Mixing Local and Distributed Reactive Power Control for Balancing Inverters’ Effort in Grid-connected Photovoltaic Systems*

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Abstract—Reactive power control methods have been proven to be a successful technique for maintaining voltages of photovoltaic (PV) distributed generators (DG) within the admissible limits without enforcing to reduce the production of active power. Usually the control goal is achieved at the expenses of stressing PV inverters unequally. As a consequence, inverters deteriorate at different velocities. This paper presents a mixed local and distributed control strategy that aims at balancing the effort posed by each inverter while achieving the control goal. The local control is a drop-like method that locates inverters’ voltages within the permissible voltage levels. Simultaneously, the distributed control, making use of a communication infrastructure, is in charge of driving the DG system to the point where all connected inverters inject the same current, thus balancing the stress between them.

I. INTRODUCTION

The installation of distributed PV systems that are interactive with the utility grid is accelerating. Although the rated power of each single PV unit is small, the accumulated power caused by several units demands the application of control strategies to overcome the possible problems that otherwise may occur such as overvoltage [1].

An approach to maintain inverters’ output voltages within the admissible limits is to control the voltage by using the inherent reactive power control capability of inverters which are commonly used for grid connected PV-plants [2]. PV inverters are able to inject or absorb reactive power while active power is fed into the grid. While active power injection increases inverters’ voltage, the injection/absorption of reactive power also increases/decreases inverters’ voltage respectively, thus allowing for local voltage control that can be used for maintaining voltages within the admissible limits, e.g. [3]–[10]. Recurrent discussion topics that can be found in the literature refer to issues related to the type of control strategy to be designed and the figures of merit used to evaluate the goodness of each strategy.

With respect to the type of control strategy, a key point is whether a communication infrastructure linking all distributed PV inverters should be deployed. The apparent advantage of using a communication infrastructure is the possibility of implementing distributed control strategies that can lead to better solutions compared to local ones (at the expenses of the deployment cost). At this point it comes into play the figures of merit used to evaluate each strategy. The most common figure of merit is power losses. For reactive power control methods, power losses become important because additional losses may be generated in inverters and lines due to the possibly higher currents that inverters must inject to achieve the control goal. In addition, the control goal is usually achieved to the detriment of stressing inverters unequally. That is, the computed currents to be injected may be different at each inverter. Therefore, inverters deteriorate at different velocities.

In this paper a novel reactive power control strategy is presented with the objective of stressing inverters equally in order to prolong their lifetime while still maintaining voltages within the limits and not incurring in an increase in power losses. The strategy mixes two approaches. The first one, implemented locally at each inverter, is a drop-like method that locates inverters’ voltages within the permissible voltage levels. Simultaneously, the second one, implemented distributed and thus making use of a communication infrastructure, is in charge of driving the DG system to the point where all connected inverters inject the same current, thus balancing the stress between them. And this is performed without compromising the performance of the DG system in terms of power losses. Note that enforcing inverters to inject equal currents can be seen as an alternative approach to the method of sharing the load demand between inverters in microgrid, which at the end enforces inverters to absorb/inject the same reactive power (see [11] and references therein for load demand sharing approaches).

The design of the novel strategy evolves from the analysis of the local reactive power control methods found in [7] and the distributed reactive power control approach presented in [4]. The novel strategy gathers the benefits and discards the disadvantages of these two approaches to serve the novel control objective: stressing inverters equally.

The rest of this paper is organized as follows. Section II introduces the PV model that will be used throughout the paper. Section III examines two existing policies. Section IV presents the novel control strategy. Finally, section V comparatively discusses the novel strategy with respect the existing ones, and section VI concludes the paper.

II. PV MODEL

The distributed PV system that will be used to illustrate the different designs presented in the paper is shown in Figure 1. Its main components are the grid, distribution lines in the form of resistance/inductance branches $R_1L_1-R_4L_4$,
four inverters G1-G4 with passive local loads connected in parallel, and standard Ethernet (IEEE 802.3 [12]). Each inverter has an inner power control loop whose inputs are a) voltages of the three phases, b) active power set-point and c) reactive power set-point, and whose outputs are the three phase currents to be injected.

