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Feasibility and Performance Assessment of Commercial PV Inverters Operating with Droop Control for Providing Voltage Support Services

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Abstract—The proliferation of PV generation systems connected to electrical distribution systems (EDSs) brings many operational challenges, and within them, over-voltage issues are regarded as the most critical. Among all the strategies available to handle these over-voltage issues, those implemented locally at the PV inverters seem to be the more promising, considering their distributed and easy-to-implement features. In this paper, the feasibility and performance assessment of a commercial PV inverter for mitigating over-voltage events in an EDS is presented. To do this, an active and reactive droop-based voltage control strategy is implemented in a commercial inverter. Real-time power hardware-in-the-loop (PHIL) laboratory tests were performed to assess the PV inverter's efficiency when absorbing reactive power, as well as its interaction with the distribution grid. According to the obtained results, the PV inverter's efficiency was not noticeably affected by the changes in reactive power. Additionally, the PV inverter responded accordingly, following the voltage control strategy implemented, providing successfully the expected voltage support services.

Index Terms—PV inverters, droop control, real-time simulations, over-voltage events.

I. INTRODUCTION

The proliferation of PV generation systems connected to electrical distribution systems (EDSs) brings many operational challenges that the distribution network operators have to face. These challenges are mainly associated with over-voltage issues, especially during times with high PV generation and low consumption; and fast transients due to natural cloud movements [1]. These technical issues have important consequences in the operation of the EDSs, as they might increase the frequency of tap changes in on-load tap changing distribution transformers (reducing their life-time spans), as well as limiting the integration of new PV installations [2], [3].

Considering this, all the stakeholders involved are putting in a significant effort to ensure a reliable and secure operation of EDSs with high PV penetration [4]. Among the strategies developed to mitigate over-voltage issues in PV-rich EDSs, it is possible to find [5]: infrastructure (network) reinforcement, active voltage regulators, such as SVCs and STATCOMs; and advance PV inverter control strategies. Regarding the PV inverter control strategies, multiple approaches can be found in the literature, including: reactive power control (RPC) [6],

[7], power factor control (PFC), and active power control (APC) [8]. All these strategies are generally based on simple control rules using electrical quantities such as voltage magnitude or power quality indexes [9], [10]. Usually, when RPC control is implemented, if the voltage magnitude at the point of connection (POC) of the inverter surpasses a voltage threshold, the inverter starts absorbing a certain amount of reactive power, and as a consequence, the voltage at the POC is reduced. In case of an under-voltage, the PV inverter start injecting reactive power, increasing the voltage magnitude at the POC. In APC, when the voltage magnitude at the POC surpasses a certain voltage threshold, the active power injected by the PV inverter is reduced (curtailed) [11]. In general, APC is more effective than RPC given the highly resistive line characteristics of low voltage EDSs [8]. Nevertheless, a coordinated approach that merge both controls (APC and RPC) has shown to be the most promising technical approach, as demonstrated by [12]–[14], reducing simultaneously the overload of the distribution transformers due to the absorption of reactive power by the PV inverters and the amount of active power curtailed.

Although effective, strategies such as the ones presented in [12]–[14] require the deployment of a large (and complex) communication infrastructure, enabling all the PV inverters (and other equipment) connected in the EDS to exchange information. This feature limits the large-scale implementation of such strategies. To overcome this, works such as [15]–[18], has proposed locally implemented strategies at the PV inverter and based on the well-known droop control. The main advantages of these droop-based APC and RPC strategies is their distributed and easy-to-implement features [15]. Nevertheless, the interaction of such droop-based control strategies (implemented in a commercial PV inverter) and the distribution network has not been tested at laboratory level yet.

Considering this, the main contribution of this paper is related to the feasibility and performance assessment of a commercial PV inverter and its capability to mitigate over-voltage events in an EDS. To do this, firstly, isolated tests were performed in order to assess the PV inverters: (i) efficiency, due to the operation of RPC strategy and; (ii) response time,

Figure 1. Droop-based APC and RPC. In the case of coordinated APC-RPC V_{thQ} is set equal to V_{thP} . For under-voltage, a voltage magnitude threshold is also defined, $V_{thQ'}$.

under a sudden increase/decrease in the voltage at the POC. Secondly, real-time (RT) power hardware-in-the-loop (PHIL) simulations were performed in order to test the PV inverter interaction with a distribution network.

