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Grid-Connected Photovoltaic Generation Plants as Alternative Energy Sources

3 Enrique Romero-Cadaval ; Bruno Francois ; Mariusz Malinowski ; Qing-Chang Zhong

Abstract— Large photovoltaic (PV) plants are being built all over the world, 4 commonly having ratings up to 1 MW and reaching the level of 250 MW. These 5 plants could be an alternative energy source replacing conventional ones and 6 solving the energy dilemma of humanity. However, the associated electronic 7 systems, mainly inverters used for interfacing with the grid, have to solve some 8 problems related to the operation in the electric distribution system. They should 9 10 be reliable, robust and manageable. This paper presents and discusses the most critical points existing in actual inverters, summarizing, explaining and proposing 11 12 approaches to solve or mitigate them.

13 **Keywords:** Photovoltaic Plants, Grid Integration, Alternative Renewable Energy Sources.

14 I. INTRODUCTION

Governments and public organizations are nowadays concerned about the 15 16 production of energy with technologies as clean as possible [1]. As a consequence, the guidelines for future energy production are established according to the Kyoto 17 protocol [2], which for European countries inspires the "20-20-20" target [3]. The 18 energy production technologies based on hydro, wind, photovoltaic and geothermal 19 energies can be considered to be clean and renewable alternatives to the non-clean 20 conventional technologies based on fossil fuels and nuclear fission. Among the clean 21 technologies, photovoltaic (PV) is one that has experienced a great growth in the last 22 years, close to 60% in Europe. 23

PV Generation Plants (PVGP) are becoming economically viable, even
without government subsidies. The PV plant capacity is increasing continuously all

over the world reaching values of hundreds of megawatts (Fig. 1, [4]), thus making
these plants a crucial part of future electric energy systems and Smart Grids. They
are becoming an important agent in Active Distribution Grids as they are distributed
energy sources, and they need special control structures [1].



5 Fig. 1 Nominal Power (in MW) of PVGPs classified by the continent where they are

- 6 installed [4] and top-ten large-scale PVGPs.
- 7 These large/medium PVGPs operate as Distributed Energy Resources (DER)
- 8 mostly in rural areas where the required surface is available. They are connected to
- 9 radial distribution grids as shown in the example of Fig. 2.





Fig. 2. Example of distribution grid where a Photovoltaic Generation Plant isconnected.

Controlling frequency and voltage has always been an essential part of operating a power system. However, since the liberalization of the electricity supply industry, the resources required to achieve this control have been treated as services that the system operator has to obtain from network stakeholders, usually known as ancillary services. Large grid-connected PVGPs should contribute to deliver this service, especially if they have to operate in the isolated mode.

Ancillary services are components of electric services, required to support the reliable delivery of electricity and operation of transmission systems [5]. These services contribute to frequency stability (e.g., frequency regulation and operating reserves, in different time scales Fig. 3), power balance (e.g., scheduling and dispatch of balancing energy), voltage control (e.g., tap changer control and reactive power control), restoration of supply (e.g., black start capability and island operation), or

- 1 system management (e.g., power quality assurance, operation and asset
- 2 management).



3

Fig. 3. Time Association of Frequency Regulation and Operating Reserves after a
Contingency Occurs

In order to maintain power system reliability, the natural intermittent 6 characteristics of primary renewable energy must be taken into account, requiring 7 a precise estimation of their ancillary service provision in advance. If necessary, 8 9 other utilities, such as Energy Storage Systems (ESS) or fast generators, must be planned. Hence, the integration of PVGPs into an electrical system implies the 10 extension of the actual hierarchical power management system that takes into 11 account different time-scales and economic dispatch. It has to pave the way to 12 develop new interactions between real-time pricing, physical constraints and 13 demand response-based loads. 14

At the present, and even more in a future Smart Grid scenario [6], PVGPs can receive operation references, mainly active and reactive power references to generate/consume energy for delivering ancillary services, from the corresponding Electric System Agent. PVGP central control systems will have to translate these global references into individual operation references for each inverter within the

plant, and taking into account the actual state of all the inverters and weather
forecast. Therefore, inverters will be the main device that must be able to interact
with the grid and with the ESS for providing these services in the required way.