Basic configuration for the distributed PV system shown in Figure 1 is as follows. The three-phase voltage source models a series connection of a resistance and an inductance, \( R_iL_i \) with \( i = 1, \ldots, 4 \), with 0.32 \( d_i \) \( \Omega \) and \( (0.082 d_i)/(2\cdot\pi\cdot50) \) H, where \( d_{1,2,3,4} = \{0.3, 0.2, 0.1, 0.1\} \) K\( \text{m} \). All four loads are mainly resistive characterized by \( R_L = 31.74 \Omega \) and \( L_L \approx 0 \) H. Unless otherwise stated, it is assumed that all PV panels are subject to the same solar radiation, thus having similar production profiles [7]. To simplify the analysis and to better illustrate the approaches described in the paper, it is assumed that all generators produce the same active power, \( P_{1,2,3,4} = 35 \) kW, that would occur with maximum solar irradiance. In the case of having each inverter injecting 35 kW, the output voltages determined that the specified loads are characterized by \( P_L \approx 5 \) kW and \( Q_L \approx 0 \) kVar.

Figure 2 shows the output voltage \( V_i \) at each inverter without applying any reactive power control strategy (only active power \( P_i \) is injected). Grid codes specify diverse tolerance thresholds for inverter’s voltages. The majority specify that the voltage operation range should be within 0.85 and 1.1 per unit (p.u.) [13]. These limits are marked with two horizontal lines in the figure. Voltages of two out of the four inverters, G3 and G4, lie above the upper voltage limit (1.1 p.u.) while G1 and G2 voltages are within the statutory limits.

The figures of merit to be considered for designing the novel control strategy can be summarized as follows. First of all, the primary control objective is maintaining inverters’ voltages between permissible limits, that is,

\[ \forall G_i, \quad 0.85 < V_i(p.u.) < 1.1 \]  

where \( V_i \) is the output voltage of inverter \( G_i \). The second objective is balancing inverters’ effort. To this extend, it will be desirable that the amount of injected/absorbed reactive power at each inverter is performed in such a way that all inverters inject the same current, that is

\[ \forall G_i, G_j, \quad I_{G,i} = I_{G,j} \]  

where \( I_{G,i} \) is the injected current of inverter \( G_i \). The third objective is to keep power losses as low as possible. Power losses are computed as

\[ P_L = P_{L,L} + P_{L,G} \]  

where \( P_{L,L} \) and \( P_{L,G} \) are the line and inverter losses respectively, given by

\[ P_{L,L} = 3 \left( \sum_{i=1}^{4} (R_i I_{L,i}^2) \right), \quad P_{L,G} = 3 \left( \sum_{i=1}^{4} (R_G I_{G,i}^2) \right) \]

where \( I_{L,i} \) is the current at each \( R_iL_i \) branch, and \( R_G \) is the equivalent inverter resistance (equal to 0.03 \( \Omega \) for all inverters).

III. REVIEW OF TWO EXISTING POLICIES

This section analyzes the local reactive power control methods found in [7] and the distributed reactive power control approach presented in [4]. The objective is to identify their pros and cons with respect to figures of merit (1)-(3).

A. Local Reactive Power Control

Local reactive power strategies can be mainly grouped as fixed reactive power, fixed power factor (PF), PF in terms of injected active power, and local grid-voltage-dependent reactive power [7]. These methods are based on internal control loops at each inverter that determine the reactive power \( Q_i \).
\[ Q_i = K_p V_i \]

**Fig. 3: Local drop-like control strategy \( Q_{drop} \)**

The proportional gain is designed offline taking into account characteristics of the PV system such as topology and type of transmission lines, active power profiles of the PV panels, loads, regulations that apply for grid-connected PV systems, etc. Once the gains are designed, they are implemented in the internal control loop of each inverter.

Hence, by design, the control meets the desired goal even being an open loop scheme. It is important to stress that for drop-like methods only local measurements are used for achieving the control goal. Henceforth, this approach will be referred to as \( Q_{drop} \) policy.

Although this method is very popular and often advised by regulations, it is an open loop strategy that requires a fine tuning prior system start up and manual re-adjustments in the event of significant changes in the system. In addition, although the proportional controller can be tuned to fulfill the first control goal, the delivered current at each inverter are in general different, thus failing to fulfill the second control goal. For example, with the model described in Section II with proportional gain \( K_p = 150000 \) (which give a PF near 0.9 at the point of common coupling), the first control objective is achieved, as illustrated in figure 4, while the second objective is not fully achieved, as illustrated in the top graph of Figure 5. Moreover, if the power injected by each PV panel is not the same, or the loads vary, the difference between injected currents may dramatically increase. For example, with a generation profile of \( P_{1,2,3,4} = \{5, 15, 25, 35\} \) kW, the first control goal is still achieved but the injected currents are \( I_{G,1,2,3,4} \approx \{10, 23, 36, 50\} \) Arms.

