle the entire power. Considering different key performance indexes, such as cost, robustness, and maintenance, centralized systems offer a better economy of scale and allow easier operation.

Up to this point, most PV plants have been designed and controlled to continuously work at their maximum power point (MPP), regardless of the electrical network conditions and consumption profiles. However, the growing penetration of these plants does not always contribute positively to the overall performance of the system, as they do not support the grid voltage and frequency as conventional synchronous generators (SGs) [4]. If the system operators rely on renewable plants while classical generation facilities are switched off, PV plants should also provide frequency and voltage support services in order to ensure the stability and reliability of the electrical system [5]. Indeed, several transmission and distribution system operators (TSO and DSO) are introducing in their grid-code-specific requirements for PV plants to provide frequency and voltage support [6]–[9].

Most grid-connected PV power converters operate as controlled current sources, thus providing active and reactive power without considering grid disturbances. However, the development of virtual synchronous machine (VSM) controllers has provided solutions for integrating interactive PV power plants (PVPPs), which emulate the SG behavior in terms of frequency and voltage support [10]–[14]. The analysis of a VSM to improve frequency regulation by emulating inertia was presented in [10], [15], and [16], respectively. Other analyses using battery energy storage systems (BESS) have been proposed to emulate large inertia values in [5], and a self-tuning algorithm based on a small-signal analysis to determine

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Fig. 1. Grid connection of power converters based on SPC.

the optimal parameters of inertia and damping to minimize the frequency variation has been presented in [17] and [18].

The synchronous power controller (SPC) is a VSM strategy, which synthesizes the electromechanical and the electrical characteristics of an SG. The electromechanical interaction regulates the inverter frequency through the virtual inertia and damping factor to compensate grid frequency disturbances. Similarly, the electrical characteristic emulates the impedance of an SG and links the ac voltage with the output current, thus providing support under voltage oscillations, sags, and harmonic compensation. The main description of this controller and its application to PV systems has been already presented in [19] and [20]. However, as other VSM strategies, the SPC is embedded inside the local control of each inverter, thus providing the frequency and voltage support at their connection points. This is a great advantage for distributed configurations, but in PVPP, the grid support is expected at the connection point with the electrical grid, which can be far away from some inverters connected inside the plant. Therefore, different levels of frequency and voltage support can be achieved.

In order to provide the appropriate frequency and voltage support, this article proposes the synchronous central angle controller (SCAC) based on the SPC for PVPP. This central configuration emulates the electromechanical characteristic of an SG in the connection point with the electrical grid, while the electrical characteristic is emulated inside of each PV converter. Therefore, the implementation of the synchronous controller is not performed independently at each converter, but it is centralized in an upper control layer to meet the grid requirements through an aggregated virtual synchronous action formed by several interconnected and coordinated converters.

This article is organized as follows. Section II describes the technical foundation of the SPC. In Section III, the main contribution of this article based on the SCAC is analyzed. Section IV provides the main differences between the SPC and the proposed control strategy. Sections V and VI validate the control operation using the simulation and experimental results. Finally, Section VII summarizes this work.

II. SPC CONCEPT

To provide frequency and voltage support functionalities, transmission system operators (TSO) have issued new grid

requirements for PVPP [9], [21], [22]. In this context, control strategies based on VSMs [23], [24] such as SPC have been proposed for the grid integration of renewable energies [13], thus providing a good response under grid disturbances.

In classical grid-connected inverters, the active and reactive currents are regulated through inner current control loops, with references defined by external power or voltage controllers. In such applications, the grid synchronization is based on a phase-locked loop (PLL), having a relevant effect on the overall performance of the converter. However, when the SPC is implemented, the ac current is regulated through the power balance between the converter and the grid, as an SG is synchronized through the power exchange.

The operation principle of a grid-connected power converter based on the SPC is conceptually described in Fig. 1. The power converter and the grid are connected through two impedances. Z_T represents the equivalent impedance between the ac filter and the low-frequency transformer, while Z_g is the grid impedance. In the SPC, the power converter emulates a virtual synchronous generator (VSG) through an internal electromotive force (EMF) $E \angle \theta_E$ in series to a virtual admittance, $1/Z_v$.

