Over-frequency support in large-scale photovoltaic power plants using non-conventional control architectures

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Abstract

Large scale photovoltaic power plants must provide a frequency regulation service, which is defined in the grid codes. This service has commonly required a response time between 15-30 seconds. But some countries are now introducing more strict regulations and requiring response times below 2 seconds. The typical centralized control architecture of photovoltaic power plants for frequency regulation can present undesired oscillatory responses (or even become unstable) when tuning the controller to achieve these small time response requirements. The present article proposes an alternative solution based on a hierarchical control architecture. In the proposed solution, inverter controllers apply a local frequency regulation action and the central controller corrects active power errors at the point of connection, which can be caused by power losses or lack of irradiance in some inverters. Simulation models are used to study and test the response of this new control approach. The proposed hierarchical control architecture is compared with a fully centralized and a fully decentralized archirectures. Results show that the hierarchical control architecture is not only capable to obtain a fast and accurate response, but also is robust against communication failures. The proposed hierarchical control architecture advantages could be extrapolated to other services. So, further research is proposed to confirm this hypothesis.

Keywords: PV power plant, grid code, control architecture, frequency, frequency regulation

Introduction

Large-scale photovoltaic power plants[1] (LS-PVPPs) must include a control system to fulfill the interconnection requirements specified by the transmission system operators (TSOs). These requirements, defined in the so-called grid codes, usually specify a set of grid services that LS-PVPPs must provide [3]. As more and more non-synchronous wind and solar power plants are being interconnected to the grid, frequency control becomes more crucial and complex [4], specially in small regions such as islands with weak interconnection [5]. Accordingly, primary frequency regulation requirements are commonly found in the grid codes. These

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[1] Despite there is not a clear definition about what is considered a LS-PVPPs, it is well accepted that they are power plants from several MW to GW scale [1]. For example, the National Renewable Energy Laboratory (NREL) sets the threshold at 5 MW [2].

requirements, are tipically based on a droop characteristic where the active power have to be increased or reduced based on the grid frequency as shown in Figure 1. A number of countries are already considering specific frequency regulation requirements for LS-PVPPs [6, 7, 8, 9, 10, 11]. In Europe, ENTSO-E defines a grid code called Requirements for Grid Connection of Generators, where frequency support is defined according to the size of the power plant [7]. LS-PVPPs can be included as type C and D power-generating modules (minimum size of 5 and 10 MW respectively). Typically, the primary frequency regulation service has required a response time between 15 and 30 seconds [6, 7, 8, 9, 10, 11]. But now, several countries such as UK, Ireland or Australia are starting to introduce a new service that, despite having different names, refers to the same concept, i.e. fast frequency response, in which the regulation must respond between 0.5 and 2 seconds [5, 12].

