Design of Controller for Virtual Synchronous Power Plant

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Abstract—**The increasing participation of renewables in power systems has forced system operators to strengthen grid codes requiring renewable power plants (RPPs) to provide fast frequency support such as inertia response and power oscillation damping. To cope with such new requirements, this article proposes the implementation of a virtual synchronous power plant controller (VSPPC) for RPPs. The VSPPC takes the most from emulating the behavior of a synchronous generator, especially in the case of grid events, as it permits emulating inertia and provides power oscillation damping capabilities. If compared with conventional control schemes, the main advantage of the VSPPC lays in the fact that it does not require to implement any modification in the existing controllers of the plant's converters, which are often controlled as grid-following generation units. This feature makes VSPPC attractive for incorporating advanced grid supporting functionalities in utility-scale RPPs. In this work, the main principles behind the VSPPC and comparative analysis based on simulation and experimental results are provided to validate its performance.**

Index Terms—**Fast frequency support, grid-forming power converters, power electronic dominated power system, power plant controller, renewable power plant (RPP).**

I. INTRODUCTION

IN THE last decade, the installation of photovoltaics (PV) and wind power plants has experienced the greatest growth in Europe among renewable energy sources (RES) [1]. In 2010, RES shared 12.7% of the total energy consumption in Europe, while its target participation is set to 27% by 2030 [2]. Such a significant increase in the penetration of distributed generation units is forcing newly integrated renewable power plants (RPPs) to provide grid-supporting functionalities. Indeed, dynamic support has been recently required by system operators [3], [4].

The power system was designed to manage large centralized generation units so that their safe operation and reliability could be closely monitored and controlled in real-time [5], [6]. The increasing penetration of RES is presenting new control and operation challenges to the existing power systems, [7]. The main challenges of increasing the renewable penetration are the overwhelming amount of information that should be processed in real-time by the operators, and the reliability of the power electronics interfaced systems in parallel operation, as thousands of power converters would be trading energy with the grid simultaneously. In fact, it has been already reported that generation systems driven by power converters are affecting both the stability and the reliability of power systems [8], [9]. It does not matter if currently the disturbances introduced by distributed RES-based units are merely taken into account due to their small participation, as this is going to change in the near future, due to the rapid rise in RES integration and retirement of fossil-fueled power plants [10]. Therefore, there is a clear need for designing and operating utility-scale RPPs in a way that they contribute to the stability of power systems, in addition to balancing generation and demand [11], [12].

RPPs, especially PV and wind, are composed of grid-connected power converters whose control strategies play a crucial role [13]. Currently, the most commonly used control schemes for such power converters are mainly based on the grid-following mechanism [14]. In this operation mode power converters are controlled to deliver active and reactive power to the electrical grid. In addition, simple grid supporting functionalities such as frequency and voltage regulations can be easily implemented [15]. In an RPP, the converters are often connected in parallel at the point of common coupling (PCC) through step-up transformers. The additional impedance introduced by the transformers and cables makes it difficult not only to ensure a precise control in the delivered power but also to implement grid services. Furthermore, these converters may interact with each other giving rise to undesired dynamics [16]. Due to these limitations, renewable power plant controllers (RPPCs) are often used to take care of the overall control at the plant level [17].

In addition to the primary control services, e.g., frequency and voltage regulation, RPPs are now required to provide dynamic services such as inertia response and power oscillation damping [18]–[22]. In order to implement these newly required

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services, there are currently two approaches. The first approach is to replace grid-following power converters with grid-forming power converters, which may count on a virtual synchronous machine-based controller [23]. By using grid-forming power converters, each power converter can act as a synchronous generator to provide synthetic inertia and damping to the grid mainly controlling the current [24] or power reference [25]. The implementation using a grid-forming power converter has been demonstrated to be feasible for a single power converter [26], [27]. However, this approach might not be economically feasible for RPP, as replacing the control system of power converters requires additional development effort and resources. Moreover, the independent parallel operation of grid-forming power converters may give rise to power oscillation issues in the plant.

Nevertheless, such limitations faced by the use of grid-forming power converters can be addressed by the second approach in which the fast frequency services are implemented in the RPPC. This implementation permits using conventional grid-following power converters, which are widely used in RPP, minimizing hence development effort and cost. However, the development of dynamic services for RPPC has not been addressed properly. Among others, the work in [28] proposed a synchronous controller for a PV power plant, where the mechanical equation of a synchronous generator is embedded in the RPPC and the phase angle control and the electrical part, i.e., impedance equation is implemented in the inverter controller. Even though the system is able to regulate the phase angle of independent units in a coordinated approach, providing considerable good results, this solution needs the implementation of a grid-forming strategy in the local control, requiring thus an extensive work to adapt the control scheme of the inverter controllers (ICs), which in fact defeats its own purpose.