According to [25], the electrical power provided from the converter to the grid yields

$$P_e = \frac{EV_g}{X} \sin(\theta_E - \theta_g) = \frac{EV_g}{X} \sin(\delta_{sm}) \quad (1)$$

$$Q_e = \frac{V_g}{X} (E \cos(\theta_E - \theta_g) - V_g) = \frac{V_g}{X} (E \cos(\delta_{sm}) - V_g) \quad (2)$$

where $V_g \angle \theta_g$ represents the grid voltage and X is the equivalent reactance. The angle difference between θ_E and θ_g , also called load angle δ_{sm} , has a direct effect on the active power, and its variation can increase or decrease the power transmitted from the converter to the grid. According to [25], this angle is related to the deviation of the rotor position, being the swing equation (3), i.e., the relationship between the mechanical and electrical power of an SG

$$\frac{d\delta_{sm}}{dt} = \Delta\omega_r \quad (3a)$$

$$J \frac{d\Delta\omega_r}{dt} = \frac{P_m - P_e}{\omega_B} - D\Delta\omega_r = \frac{\Delta P}{\omega_B} - D\Delta\omega_r \quad (3b)$$

where $\Delta\omega_r$ is the angular speed deviation of the rotor, P_m and P_e are the mechanical and electrical power, J is the moment of inertia, D is the damping constant, and ω_B is the base frequency.

Some proposals have introduced a virtual impedance in their controllers and operate the converters as controlled voltage sources. Therefore, the power is regulated directly by the power synchronization loop without an inner ac current loop. In such cases, high currents can arise due to the lack of current controller, thus increasing the risk of high current levels [26]. In any case, the derivative component of the virtual impedance may require filters to reduce the voltage noise, thus eliminating undesirable current components. On the other hand, the SPC

Fig. 2. Operation principle of a power converter based on SPC.

introduces a virtual admittance which provides a low-pass filter response, reducing high-frequency components. In addition, the virtual admittance makes the power converter behaves as a controlled current source [20], thus providing a current limitation in the converter operation. A simplified diagram of the SPC is shown in Fig. 2.

The mechanical control, based on (2) and (3), defines the phase angle θ_E of the EMF, while the reactive power controller defines the EMF amplitude. Both signals are used by the voltage-controlled oscillator (VCO) to obtain the EMF signal e , which is compared with the ac voltage at the connection point with the grid and processed through the virtual admittance to set the current reference for the inner current control loop. Parameters R_Y and L_Y represent the resistances and inductances of the virtual admittance.

III. SYNCHRONOUS CENTRAL ANGLE CONTROLLER (SCAC)

A. Operation Principle

The SCAC is a control strategy based on the SPC and oriented to manage several converters as a single VSG. This ensures that the synchronous control is not applied individually to regulate each converter, but rather an aggregation of several of them. The advantage of this control strategy relies on the capability to provide an automatic power distribution among all PV converters and the ability to generate a coordinated synchronous action to support the grid. This feature aids to minimize interarea oscillations, thus reducing energy variations. The main idea behind the control proposed is conceptually illustrated in Fig. 3. As shown, the voltage at the collector point of the plant is considered as an aggregated SG, where e emulates a virtual rotor. Each power converter connected to a PV array (from now on referred to as PV generator) emulates an independent virtual stator with a local EMF e_i , which can be adjusted to provide specific power support and harmonic compensation if required. The relationship between the local e_i and the central e determines the active and reactive power of each PV unit.

Fig. 3. Conceptual representation of the SCAC.

As described in the SG model, the load angle δ_{sm} defines the electrical power through the frequency deviation $\Delta\omega$. In the SCAC, this angle is referred to as the central load angle δ_g and represents the difference between the grid voltage v_g and the central EMF e . Therefore, when there is a frequency deviation, the central load angle δ_g increases or decreases the power reference to compensate such change.

The architecture of the SCAC is shown in Fig. 4. The control is divided into two main blocks: the central control and the local control. The central control emulates a virtual rotor and controls the central load angle δ_g required to define the active power. In addition, a reactive power control loop is implemented to set the EMF deviation ΔE . According to [27], the rotor emulation is governed by the inertia H , damping factor ζ , and frequency droop. By adjusting these parameters, it is possible to modify the dynamic performance of the system under different frequency levels. On the other hand, the local control embedded in each PV generator is responsible for controlling the power generated through the virtual admittance, which defines the current reference of each PV generator through the voltage difference between the local EMF e_i and the ac voltage $v_{c,i}$.