This paper presents new solutions that enable PVGPs inverters to provide 4 these ancillary services with the right topology, additional systems, power or 5 current ratios, control algorithms and communication systems. The paper starts 6 with a general overview of the current situation in Section I and continues by 7 presenting in Section II the control structures that are most commonly used for 8 controlling the converters that inject the energy produced by these plants into the 9 grid. In Section III Active PVGPs with embedded ESS and the associated control 10 11 strategies are discussed. Section IV presents advanced functions that these PVGPs 12 can implement in the near future, in the context of the fore coming Active 13 Distribution Grids, providing ancillary services. In Section V, synchronverters are presented as an alternative to the conventional control structures discussed in 14 15 previous sections, emulating the operation of conventional synchronous generators. Finally, this paper ends with conclusions. 16

17

II. Control of Grid-connected PVGP Inverters

During the last years, PWM converters have drastically increased their importance on the market of energy conversion for PV applications. Two technology breakthroughs enabled these remarkable developments:

- innovations in the field of power electronics, which brings improvements
 in efficiency (reduction of switching losses), power density, power quality,
 common mode voltage and electromagnetic interference, etc.;
- innovations in the field of control schemes, which contain now many
 sophisticated control functions (Fig. 4) e.g. inner current/power and

outer dc-link control [7-9], maximum power point tracking (MPPT) [4],
monitoring and grid synchronization [10], proper operation at
significantly distorted grid [11], islanding/anti-islanding operation [4],
active power feed-forward [12,13], outer control loop for active/reactive
power to support power system etc. [14,15], energy storage, harmonic
compensation or synchronous generator emulation.



7

8 Fig. 4. General control structure of grid-connected PV plant.

9 III. Current-based Control for PVGP Inverters

Various inner control algorithms have been proposed in recent works for this type of DC/AC PWM converters for MW PV applications [7,8,16] but many of them are still being developed and they have not found place in industry. Therefore this paper only describes the methods which are most promising or attractive for industry – e.g. Voltage Oriented Control (VOC), Direct Power Control Space Vector Modulated (DPC-SVM) or Predictive Control (PC) – based on the simplified system scheme shown in Fig. 5.



1

Fig. 5. Simplified DC/AC PWM converter scheme to facilitate the discussion ofcontrol algorithms.

The conventional VOC uses closed-loop current control in the rotating reference frame. A characteristic feature for this current controller is the processing of signals in two coordinate systems (Fig. 6), after converting three phase measured values to the equivalent two-phase system α - β and then to the rotating *d*-*q* coordinate system via a α - β/d -*q* block [16,17].



9

Fig. 6. Coordinate transformation of line current and line voltage from the stationary α - β coordinates to the rotating *d*-*q* coordinates.

As the d-q frame rotates with the same speed as the electrical quantities, the 12 projected coordinates are DC signals. In the voltage oriented *d-q* frame, the AC grid 13 current vector *i* is split into two rectangular components $i = [i_d, i_q]$. The component i_q 14 determines indirectly the reactive power, whereas i_d decides indirectly the active 15 16 power flow. Thus the reactive power and the active power can be controlled independently. The Unity Power Flow (UPF) condition is met when the grid current 17 vector, *i*, is aligned with the grid voltage vector *u*, which means that the *q*-axis 18 current should be set to zero in all cases while the reference current *i*_d is set by the 19

- 1 DC-link voltage controller and controls the active power flow. The output signals
- 2 from Proportional-Integral (PI) controllers after a $dq/\alpha\beta$ transformation are used to
- 3 generate switching signals via a Space Vector Modulator (Fig. 7a).





An important drawback of VOC is the high algorithm complexity (many
coordinate transformations are needed) as well as the sensitivity to grid voltage
distortion. The last drawback can be eliminated [11], but it significantly complicates
the algorithm.

11 The VOC can also be realized in the stationary α - β coordinate system but PI 12 controllers cannot be used for current regulation because they result in a steady 13 state error. However, this can be solved by replacing PI current regulators with 14 Proportional/Resonant controllers (PR), which consist of a proportional gain and a 15 resonant integrator. The transfer function of a PR controller contains a pair of 16 conjugate poles tuned at the fundamental grid frequency ω , which allows perfect 17 tracking of sinusoidal signals without any error [13].