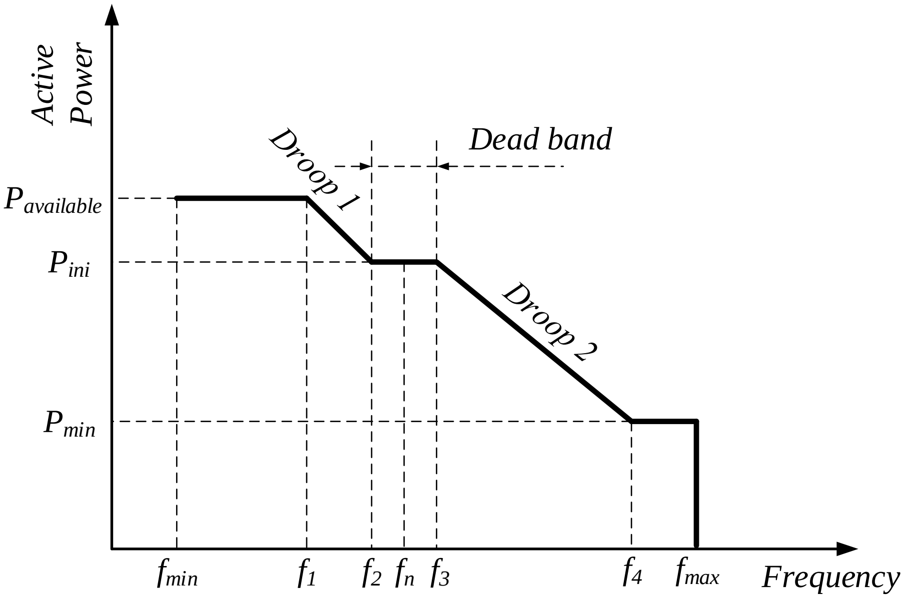


Figure 1: General scheme of a frequency droop characteristic

The control of LS-PVPPs has traditionally been designed in a centralized structure [13, 14]. While this centralized architecture has been effective during the last years, it can present several limitations in terms of time response [15, 16]. In [15], a detailed dynamic analysis of a LS-PVPP with a central control architecture has been conducted concluding that tunning the controller to obtain a response time of 1-2 seconds at the point of interconnection can present undesired oscillatory modes, even if the inverter power response is very fast, i.e. 100 ms. In [16] a typical centralized frequency control implementation is presented and challenges in terms of time response are explained, which are typically between 3 to 10 seconds. The study done in [16] achieves a total response time of 2 seconds using a centralized approach.

Considering i) this new service that has been recenlty introduced in some grid codes requires a time response of less than 2 seconds and ii) the limitations found in [15] and [16] for controlling the active power in a time scale of less than 2 seconds using fully central controllers, alternative solutions to the centralized control architecture can be explored. In addition, the centralized control relies on a communication network that must function continuously. Although the complete or partial loss of communications is a rare event, its huge impact in centralized architectures may lead to malfunction of the LS-PVPPs [17]. This also motivates the need to explore alternative control architectures.

Different control architectures can be implemented in power systems, but as explained, in LS-PVPPs mainly the centralized approach has been considered. In the field of microgrids, three control architectures have commonly been considered, namely centralized, decentralized and distributed [18, 19]. In the centralized architecture, as in LSPVPPs, all the information is collected in a central unit, where the setpoints are processed and sent back to each controllable device using direct communication links. In the decentralized approach, each unit perfoms its local control without a direct communication link but using the power lines to communicate by varying the voltage and frequency. Finally, the distributed approach includes communication links between controllable units but lacks of a central controller. According to [18], centralized approaches require high computational efforts and communication needs while a fully decentralized architecture does not offer a proper coordination level (this is important in LS-PVPPs to comply with the grid code requirements at the point of common coupling, PCC). Thus, despite the distributed control architecture could be a solution, a hierarchical approach combining the centralized and decentralized architectures is the most common solution [20, 21].

In this context, the present paper proposes a novel control architecture for LS-PVPPs based on a hierarchical control approach to provide over-frequency regulation. This alternative LS-PVPP control architecture aims to face the previous described challenges for the over-frequency support service. Thus, the present study contributes to i) introduce the concept of hierarchical control architectures in LS-PVPPs as a reliable option and to ii) analyze and compare the proposed hierarchical architecture with the traditional and decentralized options for over-frequency regulation.

Proposed control architecture for over-frequency support

State of the art: Current photovoltaic (PV) plant control architecture

Figure 2 shows a general scheme of the centralized control architecture, which is an industry standard for LS-PVPPs. In such power plants tens or hundreds of PV arrays with a rated power from 100 kW to 2 MW are interconnected, through PV inverters and 3-winding transformers, to an internal Medium Voltage (MV) AC network called collection grid. The main transmission network is connected to the collection grid through a main feeder and a High Voltage - Medium Voltage (HV-MV) transformer. Grid codes specify services to be provided at the point of connection with the transmission network, which is called point of common coupling (PCC). Therefore, a coordination between PV inverters is required. This is achieved with local controllers in the inverters that follow active and reactive power setpoints and a central controller that monitors and controls the power exchange at the PCC. [22].