B. Central Control

The central control regulates the power exchange between the plant and the electrical grid through two control loops: the electromechanical and the reactive power controllers. In Fig. 5, the structure of the electromechanical control determines the relationship between the active power and the load angle δ_g . In this configuration, the block H_M holds the transfer function that links the active power with the synchronous frequency variation $\Delta\omega_r$. This frequency is added to the nominal frequency ω_B and finally integrated to provide the phase angle θ_E . The angle θ_E represents the phase angle of the central EMF e at the connection point with the grid. The transfer function H_M is designed based on the swing equation (3), where the damping factor and the inertia can be adjusted according to the main features of the grid and the functionalities intended to be provided.

Fig. 4. Control architecture of the SCAC.

Fig. 5. Internal structure of the central control loop.

The dynamic response of the electromechanical control has been previously studied in [20]. Considering the power and frequency analysis presented in [20], the power loop H_M is expressed as

$$H_M = \frac{\Delta \omega_r}{\Delta P} = \frac{k_p + k_i s}{s + k_D} \quad (4)$$

where k_p , k_i , and k_D are designed according to the damping factor, inertia constant H , and frequency droop slope. This droop can be set independently of the damping and inertia parameters, and it is adjusted according to the grid requirements. However, in order to determine the parameters of the power loop, it is necessary to analyze the closed loop between the mechanical and electrical power in an SG. By combining (1)–(3), the relationship between P_m and P_e is given by

$$\begin{aligned} \frac{P_e}{P_m} &= \frac{\omega_B P_{\max}}{s(2Hs + D)S_N + \omega_B P_{\max}} \\ &= \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \end{aligned} \quad (5)$$

where $P_{\max}$ is EV_g/X , J is replaced by the inertia constant $H = J\omega_B^2/2S_N$, and S_N is the rated power. According to [20], the damping coefficient D provides an inherent frequency droop response between $\Delta P/\Delta \omega_r$.

Previous expression is a second-order transfer function, where the damping factor and the inertia are defined by ζ

and ω_n , respectively. Doing a similar analysis by using (4), the closed loop between P_e and P_{ref} can be written as

$$\frac{P_e}{P_{\text{ref}}} = \frac{(k_p + k_i s)\omega_B P_{\max}}{s(s + k_D)S_N + (k_p + k_i s)\omega_B P_{\max}}. \quad (6)$$

By combining (5) and (6), it is possible to define the power loop parameters in terms of the natural frequency ω_n and damping factor ζ

$$k_p = \frac{\omega_n^2}{P_{\max}} \quad (7)$$

$$k_D = \frac{\omega_n^2 D_p}{P_{\max}} \quad (8)$$

$$k_i = \frac{2P_{\max}\zeta\omega_n - \omega_n^2 D_p}{P_{\max}^2} \quad (9)$$

where D_p is the inherent frequency droop and ω_n is the natural frequency

$$\omega_n = \sqrt{\frac{P_{\max}\omega_B}{2HS_N}}. \quad (10)$$

In the central control, the electromechanical part generates the phase angle θ_E used to calculate the central load angle δ_g through the difference between θ_E and the grid angle θ_g . The Park transformation is employed to define the central load angle by rotating the grid voltage into a new virtual synchronous reference frame (VSRF). Fig. 6 shows how the grid voltage v_g is projected on the VSRF.

The grid voltage $\vec{v}_g$ is in phase with $\vec{d}_g$, as $\vec{E}$ is in phase with $\vec{d}_E$. Under steady-state operation, the frequency $\omega_E = \omega_g$ and the angle difference between $\vec{E}$ and $\vec{v}_g$ are constant. Therefore, we can rotate the grid voltage over the dq_E VSRF using the following expression:

$$v_{g,dqE} = \hat{v}_g \cos(\delta_g) - j\hat{v}_g \sin(\delta_g) \quad (11)$$

where $\hat{v}_g \cos(\delta_g)$ and $\hat{v}_g \sin(\delta_g)$ represent the d and q components of the grid voltage on the VSRF.

Once the grid voltage is rotated, a low-pass filter is used to reduce the high-frequency components. The filtered grid voltage $v_{g,dqE}^F$ is then used to calculate the central load angle δ_g as follows:

$$\delta_g = \tan^{-1}\left(\frac{v_{g,qE}^F}{v_{g,dE}^F}\right). \quad (12)$$

The reactive power control loop based on a proportional integrator (PI) controller is used to regulate the EMF amplitude at the point of common coupling. This controller can also be used to provide voltage support by adding a Q - V droop if required.