A basic block diagram of the VOC in the stationary coordinate system is 1 shown in Fig. 7b and it is based on an inner current control loop with PR and an 2 outer voltage control loop with PI. The commanded dc-link voltage *u*_{dc}^{*} is compared 3 with the measured u_{dc} voltage. The error is delivered to the PI controller, which 4 generates the amplitude of the commanded current *idc_ref*. Next, this current is 5 6 multiplied by the angle of the line voltage u_L as $\cos(\omega t)$ and $\sin(\omega t)$ to get $i_{\alpha,ref}$ and $i_{\beta,ref}$. These reference current signals in the stationary coordinate system are compared 7 with the measured grid currents i_{α} and i_{β} and the errors are delivered to the PR 8 controller. The outputs of the PR controller are directly (without transformation) 9 used to generate switching signals by a Space Vector Modulator (SVM). 10

An interesting feature of this control is the proper operation under distorted grid voltages by connecting multiple PR compensators, which are tuned at specific high order harmonics, e.g. 5th, 7th, in parallel [13,18,19].

Another less known method is direct power control – space vector modulated 14 (DPC-SVM) which uses inner loops of active and reactive power control (Fig. 7c) [20]. 15 The commanded reactive power q_{ref} (set to zero for UPF operation) and active power 16 17 *p*_{ref} values (delivered from the outer PI-DC voltage controller) are compared with the estimated q and p values, respectively. The errors are delivered to PI controllers 18 to eliminate steady-state errors because they are DC quantities. The output signals 19 from the PI controllers after transformation from the stationary to synchronous 20 rotating coordinates are used to generate switching signals by a SVM. 21

22 Recently, a very popular control scheme called Model Predictive Control (MPC) (Fig. 7d) has been applied to control inverters. It is based on the mathematical model 23 of the controlled system and the calculation (prediction) of future values of the state 24 variables. It is assumed that the system can represent a finite number of states in 25 every time period [21-25]. Thus, first of all, the model must be as accurate as possible, 26 because the control performance is highly dependent on the parameters. Using 27 measured values of grid currents, their values in the forthcoming sampling can be 28 calculated, with respect to available control states. It must be done for all switching 29 states in each iteration of the algorithm. 30

Some features of predictive control are very interesting, e.g. fast dynamics and the capability of dealing with multiple constrains, which is very attractive especially for high power converters operating at very low switching frequency (500Hz-

1000Hz). Unfortunately, MPC has some drawbacks, e.g. variable switching frequency
(causing difficulties for the design of the LC input EMI filter), high sampling frequency
needed for digital implementation (demand of fast microprocessor) and sensitivity
to parameter variations of the grid filter, etc, which cause difficulties in implementing
MPC in industry. All the above drawbacks can be eliminated when a constant
switching frequency is applied but it significantly complicates the control algorithm
[26].

8 The advantages and features of the control schemes described above are9 summarized in Table I.

10 Table I – Advantages and features of control schemes for DC/AC converter in PV

11 applications

		VOC (Fig. 7a)	VOC (Fig. 7b)	DPC-SVM (Fig. 7c)	MPC (Fig. 7d)
Operation in stationary coordinate system		NO	YES	YES/NO	YES
Power control – indirect		YES	YES	NO	YES
Power control – direct		NO	NO	YES	NO
Constant switching frequency		YES	YES	YES	NO
Low algorithm complexity		NO	YES/NO	YES/NO	YES
Low computation intensity		YES	YES	YES	NO
Low sensitivity to line inductance variation		YES	YES	YES	NO
I and appoint in the line meltage distortion	THD of line current	NO	YES	YES	NO
Low sensitivity to line voltage distortion	Power factor	YES	NO	NO	YES

12

13 IV. Active PV Generators with Embedded Energy Storage Systems

Electrical systems must ensure a balance between production and consumption at all times, while maintaining a satisfactory voltage. Historically, grid reliability was mainly ensured by having excessive capacity in the system with unidirectional flow from centrally dispatched large power plants to dispersed consumers. Dispatched production refers to sources of electricity that can be dispatched at the request of system operators. They are able to change their power production upon demand.