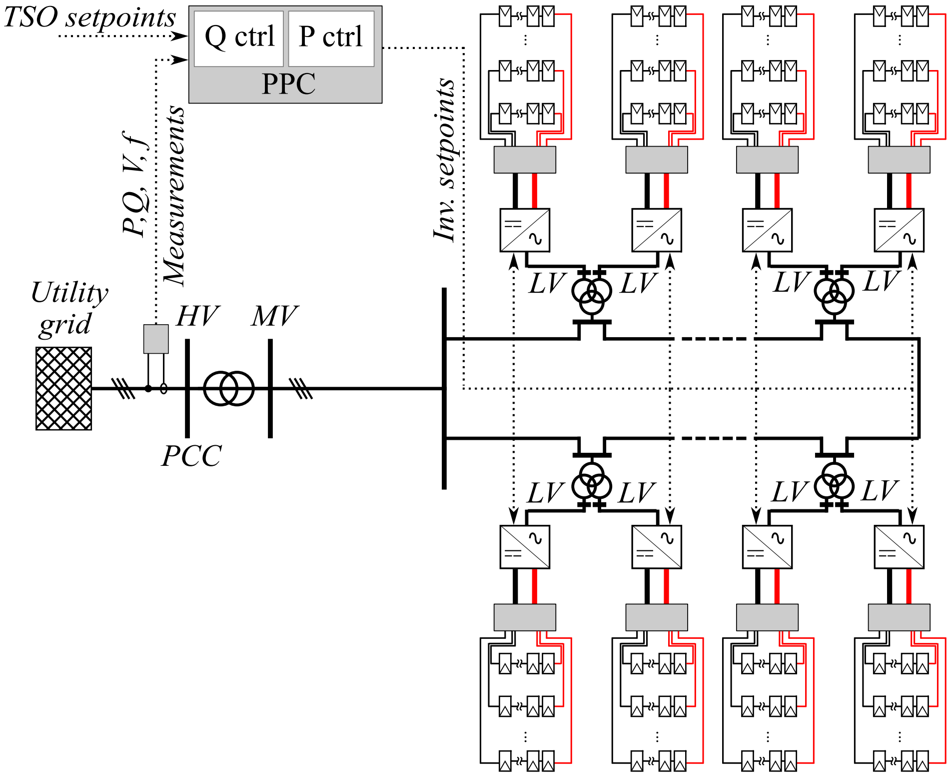


Figure 2: General scheme of a typical LS-PVPP

The central controller first computes the required setpoints at the PCC, P^*_{PCC} and Q^*_{PCC}, according to the TSO requested grid code requirements. Then, these setpoints are compared with the power measurements at the PCC, P_{PCC} and Q_{PCC} [13], and a PI controller computes the aggregated setpoint that is sent to the PV inverters, P^*_{tot}. As the rated power of the LS-PVPP is different to the rated power of PV inverters, and PV inverters can also have different power rating, a dispatcher is in charge of transforming this P^*_{tot} to a p.u. system, dividing the aggegated setpoint by the nominal power of the PV plant (P_N) and sending this signal ($P^*_{INV}[p.u]$) to all the PV inverters.

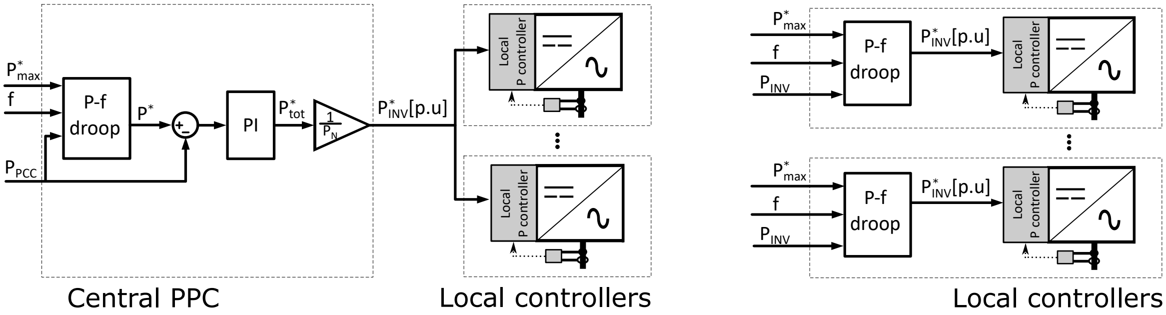
Over-frequency regulation is the service of interest in this study, which results in a reduction of the total active power generated. Figure 3a shows the general schematic of a centralized architecture for this service. As can be seen, the frequency control is implemented at the PPC while the inverters only receive power reference signals from the central controller. The P-f droop block represents the implementation of the P-f droop characteristic (see Figure 1) according to grid code requirements. The power reference P^* is equal to a power curtailment reference P^*_{max} from the TSO if the frequency control is not active, i.e. the frequency is within the deadband of the P-f droop characteristic. When the frequency control is active, i.e. the frequency exceeds the deadband, P^* is calculated based on the P-f characteristic and considering P^*_{max} and the measured power P_{PCC} and frequency.

The communication network between the central controller and the inverters is essential to ensure a proper operation. In case of communication failure, the plant would be forced to operate blindly, which could result in a breach of the grid code. In addition, a fast response of the frequency control mode is required when a destabilizing event in the grid is detected. Thus, pressure to reduce the response time of the PV plant is increasing. However, the communication network has inherent delays as well as two cascaded PI controllers (the central PI controller plus the local PI controller) that might interact, which can become a limiting factor to reduce the response time.