Furthermore, the local phase angle control is highly dependent on the point of connection of the converter, which does not necessary mean that each converter will exchange the same amount of energy with the grid. As an attempt to address the limitation of [28], a power plant controller is presented in [29]. In a brief way, the work in [29] shows the possibility to design a plant controller for delivering grid services without modifying the internal control of the power converters.

To address the limitations of previous works, this article proposes the implementation of a virtual synchronous power plant controller (VSPPC) for RPP. The proposed controller is designed to be used in plants driven by conventional grid-following power converters. In this proposal, by means of emulating the electromechanical and electromagnetic equations of a synchronous generator, the VSPPC allows RPP to provide fast frequency services to the grid. If compared to existing controllers, the VSPPC does not require to implement any modification at the inverter's controllers which is advantageous in terms of implementation and installation cost. For validation purposes, the comparative analysis and experimental results are provided.

II. Control of Renewable Power Plant

The control of renewable plants such as wind and PV is focused on maximizing energy production. As more utility-scale RPPs are installed, it becomes essential to actively control their output power not only to meet power set-points but also to support the grid in regulation and operation [30]. Therefore, to achieve such control goals, the control structure of an RPP often consists of ICs and an RPPC as shown in Fig. 1. The ICs are responsible for controlling the current and power injected by the power converter under generic conditions. There are various implementations for the ICs. However the most extended is the one where the ICs are based on the combination of a current controller, a power controller, and a synchronization unit as shown in Fig. 2 [31]. As it can be seen in Figs. 1 and 2, the ICs only control the power of the grid-connected inverters considering the measurements at the output. Therefore, the accuracy of the power delivered at the PCC cannot be guaranteed by only using ICs, due to the effect of the impedance between the inverter and the PCC.

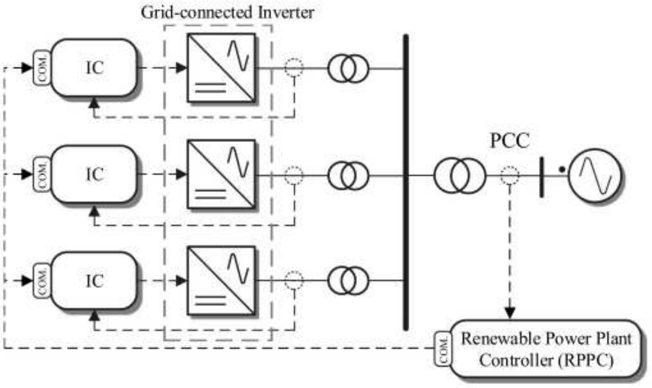


Fig. 1. Simplified control system of an RPP.

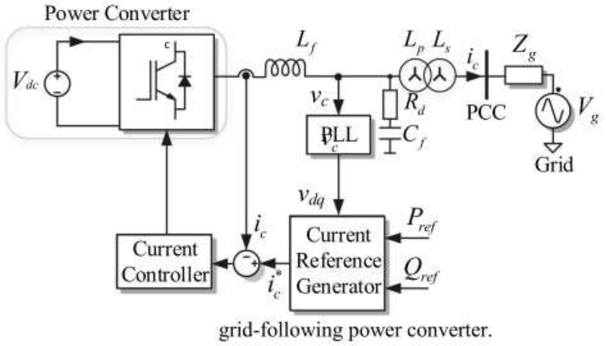


Fig. 2. Control scheme of a grid-following power converter.

The RPPC is used to ensure a proper control of the power delivered by the entire plant. The RPPC takes measurements from the PCC to generate control outputs, which are the references for the ICs. Due to the fact that the RPPC is located physically away from the power converter, communications are used to transfer power references from the RPPC to each IC. Moreover, grid services such as voltage control, reactive power control, frequency control, and power factor control can be implemented in the RPPC [32]. These primary services aim to support the grid mainly during the steady-state operation.

As the penetration of renewables increase, RPPs are required to provide fast frequency response in addition to primary regulation services. In order to comply with this requirement using