The large scale development of intermittent PV sources causes large amount of variable power [27]. Renewable energy based generators with intermittency decrease the reliability of a power system. As the percentage of intermittent generation capacity increases and becomes more significant, an additional uncertainty is appearing in the real time management of the electrical system
balance between demand and generation. This requires increasing amounts of
conventional power reserve capacity that can be available immediately (spinning
reserve) and of plants capable of providing ancillary services (frequency response
and voltage control as example), which are required to manage the electrical power
system securely [28].

However, an electrical generation system depending entirely on the renewable
energy sources is not reliable because the availability of the renewable energy
sources cannot be constantly ensured.

Because of the intermittency of PV power generation, PVGP cannot be used as 10 a stable, reliable and controllable power source and cannot provide ancillary 11 12 services like conventional generators. One solution is to upgrade PVGP with an embedded Energy Storage System (ESS) and a Local Energy Management System 13 (LEMS) for the coordination of inner power flows. Storage technologies are varying 14 and first it is essential to characterize the required need and complementary 15 performances they must offer. Typically, an energy reserve must be provided to the 16 17 electrical system and can be implemented by long-term energy storages. Moreover, the supply of power with fast dynamics is also mandatory to smooth the generated 18 PV power, compensate the power gap and absorb instantaneous high power peaks. 19 At the present state of art, a high energy storage unit, delivering high power with 20 fast dynamics in a reduced volume, does not exist and a mix of storage technologies 21 has to be considered [29]. Lead acid batteries for long term energy storage device 22 and ultracapacitors for fast dynamic power regulation are today realistic and 23 economic choices [30], but other technologies can also be considered [31], as Fuel 24 25 Cells, REDOX batteries [32,33] or Flywheels [34].

Storage devices can be used to store or to release electrical power like an energy buffer. Therefore, they can help to solve problems due to renewable energies' intermittent availabilities and fast transients. A PVGP combined with ESS can be considered as an Active PV Generator for the grid since it can supply ancillary services as conventional generators. Moreover it can be dispatched and then provide a power reference that is demanded by the grid operator [35].

A general structure that has been widely used in isolated power systems for integrating ESS is based on the direct connection of a battery bank to the DC-bus of the grid-connected inverter. A PV controller is used to extract the Maximum Power from PV panels and send it to the battery bank. However, the stochastic nature of the PV power output and power demand leads to fast charge/discharge actions of batteries and a fast battery ageing.

To enable a more efficient use of batteries, AC-coupled and DC-coupled power 13 electronic converters can be considered in order to have control abilities of the 14 15 exchanged powers with the batteries thanks to the development of power electronics. In an AC-coupled Hybrid Power Generators (HPG) structure, all sources 16 17 are connected to the main AC network (Fig. 8a) [35]. A communication network is required to implement the coordination of this set. In a DC-coupled HPG, all sources 18 are connected to a common inner DC-bus before being connected to the grid through 19 a main inverter (Fig. 8b) [36]. One advantage is that the battery bank is connected 20 to the dc-bus via a DC/DC converter, which can be used to implement an optimized 21 charge/discharge operation mode. The second advantage is that a super capacitor 22 23 bank is added and is also connected to the DC bus via another DC/DC converter. Hence fast power compensation can be performed. The PV array is connected to the 24 DC bus via a PV converter. Apart from these two coupling structures, a mixed 25

- 1 structure can be also used (Fig. 8c) with some advantages taken from both of DC and
- 2 AC coupled structures.

- Fig. 8. Various structures of Hybrid ESS embedded in PVGPs: (a) AC-coupled, (b) DCcoupled, and (c) Mixed structure.
- Fig. 9 outlines the main required devices to design a DC-coupled Active PV Generator HPG prototype. The grid connection is performed by a three-phase inverter. Chokes and capacitors are used to filter the modulated electrical waveforms.



