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Active and Reactive Power Control Schemes for Distributed Generation Systems Under Voltage Dips

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Abstract—During voltage dips continuous power delivery from distributed generation systems to the grid is desirable for the purpose of grid support. In order to facilitate the control of distributed generation systems adapted to the expected change of grid requirements, generalized power control schemes based on symmetric-sequence components are proposed in this paper for inverter-based distributed generation, aiming at manipulating the delivered instantaneous power under voltage dips. It is shown that active power and reactive power can be independently controlled with two individually adaptable parameters. By changing these parameters, the relative amplitudes of oscillating power can be smoothly regulated, as well as the peak values of three-phase grid currents. As a result, the power control of grid-side inverters becomes quite flexible. Furthermore, two strategies for simultaneous active and reactive power control are proposed that preserves adaptive controllability. Finally, the proposed schemes are verified experimentally.

I. INTRODUCTION

Voltage dips, usually caused by remote grid faults in the power system, are short-duration decreases in rms voltage. Most voltage dips are due to unbalanced faults, while balanced voltage dips are relatively rare in practice [1] [2]. Conventionally, a distributed generation (DG) system would be required to disconnect from the grid when voltage dips and to reconnect to the grid when faults are cleared. However, this requirement is changing. With the increasing application of renewable energy sources, more and more DG systems actively deliver electricity into the grid. In particular, wind power generation becomes an important electricity source in many countries. Consequently, in order to maintain active power delivery and reactive power support to the grid, grid codes now require wind energy systems to ride through voltage dips without interruption [3] [4]. For the future scenario of a grid with significant DG penetration, it is necessary to investigate the ride-through control of wind turbine systems and other DG systems as well. Disregarding various upstream distributed sources and their controls, the control of DG inverters will be focused on in this paper.

Concerning the control of DG inverters under voltage dips, especially unbalanced situations, two aspects should be noticed. Firstly, fast system dynamics and good reference tracking are necessary. Controllers must be able to deal with all the symmetric-sequence components and to have fast feedback signals for closed-loop control. Secondly, in case of unbalanced voltage dips, the generation of reference currents is important. Because this paper focuses on the second aspect, the control structure of such inverters will be presented in the part of experimental verification.

Under unbalanced voltage dips, current reference generation is constrained by trade-offs. Considering the power-electronics converter constraints, a constant dc-link voltage is desirable [5] and [6]. However, a constant dc bus is achieved at the cost of unbalanced grid currents, and this results in a decrease of maximum deliverable power. In [7], a power reducing scheme is used to confine the current during a grid fault. On the other hand, the effects of the grid currents on the power system side should also be taken into account when assigning reference currents for DG inverters. As presented in [8][9], several specific strategies are possible in order to get different power quality levels at the grid connection point in terms of instantaneous power oscillation and current distortion. One of the methods in [8], which is based on instantaneous power theory [10], obtains zero instantaneous power oscillation but generates distorted grid currents due to asymmetry of grid voltages. Other methods in [8] lead to sinusoidal output currents. These strategies show flexible control possibilities of DG systems under grid faults. However, they only cope with specific cases. Therefore, starting from the ideas in [8], a generalized strategy on reference current generation is carried out in the following.

This paper proposes generalized and independent active and reactive power control strategies based on symmetric-sequence components and shows explicitly the contributions of symmetrical sequences to instantaneous power under unbalanced voltage dips. The proposed strategy enables DG inverters to be optimally designed. Furthermore, two strategies for simultaneous active and reactive power control are proposed that preserves the adaptive controllability.

II. INSTANTANEOUS POWER CALCULATION

To investigate power control strategy, the instantaneous power theory [10] [11] is revisited in this section. Then instantaneous power calculation based on symmetric sequences
is developed, and the notation for the reference current design in the next sections is defined.

