Photovoltaic solar system connected to the electric power grid operating as active power generator and reactive power compensator

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Abstract-- ***In the case of photovoltaic solar systems (PV) acting as a distributed generation (DG), the DC energy obtained is fed through the power-conditioning unit (inverter) to the grid. The majority of contemporary inverters used in DG systems are current source inverters (CSI) operating at unity power factor. If, however, we assume that voltage source inverters (VSI) can be utilized instead of CSI, we can generate reactive power commensurate with the remaining unused capacity at any given point in time. According to the theory of instantaneous power, the reactive and active power of inverter can be regulated by changing the amplitude and the phase of the output voltage of the inverter. Based on this theory, the active power output and the reactive power compensation (RPC) of the system are realized simultaneously. When the insolation is weak or the PV modules are inoperative at night, the RPC feature of PV system can still be used to improve the utilization factor of the inverter. The MATLAB simulation results validate the feasibility of the method.***

Index Terms-- **photovoltaic solar systems (PV), distributed generation (DG), reactive power, active power**.

I. INTRODUCTION

ELECTRIC utilities have, historically, satisfied customers demand by centralized electricity generation and distributing it through an extensive transmission and distribution lines. When the demand increases, the company needs to generate extra energy. If demand increases beyond a certain level, generation, transmission and distribution capacities can be unable to offer the necessary amount of energy, becoming mandatory new investments.

An alternative to this problem is to answer locally the demand, through investments in distributed generation (DG). DGs are strategically placed near consumption points where the delivery of electric energy is needed. This can relief generation, transmission and distribution and, consequently, delay the need of new investments [1]. Besides, it can improve the load curve and voltage profile of the feeder, reducing the level of charge of feeders and transformers, bringing environmental benefits, avoiding the emission of polluters if the primary source of energy is renewable [2]. Economic benefits to the energy company also include reduction in electric loses, decrease of energy cost production, bigger capacity of generation, delay of investments in the transmission and distribution capacity, and reduction of risks due to fossil fuel market uncertainties. Another important advantage is the production of small blocks of energy by renewable sources, as small hydroelectric centrals, biomass, wind energy generation, and photovoltaic systems.

There are many reasons to the use of photovoltaic systems as a DG: considerable energetic potential, free of polluting emissions, decrease of the current price of the photovoltaic system components, high reliability, high efficiency of the PV system connected to the power grid, and multi functional features of the building elements [3].

Based on international data, currently, the main application of the PV has been the connection to the electric grid, especially in developed regions as, for example, Japan, USA, and Europe [3]. German should be highlighted because its program of 100.000 solar roofs and its program of installation of PV system in schools that is supported by the federal government and by local energy companies [3].

However, currently, the majority of inverters that are used to connect the PV to the electric power grid are CSI operating with a unity power factor. Then, the power factor of the distribution grid supplied by the PV system that uses this inverter will go to a lowest value because it will supply only the active power. Thus, the reactive power used by the local charges will continue to be supplied by the electric grid, through the capacitor installed in the primary of the distribution grid or by the substation. Nevertheless, this is a disadvantage of the PV systems because they loose their capacities and become useless when the insolation is weak or during the night. At these moments, all charges are supplied by the electric grid. Furthermore, as the PV is turned off during the night, its control is more complex. However, if the VSI

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inverter is applied instead of the CSI, reactive power can be generated and absorbed using the available capacity of the inverter in a specific moment in accordance with the demand of the electric power grid [5].

Thus, in this work, the inverter connected to the electric power grid supplies active power generated by the PV system and supply or absorbed the reactive power, in accordance with the necessity of the distribution grid and the availability of the PV system, simultaneously. So, when the insolation is weak or the PV system is turned off during the night, the function of RPC is used. This extra function increases the availability as well as improves the energy quality of the grid because there is a local power compensation control. The theoretical analysis and the simulation results validate the proposed method.

II. Operation principles

The inverter analysis, related to the generation and consumption of power, can be done similarly to the analysis of a synchronous machine connected to an infinity bus. However, the inverter presents a faster dynamic due to the absence of the inertia of the rotor. On the other hand, the necessity of imposing to the inverter a similar behavior with the synchronous machine becomes the control of the inverter dependent on the feedback of the grid voltage signal.