This paper is structure as follows: Sec. II introduce the main features of droop-based APC and RPC strategies. Then, Sec. III presents the experimental setup used and the results obtained based on the laboratory measurements performed. Finally, conclusions are drawn in Sec. IV.

II. DROOP-BASED APC AND RPC STRATEGIES

Droop control is a well-known approach used for power sharing among multiple distributed generation units running in parallel [19]. In general, the standard droop control strategy runs continuously with only local measurements. Thus, droop-based APC and RPC can be implemented in the inverter's control system, following the strategy defined in Fig. 1, where P_{max} and Q_{max} represents the maximum active and reactive power output set by the control, respectively; and V_{thP} and V_{thQ} represent the voltage thresholds after which APC and RPC are activated. In the case of coordinated APC-RPC, V_{thQ} is set equal to V_{thP} [18]. The definition of these parameters, including the maximum and minimum voltage magnitude limits, must take into account the European Standard EN 50160. Notice that as droop-based APC and RPC runs continuously, the inverters control must be able to follow the voltage at the POC and simultaneously update the maximum power point (MPP) generation. These features are usually available in the last generation of commercial inverters.

III. EXPERIMENTAL RESULTS

In this section, first, the experimental setup used is described. Then, experimental results are presented and analyzed.

A. Experimental Setup

In the test, both the AC distribution network and the PV array (DC input) are emulated using realistic, full-scale power emulators. This allows the full operating range of the commercial PV inverter, both for AC and DC sides. The AC distribution network and the PV emulators consists of high-bandwidth power amplifiers driven by a real-time simulator models of the grid and PV arrays. The features of the commercial PV inverter under test are presented in Table I. The schematic representation of the real-time PHIL setup is

Table I
INVERTER'S TECHNICAL SPECIFICATION

DC Max. Input Voltage	1100 [V_{dc}]
Num. MPPTs	4
DC Max. Input Current (per MPPT)	28.5 [A]
I_{sc} (per MPPT)	44.5 [A]
DC MPP Range	200 – 1000 [V_{dc}]
AC Nominal Output Voltage	400 [V_{ac}]
AC Nominal Output Frequency	50 [Hz]
Rated Active Output Power	50 [kW]
AC Max. Output Power (S_0)	55 [kVA]
AC Max. Output Current	83.3 [A]

Figure 2. Real-time (RT) PHIL setup used for the experimental tests. The red lines represent flow of active and reactive power. The dashed black lines represent data/measurement flow.

shown in Fig. 2, displaying the interface and connections between the real-time simulators, the power amplifiers and the commercial PV inverter. As can be seen in Fig. 2, the physical measurements are taken from the output of the power amplifiers, then, fed back into the real-time simulator, which recalculate their outputs. In this way, the model is able to represent and respond to the dynamic operation of the PV inverter within the simulated distribution network.

B. Inverter's Efficiency and Droop Control Performance

This first test was built with the aim of measuring any decrease in the inverter's efficiency (i.e., measuring any extra losses) due to controlling its reactive power output, when compared with the case $\cos \phi = 1$. Thus, efficiency is calculated as,

$$\eta_{inv} = \frac{P_{ac}}{P_{dc}} [\%] \quad (1)$$

For this test, the inverter was operated at nominal output power. The PV emulator was set with the information shown in Table II, with irradiance of 1000 W/m^2 . The droop control settings to implement APC and RPC are presented in Table III and Table IV, respectively; and plotted as continuous lines also in Fig. 3. The results from this test are displayed in Fig. 3. To obtain this, the AC voltage is stepped up and down in steps of 0.01 p.u. from 1.0 p.u. to 1.1 p.u., and from 1.0 p.u. to 0.9 p.u.. Each step is measured for 2 minutes in steady-state operation, and the efficiency is calculated using the average of the measurements.