A. Instantaneous Power Theory

For a three-phase DG system, instantaneous active power and reactive power at the grid connection point are given by, respectively,

\[ p = \mathbf{v} \cdot \mathbf{i} = v_a i_a + v_b i_b + v_c i_c, \]

\[ q = \mathbf{v} \perp \cdot \mathbf{i} = \frac{1}{\sqrt{3}} \left[ (v_a - v_b) i_c + (v_b - v_c) i_a + (v_c - v_a) i_b \right], \]

where \( \mathbf{v} = [v_a \ v_b \ v_c]^T \), \( \mathbf{i} = [i_a \ i_b \ i_c]^T \), bold symbols represent vectors, and the operator “\( \cdot \)” denotes the dot product of vectors. Note that the subscript “\( \perp \)” is used to represent a vector derived from the matrix transformation in (2), although vectors \( \mathbf{v} \perp \) and \( \mathbf{v} \) are orthogonal only when the three-phase components in vector \( \mathbf{v} \) are balanced.

B. Symmetric-sequence Based Instantaneous Power

Symmetric-sequence transformation is a proven way to decompose unbalanced multi-phase quantities [12]. Consequently, instantaneous quantities for unbalanced a-b-c voltages are represented by

\[ \mathbf{v} = \mathbf{v}^+ + \mathbf{v}^- + \mathbf{v}^0, \]

where \( \mathbf{v}^+,-,0 \) are defined as

\[ \mathbf{v}^+ = [v_a^+ \ v_b^+ \ v_c^+]^T, \quad \mathbf{v}^- = [v_a^- \ v_b^- \ v_c^-]^T, \quad \mathbf{v}^0 = [v_a^0 \ v_b^0 \ v_c^0]^T. \]

For a three-phase DG system, instantaneous active power and reactive power in (1) and (2) can be decoupled into two orthogonal quantities, as depicted in Fig. 1. The subscript “\( p \)” represents the positive-sequence voltage vector, and “\( q \)” represents the negative-sequence voltage vector.

Because the calculation of instantaneous power and current references is carried out in terms of vectors, it can also be used in other reference frames, simply by substituting the vectors in the a-b-c frames with vectors derived in other frames, for example, the stationary \( \alpha-\beta-\gamma \) reference frame.

In next sections, current control based only on positive-sequence and negative-sequence components is investigated. Because zero-sequence voltages of unbalanced voltage dips do not exist in three-wire systems, nor can they propagate to the secondary side of star-ungrounded or delta connected transformers in four-wire systems, most case-studies only consider positive and negative sequences. Even for unbalanced systems with zero-sequence voltage, four-leg inverter topologies can eliminate zero-sequence current with appropriate control. Simplifying assumptions we will use:

- Only positive-sequence and negative-sequence currents are present;
- Only fundamental voltages exist, in practice they can be extracted out;
- The amplitude of the positive-sequence voltage is higher than the negative sequence.

III. STRATEGIES FOR INDEPENDENT P&Q CONTROL

In order to separately analyze the contribution of currents to independent active and reactive power control, sequence currents \( \mathbf{i}^+,^- \) can be decoupled into two orthogonal quantities, i.e. \( \mathbf{i}^+_p \) and \( \mathbf{i}^-_q \), respectively, in terms of \( \mathbf{i}^+_q \) and \( \mathbf{i}^-_q \), we obtain

\[ p = \mathbf{v}^+ \cdot \mathbf{i}^+_p + \mathbf{v}^- \cdot \mathbf{i}^-_q, \]

\[ q = \mathbf{v}^+ \cdot \mathbf{i}^+_q + \mathbf{v}^- \cdot \mathbf{i}^-_p + \mathbf{v}^0 \cdot \mathbf{i}^0. \]
\[ i_\perp = \frac{-k_q v_\perp \cdot i_\perp}{\| v_\perp \|^2}, \quad 0 \leq k_q \leq 1, \]  

where \( \| v_\perp \|^2 = \| v^+ \|^2 = v^+ \cdot v^+ \) is the norm of a vector.