In addition, a decentralized control architecture can be considered in LS-PVPPs to reduce the response time. The decentralized control architecture can be found in microgrid applications, but is less common in LS-PVPPs, where it is mainly used for controlling fast current injection during faults that requires a response in the range of hundreds of milliseconds [23]. The decentralized architecture is based on separated local controls at inverter level. System operation only requires the inverter's local measurements and TSO setpoints. Figure 3b shows the over-frequency regulation based on a decentralized architecture. The frequency droop characteristic is implemented at each PV inverter, based on their local measurements. In particular the inverter power reference P^*_{INV} is the output of the P-f droop block. Thus, the output active power setpoint is controlled through the active power controller of the PV inverter and the effect of cascaded PI controllers is avoided. Communication requirements are minimal for this architecture, which results in a reliable option. Also, faster responses are achieved when a change of the setpoint is detected. However, measurements at the PCC are not included in the control system. This lack of information results in a low performance of the plant, as neither power losses nor power deviations caused by the loss of an inverter or the reduction of irradiance (e.g. due to a cloud) are corrected. This blind operation leads to a power injection below the maximum allowed value and might result in a mismatch with grid code requirements.

Proposed hierarchical control architecture for over-frequency support

Thus, the present paper proposes a hierarchical control architecture to take the advantages of both, the centralized and decentralized approaches. The scheme of this proposed hierarchical control architecture for over-frequency support is shown in Figure 4. In this scheme, each local inverter controller provides a power reference $P^*_{INV,0}[p.u]$, which is calculated considering the P-f droop characteristics and the power



(a) Centralized control architecture

(b) Decentralized control architecture

Figure 3: Existing control architectures for over-frequency regulation.

curtailment reference P^*_{max}. Also, the central controller corrects the errors at the PCC with a compensation power reference $\Delta P^*_{INV}[p.u]$. Then, the main control is performed by local controllers at inverter level, but it is supported by a central controller. As the control function is performed locally, communication delays as well as the effect of having cascaded PI controllers are avoided. Thus, a fast response is achieved. The central control will have the same dynamics as in a central control architecture, but only applied to the errors caused by the decentralized control architecture (by the local controllers). In particular, the central controller monitors the PCC, receives TSO setpoints and compensates any control function mismatch caused by internal PV plant power losses or by external events, such as loss of an inverter or reduction of irradiance (e.g. due to a cloud). This is done thanks to a central PI controller. By implementing this additional closed loop of control, the PV plant output can be maximized to the desired value. In case of central communication network failure, the local controls of the hierarchical structure ensure that the PV plant can keep operation. Commercial inverters are not yet prepared to receive a $\Delta P^*_{INV}[p.u]$. as an action of control. Modifications of the actual inverters would be required to implement this non-conventional control architecture. Nevertheless, the potential advantages of this proposed architectures will be shown in this paper through a set of simulations.