Differently from the synchronous machine, power inverters don´t have a natural linkage neither between the active power and the phase shifts of generator voltages nor between the output voltage amplitude and the reactive power. Thus, to connect an inverter to an infinity bus, it is necessary that these linkages are created by the control system so that a stable operation can be maintained.

Active and reactive powers carried by the electric grid can be calculated through equations (1) and (2) [7].

$$P = \frac{V_i V_s}{2\pi f L_C} sen\delta = P_{MAX} sen\delta \tag{1}$$

$$Q = \frac{V_i^2}{2\pi f L_C} - \frac{V_i V_s}{2\pi f L_C} \cos\delta \tag{2}$$

where:

V_i = voltage on terminals of the inverters
V_s = voltage of the electric grid
L_C = Inductance of the coupling inductor
δ = Phase difference between voltages V_i and V_s
f = Frequency of the system.

In order to have reactive energy transfer between the inverter and the electric grid, one has the necessity of a voltage amplitude difference between them. If the voltage V_i is bigger than voltage V_s, but in phase, the inverter provides only reactive power to the grid (capacitive mode). On the other hand, is the voltage V_i is smaller than voltage V_s, but still in phase, the inverter absorbs reactive power from the grid (inductive mode).

If the inverter has a store or an energy generator equipment (battery, fuel cell, or photovoltaic system) in the DC side, it can carry out active power change between the inverter and the electric grid. The active power change can be controlled by the phase shift between voltages V_i and V_s. Thus, if it is desirable to absorb active power from the grid, the output voltage is generated with a delay and with the same magnitude of the grid voltage, defining the sense of the active power flow as been from the grid to the inverter. Besides, the inverter can also provide active power to the grid, since the output voltage of the inverter has been produced advanced and with the same magnitude of the grid voltage. This operation is possible since there is a suitable design of the energy generator or storage appliance in the DC side. So, when the voltage V_i is delayed or advanced from V_s (by an angle smaller than 90^o) and with the same voltage magnitude, it has the active power absorption or generation, respectively. Figure 1 shows the phasorial diagram of the operation of the inverter under many working conditions.

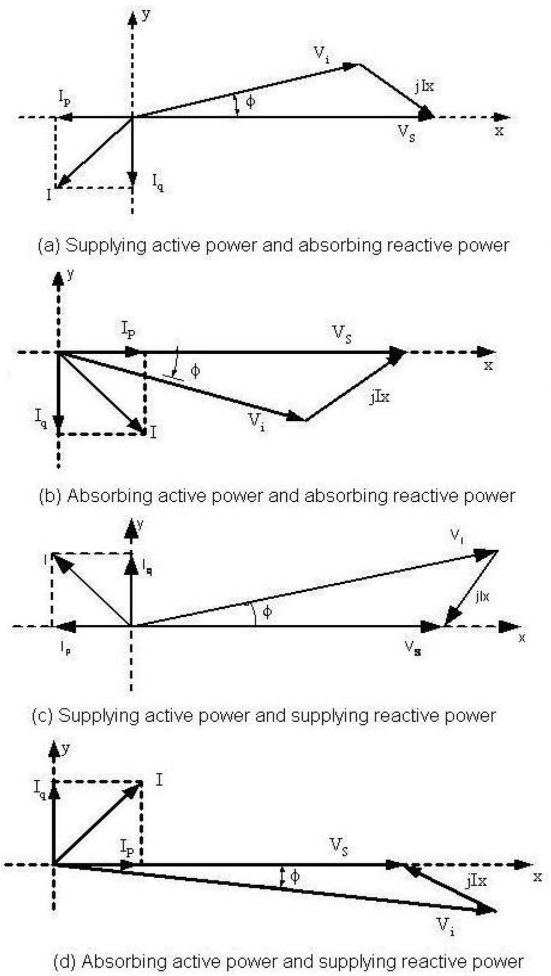

Figure 1. Phasorial diagram of the inverter operation

All functions described previously, absorption or generation of active and reactive power can be controlled independently. Thus, any combination of active power and reactive power is possible. So, the active power that the system generates in its

DC terminals, through a store or generation system, is provided by the inverter to the grid. On contrary, the changed reactive power is provided by the internal characteristics of the inverter, as a function of the commutation operation of the switches.

The active power of the inverter is determined by the value of the power provided by the PV system and by the performance of the inverter. To a specific value of active power, the reactive power provided or absorbed by the inverter is limited by the nominal apparent power, as shown if figure 2. Commonly, the power of the inverter is determined by the maximum active power provided by the PV.