Substituting (13) into (11), and using \( \| v_\perp \| = \| v^+ \| = \| v^- \| \), we obtain

\[
Q \| v^+ \|^2 = (\| v^+ \|^2 - k_q \| v^- \|^2) \left( v_\perp \cdot i_\perp \right). 
\]

Then, based on (13) and (14), currents \( i_\perp^+ \) and \( i_\perp^- \) can be calculated as

\[
i_\perp^+ = \frac{Q}{\| v^+ \|^2 - k_q \| v^- \|^2} v_\perp,
\]

\[
i_\perp^- = \frac{-k_q Q}{\| v^+ \|^2 - k_q \| v^- \|^2} v_\perp.
\]

Finally, the total current reference is the sum of \( i_\perp^+ \) and \( i_\perp^- \), that is

\[
i_\perp = \frac{Q}{\| v^+ \|^2 - k_q \| v^- \|^2} (v_\perp + k_q v_\perp), \quad 0 \leq k_q \leq 1. \quad (17)
\]

2) **Controllable oscillating active power:**

Instead of compensating the oscillating reactive power in (10), we can similarly control the oscillating active power in (9). For this purpose negative-sequence currents are imposed to meet

\[
v^+ \cdot i^- = -k_q v^- \cdot i_\perp^+ , \quad 0 \leq k_q \leq 1 \quad (18)
\]

By considering equation \( v^+ \cdot i^- = v_\perp \cdot i_\perp^- \) (because \( v_\perp \) lags \( v^+ \) by 90° and \( i_\perp^- \) leads \( i^- \) by 90°), the left side of (18) can be rewritten as

\[
v^+ \cdot i^- = v_\perp \cdot i_\perp^- = -k_q v^- \cdot i_\perp^+ , \quad (19)
\]

where \( i_\perp^- \) denotes the orthogonal vector of \( i_\perp^+ \) according to (2). Then, it follows that

\[
i_\perp^- = \frac{k_q v^+ \cdot i_\perp^+}{\| v^+ \|^2} v_-.
\]

Hence the negative-sequence current \( i_\perp^- \) follows directly from (20) as

\[
i_\perp^- = \frac{-k_q v^+ \cdot i_\perp^+}{\| v^+ \|^2} v_-.
\]  

Solving (21) and (11), the positive-sequence current and negative-sequence current are derived as

\[
i_\perp^+ = \frac{Q}{\| v^+ \|^2 + k_q \| v^- \|^2} v_\perp^+ ,
\]

\[
i_\perp^- = \frac{k_q Q}{\| v^+ \|^2 + k_q \| v^- \|^2} v_\perp^- .
\]

Again, the total current reference is the sum of \( i_\perp^+ \) and \( i_\perp^- \), that is,

\[
i_\perp = \frac{Q}{\| v^+ \|^2 + k_q \| v^- \|^2} (v_\perp^+ + k_q v_\perp^-) , \quad 0 \leq k_q \leq 1. \quad (24)
\]

3) **Merging strategies 1) and 2:**

Simple analysis reveals that (17) and (24) can be put together as

\[
i_\perp = \frac{Q}{\| v^+ \|^2 + k_q \| v^- \|^2} (v_\perp + k_q v_\perp) , \quad -1 \leq k_q \leq 1. \quad (25)
\]

Further, by substituting (25) into (9) and (10), it follows that

\[
p = \frac{Q (1 - k_q)}{\| v^+ \|^2 + k_q \| v^- \|^2} (v^+ \cdot v^-) ,
\]

\[
q = Q + \frac{Q (1 + k_q)}{\| v^+ \|^2 + k_q \| v^- \|^2} (v^+ \cdot v^-). \quad (27)
\]