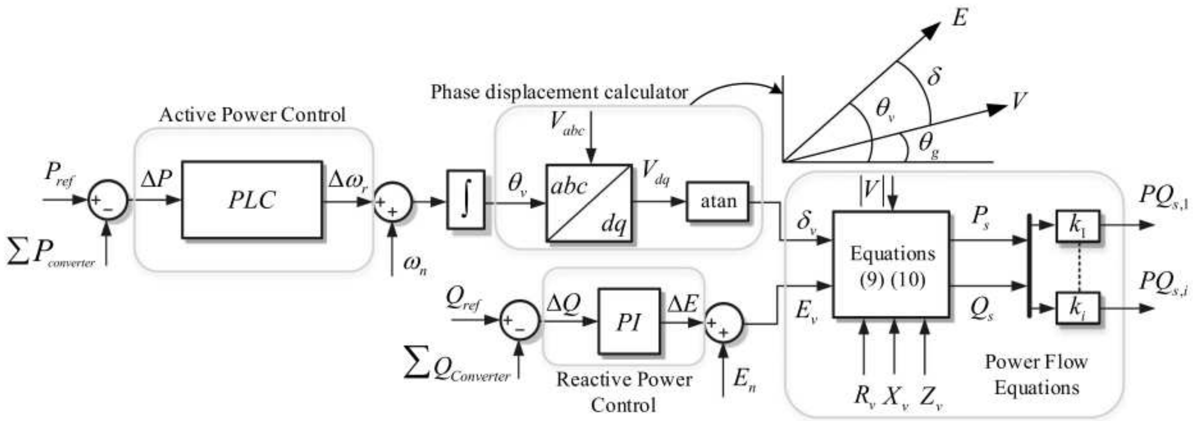


Fig. 3. Control block diagram of the proposed VSPPC.

grid-forming power converters have been proposed [26]. Grid-forming power converters, which are often based on the virtual synchronous machine concept, provide a natural interaction with the electrical grid thanks to their power synchronization mechanism. This feature allows them to provide dynamic frequency and voltage regulation.

In spite of the good behavior of grid-forming control in applications with a single power converter, or with few of them working in parallel, its adaptation to an RPP where thousands of power converters are interconnected is not straightforward. This is due to the fact that each grid-forming power converter reacts to the voltage at their point of connection. Due to the difference in line impedances, such voltages might differ significantly in different points of the plant, and hence power oscillations may appear between power converters.

III. VIRTUAL SYNCHRONOUS POWER PLANT CONTROLLER

To cope with new grid codes from a practical perspective, this article proposes the implementation of a virtual synchronous power controller (VSPPC) for RPP. The main idea behind the VSPPC is the use of a central controller to control the whole plant in a way that replicates the dynamic behavior of a synchronous generator.

This implementation enables VSPPC not only to support the grid but also to provide dynamic services such as inertia emulation and power oscillation damping.

Fig. 3 shows the control block diagram of the VSPPC, which is composed of four main control blocks: a power loop controller (PLC) [33], a reactive power controller [8], a phase displacement calculator, and a power reference generator. The inputs for the VSPPC are the measured voltage and power at the PCC, while the outputs are the power references for the power converters. It is worth noting that providing power references at the output permits the VSPPC to work with conventional grid-following power converters, the most extended ones in an RPP.

To emulate the dynamics of a synchronous generator there are two main blocks to be considered. The first one is the mechanical part, which is often presented by a swing equation. In the VSPPC, the mechanical part is presented by the active power controller using the following transfer function

$$G_P(s) = \frac{\Delta\omega}{\Delta P} = \frac{G_c}{s+\omega_c} \tag{1}$$

where gain G_c and cut-off frequency ω_c are defined as

$$\omega_c = \frac{2 \cdot D}{\sqrt{\frac{X_v}{S_n} J \cdot \omega_g}} \tag{2}$$

and

$$G_c = \frac{1}{J \cdot \omega_c \cdot \omega_g}. \tag{3}$$

In these equations, S_n is the rated total power of all sources, ω_g is the nominal grid frequency, and X_v is a virtual impedance. The inertia and damping of the VSPPC can be set through J and D , respectively.

The output of the active power controller $\Delta\omega$, after being added with nominal grid frequency, is integrated to obtain the phase angle of the synchronous phase angle of the VSPPC

$$\theta_v = \int \Delta\omega_r + \omega_n. \tag{4}$$

The use of this phase angle to transform the grid voltage, from the stationary reference frame into the synchronous reference frame, gives rise the voltage difference component between both phases in the *dq* frame

$$\begin{bmatrix} V_d \\ V_q \\ 0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \cos(\theta_v) & \cos(\theta_v) & \cos(\theta_v) \\ -\sin(\theta_v) & -\sin(\theta_v) & -\sin(\theta_v) \\ {}^{1}\!/\!\sqrt{2} & {}^{1}\!/\!\sqrt{2} & {}^{1}\!/\!\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{5}$$

where the phase displacement δ can be obtained by using the arctangent function, obtaining the angle from the trigonometric *dq* components as

$$\delta_v = \operatorname{atan}\left(\frac{V_q}{V_d}\right). \tag{6}$$

In addition to the active power, the reactive power can be also controlled by the VSPPC by mean of the reactive power controller whose transfer function is

$$G_q(s) = \frac{\Delta E}{Q^* - Q_m} = \frac{K_p \cdot s + K_i}{s} \tag{7}$$

where k_p and k_i are the proportional and integral gains respectively. In this equation ΔE is the change in the electromotive force and Q^* and Q_m are the reference and measured reactive power respectively. The reactive power controller can be used for voltage supporting services. From (6), the magnitude of the virtual emf can be calculated as