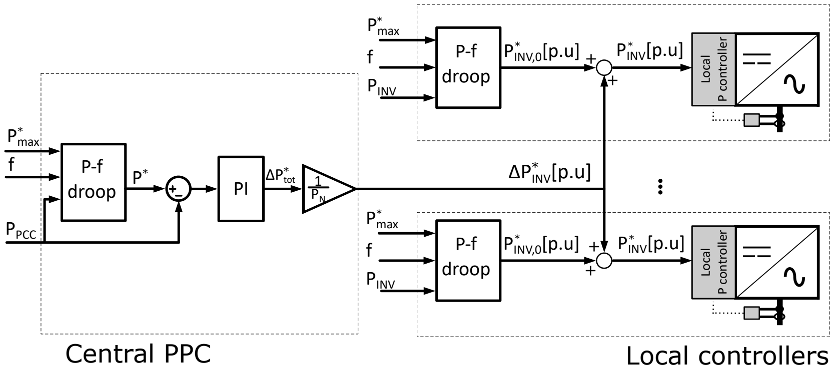


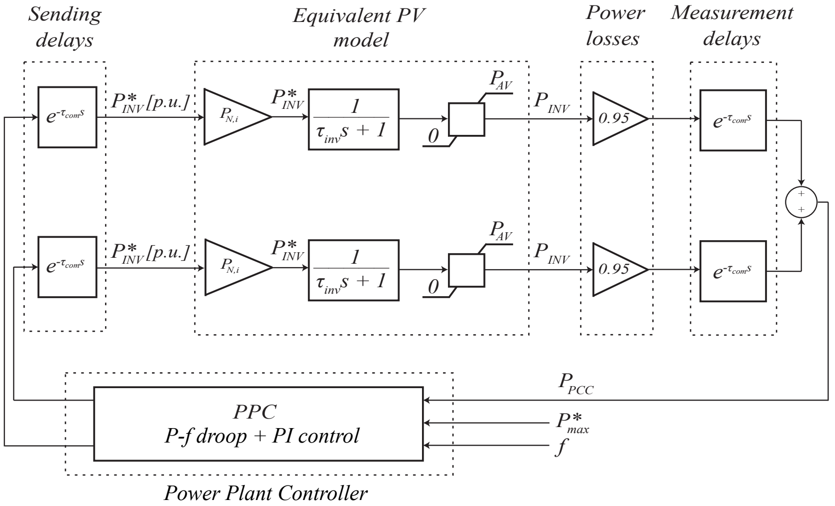
Figure 4: Proposed hierarchical control architecture for over-frequency regulation

Validation of the control architecture

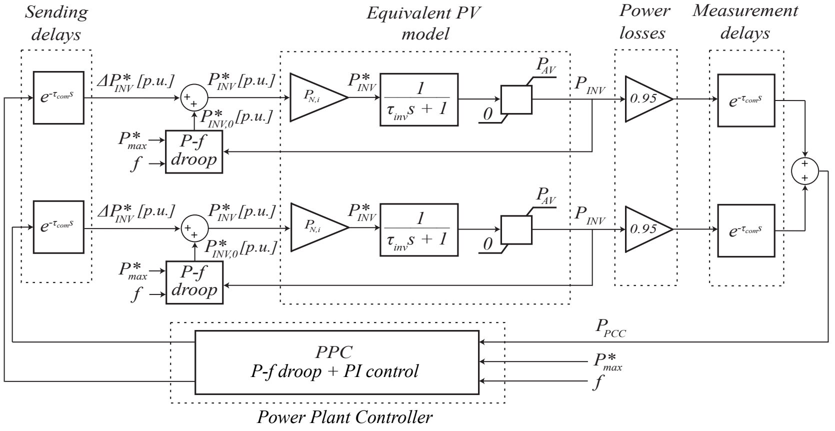
Case study

The performance of the centralized, decentralized and the proposed hierarchical control architectures are validated employing a common PV plant model. This is based on a LS-PVPP with 20 PV arrays of 1 MW including their associated converters. Then, the model is simplified as 2 PV arrays and 2 converters, where each one represents the aggregation of 10 PV arrays with a total of 10 MW. Figure 5 shows the simplified model with the centralized and hierarchical architectures. The decentralized architecture is not shown since is based on the same model as the hierarchical architecture without the PPC. In the centralized control the power reference of the inverter model is the output of the PPC after the sending delays, $P^*_{INV}[p.u]$, while in the hierarchical control is the sum of the local inverter reference, $P^*_{INV,0}[p.u]$, and a correction from the central controller, $\Delta P^*_{INV}[p.u]$. In both cases, the output of the inverter model is the active power generated by the inverter, P_{INV}. The inverters are represented as a first order function, with the output saturated by the available power [24]. This available power have been obtained by i) downloading irradiance data at 1 Hz resolution, corresponding to Oahu, Hawaii, from the National Renewable Energy Laboratory (NREL's) database [25], ii) converting the irradiance data to available active power generation using the model developed in [26], where a high accuracy have been obtained and iii) applying a delay between each converter profile to simulate the effect of clouds passing above the PV plant. The parameters of this case study are shown in Table 1, where τ_{PPC} refers to the sample time of the central controller, τ_{com} is the communication delay or the sending delay as shown in Figure 5 (it is defined constant in this paper), τ_{inv} is the time constant of the inverter response (first order function) and the rest of the parameters are the P-f droop characteristics. Also, the losses are modelled as a 5% of the generated power P_{INV}.

All the simulations show the PV plant operating under curtailment mode when an over-frequency event is detected. This event activates the frequency controller following the P-f droop characteristic, which is executed as an active power reduction. For the central controller, the new setpoint is set as a percentage reduction respect to the last active power measured value at the PCC, P_{PPC}. For the local controllers, the reduction is done respect the last P_{INV} value. The $P-f$ characteristic is different for each grid code. This study implements a generic active power reduction in response to the over-frequency event, defined in Table 1. Then, four scenarios are exposed in order to evaluate the over-frequency regulation performance of each architecture. Since the P-f characteristic is different for each grid code, in this case study the requirement from South Africa are considered as example [27].