**B. Distributed Reactive Power Control**

Distributed reactive power control may represent an evolution with respect to local strategies because permits developing new strategies where control actions at each DG may be decided using both local and global information while serving different control goals. For example, in [4] a dual control approach, which is illustrated in Figure 6 is presented to fulfill the first control goal (1) while ensuring that each inverter absorbs the same amount of reactive power (as also achieved in the drop control method traditionally applied in load demand sharing approaches)

At each inverter, an internal control loop governed by a proportional/integral (PI) controller performs local voltage control. The per unit output voltage \( V_i \) is measured, and in the event of being above the statutory upper limit (1.1 p.u.), the control loop determines the reactive power to be absorbed in such a way that the voltage is brought at 1.1 p.u.
When the control goal is achieved ($V_i \leq 1.1$), the internal loop is disconnected. Additionally, an external control loop is used for improving a balance among all of inverters. The balance is achieved by having all the inverters modifying their output reactive power to follow via a PI controller a set point which is defined to be the minimum reactive power value among all them (note that minimum should be understood as the maximum amount of absorbed reactive power). In terms of operation, and assuming $n$ inverters in a distribution line topology, all inverters have to send at a given rate their measured reactive power value $Q_i$ over the communication line. Each inverter, using the received values from the $n - 1$ remaining inverters, selects the minimum value that is used for PI set-point control. According to [4], the defined balance helps to further reducing the overvoltage at the distribution line while enforcing all inverters to equally share the absorption of reactive power. Henceforth, this approach will be referred to as $Q_{\text{min}}$ policy.

An interesting property of this method is that the local voltage control in each inverter is in closed loop form, which implies automatic adaptation in the face of changes in the DG system. This property offers the possibility for applying PI self-tuning techniques. However, having at each inverter two PI controllers working towards the same objective may lead to more expensive steady state solutions in terms of, for example, losses. It also may lead to a situation where both PI controllers fight one against the other. As a consequence, although an stable output variable, $Q$, may be achieved, the internal signals (those coming from both PI) may be unstable (growing infinitely). This is an extremely undesirable scenario that may imply damage in the equipments.

Figures 7 and 8 show the behavior of the $Q_{\text{min}}$ approach in terms of voltages, and in terms of injected currents and absorbed reactive power, respectively. The control gains for the PIs of the internal and external control loops for all generators have been set to $K_{p,i}^{\text{int}} = 1000$ and $K_{i}^{\text{int}} = 10000$, and to $K_{p,i}^{\text{ext}} = 0.05$ and $K_{i}^{\text{ext}} = 0.5$, respectively. The transmission rate for the data exchange of the external loop is 1 s. It can be observed in Figure 7 that voltages lie between the limits, fulfilling the first control goal. In addition, it can be observed in Figure 8 that this approach has the ability to equally share among inverters the absorption of reactive power (bottom graph) at the expenses of having different currents injected by each inverter (top graph).

C. An Intuitive Method

The previous approach has the advantage that is able to serve a secondary goal, which is to enforce inverters to equally share the absorption of reactive power. Therefore, it seems straightforward to adapt the previous approach in order to do the same with currents. In particular, the external loop of the scheme shown in Figure 6 can be slightly modified to enforce inverters to inject the same current. This would mean to have all the inverters modifying their output reactive power to follow via a PI controller a set point which in this case would be defined as the average current value among all of them. In terms of operation, and assuming $n$ inverters in a distribution line topology, all inverters would have to send at a given rate their injected current value $I_{G,i}$ over the communication line. Each inverter, using the received values from the $n - 1$ remaining inverters, selects the average value that is used for PI set-point control. Henceforth, this approach will be referred to as $I_{\text{avg}}$ policy.

Figure 9 shows the behavior of this approach in terms of injected currents and absorbed reactive power, respectively. The voltages’ figure has been omitted because has the same shape as the profile shown in Figure 4, which corroborates the thes policy also fulfills the first control goal. The control gains for the PI of the internal control loops have the same value as before, but for the external one have been set to $K_{p,i}^{\text{ext}} = 22$ and $K_{i}^{\text{ext}} = 220$. It can be observed in Figure 9 that this approach has the ability to equally share among inverters the injection of current (top graph), thus fulfilling the second control goal.