- 9 10
 - Fig. 9. Example of a Grid-connected Active PV Generator with control.
- 11 In order to ensure an optimal operation and coordination, a LEMS of the active
- 12 PV generator must calculate and send control signals to each power electronic
- 13 converter in order to enable
- 14
- the production of power demand for the grid operator,

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1	• the management of renewable energy intermittency,
2	• the management of storage State of Charges,
3	• the power system protection,
4	• the provision of grid ancillary services.
5	For example, a hierarchical structure of the control system is shown in Fig. 10 and
6	has four stages:
7	• the Switching Control (SC),
8	• the Automatic Control (AC),
9	• the Power Control (PC),
10	• the Mode Control (MC).
11	The SC stage implements the modulation technique to each converter and
12	generates the switching signals. The AC stage implements control algorithms in
13	order to meet the current or voltage references. The PC stage calculates these
14	references according to power references from the MC level and measured values.
15	The MC level decides the operating mode for the whole hybrid generator according
16	to the availability of the PV production, the state of each storage unit and the actual
17	power demand from the grid.



1

2 Fig. 10. Global control scheme of active PV generator.

The power reference for the PV generator, $p_{PV_ref}(t)$, is classically calculated from a Maximum PV Power Tracking algorithm. The inner power balancing shows that powers from the PV, $p_{PV}(t)$, the battery, $p_{BAT}(t)$, the ultracapacitor, $p_{UC}(t)$ must be decreased by the required power to regulate the DC bus, $p_{DC}(t)$, and constitutes the total generated power [37]:

$$p_{ag}(t) = p_{BAT}(t) + p_{UC}(t) + p_{PV}(t) - p_{DC}(t)$$
(1)

8 With a "Grid following strategy" (Fig. 11a), the reference for the power to be 9 generated by the inverter is deduced by using the measured power and contributes 10 to the regulation of the DC bus:

$$p_{ag_ref}(t) = \hat{p}_{BAT}(t) + \hat{p}_{UC}(t) + \hat{p}_{PV}(t) - p_{DC_ref}(t)$$
(2)

- 1 Then the required power reference from the grid operator is provided by the
- 2 storage units by taking into account the available PV power.

$$p_{sto_ref}(t) = p_{gc_ref}(t) - \hat{p}_{PV}(t)$$
 (3)

3 A simple method to dispatch the power between batteries and ultracapacitors is

- 4 used with a low-pass filter [38]. Ultracapacitors are controlled to supply the
- 5 required transient power from storage units.



Fig. 11. Operation strategies: (a) Grid following strategy, (b) Source supplyingstrategy.

8 With a "Source supplying strategy" (Fig. 11b), the power from the storage units is 9 adjusted according to the sensed PV power to regulate the DC bus. The required 10 power reference fixed by the grid operator is directly provided by the inverter.

11 With both strategies, the PV generator can be dispatched by the grid operator 12 since it is now able to deliver the prescribed active and reactive powers ($p_{gc_ref}(t)$, 13 $q_{gc_ref}(t)$), but only "Source supplying strategy" is able to work without a connection 14 to the grid because the DC bus is regulated by the inner power. This strategy is 15 preferred since autonomous, or isolated, operation is possible and may be used to 16 store PV energy without grid connection. Another advantage is the possibility to stay 17 connected in case of grid AC undervoltage because the dc bus voltage is 1 autonomously regulated by inner sources (PV panels and storage units). Hence, real

2 and reactive power generation is possible to help the electrical network in this

3 situation.

An experimental test is presented on Fig. 12 using this strategy, having a step change in the reference power to be injected into the grid (p_{gc_ref}). During the test, the batteries cannot immediately supply all the surplus production when the PV power production changes or when the PV production decreases fast, so the ultracapacitors help to perform the power balancing.



9 Fig. 12. Experimental performances of an active based generator.

10 V. Ancillary Services: Active, Reactive and Harmonic Control

As previously discussed, most PVGPs operate as current sources and inject into the grid the energy produced by photovoltaic cells tracking the Maximum Power Point (MPP) [4]. The electronic converters generate a reference current that is sinusoidal, in phase with the grid voltage, and with the required root mean squared (RMS) value to achieve the operation in the MPP.