(a) Centralized control architecture



(b) Hierarchical control architecture

Figure 5: Simplified control architecture models

Table 1: Parameters used for the over-frequency simulations

Parameter	τ_{PPC}	τ_{com}	τ_{inv}	Deadband	Δf_{max}	$P_{Pnom,i}$	Droop constant
Value	100 - 500 ms	20 ms	100 - 500 ms	50 - 50.5 Hz	1.5 Hz	10 MW	0.467 MW/Hz

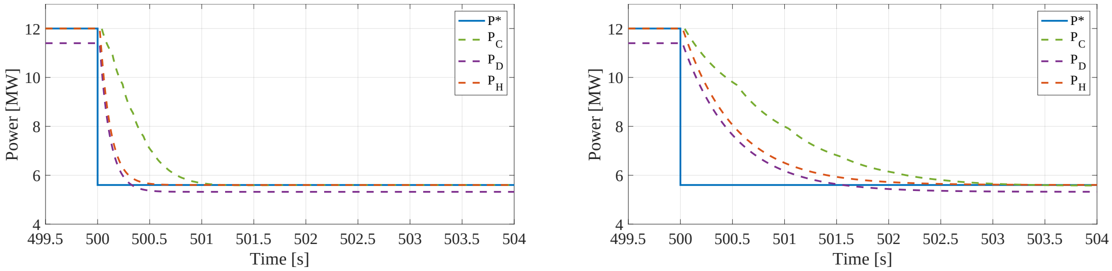
Response time

The typical primary frequency response currently requires a response time around 15 and 30 seconds at the PCC, but future services, such as the Fast Frequency Response (FFR) in the UK, will require a faster response [12]. Then, improving the current response time is desirable. The response time can be affected by limitations set by the characteristics of the control architecture, the PI controller parameters, the inverters, the measurement devices and communication delays, specific to each PV plant installation. Hence, the interest in this case study is to compare the response time of these control architectures. The response time of the inverters and the sampling time of the PPC are relevant parameters to consider. Figure 6 shows two simulations to understand the impact of these parameters on the system response. Table 2 shows the selected values for each simulation as well as the control parameters of each architecture. The PI parameters of the PPC, in both the centralized and the hierarchical control structure, are selected using the Control System Tuner Toolbox of Matlab to obtain the fastest dynamic response with a small overshoot (a maximum of 0.5 %).

Table 2: Comparison of the two simulations

Simulation	Inverter time constant (τ_{inv})	PPC sampling time (τ_{PPC})	Architcture	Central controller		System time constant
				KP	KI	
1	100 ms	100 ms	Centralized	0	2.63	389.6 ms
			Hierarchical	0.23	5.47	121.5 ms
			Decentralized	-	-	119.9 ms
2	500 ms	500 ms	Centralized	0.15	0.90	1016.9 ms
			Hierarchical	0.23	1.09	521.3 ms
			Decentralized	-	-	519.9 ms

Figure 6a shows the results when small time constants are considered. At 500 s, the setpoint P^* drops as an over-frequency is detected. Compared to the centralized architecture (P_C), the decentralized (P_D) and hierarchical (P_H) architectures respond faster. This is due to the fact that the centralized architecture is governed by 2 cascaded PI controllers (the local PI controller plus the central PI controller), while the decentralized and hierarchical architectures are governed only by the local PI controller. Note that in the hierarchical architecture, the central controller only applies a correction in the setpoint. On the other hand, it can be observed that the decentralized architecture does not reach the setpoint due to the power losses within the power plant, while the centralized and hierarchical architectures are capable to deal with this issue thanks to the central controller. This will be explained in the following sections in detail. As shown, the hierarchical architecture is taking the advantages of both i) the fast response of the decentralized architecture and ii) the capability to compensate the power losses of the centralized architecture. Figure 6b shows the results when time constants are increased. This second simulation validates that the comparison between control architectures does not depend on the inverter characteristics.