C. Local Controller

The load angle and the EMF set by the central controller are used in the local controller to determine the ac current reference. In Fig. 7, the structure of the local controller is divided into two blocks. The load-angle control block defines the phase angle $\theta_{E,i}$ required by the VCO to generate the $\alpha\beta$ components of the local EMF e_i . The electrical interaction

Fig. 6. Grid voltage and EMF in the dq reference frame.

Fig. 7. Layout of the local control structure. (a) Load-angle control block. (b) Electrical interaction block.

block defines the current reference for the power converter by processing, through the virtual admittance, the voltage difference between e_i and the voltage at the ac side.

The load-angle control loop shown in Fig. 7(a) regulates the phase angle $\theta_{E,i}$ according to the central load-angle reference. The error between the central and the local load angle is processed through a PI controller and then integrated to generate the phase angle required to project the ac voltage $v_{c,i}$ over a VSRRF, giving rise to the local load angle $\delta_{E,i}$.

As the PVPP has to contribute to the grid support at certain times, a power reserve is required. This power reserve can be provided by either a stand-alone energy storage unit or by a power curtailment operation in the PV panels. In the power curtailment operation, the MPP mode is no longer feasible since a power variation ΔP is required to provide such grid support. If the required power exceeds the MPP level, the dc voltage tends to decrease uncontrollably; hence, a dc voltage compensator Δv_δ is included to maintain the dc voltage within a certain range. The minimum and maximum dc voltage levels

are set to provide a power range between the voltage level at maximum power operation and the voltage level at open-circuit operation. While the analysis of a power curtailment operation is beyond the scope of this study, this scenario has been chosen to illustrate a critical operation.

The voltage limiter block holds the dc voltage between the minimum and maximum voltage levels through the voltage compensator

$$\Delta v_\delta = \begin{cases} V_{dc} \geq V_{dcMin}, & 0 \\ V_{dc} < V_{dcMin}, & (V_{dcMin} - V_{dc}) \cdot PI_v(s) \\ V_{dc} > V_{dcMax}, & (V_{dcMax} - V_{dc}) \cdot PI_v(s) \\ V_{dc} \leq V_{dcMax}, & 0. \end{cases} \quad (13)$$

When the dc voltage is between the minimum and maximum voltage levels, no compensator angle is required. However, when the dc voltage reaches one of its limits, a PI controller adjusts the angle compensator to avoid a voltage level out of range. In this way, the power generated by each PV generator can be controlled independently.

As previously discussed, the virtual admittance processes the voltage difference between e_i and v_{ci} to determine the current reference. Note that all PV generators receive the same central load angle; hence, an appropriate value of the virtual admittance will define the power distribution between all converters connected. This power distribution can be calculated in terms of the weight factor parameter k_{Yi} as

$$k_{Yi} = \frac{P_{i,\%}}{\sum_{i=1}^N P_{i,\%}} = \frac{P_{i,\%}}{P_{PCC,\%}} \quad (14)$$

where $P_{i,\%}$ is the power level to be injected by each PV generator, $P_{PCC,\%}$ is the total power of the plan, and N is the number of PV generators. The power distribution in all converters is performed through the weight factors and the virtual admittance by

$$Y_i = \frac{k_{Yi}}{L_i s + R_i}. \quad (15)$$

Once the virtual admittance provides the current reference, a current controller regulates the ac current of each PV unit. This controller is based on a well-known proportional resonant (PR) structure to ensure perfect tracking with zero steady-state error.

D. Effects of Communication Delays

Communication between the central and local controllers may trigger large communication delays, thus affecting the stability and performance of the plant. In consequence, it is critical to select the right control parameters to operate at a stable point. From previous studies [28], it is known that the electromechanical interaction is commanded by the inertia and damping parameters, which are able to mitigate power oscillations. Since these parameters have a direct effect on the stability margin, they can be selected to compensate for communication delays and achieve the desired response.

In order to study the effect of different inertia and damping values in the electromechanical interaction under a certain communication delay, it is possible to simplify the analysis

Fig. 8. Bode diagram of power response under 100 ms of communication delay. (a) Inertia variation with damping factor $D = 1$. (b) Damping variation with inertia $H = 5$ s.

and focus our attention on the active power response by inactivating the reactive power compensation, thus bringing about a constant EMF value. Considering the central controller of Fig. 5, the active power is commanded by the central load angle, which has a slow dynamic and direct effect on the electrical power, as shown in (1).