$$E_v = E_n + \Delta E \tag{8}$$

where E_n is the desired nominal voltage, and ΔE is the variation to regulate the reactive power. From (4) and (8), θ_v and E_v can be given as a reference to the power converter as shown in [28]. However, this approach is not practically feasible, mainly because most commercial power converters usually accept only active and reactive powers as references. In order to provide power references to the power converters, the well-known power flow equation are considered. By means of them, the power that should be delivered by the plant can be found as follows:

$$P_s = \frac{V_{\mathrm{PCC}}}{R_v^2 + X_v^2} \left[R_v \left(V_{\mathrm{PCC}} - E_v \cos\left(\delta_v\right) \right) + X_v E_v \sin\left(\delta_v\right) \right] \tag{9}$$

$$\begin{aligned} &Q_s \\ &= \frac{V_{\mathrm{PCC}}}{R_v^2 + X_v^2} \left[-R_v E_v \sin\left(\delta_v\right) + X_v \left(V_{\mathrm{PCC}} - E_v \cos\left(\delta_v\right) \right) \right] \end{aligned} \tag{10}$$

where R_v and X_v are the virtual resistance and reactance, respectively.

The advantage of emulating impedance at the plant level is that the dynamic response of all power converters is controlled with respect to the PCC regardless of the local line impedances, thus eliminating interconverter oscillations.

To share the active and reactive power between power converters, proportional gains k_{pi} and k_{qi} are employed, acting as weights to distribute power delivery duties. A simple way to set these gains for each converter is to use the ratio between the nominal power of the converter and the nominal power of the plant, as written in (11)

$$k_{\mathrm{pi}} = k_{\mathrm{qi}} = \frac{S_i}{\sum_{i=1}^{N} S_i} \tag{11}$$

where *S* denotes nominal power and *N* is the number of power converters. As the composition of the power plant may differ in power unit's nominal capacity, this distribution gain allows to set a percentage equivalent weight based on the nominal power of the unit.

IV. PERFORMANCE ANALYSES

One of the main advantages of the VSPPC is the implementation of the virtual admittance at the plant level, which allows unifying the dynamic response of RPP. To further illustrate the advantages of the VSPPC, this section compares the performance of VSPPC and a conventional control scheme. The parameters of the system are described in Tables I and II. It should be noted that these parameters are used as they match the ones of the experimental setup. For comparison purposes, two control schemes are considered. Fig. 4(a) describes the conventional control scheme where each power converter is equipped with an synchronous power controller (SPC)-based grid-forming controller. Likewise, Fig. 4(b) illustrates the configuration for the proposed VSPPC where grid-following power converters are employed together with the proposed VSPPC. Fig. 5 shows the simulation results of the two control schemes depicted in Fig. 4 under a phase shift event in the grid voltage. It can be seen from Fig. 5(a) that the dynamics of the active power of the power converters considerably differ from each other resulting in oscillations between the power converters. This internal oscillation leads to a reduction of the equivalent damping factor and inertia constant of the whole power plant, affecting the response of the RPP during frequency events at the PCC. In fact, the active power measured at the PCC resembles a second-order system rather than an inertia response. These undesired dynamics obtained with the conventional control scheme is due to the different line impedances that each converter has with respect to the PCC, mainly due to the different line lengths. As the power converters can only sense the voltage at the PCC, the line impedance between the converters and the PCC plays an important role in the final response of the converter. On the other hand, in the case of the proposed VSPPC shown in

TABLE I
PARAMETERS OF THE POWER CONVERTER

Symbol	Quantity	Values
P	Converter nominal power	2kW
L_f	Inverter-side inductance	5mH
C_f	Capacitance	5μF
R_d	Damping resistance	1Ω
L_p+L_s	Grid-side inductor	2mH
Z_L	Additional inductor	0.0942Ω
Z_g	Grid impedance	1,57Ω
P_{dc}	DC source nominal power	20kW
V_{dc}	DC nominal voltage	750V

TABLE II
PARAMETERS OF THE PLANT CONTROLLER

Symbol	Quantity	Values
S_n	Nominal power	8kVA
V_n	Nominal voltage	400V
f_n	Power plant nominal frequency	314.15 rad/s
H	Power plant inertia factor	5
ξ	Power plant damping factor	0.7
R_v	Power plant virtual resistor	2Ω
X_v	Power plant virtual reactance	6Ω
k_{pQ}	Reactive power proportional gain	1e-6
k_{iQ}	Reactive power integral gain	1e-6