It can be seen that the variant terms of (26) and (27), i.e. oscillating active power and reactive power, are controlled by the coefficient \( k_q \). These two parts of oscillating power are orthogonal and equal in maximum amplitude. Simulation results are obtained in Fig. 2 by sweeping parameter \( k_q \). It is illustrated that either oscillating active power or oscillating reactive power can be controlled.
Detailed derivation of (28) is presented in [13], as well as the control (AARC), and balanced positive-sequence (BPS) are sequence compensation (PNSC), average active-reactive control that the strategies proposed in [9] namely positive-negative-flexibility and facilitates system optimization. It is pointed out with respect to the amplitude drop of voltages, DG systems to contribute with reactive power [3]. For example, be derived by adding (25) and (28), as expressed by

\[ i_p^* = \frac{P}{\|v^+\|^2 + k_p \|v^-\|^2} (v^+ + k_p v^-), \quad -1 \leq k_p \leq 1, \quad (28) \]

where \( k_p \) is the adjustable coefficient for active power control. Detailed derivation of (28) is presented in [13], as well as the applicability for optimization based on this strategy.

**IV. STRATEGIES FOR COMBINED P&Q CONTROL**

As already mentioned, some grid codes also require DG systems to contribute with reactive power [3]. For example, with respect to the amplitude drop of voltages, DG systems having agreements with grid operators are expected to deliver both active power and reactive power during grid faults. Hence the reference currents for this case, named \( i_{pq}^* \), can be derived by adding (25) and (28), as expressed by

\[ i_{pq}^* = i_p^* + i_q^* = \frac{P}{\|v^+\|^2 + k_p \|v^-\|^2} (v^+ + k_p v^-) + \frac{Q}{\|v^+\|^2 + k_q \|v^-\|^2} (v^+_q + k_q v^-_q), \quad (29) \]

oscillating reactive power can be controlled and even can be eliminated at the two extremes of the \( k_p \) curve. This controllable characteristic allows to enhance system control flexibility and facilitates system optimization. It is pointed out that the strategies proposed in [9] namely positive-negative-sequence compensation (PNSC), average active-reactive control (AARC), and balanced positive-sequence (BPS) are equivalent to the results of the proposed strategy when \( k_q \) equals -1, 1, and 0, respectively.

**B. Active Power Control**

For given power \( P \), the current reference for active power control can be derived similarly, as calculated by

\[ i_p^* = \frac{P}{\|v^+\|^2 + k_p \|v^-\|^2} (v^+ + k_p v^-), \quad -1 \leq k_p \leq 1, \quad (28) \]

Note that

\[ \|v^+\|^2 = \|v_\alpha^+\|^2 + \|v_\beta^+\|^2, \quad \|v^-\|^2 = \|v_\alpha^-\|^2 + \|v_\beta^-\|^2 \]

with \(-1 \leq k_p \leq 1, -1 \leq k_q \leq 1\).

It can be seen that there are infinite combinations for (29) with independent coefficients \( k_p \) and \( k_q \). This also implicates that the linear controllability benefitting from previous independent control strategies does not really exist. In order to preserve the controllability, two joint strategies are proposed to simplify (29) by linking the two coefficients.

**A. Joint Strategy with Same-Sign Coefficients**

By setting \( k_p = k_q = k_{pq} \) in (29), reference current calculations are simplified and rewritten as

\[ i_{pq}^* = \frac{S}{\|v^+\|^2 + k_{pq} \|v^-\|^2} \mathbf{R}(\varphi) (v^+ + k_{pq} v^-), \quad (30) \]

where \( S \) is the apparent power with \( P = S \cos \varphi, \quad Q = S \sin \varphi \), and \( \varphi \) the power factor angle. Since the \( \alpha \beta \) reference frame is used in the experiments, it can be derived that

\[ \mathbf{R}(\varphi) = \begin{bmatrix} \cos \varphi & \sin \varphi \\ -\sin \varphi & \cos \varphi \end{bmatrix}. \quad (31) \]

Note that \( \mathbf{R}(\varphi) \) will be different in the a-b-c reference frame.

On the basis of (30), the resulting currents and oscillating powers can now be predicted and adaptively adjusted. To help understanding, a vector diagram representing voltage and current trajectories and the relationship between oscillating power are plotted with \( k_{pq} \) as an adjustable parameter under an unbalanced voltage dip, where \( \varphi = 30^\circ \).

