

Control Strategies for Three-Phase VSIs During Grid Faults: A comparative study of selection criteria of currents reference

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Abstract—Despite the increasing exponentially of the penetration of renewable sources-generated electrical energy into the grid, the increasingly stringent grid requirements aiming the maintenance of grid stability remain as a limiting factor. Renewable energies power plants are usually connected to the grid through powers electronic devices which transform the generated DC power to the AC grid. These converters should be controlled to provide various advanced functions. These functions imposed by grid operators include active and reactive power dynamic control, voltage ride-through, ancillary services like primary frequency control, stationary operation within a range of voltage and frequency, reactive current injection falling on faults, etc... Therefore the aim of this paper focuses on a comparative study between control system topologies designed for the grid side converter, during unbalanced conditions, according to the recent grid codes. The proposed comparative study can be used as a general basis to develop a flexible strategy for control of active and reactive power flow. Depending on the requirements of each application: balanced currents, constant active and/or reactive power, the control and the power flow characteristics are selected.

Keywords—*Renewable Energies; Energy Management; Grid-connected VSI; Grid disturbances; Grid Synchronization; Symmetrical Components.*

I. INTRODUCTION

Driven by economic, environmental, and technical reasons, the energy sector is moving into an area where large sections of increases in electrical energy demand will be met through widespread installation of distributed generation (DG) [1-3]. All actors has brought the recognition that the environment is fragile and global warming due to excessive carbon dioxide emissions and about the other greenhouse gases are considered real concerns to discuss and to resolve. Furthermore, due to their no exhausted nature and benign environmental effects, renewable energy sources are becoming as important generation alternatives in modern electric power systems for both developed and developing countries. Nevertheless, some literatures reveal that, the behavior of power system is mainly related to the behavior and interaction of generators connected to it [4-6]. When the penetration of distributed generation increases its effects on power system also increase.

On the other hand, recent large scale system blackouts have been due to voltage collapses caused by reactive power deficiency, rather than frequency drops [7]. For this reason, strict precautions must be taken to take advantage of distributed generators which are more sensitive and vulnerable to voltage disturbances. This mission can be achieved through power electronic converters since they are used as interfaces for renewable energy distributed generation systems [6]. New robust control strategies must be developed in order to make these devices able to support bi-directional power flow and to ensure continuously power system stability regardless the grid conditions.

Given the electrical grids complexity and dynamism forced by multiple eventualities, when distributed energy systems based on renewable energies are connected to the grid, all grid variables should be continuously monitored in order to ensure power system stability and safety conditions in both regular steady-state and abnormal transient conditions [6], [7]. Voltage-oriented control (VOC) [1] is one of the most used techniques for the operation and control of a distributed power generation system connected to the grid through a controlled VSI. In addition, the well known direct power control (DPC) [8] is one of the most popular direct control strategies. Like VOC technique which can be based on virtual flux (VF-VOC) [9], DPC technique can be implanted under VF concept leading to VF-DPC [8]. Moreover, two DPC based techniques to minimize the Common Mode (CM) emissions have been designed and called DPC-EMC1 and DPC-EMC2 [10]. Other works focused their attention to the predictive DPC (P-DPC) [11] which is based on the combination of the DPC with predictive selection of a voltage-vectors sequence. If the grid voltages are distorted and unbalanced or during voltage sags, many approaches [12-14] have been proposed in order to mitigate unbalanced voltage sag by grid-connected voltage source inverter (VSI). One approach is the feed forward (FF) controller [14]. Its objective was to minimize the impact of unbalanced voltage in the disruption of the DC-bus voltage by adopting two FF controllers tuned at double fundamental grid frequency. Another approach called dead-beat predictive direct power control (DPC) strategy has been presented in [15] to improve voltage-vector sequences for reversible three-phase grid-connected VSIs. In order to solve the issue, that the values of the predicted duration times for the two conventional

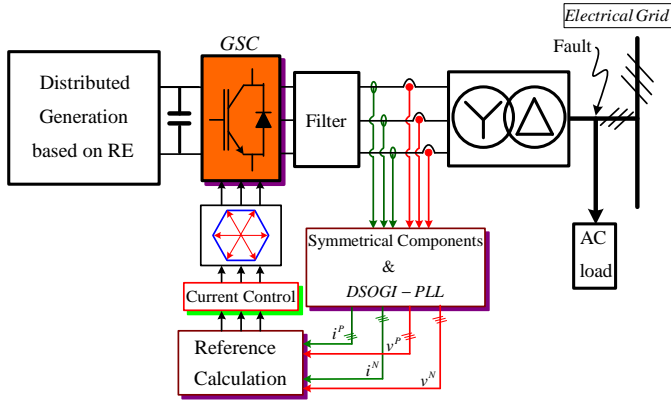


Fig. 1. Overview of the studied system.

active converter voltage vectors are less than zero, two new alternative vector sequences have been proposed based on the instantaneous variation rates of active and reactive powers.

This paper focuses on a careful comparative study of four control strategies designed for power electronics devices interfacing a DG hybrid system with the electrical grid.