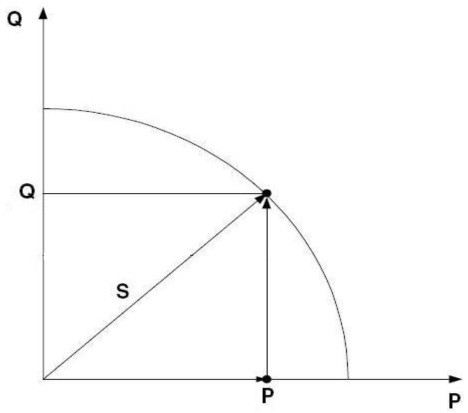

Figure 2. Operational modes of the inverter

III. CONTROL TECHNIQUE AND POWER CIRCUIT

The main objective of the control system of the inverter comprises of setting the power angle, in accordance with the provided energy by the photovoltaic system, carrying out the control of the voltage Vc of the DC bus capacitor, where the PV is connected, to a fixed value. Thus, it provides more or less active power to the electric grid in accordance with the variation of the generated energy. This energy changes with insolation level. Furthermore, this system has the objective of changing the magnitude of the voltage vector in the inverter terminals, doing the inverters absorb or generate reactive power to or from the grid, in accordance with the necessity of the grid. So, when there is few or none energy generation by the PV, in case of cloudy weather or during the night, the idleness of the grid is used.

This aim can be achieved changing the active and reactive power flow between the equipment and the electric grid, through the active I_p and reactive I_q components of the current vector *I*, respectively, as shown in figure 1.

In relation to equations (1) and (2), and in accordance with the analysis carried out, statements of table I can be given:

TABLE I
INVERTER OPERATION

Cases	Inverter
P>0	Supplying active power
P<0	Absorbing active power
Q>0	Supplying reactive power
Q<0	Absorbing reactive power

From all above, as shown in figure 1, it can be seen that, in order to control the flow of the active and reactive powers of the inverter, it should act in the components of currents I_p and I_q, respectively. Such components can be alternated by working properly with the inverter, so that voltage V_i is provided in its terminals and currents I_p and I_q are set in suitable values to the desired compensation.

The full system comprises of PV, boost converter DC/DC, capacitor in the DC side (Cdc), full bridge inverter with PWM control of the switching frequency f_s, filter (Lf and Cf), coupling inductor of the side AC (L_C), voltage and current sensors, and control. The structure of this system is shown by figure 3. Measured variables of the inverter circuit are: voltage DC of the capacitor (V'dc), voltage of the electric grid (Vgrid) and the current of the PV (Ipv).

The boost circuit is used to realize the maximum power point tracking (MPPT) for the PV array output. The incremental conductance method for MPPT is used here [6].

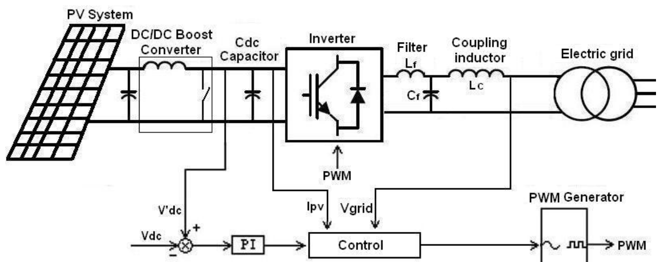

Figure 3. Power system and control of the PV connected to the electric grid

The closed loop control of the DC link voltage is needed because the output power of the PV array is variable with the insolation level and the temperature of the cells. The error between the measured DC link voltage V'dc and the reference DC link voltage Vdc is used to control the output active current of the inverter. Let the reference DC link voltage be the negative input and the measured voltage be the positive input. When the measured DC value is higher than the reference DC value, the error is positive and the inverter produces the active power. The more the error, the more the output of the active power. When the measured DC value is lower than the reference DC value, the inverter decreases or stops delivering the active power.

The control should also set the output voltage amplitude of the inverter, so that this voltage increases or decreases in relation to the reference voltage amplitude due to the decrease of Ipv that is directly related to the fall of the insolation level. So, in accordance with the need of the electric grid, the supply or the absorption of the reactive power by the inverter will increase following the decrease or the stop of the supply of active power, doing the inverter not idle.