As shown in Fig. 3(a), when \( k_{pq} \) changes from 1 to -1, the length of current vectors changes and reaches a minimum value at \( k_{pq} = 0 \). In Fig. 3(b), the amplitudes of the oscillating powers also vary with the change of \( k_{pq} \), which can be predicted by substituting (30) into (7) and (8). Note that when \( \varphi \) is not 0\(^\circ\) or 90\(^\circ\), i.e. active power and reactive power are.
not zero, \( \tilde{p}_{2,\omega} \) or \( \tilde{q}_{2,\omega} \) cannot be eliminated since either active power or reactive power delivery will introduce oscillating power at the two extremes of \( k_{pq} \).

**B. Joint Strategy with Opposing-Sign Coefficients**

By setting \( k_p = -k_q = k_{pq} \) in (29), the reference current is represented by

\[
i_{pq}^* = \frac{S \cos \varphi}{\|\mathbf{v}^+\|^2 + k_{pq} \|\mathbf{v}^-\|^2} (\mathbf{v}^+ + k_{pq} \mathbf{v}^-)
+ \frac{S \sin \varphi}{\|\mathbf{v}^+\|^2 - k_{pq} \|\mathbf{v}^-\|^2} (\mathbf{v}^+ - k_{pq} \mathbf{v}^-).
\]

Illustrative plots are drawn in Fig. 4. It can be seen from (32) that this joint strategy actually requires twice the computation time of joint strategy A. Fortunately, zero \( \tilde{p}_{2,\omega} \) or \( \tilde{q}_{2,\omega} \) can be achieved at the two extremes of \( k_{pq} \), as shown in Fig. 4 (b). Similar to joint strategy A, when shifting \( k_{pq} \) towards zero the length of current vectors decreases and the current trajectory tends to be a circle.

Therefore it can be summarized that the simple adaptive controllability of independent power control is preserved in the two joint strategies above. This enables DG systems to be optimized under unbalanced voltage dips, e.g. the output power maximization, and the limitation of oscillating active power / reactive power.

**V. EXPERIMENTAL RESULTS**

To verify the proposed strategy, experiments are carried out on a laboratory experimental system constructed from a four-leg inverter that is connected to the grid through LCL filters, as shown in Fig. 5. The system parameters are listed in Table I. By using a four-leg inverter, zero-sequence currents can be eliminated when the grid has zero-sequence voltages. For the cases where the zero-sequence voltage of unbalanced grid dips is isolated by transformers, a three-leg inverter can be applied. A 15kVA three-phase programmable AC power source (SPITZENBERGER+ SPIES DM 15000/PAS) is used to emulate the unbalanced utility grid, and the distributed source is implemented by a dc power supply. The controller is designed on a dSPACE DS1104 setup by using Matlab / Simulink.

**A. Control Realization**

The proposed controller is realized with a double-loop current controller, which consists of an outer control loop...
with proportional-resonant (PR) controllers for eliminating the steady-state error of the delivered currents, and an inner inductor current control loop with simple proportional gain to improve stability. In addition, a feed-forward loop from the grid voltages is used to improve system response to voltage disturbances.

The control for both positive-sequence and negative-sequence components would be much too complicated and computation-time consuming when conventional PI control with coordinate transformation is used. Furthermore, the sequence detection of feedback currents can be left out. Therefore, it is preferred to choose a PR controller in the stationary frame. A quasi-proportional-resonant controller is used here to calculate the angle $\phi$ according to the grid code in [15]. Specifically, the DG system should inject at least 2\% of the rated current for each percent of the fundamental-sequence voltage dip. Therefore the desired angle $\phi$ is calculated by

$$\phi = \sin^{-1} \left( \frac{2 |V^+ - V_N|}{V_N} \right),$$

where $V_N$ is nominal voltage amplitude, and $V^+$ the positive-sequence voltage amplitude. Furthermore, it is also required in [3] that a reactive power output of at least 100\% of the rated current is possible when necessary. Hence also $\phi = 90^\circ$ is assigned directly to test a complete power change from active power to reactive power.