The impact of different inertia and damping factors under 100 ms of communication delay is studied through a bode diagram. Assuming all parameters in per unit and a first-order transfer function delay, the bode diagram under different inertia values with a damping factor $D = 1$ is shown in Fig. 8(a). Note that how the lower inertia values increase the phase margin and the gain margin at certain frequencies, thus inducing high-power oscillations. Similarly, in Fig. 8(b), the bode diagram is studied under different damping values with a constant inertia value equal to 5 s. It is concluded that as the damping factor increases, the gain margin is considerably reduced, thus contributing to the control stability at low-frequency oscillations. This analysis makes sense because the damping factor is directly linked to power oscillations. In consequence, it has been demonstrated that increasing either the inertia or damping factor, power oscillations due to communication delays can be mitigated.

IV. COMPARATIVE ANALYSIS BETWEEN SCAC AND SPC

In order to illustrate the advantages of using the SCAC over the SPC for central configurations, the main characteristics of both control strategies are described in this section. All the comparative features are focused on control architecture, power distribution, and grid-support functionalities.

A. Control Architecture

As outlined in [19], the SPC has a distributed control architecture, which emulates a dedicated VSM in each PV generator. A PVPP with converters based on the SPC is divided into two layers. The top layer is called the central plant controller and provides the global active power reference to all units, as well as the reactive power reference according to the voltage measured at the point of connection with the electrical grid. These references are set according to the total power of the plant and the droop characteristics. The bottom layer adjusts the references for the SPC based on participation factors.

Similarly, the SCAC has two control layers. The central controller emulates the electromechanical interaction of an SG based on the inertia, damping, and droop characteristics, thus providing the benefits of a single VSM in the connection point with the electrical grid. In addition, the local controller includes the load-angle control and the electrical interaction of an SG to synchronize all PV generators and regulate the ac current.

The difference between both control strategies relies on how they emulate the SG response. While the SPC emulates an SG in each converter, thus providing a synchronous response at their connection point, the SCAC emulates a single SG at the connection point with the grid. This configuration reduces power fluctuations among PV generators given by interarea oscillations as in real SGs. One of the reasons for these interarea oscillations is the large impedances in cable connections between PV generators and the electrical grid [30].

B. Power Distribution

In the steady-state operation, power converters based on the SPC distribute their power level through participation factors, which adjust the power reference provided by the central plant controller. In the case of the SCAC, the weight factors modify the virtual admittance required to define the current reference through the voltage difference between the local EMF and the voltage measured at the ac side. Both control strategies distribute their power level according to specific parameters, thus giving rise to a similar response in the steady-state operation. The main differences are observed in their dynamic response. In the SPC, the dynamic response is given by the electrotechnical parameters, thus providing an independent response in each unit. However, the control proposed has a coordinated action because all converters are controlled with the same load angle and EMF reference. This feature allows the same dynamic in all converters unless power limitations adjust the converter response.

TABLE I
DIFFERENCES BETWEEN SPC AND SCAC

	SPC	SCAC
Inertia and Damping	<ul style="list-style-type: none"> - Unique in each PV generator - Possibility of different dynamic responses 	<ul style="list-style-type: none"> - Central configuration - Coordinated dynamic response reduces inter-area oscillations
Central control	<ul style="list-style-type: none"> - Active and reactive power 	<ul style="list-style-type: none"> - Central load angle and EMF allows a coordinated action between all PV generators
Dynamic response	<ul style="list-style-type: none"> - Equivalent dynamic response depends on each PV generator 	<ul style="list-style-type: none"> - Equivalent dynamic response is given by the control parameters in the central controller

C. Grid Support

One of the main advantages of using VSMs is the capability to provide frequency and voltage support functionalities. As mentioned above, the SPC has the flexibility to define the inertia and damping in each converter, thus giving the possibility to set different control parameters and, thus, different dynamics. According to [19], the inertia and damping of an equivalent PVPP with power converters based on the SPC can be defined as follows:

$$H_T = \frac{\sum_{k=1}^N H_K S_K}{S_T} \quad (16)$$

$$\frac{D_T}{H_T} = \frac{D_k}{H_k} \quad \forall k \quad (17)$$

where H_k , D_k , and S_K are the inertia, damping, and nominal power of each PV generator, and H_T , D_T , and S_T are the inertia, damping, and nominal power of the plant. These expressions are valid only if a common virtual impedance ratio and a coherent active and reactive power responses for all converters are used [19]. However, when these conditions are not fulfilled, the estimated parameters may be inaccurate and not admissible, thus increasing the complexity to estimate the equivalent inertia and damping.