If the PVGPs want to become an alternative to conventional energy sources
they also have to provide ancillary services [1,39,40] including the control of active

1	power [39], reactive power [39,41] and compensation of harmonics [42,43]. In
2	order to achieve this, most of the Distribution System Operators (DSO) are
3	establishing various codes to regulate how these plants should operate.
4	If it is assumed that the distribution grid voltage is sinusoidal, then the
5	following current components can be defined, according to power definitions given
6	by IEEE-Standard 519 [44]:
7	• Active or Direct current component, <i>i_P</i> , that is related to the average active
8	power (P).
9	• Reactive or in-Quadrature component, i_Q , related to the fundamental
10	reactive power (Q)
11	• Harmonic component, <i>i_H</i> , related to the Harmonic Power (H).
12	Usually only the active current component is controlled in conventional
13	PVGPs and the others are set to zero.
14	In a Smart Grid context, where Active Distribution Grids are an strategic
15	priority [45], PVGPs offer a unique opportunity to increase the operation
16	possibilities of energy generators as they are distributed sources that have free
17	capacity (because most of the time they operate under its nominal power, mainly
18	during nights) to be used to help grid management.
19	If we consider an ideal photovoltaic generation day where the maximum
20	power reaches the 90% of the nominal power ratio of the Inverter, we can discount
21	the active component from the nominal current obtaining the available current

22 (non-active current), I_{NA} , given by (4)

$$I_{NA}^{2} = I_{N}^{2} - I_{P}^{2} = I_{Q}^{2} + I_{H}^{2}$$
(4)

In the proposed case of Fig. 13a, *I_{NA}* (Fig. 13b) could reach values that, depending on the time of the day, vary from 40% to 100% of the nominal current. In the previous section it has been discussed how the active component can be controlled by using ESS, in this section the attention is focused on how this non-active current component availability can be used to generate other current components, such as reactive or harmonic ones.



Fig. 13. Non-active current (p.u.) (b) that can be produced depending on the power generated by the PVGP, P_G (p.u.) in relation with its nominal power, P_N (a).

9 By controlling the reactive component it is possible to stabilize the grid via 10 controlling the grid frequency [41] or the voltage [46] at the Point of Common 11 Coupling (PCC) where the PVGP is connected. By controlling the voltage at this point, 12 it is also possible to prevent over-voltages and reduce grid losses [47]. Grid losses 13 can be reduced further if an optimization strategy is applied in multi-bus systems 14 [48].

Therefore, the reactive component can be used during abnormal grid or transient states, mainly during faults or after-faults, in order to compensate voltage sags [49]. In three-phase balanced voltage sags, the PVGP should inject reactive power in order to raise the voltage in all phases. In one- or two-phase faults, the

main concern of the PVGP is to equalize voltages by reducing the symmetric negative 1 2 and, if possible, the homopolar (or zero) sequences [46].

PVGPs can generate harmonic component to prevent the effects of the 3 current harmonic produced by non-linear loads connected to the grid, operating as 4 integrated Active Power Filters [42,43,50,51]. PVGPs could even compensate 5 current unbalance [50] or control the leakage or earth current [52] avoiding the 6 propagation into the grid. For example, in the case presented in Fig. 14, the current 7 produced by the PVGP is not sinusoidal because it contains the harmonic 8 components demanded by the load achieving in this way a sinusoidal current 9

flowing into the grid (and so a harmonic compensation). 10



(a)

(b)

Fig. 14. Example of injecting the harmonic component: (a) harmonic injection 11 turned OFF, and (b) harmonic injection turned ON. Curves from top to bottom:

12

Phase-to-neutral grid voltage, Inverter current, Local load current, and Current 13 flowing to the substation. 14

In some cases, dual or collaborative topologies are used, associating the 15

different current components under control to different converters [50,51]. 16

17 When the active, reactive and harmonics components that PVGP should generate are greater than the available non-active components, some kind of 18 19 priority has to be established. This operation priority could be dependent on the 20 status of the grid, being different in normal and abnormal states [53].