As can be seen Fig. 3, the inverter's efficiency is mostly affected by the active power output, decreasing sharply when the active power is reduced to less than 24%. Thus, it is expected that if APC is implemented, and the voltage of the POC is close to the maximum limit, the inverter will operate with an efficiency near to 90%. Similarly, when the voltage

Figure 3. Measured active and reactive power (as a percentage of the inverter's nominal output power, $S_0 = 55 \text{ kVA}$) vs. voltage. Inverter's efficiency vs. voltage.

Table II
PV SETTINGS FOR NOMINAL OPERATION

V_{oc}	I_{sc}	I_{rr}	V_{mp}	I_{mp}	P_{mp}
[V]	[A]	[W/m^2]	[V]	[A]	[kW]
730	100	1000	584.1	90.4	52.8

decreases, the efficiency also decreases up to 96% from the maximum measured efficiency of 96.6%. It is important to highlight that when the voltage decreases at the POC, and the RPC strategy is implemented following the defined droop settings, the active power also decreases, in this case reaching a value near to 80% at the lowest applied voltage. This decrease in the active power is due to the inverter's internal protections, activated due to the overcurrent caused by the low AC-side voltage.

Finally, noticed in Fig. 3 that in nominal operation, the reactive power consumption of the device was measure to be 20% of the nominal output power (S_0). It was not possible to explain this behaviour, and according to the manufacturer, it can be due to an error in the control upgrade done in order to implement the droop control settings. This is currently under investigation by the inverter's manufacturer.

C. Inverter's Response Time

This test was performed in order to understand how fast the inverter's voltage regulation control will respond to a change in voltage at the POC. In this test, the AC voltage is stepped up from 1.0 p.u. to 1.1 p.u., then down to 0.9 p.u., and then back to 1.0 p.u.. Each step is made after the PV inverter has reached a new steady state of operation. Results are displayed in Fig. 4, and the measured response times in Table V. Rise and falls times were measured from the previous steady-state voltage magnitude to the point of 90% of the new steady-state value. As expected, the inverter's response time it is within the operational time of power electronics i.e., below 600 ms. Thus, it is possible to conclude that APC and RPC implemented through the PV inverters control algorithms are sufficiently fast to be used as a tool for performing voltage regulation.

Table III
 $P - V$ DROOP TO IMPLEMENT APC

V [p.u.]	P [% S_0]
1.03	100
1.06	50
1.10	0

Table IV
 $Q - V$ DROOP TO IMPLEMENT RPC

V [p.u.]	Q [% S_0]
0.92	50 Leading
0.97	0
1.03	0
1.06	50 Lagging

D. Real-Time PHIL Operation

In this final test, the inverter's performance is tested using the full real-time PHIL set up. In this test, the current at the POC is measured back into the distribution network model and the model and physical output voltage responds accordingly. The model used corresponds to the one presented in Fig. 2. Results are displayed in Fig. 5, while Fig. 6 and Fig. 7 display a zoom view for some specific time periods of the real-time simulations. All the measurements were taken from the AC-side of the inverter.

From time 50 s to 186 s, the inverter is initialized, but its output current is not fed back into the PHIL model. The irradiance was set initially to 200 W/m^2 and then adjusted. Fig. 6 displays the output power changing in steps, each of these steps corresponds to a change in the set irradiance value in the PV emulator.

At time 186 s, the inverter is connected and the PHIL model is thus in full operation. Notice in Fig. 6 that as the irradiance of the PV emulator is changed, the voltage of the PV inverters at the POC also changes, and as a consequence, the PV inverter starts consuming reactive power (RPC strategy), while the active power is also reduced (APC strategy). Based on this, it is possible to conclude that droop control operates as expected.

At time 290 s, the irradiance is suddenly reduced to 0 W/m^2 , which causes the inverter to disconnect its output. Then, the irradiance is stepped up to 1000 W/m^2 . The slow rise in the output power that can be seen in Fig. 5 from 310 s to 500 s corresponds to the inverters internal controls which restricts the ramp rate of output power when reconnecting after a disconnection.