Since the synchronous load angle emulates a single rotor, the complexity of estimating the equivalent inertia and damping is reduced, thus contributing to define easily proper values to support the grid.

An overview of SPC and SCAC is described in Table I.

V. SIMULATION RESULTS

In this section, simulation results are presented to validate the performance of the SCAC in a plant formed by four power converters. The dc side is connected to constant dc sources in series to resistors to emulate the behavior of a PV panel. Two different scenarios have been considered to verify: power distribution and frequency support functionalities. In addition, a comparative analysis between SCAC and SPC is described.

In the first scenario, a power step is set to study the power distribution among all PV units. To achieve this power distribution, different weight factors are assigned in the local controller. In the second scenario, the power support under a

Fig. 9. Electrical and control layout of the simulation and experimental setup.

grid frequency change is studied by modifying the frequency with a certain slope. Control and simulation parameters used for these tests are listed in Tables II and III, respectively. Note that the parameters have been selected to compare simulation and experimental results at the same power levels. The virtual admittance has been selected according to [29].

A. Active Power Step

In this section, the coordinated power sharing between the PV generators is validated in normal operation and under a converter disconnection. The power and current responses for the power converters are shown in Fig. 10. In the simulation test, the initial power reference for the power plant is intentionally set to 75% of its rated power, thus emulating a curtailment situation. After the power reference changes, the active power of the plant increases while the reactive power remains at zero. Since the PV generators have different weight factors, the power delivered by each converter is distributed at different levels. Therefore, PV generators 1 and 4 provide 25% of the total power, PV generator 3 provides 30%, and PV generator 2 provides 20%. The ac current in each converter is illustrated in Fig. 10(d).

The power sharing in the plant changes when converter 3 is abruptly disconnected at $t = 1$ s. As a result, the rest of PV generators automatically increase their power to supply the missing power, as shown in Fig. 10(b). However, due to the converter disconnection, the active power exhibits a perturbation, which is compensated after 250 ms. Note that

TABLE II
CONTROL PARAMETERS USED IN SIMULATION
AND EXPERIMENTAL RESULTS

Parameters	Symbol	Value
Inertia	H	5
Damping factor	ζ	1
Frequency droop	D_p	0.4
Weigh factor C_1	k_{Y1}	1
Weigh factor C_2	k_{Y2}	0.8
Weigh factor C_3	k_{Y3}	1.2
Weigh factor C_4	k_{Y4}	1
Virtual impedance	L_i	0.0764H
Virtual resistance	R_i	8Ω

TABLE III
SIMULATION AND EXPERIMENTAL PARAMETERS
OF THE POWER PLANT

Parameters	Symbol	Value
Nominal power	S_N	8kVA
Nominal power per PV generator	P_M	2kW
Grid voltage	v_g	400 V
Grid frequency	f_s	50Hz
Number of PV generators	N	4
DC voltage at open circuit	V_{dcO}	800V
DC voltage at maximum power	V_{dc}	700V
DC-link capacitance	C_{dc}	4700uF
DC-link resistance	R_{dc}	34Ω
Switching frequency	f_c	8200Hz
Inductance LC filter	L_f	3mH
Capacitance LC filter	C_f	5uF
DC base voltage	$V_{DC,B}$	700V
AC base voltage	V_B	400V
Base power	S_B	8kVA

how converter 3 reduces its power to zero at $t = 1$ s, while the rest of PV generators increase their power level. This behavior is given by the central load angle shown in Fig. 10(c), which forces all converters to increase their power level based on their virtual admittance, thus maintaining the active power at its reference value.