The possibilities of PVGP, as a manageable distributed generation, are much 1 2 more interesting than conventional centralized energy resources. For example, in the proposed initial system of Fig. 2, PVGP could generate the reactive power for 3 controlling the voltage at the PCC or to compensate the reactive power consumed 4 by connected loads. PVGP can also generate the harmonic component needed to 5 compensate the harmonics components of current i_{Ll} and i_{L2} , which prevent these 6 harmonic currents from flowing from the substation. By controlling properly the 7 PVGP we can assure that the current demanded from the grid, *i*_{Grid}, will be sinusoidal 8 and in phase with the substation voltage, achieving a unity power factor, reducing 9 distribution losses and preventing any undesirable effect on the substation 10 transformers. 11

12 13

VI. Grid-friendly connection of PVGP through inverters that mimic

synchronous generators (Synchronverters)

As previously discussed, most of PVGP operate as current sources to inject the energy produced into the grid. When the penetration level of PVGP reaches a certain level, PVGPs should also provide ancillary services. As demonstrated in the previous section, these can be achieved by controlling the current injected into the grid. Another way is to control the grid-connected inverters to behave like conventional synchronous generators so that PVGPs can interact with the grid in a friendly way [1, 54-56,71-77].

21 Synchronverters [54,56] are inverters that mimic synchronous generators. 22 As shown in Fig. 15a, the basic idea is to embed the mathematical model of a 23 synchronous generator [57-59] given below as the core of the controller for the 24 inverter in the general scheme (Fig. 4):

$$\begin{pmatrix} \ddot{\theta} &= \frac{1}{J} (T_m - T_e - D_p \dot{\theta}) \\ T_e &= p M_f i_f \langle i, \widetilde{\sin}\theta \rangle \\ e &= \dot{\theta} M_f i_f \widetilde{\sin}\theta \\ Q &= -\dot{\theta} M_f i_f \langle i, \widetilde{\cos}\theta \rangle$$
 (5)

1

where T_m is the mechanical torque applied to the rotor; T_e is the electromagnetic torque; e is the three-phase generated voltage; θ is the rotor angle; Q is the reactive power; J is the moment of inertia of all the parts rotating with the rotor; D_p is the friction coefficient, p is the number of pairs of poles of the magnetic field, i is the stator current; i_f is the field excitation current; M_f is the maximum mutual inductance between the stator windings and the field winding and $\dot{\theta}$ is the angular speed of the machine. The vectors $\tilde{\sin}\theta$ and $\tilde{\cos}\theta$ are defined, respectively, as

$$\widetilde{\sin\theta} = \begin{bmatrix} \sin\theta \\ \sin(\theta - \frac{2\pi}{3}) \\ \sin(\theta - \frac{4\pi}{3}) \end{bmatrix}, \qquad \widetilde{\cos\theta} = \begin{bmatrix} \cos\theta \\ \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{4\pi}{3}) \end{bmatrix}.$$
(6)





1 this, the matured frequency droop and voltage droop control strategies are applied 2 to regulate the frequency and voltage of the synchronverter through the frequency 3 droop coefficient D_p and the voltage droop coefficient D_q , which are defined, 4 respectively, as

$$D_p = \frac{\Delta T}{\Delta \dot{\theta}}, \quad D_q = \frac{\Delta Q}{\Delta V},$$
 (7)

5 according to the desired change of real power (torque ΔT) with respect to the 6 change of the frequency $\Delta \dot{\theta}$ and the desired change of reactive power ΔQ with 7 respect to the change of the voltage ΔV . Note that the friction coefficient D_p actually 8 performs the function of frequency droop control so there is no need to introduce 9 an extra loop to regulate the frequency, which simplifies the control structure and 10 the associated parameter tuning process.

11 The controller of a synchronverter shown in Fig. 15a has two channels. The 12 upper channel has a cascaded structure, where the inner loop is the frequency loop 13 (with the feedback gain D_p) and the outer loop is the real power loop (with the 14 feedback coming from the current *i* via the torque T_e). For a given time constant of 15 the frequency loop τ_f , the virtual moment of inertia *J* is

$$J = \tau_f D_p \tag{8}$$

This channel regulates the (imaginary) frequency of the generated voltage e and creates the phase angle θ for the control signal e. The lower channel has a cascaded structure, with the inner loop to regulate the voltage and the outer loop to regulate the reactive power. This channel regulates the field excitation $M_f i_f$ to control the amplitude of the generated voltage. For a given time constant of the voltage loop τ_v , the parameter K can be chosen as [57-59]

$$K = \dot{\theta}_n \tau_v D_q,\tag{9}$$

23

1 where $\dot{\theta}_n$ is the nominal angular frequency. Hence, the frequency control, voltage 2 control, real power control, and reactive power control are all integrated in one 3 compact controller with only four parameters. Fig. 16 demonstrates the frequency 4 regulation capability of a synchronverter tested in the lab, where the real power 5 output of the syncrhonverter automatically changed according to the change of the 6 frequency.