IV. RESULTS AND SIMULATIONS

The software MATLAB was used in the simulations to obtain the results for the active, reactive, and apparent powers that are supplied to the electric grid.

The inverter is used to supply active power from a DC source to the grid. To this application, the inverter is associated to the PV modulus that acts as this DC source.

The computational simulations are performed in order to analyze, under different generation conditions, the profile of the active, reactive, and apparent powers.

Furthermore, to the development of this work, the PV system model was used, where the DC reference voltage in the capacitor Cdc of the inverter is set to 390 Vdc in the simulation, while the nominal effective voltage of reference of the grid is 220 Vac. Nominal features of the system PV are: 3250 W, 390 V, to the condition of maximum power, with 1000 W/m^2 of insolation level and temperature of 25^o C. This system is connected to a secondary one of a distribution grid.

As a reference nominal voltage of 220V was obtained, it means that reactive power need to be absorbed by the grid when the voltage in below this value. On the other hand, the voltage is above this value, it is with extra reactive power that needs to be absorbed from the grid. So, the control sets the inverter to supply reactive power to the grid when it has a voltage smaller than 220 V and to absorb reactive power from the grid when it has a voltage bigger than 220 V.

Parameters of the circuit used in the simulation are shown in table II.

TABLE II
PARAMETERS OF THE POWER CIRCUIT

f_s (kHz)	V_{dc} (V)	C_{dc} (μF)	L_f (mH)	C_f (μF)	L_c (mH)
18,00	390	500	0,8	60	5

Results obtained for the stable operation state are shown in figures 4 to 11 that are active, reactive and apparent powers to the four operation conditions. This figures are divided in two situations: from figure 04 to 7 the grid voltage is under the nominal reference value (220 V), demanding the inverter to supply reactive power to the grid, and from figure 8 to 11 the voltage of the grid is above the nominal reference value, demanding an absorption of reactive power from the grid. These conditions of reactive power supply or absorption should act considering the nominal power limit of the inverter.

Apparent power is S (VA), active power is P (W) and reactive power is Q (Var).

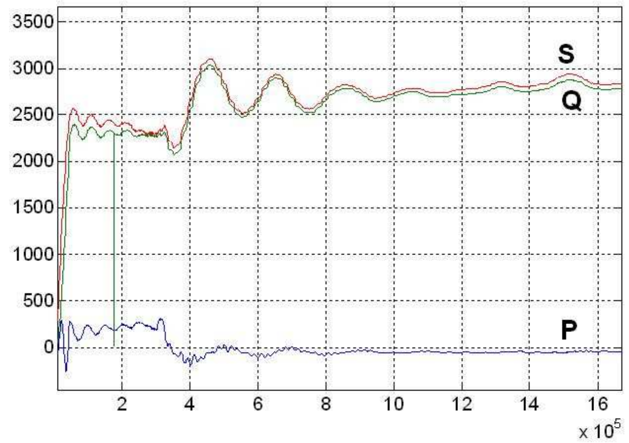

Figure 04: Active, reactive and apparent powers supplied by the inverter with 0% of generation in the PV system.

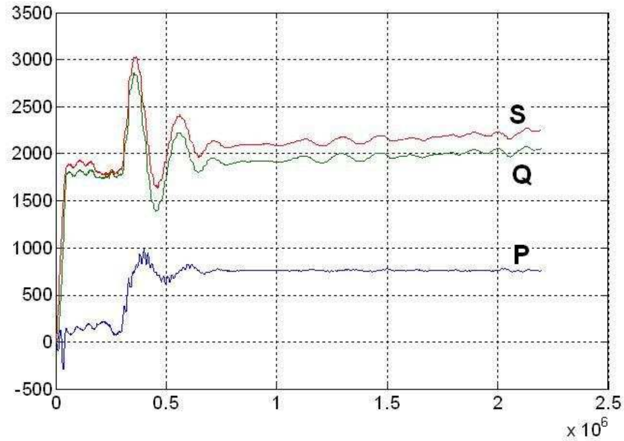

Figure 05: Active, reactive and apparent powers supplied by the inverter with 25% of generation in the PV system.