B. Grid Frequency Support

In order to study the frequency support provided by the PV plant when the SCAC is used, a grid frequency change is emulated. In the first scenario, the inertia constant has been intentionally set at $H = 10$ s to study the behavior of the plant when one PV generator reaches its maximum power level. In this scenario, the weight factors remain the same as in the previous study. Since there is a direct relationship between the active power delivered and the dc voltage, those PV generators that reach their dc voltage limit will curtail the power generated. Fig. 11 shows the power response of the PV plant when the grid frequency decreases with a rate of -0.4 Hz/s. We can see how the active power provided by the plant increases as long as the grid frequency changes.

As shown in Fig. 11(c), the higher the active power generated, the lower is the dc voltage reached. The minimum dc voltage has been set at 0.92 p.u. to guarantee an appropriate ac current control when providing grid frequency support.

Fig. 10. Power, current, and angle waveforms in response to an active power change. (a) Active and reactive power delivered to the grid. (b) Active power delivered by each PV generator. (c) Central load angle. (d) Current in the steady-state operation.

Once converter 3 reaches its minimum dc voltage, its active power is curtailed. In consequence, the rest of the power converters continue increasing their power to provide the required level at the connection point. Therefore, the proposed control strategy is able to manage the power sharing in the plant, thus providing grid frequency support even if PV power converters are affected by different operating conditions.

To focus our attention on the inertia response, the droop D_p has been set at 0.4 to minimize its impact on the power support. This is the reason why the power support decreases as soon as the grid frequency reaches its steady state. Note that the dynamic response is mainly supported by the inertia, while the steady state is supported by the frequency droop. Based on the analysis presented in [20], (16) shows the relationship between ΔP_o and the frequency change $\Delta \omega_g$

$$\frac{\Delta P_o}{\Delta \omega_g} = \frac{S_N}{\omega_B D_p}. \quad (18)$$

In the second scenario, different inertia values are emulated to evaluate their effect on the SCAC. According to (5), different inertia values give rise to different transient responses in the active power. As expected, the higher the inertia constant, the stronger the power support under frequency changes. Fig. 12 shows the active power response when the grid frequency changes with a rate of -0.4 Hz/s. It can be observed from Fig. 12(a) that the highest power support is reached

Fig. 11. Power response under a grid frequency variation with inertia $H = 10$ s. (a) Total active power provided by the plant. (b) Active power generated by each converter. (c) DC voltage. (d) Grid frequency variation.

Fig. 12. Active power response under different inertia values. (a) Active power delivered by the plant. (b) Grid frequency variation.

with an inertia constant of $H = 7$ s, whereas the lowest one corresponds to $H = 1$ s. Once the frequency value reaches 49 Hz, it remains constant and the instantaneous power support provided by the plant decreases.

C. Comparison Between SCAC and SPC Under Grid Frequency Changes

In order to illustrate the differences between SPC and SCAC, the same frequency change introduced in Section V-B is implemented when the power converters of the PVPP are

Fig. 13. Active power response of the PVPP based on SCAC and SPC. (a) Active power delivered by the plant. (b) Grid frequency variation.

controlled with both control strategies. Note that in both cases, the inertia and damping factor are equal to 5 s and 1, respectively. In addition, in order to simulate different distances from the grid connection, cable impedances based on the analysis described in [19] have been introduced.

Fig. 13 shows how a frequency change of -0.4 Hz/s triggers to an increase in the output power to support the grid. However, a small difference between the power support given by the SCAC and the SPC is observed. This difference is due to the effect of different cable impedances, which induce a lower power support in the SPC. Note that the power converters based on the SPC provide support at their connection point, while the SCAC is focused on the connection point with the electrical grid.

VI. EXPERIMENTAL RESULTS

The performance of the SCAC is experimentally validated using the downscale laboratory setup shown in Fig. 14. As in the simulation results, the experimental setup consists of four PV generators connected to the grid. The experimental parameters are listed in Table III.

Each PV generator has a three-phase inverter [Danfoss model of commercial variable speed drive (VLT)], an inductance–capacitance–inductance (LCL) filter, and a control platform based on a digital signal processor (DSP) (Texas Instruments TMS320F28335), which is used to manage the local control algorithm, physical signals, and protections. A programmable dc source (Magna-Power TSD1000-20/36) with multiple outputs in series with dc resistors supplies the dc side for all inverters, thus emulating the effect of four independent PV strings. The ac side of the power converters is connected to the point of connection with the grid through low-frequency transformers. The connection between the plant and the stiff ac grid is emulated through a variable autotransformer, while the connection to a weak grid is emulated using a 30-kW SG (Leroy-Somer LSA 42.2).