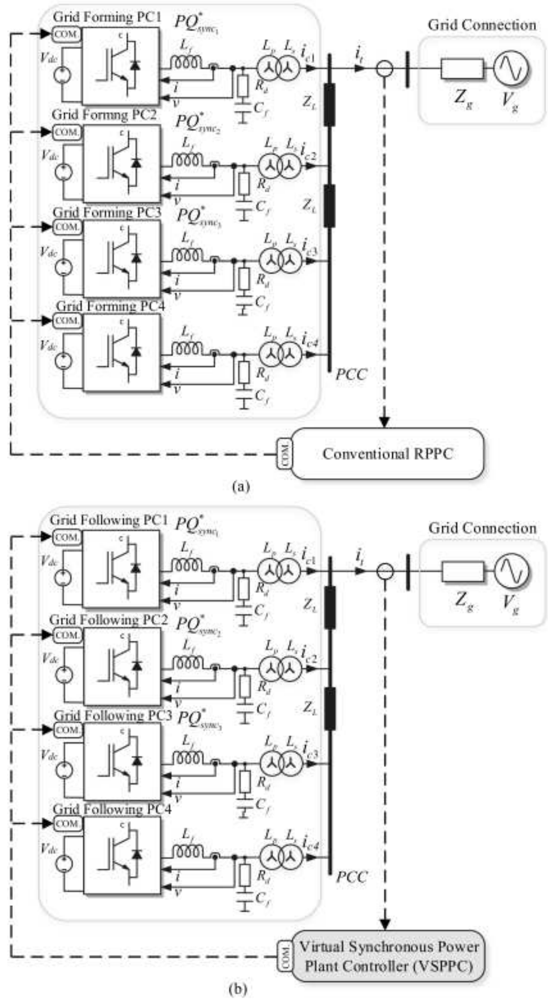


Fig. 4. Setups for performance comparison. (a) Using grid-forming power converters working independently. (b) Using the proposed VSPPC.

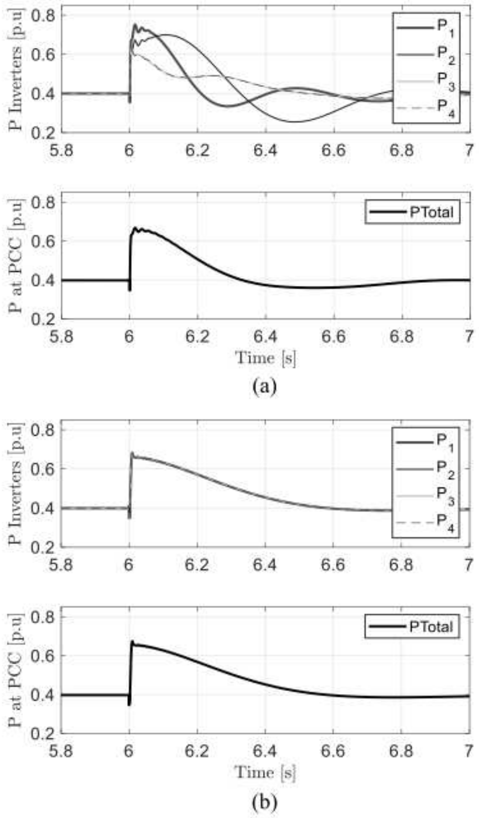


Fig. 5. Control performance of (a) the conventional control scheme and (b) proposed VSPPC.

Fig. 5, as the virtual admittance is implemented in the RPPC, the effect of line impedance can be removed. Thus, an equal power-sharing between the power converters can be achieved. As a consequence, the active power at the PCC exhibits the inertia-like response in active power.

The aforementioned observation can be confirmed by analyzing the pole-zero maps depicted in Fig. 6, which has been obtained by using the parameters of Table I, for the electrical system and Table II for tuning the controllers. It can be easily seen that there are three pairs of complex poles in the case of the conventional control scheme. Even though the parameters for the SPC embedded in the ICs are identical, the different line impedance causes the poles to move away from each other. In contrast, the VSPPC implements only one mechanical equation for the whole plant therefore has only one pair of complex poles. Therefore, undesired oscillations can be avoided.

V. EXPERIMENTAL RESULTS

To practically validate the proposed VSPPC, a set experiments have been carried out in a workbench in the lab. The RPP, as shown in Fig. 4, consists of four power converters (Danfoss: FC-302P2K2T5E20H1), which are controlled by digital controllers based on a microcontroller TMS320C28335. The dc-link voltage is provided by a 20 kW dc voltage source (MagnaPower: TSD1000-20). The converters are connected to the grid through a 30 kVA transformer. A picture of the experimental setup is shown in Fig. 7. As in the case of the inverter, the RPPC is implemented in a control board based on a TMS320C28335 DSP which communicates with each IC via CAN communication at 125 kps. The system parameters are listed in Tables I and II.

Using the previously described system, the following experiments have been carried out.

1) A step-change in power reference to verify the dynamic response of the VSPPC.
2) Connection and disconnection of a power converter to validate the robustness of the VSPPC under unplanned events in the RPP.
3) Connection of a synchronous generator to analyze the damping capacity of the VSPPC.
4) Load connection at the PCC to compare the performance of a conventional controller and the VSPPC under a grid event.