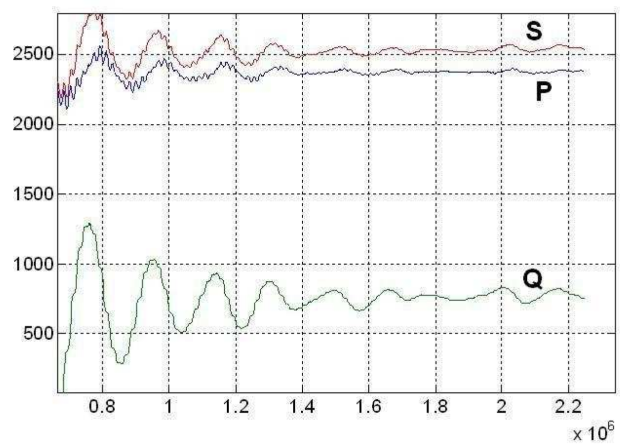

Figure 06: Active, reactive and apparent powers supplied by the inverter with 75% of generation in the PV system.

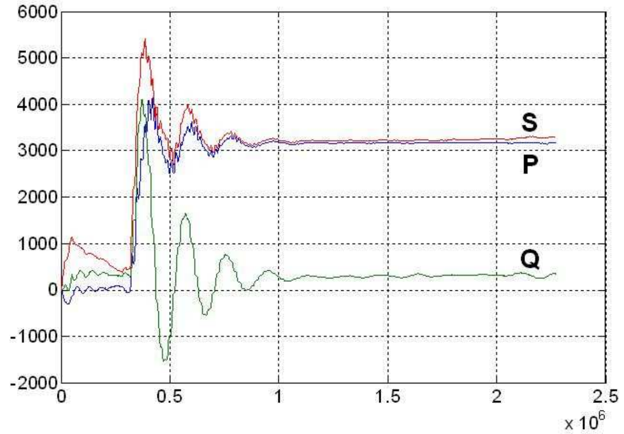

Figure 07: Active, reactive and apparent powers supplied by the inverter with 100% of generation in the PV system.

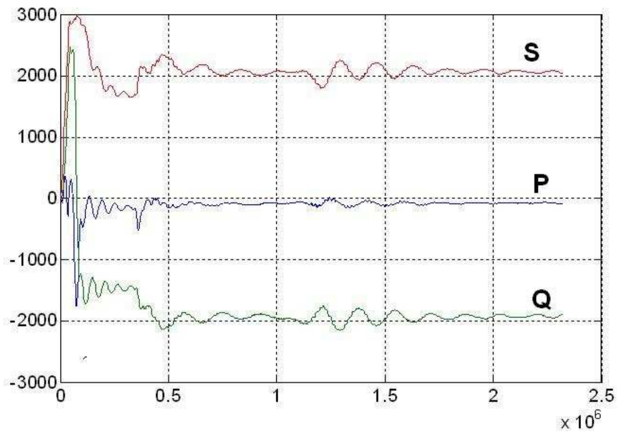

Figure 08: Active, reactive and apparent powers supplied by the inverter with 0% of generation in the PV system.

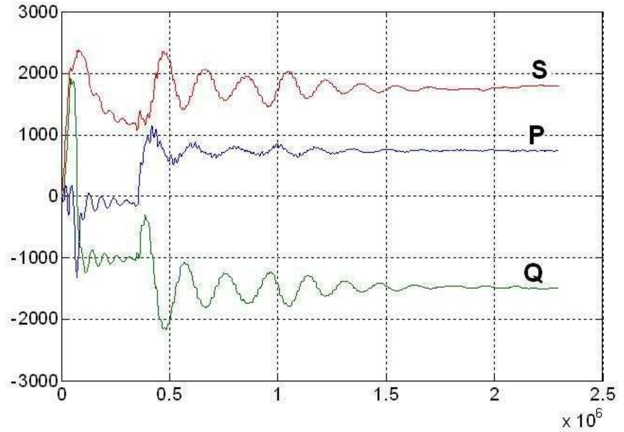

Figure 09: Active, reactive and apparent powers supplied by the inverter with 25% of generation in the PV system.