(a) PV plant response with both central controller sampling time and inverters response time of 100 ms

(b) PV plant response with both central controller sampling time and inverters response time of 500 ms

Figure 6: Droop response time using different configuration parameters

Loss of communications

A network of communications is required by the central controller and in some situations can fail. In addition, the central controller itself could also experiment a failure. The loss of PCC measurement, the loss of the central controller or the loss of the communication network can lead to the plant malfunction. This is often prevented by duplicating the equipment (i.e. with redundancy). However, it is important to note that communication failure can still occur. In the event of a communication error detection, inverters could have different modes of configuration, e.g. they can either maintain the last measured value, take a specified value or zero as constant value. There is no standard mode of configuration and it might differ between PV plants. Thus, this paper assumes that the action of control is set at zero when an interruption is detected, i.e. the central controller is turned off. Figure 7 shows the P^* setpoint dropping at 240 s as a result of an over-frequency detection. At 400 s the loss of communication between the PPC and the inverters is detected and the central controller is turned off. The decentralized architecture is not shown because does not have a central PI controller. Only the hierarchical control is capable to provide a general solution to the presented problem. When the central controller of the hierarchical architecture is turned off, the control becomes local. In general, when only the local control is operative, power losses are not compensated. However, during droop operation the reduction in active power is performed with respect to the last local value sent by each inverter at 240 s, so the central controller does not act to compensate power losses for over-frequency response, unless the available power P_{AV} is lower than the setpoint P^*. According to Figure 7, the hierarchical PV plant output (P_H) is able to reach the desired setpoint with no interruption. If the same solution is applied to the centralized architecture (P_C) at 400 s, the centralized PV plant shuts down.

Losses compensation

Power losses are present in power systems as a result of unwanted energy dissipation effects. They can be as high as the 5% of the generation [28], which results in a big loss of power for LS-PVPPs. In order

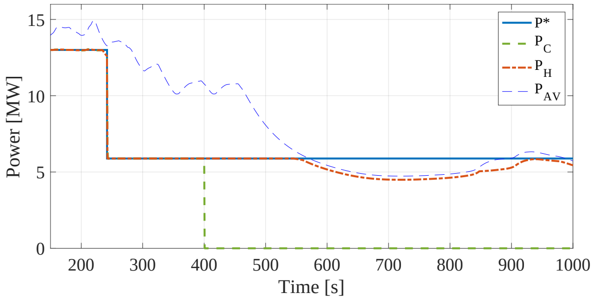


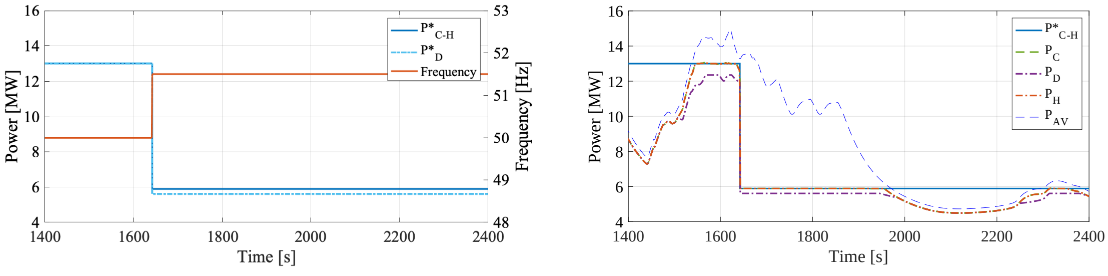
Figure 7: Loss of communications during droop mode

to maximize profits, the system may inject the maximum power allowed by the TSO into the grid. Thus, compensation of losses provided by the control system is desired. Due to power losses, the aggregated P_{INV} output of the inverters is always higher than the PCC measurement. For the centralized and hierarchical architectures, power losses are corrected by the central controller, so the PCC measurement reaches the setpoint when enough power is available. If there is no central controller, the aggregated inverter output equals the setpoint. Thus, in the decentralized architecture the PCC measurement is lower than the setpoint.

Note that at the moment that an over-frequency is detected, the latest PCC measurement is stored by the central controller and the latest inverter output P_{INV} is stored by each local controller. Then, the P-f droop is performed with respect to these values. The implications of this operative are clear, as the hierarchical and centralized architectures manage to achieve the active power output during curtailment, while the decentralized architecture achieves a lower value. Thus, Figure 8a shows that the droop setpoint of the hierarchical and centralized architectures (P^*_{C-H}) is maximized, which is higher than the droop setpoint of the decentralized architecture (P^*_D). The central controller present in the hierarchical and centralized architectures is essential to provide the maximum power allowed at all times. Through the PCC measurement, the system is able to compute the necessary power that must be injected into the grid at every given moment and maximize it. As a result, Figure 8b shows that the hierarchical (P_H) and centralized (P_C) PV plant output is equal and maximized, while the decentralized (P_D) PV plant output is lower when enough power is available.