A. Performance in Front of Power Changes

Fig. 8 shows the experimental results of the proposed VSPPC under a step-change in the active power reference. It can be seen that the active power measured at the PCC exhibits a stable

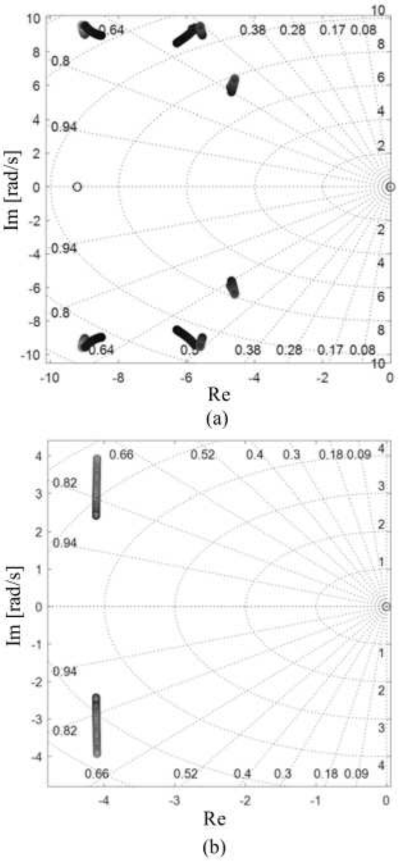


Fig. 6. Pole-zero maps for different value of short circuit ratio of (a) the conventional controller and (b) the proposed VSPPC.

dynamic, outperforming the one of a synchronous generator. This is accomplished by the damping coefficient, that can be tuned specifically to the desired performance, and the virtual resistor which provides additional electrical damping without increasing power losses. Regardless of the difference in the line impedance, the three power converter shares active power equally. In addition to the overall dynamics, the zoomed-in waveforms also confirm the good quality of the injected currents of each power converter.

B. Connection and Disconnection of Generation Units With the VSPPC

Figs. 9 and 10 show the experimental response of RPP with VSPPC in the event of disconnection and connection a power converter. The experiments start with a constant injection of active power which is shared equally between the converters. At around 0.0431 s, a power converter unit is disconnected/connected from/to the RPP. The disconnection and connection of a generation unit, in this case the inverters, give rise to a transient mismatch between generation and consumption at the PCC that should be corrected. As soon as the VSPPC detects the mismatch in measured and reference power, it tries to regulate the power such that the reference powers are always tracked in the steady-state. The dynamic performance of the active power is mainly due to the inertia of the VSPPC. It is confirmed from these figures that the VSPPC can handle properly the disconnection and reconnection of a power converter.

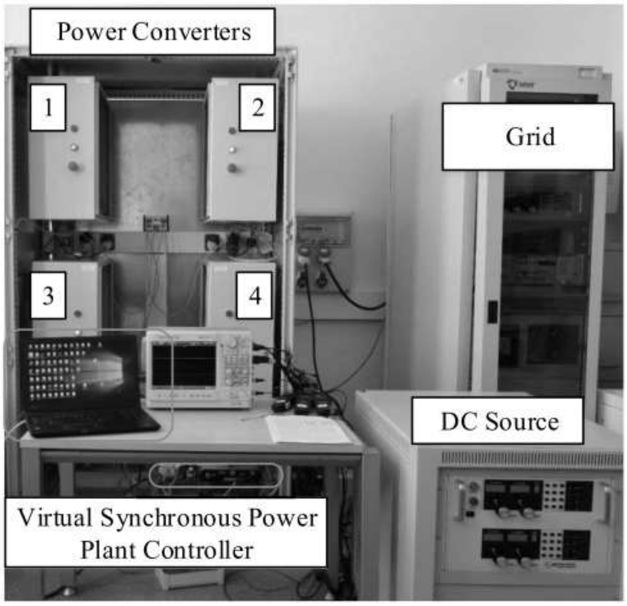


Fig. 7. Experimental setup.

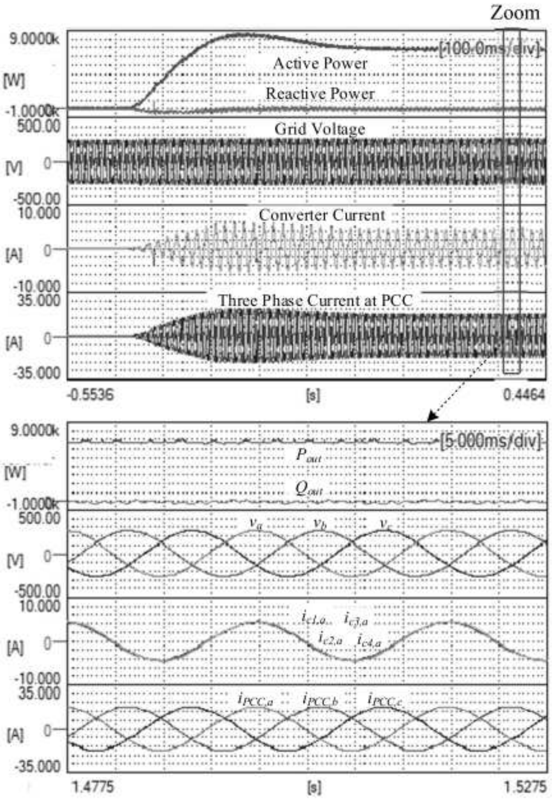


Fig. 8. Response of the RPP with VSPPC under a step change in reference power.