In the experimental setup, the central control is integrated into a high-level system, which measures the grid signals to control the total power delivered to the grid through the central load angle and the central EMF. These control

Fig. 14. Laboratory setup.

variables are transferred to each PV generator through a communication controller area network (CAN) bus.

In order to prove the feasibility of the SCAC, different scenarios have been considered to validate the performance of the system in steady state and during transients. The control parameters used are listed in Table II.

A. Active Power Response

Current and voltage waveforms of the PV plant in response to an active power step under equal power sharing are shown in Fig. 15. In this case, each PV generator has a virtual admittance with a weight factor equal to 1.0, i.e., the total active and reactive power are equally shared among all PV generators. Prior to the power step, no power is delivered to the grid; therefore, the grid and the converter currents are equal to zero. This scenario changes when the active power reference increases to 6.4 kW. Fig. 15(a) shows the dynamic response of the active and reactive power, where it can be seen how the active power reaches its reference after 280 ms. The settling time is directly related to the inertia and damping factor defined in the central controller. In order to analyze the grid and the converter current waveforms in detail, a zoomed-in view of Fig. 15(a) is highlighted. Note that no reactive power is delivered into the grid; therefore, the grid voltage and current are synchronized. Fig. 15(d) demonstrates that the phase *a* of the converter currents is perfectly synchronized since all currents are controlled with the same load angle.

B. Power Converter Disconnection Under Unequal Power Sharing

In this experiment, PV generator 3 is suddenly disconnected, while the PV plant generates 5.6 kW. Fig. 16(a) shows the power delivered to the grid, where the active power registers a small perturbation due to the sudden converter disconnection. This perturbation is compensated after 200 ms, thus returning the active power to its reference. It is important to mention that there is enough power reserved to supply the missing power by converter 3.

The disconnection of the power converter is observed in the ac currents, as shown in Fig. 16(b). When the disconnection happens, the current i_{c3} decreases to zero, while the rest of

Fig. 15. Power, voltage, and current waveforms under an active power step. (a) Active and reactive power. (b) Grid voltage. (c) Grid current. (d) Converter current.

converters increase their current to supply the missing power. In Fig. 16(d), a finer detail of the converter currents indicates how they are redistributed according to the updated power sharing defined by the weight factor parameters. Note that how the converter currents i_{c1} and i_{c4} increase to the same level, while the current i_{c2} is smaller.

C. Grid Frequency Support

In this section, different inertia values are used to validate the power support under a frequency change. In order to recreate the same event presented in the simulation results, the experimental PV plant is connected to a microgrid formed by a 30-kVA SG, which is controlled through a variable speed drive to change the grid frequency following a rate of -0.4 Hz/s. In this test, the active power response is studied under three different values of inertia ($H = 1, 5$, and 7 s).

Fig. 17 shows how the active power generated by the PV plant increases as the grid frequency decreases. Prior to the grid frequency decrease, the plant generates 6.4 kW. The power increase is related to the inertia set in the central controller. As shown in Fig. 17(a), the higher the inertia value, the higher is the active power support. Once the grid frequency reaches its steady state at 49 Hz, the active power support provided by the inertia takes no more action, and thus, the power decreases. Note that the grid frequency support in the steady state is provided by the frequency droop as in the simulation results.

Fig. 16. Current and power waveform responses under different weight factors when inverter 3 is disconnected. (a) Active and reactive power. (b) Converter current. (c) Zoomed-in view of the grid current. (d) Zoomed-in view of the converter current.

Fig. 17. Active power response with different inertia values under a grid frequency variation. (a) Active power. (b) Grid frequency change.

VII. CONCLUSION

In this article, the SCAC intended for PVPP has been presented. This control strategy is capable of managing several PV generators as a single synchronous unit, thus providing grid support functionalities, such as inertia, damping, and frequency droop through the load angle and the EMF. The SCAC emulates the rotor behavior at the connection point with the electrical grid, while several virtual stators around it are emulated by several PV generator, thus giving rise to a coordinated synchronous action and an automatic power distribution.

The advantages of using the control proposed for PVPP has been discussed and proved. In addition, a testbench with four PV generators has been used to validate the effectiveness of the control proposed using the simulation and experimental results under power changes, converter disconnections, and grid frequency support. These scenarios validate the operation principle of the SCAC to provide a coordinated joint action between several PV converters at the plant level.

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