PV plant under partial irradiance limitation

Losses due to temporary shading are an important issue in PV generation. They are caused by clouds passing through or sharp elements present in the surroundings of the PV plant. The consequences of a shade can be mitigated by increasing the setpoint sent by the central PI controller to all of the inverters, which results in an increase of the output power. Thus, the desired production can be achieved or maximized. The decentralized architecture has no central controller and cannot compensate these losses.



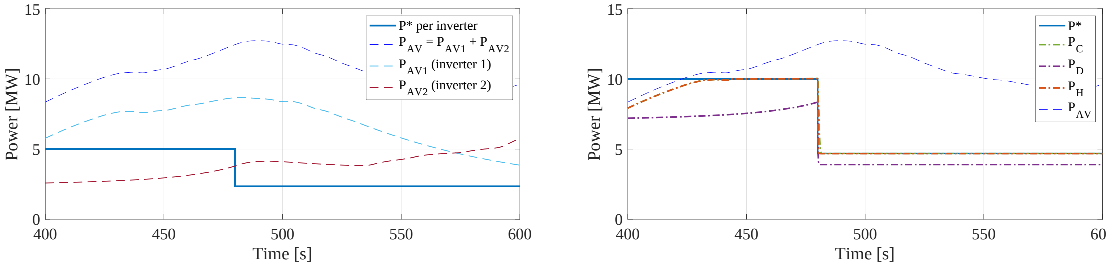
(a) Active power setpoint depending on the frequency

(b) PVPP output depending on the control architecture

Figure 8: Power output during curtailment and droop operation

To understand this issue for the decentralized architecture, Figure 9a shows the setpoint for each group of inverters and their available power (P_{AV1} and P_{AV2}). Also, the total available power is also shown as P_{AV}.

In spite of the availability from the aggregated power, Figure 9b shows that from 430 to 480 s the output power of the decentralized PV plant does not only suffer from power losses but also from the effect that the lack of irradiance has on the inverters (P_{AV2} is lower than P^*_{INV} of each inverter). Then, the frequency droop activated at 480 s is applied with respect a much lower value of active power than for the centralized and hierarchical case, leading to a lower output power during over-frequency support. As Figure 9b shows, the decentralized architecture performance (P_D) is lower than in the other architectures, both during curtailment and frequency droop. On the other hand, the centralized (P_C) and hierarchical (P_H) architectures are shown to perform similar results during the event. The maximum power allowed by the TSO is reached during curtailment as a result of the central controller action.



(a) Power avaliable

(b) Cloud passing through

Figure 9: Effect of irradiance limitation on some inverters

Comparison of control architectures characteristics

The control architectures have been presented and analyzed in different scenarios. Table 3 compares the characteristics and capabilities of each control architecture.

Table 3: Comparison of the control architectures based on the over-frequency support service

	Centralized	**Decentralized**	**Hierarchical**
Control level	Central	Local	Central and local
Need of communications	Important	Not necessary	Mainly for central control
Correction of power losses, irradiance limitations or inverter failure	Yes	No	Yes
Response time	Slow	Fast	Fast
Operation without communications	Not possible	Possible	Possible
Modification in actual inverters	No	No	Yes
Complexity of implementation	Low	Low	Medium
Compliance with grid code	Ensured	Might not be ensured	Ensured
State of the art	Commonly used	Less used	Not currently used

Conclusion

This paper has proposed a hierarchical control architecture for over-frequency support in large scale photovoltaic power plants. The suggested architecture has proven to take the advantages of both the centralized and the decentralized architectures. In particular, the hierarchical architecture offers a similar response to the decentralized architecture, i.e. a faster response than the conventional centralized architecture. Thus, it is an interesting option for future severe requirements related to response time during an over-frequency event. In addition, the hierarchical architecture offers a response as robust as the decentralized architecture in front of communication failures, since it ensures the continuance of service, while the conventional architecture cannot support the operation under the same fault. Finally, the hierarchical architecture can compensate power losses, irradiance limitation or inverter failure as the centralized option.

The presented advantages show the potential of the hierarchical architecture, which might be more relevant for large scale photovoltaic power plants as future grid requirements become more strict. This paper has only shown the proposed architecture characteristics for over-frequency regulation, but these conclusions could be also applied for other services. Therefore, further research is required to validate the implementation and advantages of this proposed control architecture.

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