C. Power Oscillation Damping With the VSPPC

To illustrate the damping capability of the proposed VSPPC, a 20 kVA synchronous generator, which is naturally underdamped,

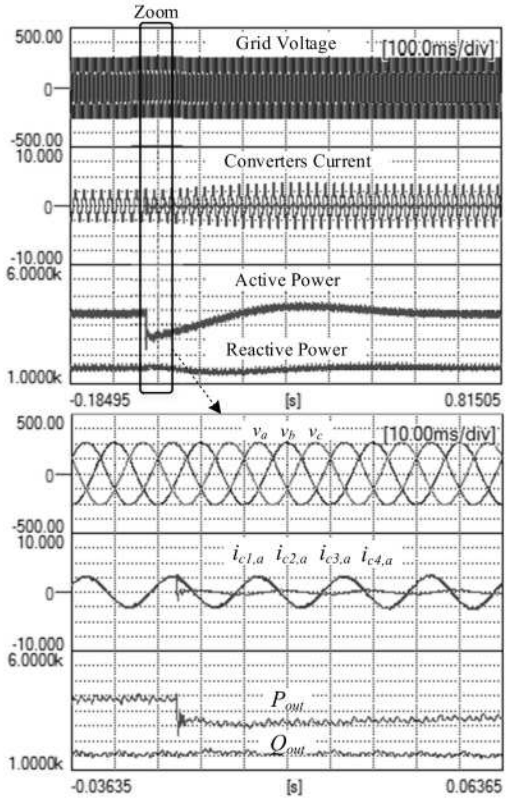


Fig. 9. Experimental response of the VSPPC to disconnection of one power converter.

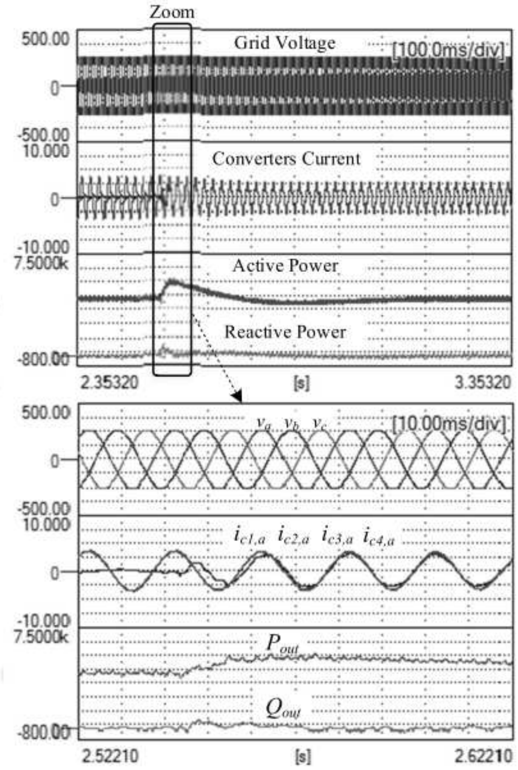
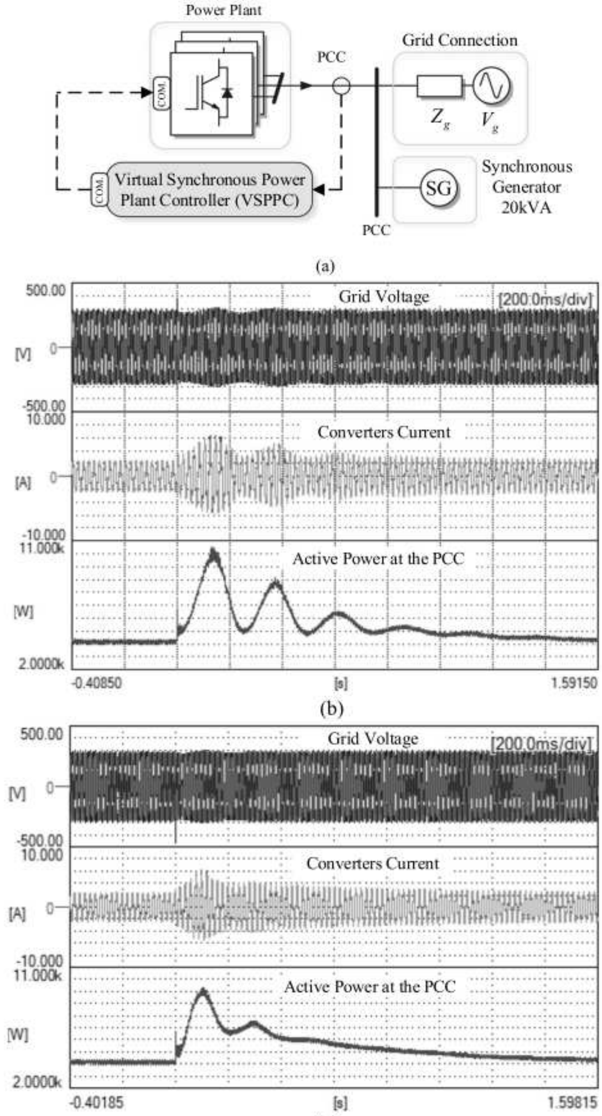


Fig. 10. Experimental response of the VSPPC to connection of one power converter.