Note that dc-link voltage control is not added here. Usually, based on a stationary frame filter cell in the $\alpha - \beta$ frame [15]. The basic filter cell can be easily implemented using a multi-state-variable structure. Besides, a high performance output can still be achieved under distorted grid voltages.

Concerning the power factor angle $\phi$, two values are tested in the experiment. Firstly, a slightly modified approach is used here to calculate the angle $\phi$ according to the grid code in [3]. Specifically, the DG system should inject at least 2\% of the rated current for each percent of the fundamental-sequence voltage dip. Therefore the desired angle $\phi$ is calculated by

$$\phi = \sin^{-1} \left( \frac{2 |V^+ - V_N|}{V_N} \right),$$

where $V_N$ is nominal voltage amplitude, and $V^+$ the positive-sequence voltage amplitude. Furthermore, it is also required in [3] that a reactive power output of at least 100\% of the rated current is possible when necessary. Hence also $\phi = 90^\circ$ is assigned directly to test a complete power change from active power to reactive power.

Note that dc-link voltage control is not added here. Usually,
a dc-link voltage control loop is included in the control structure, for instance, in a rectifier system [6] or for a wind turbine inverter [7]. The dc bus in the experimental system is only controlled by the dc power supply with a quite low bandwidth to maintain a stable dc bus in an average sense. Since the experiment intends to investigate the effects of the proposed strategy when choosing different $k_{pq}$, it is convenient to leave out the dc voltage control in order to only observe the performance of the proposed strategy.

B. Experimental Results

By shifting the controllable parameter $k_{pq}$, the system is tested under unbalanced voltage dips with the joint strategies. In order to capture the transient reaction of the system, three situations are intentionally tested for comparison at the start moment voltage dips.

As shown in Fig. 6, grid voltages are emulated to be faulty at $t = 0.03$s where phases A and B dip to 70%. Consequently, the power factor angle $\varphi$ derived in the control is $23^\circ$ and the corresponding results of joint strategy $A$ are obtained in Fig. 7. It can be seen that the reactive power support starts within half a cycle after voltage dips. As analyzed in Section IV, the instantaneous active power and reactive power always have oscillating power ripples, and the injected grid currents get balanced only when $k_{pq}$ gets near to zero. In case of $\varphi$ equals $90^\circ$, the joint strategy $A$ turns out to be a reactive power control strategy as expressed by (25). Therefore, comparing with the simulation results in Fig. 2 at the point of $k_{q}=-1$, 0 and 1, it can be seen that the results in Fig. 8 show the same effects on the regulation of oscillating power ripple and reference current.

Under the same test conditions, experimental results are also measured for joint strategy $B$. As shown in Fig. 9, zero oscillating reactive power and active power are achieved at $k_{pq}=1$ and -1, respectively. When $k_{pq}=0$, the results of joint strategy $B$ are same as the results of joint strategy $A$, since both joint strategies only depend on positive-sequence components in this case. The results with $\varphi=90^\circ$ are given in Fig. 10. Comparing with the results in Fig. 8 of joint strategies $A$, it is easily found that both joint strategies turn out to be the same but needing an opposing sign of $k_{pq}$.

VI. Conclusion

This paper proposes generalized strategies for independent active and reactive power control of distributed generation inverters operating under unbalanced voltage dips. Using
derived formulas and graphic representations, the contributions of symmetric-sequence components to the instantaneous power and the interactions between symmetric sequences were explained in detail. Furthermore, for simultaneously controlling active and reactive power, two joint strategies are proposed that preserves the adaptive controllability. The flexible adaptivity of the proposed strategy allows it to cope with multiple constraints and to be optimized in practical applications. The performance of the proposed control strategies is verified by experiments.

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