7 Fig. 16. Frequency regulation of a synchronverter.

A phase-locked loop (PLL) is adopted to obtain the grid frequency and phase 8 9 so that the synchronverter is able to synchronize with the grid. However, PLLs are difficult to tune and often cause problems [60,61]. The PLL in a synchronverter can 10 11 be removed to achieve a self-synchronised synchronverter [62], as shown in Fig. 15b, after making some changes (highlighted in red) to the original synchronverter. This 12 has taken advantage of the inherent synchronization property of synchronous 13 generators. As a result, a self-synchronized synchronverter can synchronize with 14 the grid before it is connected to the grid and keep synchronized with the grid after 15 it is connected to the grid, without the need of a dedicated synchronization unit. 16

17 <u>Table II – Examples of commercial high power DC/AC converters for PVGPs [18].</u> <u>Parameter</u> <u>ABB</u> <u>Danfoss</u> <u>Satcon</u> <u>Siemens</u> <u>SMA</u> <u>PVS800-MWS</u>, <u>Central PV</u> <u>Satcon</u> <u>Sinvert</u> <u>Sunny Central</u>

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	PVS800-IS*	Inverters*	Prism Platform Equinox*,	PVS 600 series to PVS2400*	
Power	up to 1,25MW up to 2MW*	up to 1,5MW	up to 1,25MW	up to 2,4MW	up to 1,6MW
dc voltage range	525-825V 525-850V*	455-950V	525-825V	570-750V	583-820V
Max. dc voltage	1000V 1100V*	1000V	1000V	820/1000V	1000/1100 V
Output AC voltage	20kV 400V*	430V*	320V*	370V*	20kV
Max. Efficiency	97.8% 98.8%*	98%*	98.5%*	98.6%*	98.2%
Harmonic distorion	<3%	<3%	<3%	-	<3%
Independent MPPT	2	-	2	4	2

1

*- converter without MV separation transformer

2 VII. CONCLUSIONS

PVGPs connected to the grid are increasing both in the number of
installations and also in the rated power of each plant, becoming a significant part
of the electric generation mix, and offering an important opportunity to change the
present distribution grid toward a more intelligent and efficient operation.

In this paper, a comprehensive overview of control structures and their 7 abilities to implement active distribution grid functions have been presented, with 8 the aim of giving ideas for future improvements and research activities in the field. 9 10 Some of these methods and functions described in this paper are already used by commercial MW rated PVGP converters, as shown in Table II. Other 11 12 functions are being considered for next generation of Smart Inverters, opening for 13 Industrial Electronic Researchers an interesting working field that will change in the near future the electric grid from the one we know at the present. 14

The current research and industry trends for power electronics converters
used in PVGPs focus on several important aspects including costs, losses, failure rate,
weight and volume [63].

18 The design of power electronic converters and passive elements must be 19 optimized to decrease losses and increase efficiency. Possible solutions are based on 20 new topologies [64] and new semiconductor components such as silicon carbide

1	(SiC)	components [65,66], the elimination of transformer and direct operation in MV		
2	grid,	the replacement of low frequency passive components by high frequency		
3	trans	formers and inductances [16], the fast and precise GMPPT [67] and new		
4	modu	ulation methods [68].		
5		Other very important trends especially in industry include modular and		
6	redu	ndant systems for proper post fault operation, highly reliable and commercially		
7	avail	able topologies [69], enhanced energy storage technologies and the integration		
8	of ph	notovoltaic plants into smart grids including additional functions such as grid		
9	9 support (V, f, Q control), fault ride through and harmonic compensation [69,70].			
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