(c)

Fig. 11. Damping performance of the VSPPC. (a) System configuration. (b) VSPPC with $G_c = 4.796e^{-4}$ and $\omega_c = 8.186$. (c) VSPPC with $G_c = 2.741e^{-4}$ and $\omega_c = 14.326$.

is connected at the PCC as shown in Fig. 11(a). Two test cases are considered for different damping of the VSPPC. In the first case, as shown in Fig. 11(b), due to the low damping of the VSPPC and the synchronous generator, the active power measured at the PCC is highly oscillatory. As the damping of the VSPPC is increased, the power oscillation at the PCC is significantly attenuated as it can be observed from Fig. 11(c). This result suggests that not only VSPPC provides additional damping to power oscillation but also its damping factor can be adjusted easily through G_c and ω_c.

D. Frequency Support With the VSPPC

Fig. 12 shows the comparison results for the conventional controller and the proposed VSPPC under a load step. It is shown that, in both cases, the power converters try to inject active power

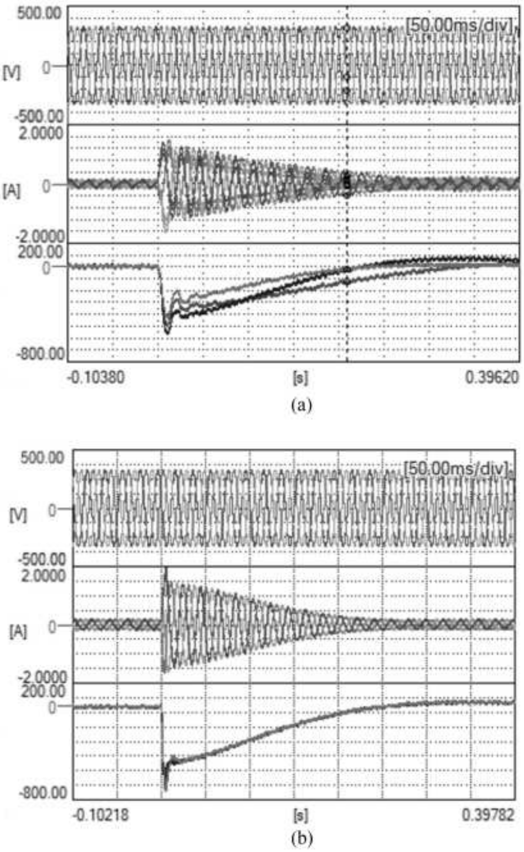


Fig. 12. Experimental results of RPP under a load step with (a) the conventional controller corresponding to Fig. 4(a), and (b) the VSPPC corresponding to Fig. 4(b).

in order to support the grid. Such response implies that both control schemes provide inertia to the grid, of course scaled to the power of the plant. However, as stated earlier, the response of the conventional controller is not preferable considering unequal power sharing. On the other hand, in the case of VSPPC, almost identical responses of the power converters can be observed. It is reasonable to conclude that the VSPPC offers better dynamic performance, as it requires no modifications in the ICs, which make the VSPPC an attractive solution for RPPC.

VI. CONCLUSION

In this article, the VSPPC was proposed as a good solution to be used in RPP for providing required grid supporting functionalities, mainly inertia response and power oscillation damping. The proposed VSPPC, which is primarily based on the well-known synchronous power controller with key characteristics of a synchronous generator, is emulated in the control loop. However, in this VSPPC, in addition to the motion equation and the virtual impedance, power flow equations are also included in the VSPPC to convert angle references to power references. The advantage of having these outputs in a form of active and reactive power setpoints is twofold. The most important one lays on the fact that the VSPPC is compatible with most power converters used nowadays in RPP, so no new modern converters are required to upgrade the performance of the plant. In addition, the protection algorithm can be easily implemented.

In this work it has been proven that the aggregation of grid-forming converters, does not provide overall an optimal performance in the plant. One of the most relevant contributions of the VSPPC is its capability to control the synchronous mechanical performance of the plant aggregating all the power. In this way power oscillation damping functionalities are boosted and a better dynamic performance is achieved. The simulation and experimental results demonstrated that the VSPPC offers not only fast frequency services but also better control performance.

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