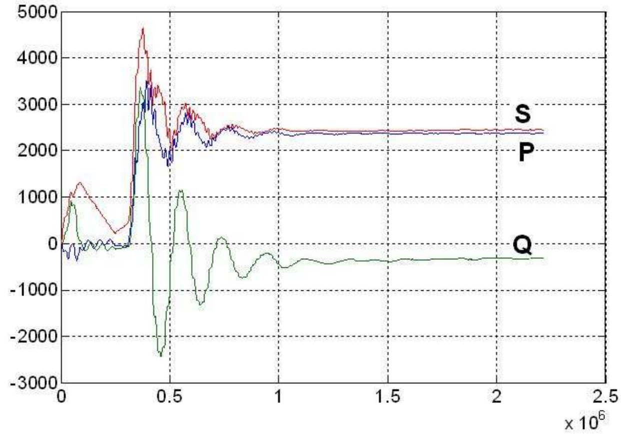

Figure 10: Active, reactive and apparent powers supplied by the inverter with 75% of generation in the PV system.

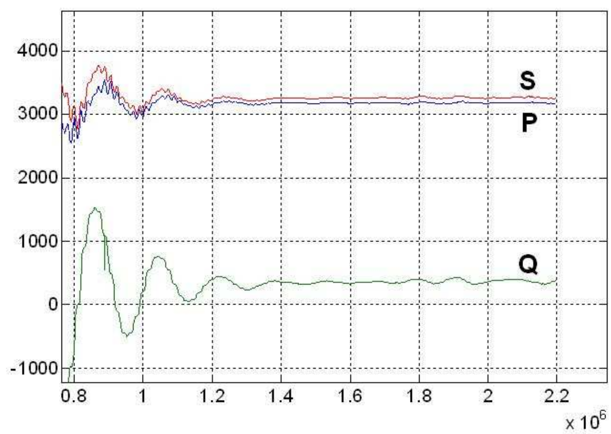

Figure 11: Active, reactive and apparent powers supplied by the inverter with 100% of generation in the PV system.

Figure 4 to 7 show the active, reactive, and apparent power supplied by the inverter to the grid when is necessary to absorb reactive power (V<220 V). They are divided in four insolation level: Case 1 is for insolation level equal to 0%; Case 2 is for 25%; Case 3 is for 75%; and Case 4 is for 100%.

Based on the obtained results, some conclusions can be presented to the active, reactive, and apparent powers generated under the simulated conditions.

The active power supplied by the photovoltaic system to the grid, shown in figures 4 to 7, present a good performance in relation to the control action, because it become stable after some transient oscillations.

In relation to the reactive power, the control worked properly, because it increased the reactive power supply from the inverter to the grid as the active power decreased due to the decrease of the insolation level and vice-versa. This fact becomes the system not idle, having the advantage of compensating the reactive power when little active power is generated.

With the power variation supplied by the PV, it can be verified that an active power generation prevails when the insolation level is high. On the other hand, the reactive power generation prevails when the insolation level is low or during the night.

In relation to the apparent power, it remained with values near the nominal power of the inverter, even with the decrease of the insolation level to zero, during the night. This is an advantage of control model of PV systems using inverters VSI instead of CSI as it is currently done.

Figures 8 to 11 show the active, reactive, and apparent power supplied in case of the grid need that reactive power has to be absorbed (V > 220 V). They are divided in the same four conditions of the generation. However, to this situation, figures present negative reactive power, meaning that the inverter was absorbing it. This has shown that the control worked properly also with the necessities of the grid to this item.

V. Conclusions

Results of the simulation have shown that the control system developed to set the power angle and the amplitude of the voltage and, consequently, to control the active and reactive powers supplied or absorbed by or from the grid presented a satisfactory performance for the analyzed photovoltaic system.

The use of the proposed set for the interface of the photovoltaic system allowed to obtain a better cost-benefit ratio in the implementation of this kind of alternative energy generation, because it become possible to operate a photovoltaic system in many different conditions, independently of the insolation level, supplying both, active and reactive power, in accordance with availability of solar radiation and necessities of the electric grid.

Results have shown that, through the control in the supply or absorption of reactive power, the grid will work with a better power factor, avoiding overloads in transformers and cables, decreasing loses and giving support to the local voltage.

Thus, the inverter supply capacity of active power, i.e., the capacity of absorbing energy of the generation appliance or store of energy (photovoltaic system, fuel cell, or battery) and provide to the grid, become it a good support to the electric system, allowing to improve the global efficiency. Furthermore, in combination with a fast control of reactive power, this toll becomes quite suitable to improve the transient and dynamic stability of a power electric system.

VI. References

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VII. Biographies

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