At time 650 s, the grid voltage is decreased. This action also reduces the voltage at the POC of the PV inverter. Notice in Fig. 5 that once the PV inverter perceived the change in the POC voltage, it begins to operate at nominal power (recalling that in nominal operation a reactive power of $20\%S_0$ was measured). After time 650 s, several changes in the irradiance and grid voltage were performed, as shown in Fig. 7, in order to test in real-time the interaction between the distribution network and the PV inverter operating with the droop-based APC-RPC strategy. The interactions were

Figure 4. Response time of the commercial PV inverter after a change in the voltage at the POC.

Table V
INVERTER'S RESPONSE TIME

U_{set} [p.u.]	P [ms]	Q [ms]
1.0 – 1.1	400	100
1.1 – 0.9	150	600
0.9 – 1.0	150	250

performed sequentially as described next:

- When the irradiance decreased from 1000 W/m^2 to 400 W/m^2 , the output active power also decreased. As a under-voltage was perceived, the PV inverter start injecting reactive power.
- When the irradiance increased from 400 W/m^2 to 800 W/m^2 , the output active power increased. An acceptable voltage appeared at the POC. Thus, the reactive power drops to its nominal operation output.
- When the grid voltage was increased from 0.9 p.u. to 1.0 p.u. , an over-voltage appeared at the POC. Thus, reactive power absorption is increased at its maximum (RPC strategy), while the active power is reduced (APC strategy).
- When the irradiance increased from 800 W/m^2 to 1000 W/m^2 , no noticeable change was observed, as the PV inverter was already operating at its maximum capacity.
- When the grid voltage was decreased from 1.0 p.u. to 0.9 p.u. , the voltage at the POC drops to an acceptable value, and the inverter started operating once again in nominal operation.
- When the irradiance decreased to 0 W/m^2 , the output active power dropped to 0 kW . An under-voltage appeared at the POC and the PV inverter started increasing its reactive power output.
- After a short period of time, the PV inverter sensed no irradiance, and thus, disconnected its AC-side.

E. Reflections on Technical Issues

Some technical issues were found during development and running of the tests: a non-expected reactive power consumption from the PV inverters at nominal operation (close to 20%), which is currently under investigation by the inverter's manufacturer. Additionally, although different inverters (from different manufacturers) were available for testing (within this research project), it was not possible to unlock the inverter's features to set advance droop control parameters, mainly due to a lack of the manufacturer's support. Firmware upgrades and special manufacture permissions are required in order to implement and develop the droop control features in these commercial PV inverters. Regarding this, there is still a long way in which manufacturers, system operators and academia, need to work together before wide-spread voltage support services can be applied by the end users.

IV. CONCLUSION

The tests reported in this paper were designed to investigate the feasibility of using power electronic equipment i.e., commercial PV inverters, to support voltage regulation in distribution networks, implemented using a droop-based APC-RPC strategy. According to the obtained results, it is possible to conclude that the efficiency of the inverter is not noticeably affected by changes in the reactive power output and remained steadily between 96% and 97%. Thus, droop-based RPC does not affect the inverter's efficiency. Nevertheless, the efficiency showed a decline as a result of changes in the active power output. Regarding the inverter's response time, this is within the range expected from power electronics, thus, it can be conclude that it is sufficiently fast to be used for voltage support and management. Based on the real-time PHIL test presented, the interaction between the PV inverter and the distribution network was as expected. The PV inverter responded accordingly, following the voltage control strategy implemented, providing successfully the expected voltage support services. For future work, it is expected to study the interaction of multiple PV inverters and other equipment, such as on-load tap-changer transformers or bank capacitors, operating within the distribution network.

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Figure 5. Measurements in the PHIL model after varying the irradiance and the grid voltage.

Figure 6. Inverter's response to changes in the irradiance before running online with the PHIL model.

Figure 7. Inverter's response to changes in the irradiance and the grid voltage running online in the PHIL model.

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