However, as also discussed in the previous section, this approach still presents the problem of having competing PIs. Moreover, instability can appear depending on particular system conditions. For example, if the first load that originally
was characterized by $P_L \simeq 5$ kW increases up to 15 kW, the behavior of the system radically changes, bringing the DG systems to the instability as illustrated in Figure 10. This situation can be explained by looking at the relation between the inverter current $I$ and reactive power $Q$ in three-phase systems given by

$$I = \frac{\sqrt{P^2 + Q^2}}{3V}. \quad (4)$$

According to (4), for $Q = 0$, the current is at its minimum, and the current is increased whenever $Q$ is absorbed or injected. In the situation shown in Figure 10, at system start up, the external loop dictates that inverters may follow the average current. This implies that at some point near 5 s, G4 has to decrease its current, which is achieved by not absorbing all the $Q$ that was absorbing just before. Meanwhile G1, G2 and G3 have to increase their currents. For G2 and G3, currents are increased by absorbing $Q$ while for G1 the current is increased by injecting $Q$. The long term effect is that G1 will be injecting more and more $Q$ while G2, G3 and G4 will be absorbing more and more $Q$. This is an unrealistic behavior because inverters do not have infinite capabilities. Moreover, even assuming these capabilities, the system is brought to a failure (currents tend to $\infty$).

IV. NOVEL MIXED STRATEGY

The previous undesirable scenario, the advise given by regulations, and the pros and cons assessed for the three policies analyzed in the previous section, leads to the design of a new strategy illustrated in Figure 11 that mixes the $Q_{drop}$ and $I_{avg}$ policy, named $I_{avg}$.

The internal control loop is characterized only by a proportional controller and the external control loop enforces all inverters to inject the same current value, which is computed as the average of all inverters currents. With the same settings as before, that is with $K_p = 150000$, and with $K_p^{ext} = 22$ and $K_i^{ext} = 220$, with all inverters injecting the same active...
power with equal loads, Figure 12 shows the behavior of this approach in terms of injected currents and absorbed reactive power, respectively. Again, the voltages’ figure has been omitted because has the same shape as the profile shown in Figure 4, which corroborates that this policy fulfills the first control goal. From Figure 12 it can be also concluded that the novel policy fulfills also the second control goal. That is, the internal control loop has the ability to bring all inverters’ voltages within the admissible ranges, while the external control loop, with slower dynamics, regulates the system by slowly varying the absorbed reactive power at each inverter towards the steady state scenario where all inverters are injecting the same current.

To avoid the undesirable scenario described before, the novel policy incorporates a saturation on the reactive power in such a way that it does not permit to increase currents by injecting reactive power. Therefore, whenever a generator is in this situation, $Q_i$ is set to zero. In this event, the rest of generators continue with the standard operation dictated by the external control loop, taking into account that the current average that is transmitted over Ethernet is computed considering only those inverters that do not have a saturation on $Q_i$. In addition, the proposed control structure eliminates the double PI in each inverter, thus eliminating possible conflicts between them (as explained in the analysis of the $Q_{min}$ policy and not illustrated here due to space limitations).

V. DISCUSSION

The novel strategy fulfills the first two control goals, (1) and (2), presented in Section II. In addition, its benefits with respect to previous approaches have been discussed. However, the third goal, which is to maintain losses (3) as low as possible, has not been evaluated. Table I shows the losses of the distributed policies $Q_{min}$, $I^*_i$, and $I_{avg}$ in comparative percentage with respect to the losses generated by the local policy $Q_{drop}$. Losses have been computed as indicated in (3). The $Q_{drop}$ losses have been taken as a baseline number because it represents the most common approach used for reactive power control as well as because it is the approach advised by regulations. Hence, numbers near to zero means that the particular distributed policy does not increase the losses. Positive numbers indicate that the negative fact that losses are increased while negative numbers indicate that losses are decreased.

As it can be seen in Table I, the $Q_{min}$ strategy increases the losses. This was expected because all inverters are forced to absorb excessive reactive power, which is translated into the fact that for example the voltage $V_i$ in Figure 7 for the $Q_{min}$ strategy is unnecessarily far below 1.1 p.u., and lower than the voltage $V_i$ in Figure 4 for the $Q_{drop}$ strategy. On the other hand, the $I_{avg}$ strategy give a 6% of improvement. Therefore, although this improvement is very satisfactory, the commented drawbacks of this strategy impair their implementation. Finally, the $I_{avg}$ strategy does not improve nor penalize in losses. Hence, $I_{avg}$ is able to serve the additional control objective (2) achieved by the external control loop without incurring in an increase in system losses, thus fulfilling the third goal (3).

VI. CONCLUSIONS

In a grid-connected photovoltaic system, the problem of designing a reactive power control strategy able to keep inverters’ voltages within permissible ranges while balancing the effort demanded to each inverter without incurring in excessive system losses has been considered. A novel strategy has been presented that mixes a local and a distributed policy designed after analyzing state of the art solutions. It has been shown that the novel strategy fulfills all the specified control goals while overcoming the problems identified in previous solutions. Future work will analyze its application to a higher and more realistic DG system and will consider its implementation.

REFERENCES