II. GRID SIDE CONVERTER CONTROL STRATEGIES

A. Grid Synchronization

Given that the signals of the electrical distribution network can be affected by harmonics and noise, fixed and adaptive filters are crucial for mitigating interferences. Specifically, during asymmetric faults conditions, adaptive filters are quite useful for a variety of applications. In this paper, a phase locked loop (PLL) based on adaptive filtering technique was used to detect correctly the phase angle of the positive-sequence grid voltages [1], [6], [12]. In this context, the concept of separation of symmetrical sequences was studied.

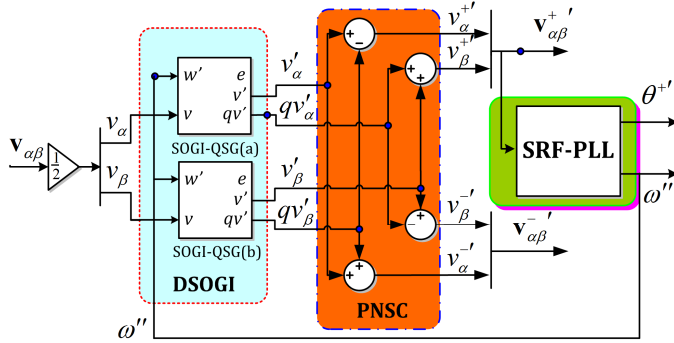


Fig. 2. Positive-/negative-sequence calculation and grid synchronization system based on the DSOGI-PLL.

1) symmetrical components

The concept of symmetrical components, as presented by Fortescue, is well known for power systems to analyze unbalanced conditions. In the literature, a multitude of studies have dealt with the separation techniques of symmetric sequences [6], [12]. Some of them exploit the three sequences:

Positive-, Negative- and Zero- in the dq synchronous reference frame, and some other studies [13], [12] have been limited to the extraction of Positive- and Negative- sequences. These two last sequence's components can be readily expressed in the stationary reference frame $\alpha\beta 0$ by the following relations:

$$\begin{bmatrix} v_{\alpha}^p \\ v_{\beta}^p \end{bmatrix} = \frac{1}{2} \cdot \begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix} \cdot \begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{\alpha}^N \\ v_{\beta}^N \end{bmatrix} = \frac{1}{2} \cdot \begin{bmatrix} 1 & q \\ -q & 1 \end{bmatrix} \cdot \begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix}$$

Here,

q is shift operator corresponding to a delay of 90°

$v_{\alpha}^p, v_{\beta}^p$: $\alpha\beta$ components of the grid voltage vector.

$v_{\alpha}^p, v_{\beta}^p$: $\alpha\beta$ components of the positive sequence voltages.

$v_{\alpha}^N, v_{\beta}^N$: $\alpha\beta$ components of the negative sequence voltages.

Various different approaches for implementing practically the required phase shift have been presented. In this paper, we focused on frequency-adaptive filter based on Second Order Generalized Integrator configured as a quadrature signal generator SOGI-QSG [12]. This choice has been justified by the ability of this filtering method to reduce distortions in either stationary or rotating reference frame.

In presence of sinusoidal signals, the estimated positive and negative sequence components can be expressed by [12]:

ω fundamental angular grid frequency,

s est l'opérateur de Laplace,

$\omega' = 3 \cdot \omega$ resonance frequency

k damping factor.

$$\begin{bmatrix} v_{\alpha r}^p \\ v_{\beta r}^p \end{bmatrix} = \frac{1}{2} \cdot \begin{bmatrix} \frac{k \cdot \omega' \cdot s}{s^2 + k \cdot \omega' \cdot s + \omega'^2} & -\frac{k \cdot \omega'^2}{s^2 + k \cdot \omega' \cdot s + \omega'^2} \\ \frac{k \cdot \omega'^2}{s^2 + k \cdot \omega' \cdot s + \omega'^2} & \frac{k \cdot \omega' \cdot s}{s^2 + k \cdot \omega' \cdot s + \omega'^2} \end{bmatrix} \cdot \begin{bmatrix} v_{\alpha r} \\ v_{\beta r} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} v_{\alpha r}^N \\ v_{\beta r}^N \end{bmatrix} = \frac{1}{2} \cdot \begin{bmatrix} \frac{k \cdot \omega' \cdot s}{s^2 + k \cdot \omega' \cdot s + \omega'^2} & \frac{k \cdot \omega'^2}{s^2 + k \cdot \omega' \cdot s + \omega'^2} \\ -\frac{k \cdot \omega'^2}{s^2 + k \cdot \omega' \cdot s + \omega'^2} & \frac{k \cdot \omega' \cdot s}{s^2 + k \cdot \omega' \cdot s + \omega'^2} \end{bmatrix} \cdot \begin{bmatrix} v_{\alpha r} \\ v_{\beta r} \end{bmatrix}$$

Having established the expressions of positive and negative symmetrical sequences, we justify in what follows the adopted synchronization technique choice.

2) DSOGI-PLL synchronization technique

In previous works [1], [6], [12], several methods have been used widely for grid synchronization. The synchronous reference frame phase-locked loop (SRF-PLL), which uses a combination of Clarke's and Park's transformations, shows fast and accurate PLL performance under ideal grid conditions especially with high bandwidth feedback loop. Nevertheless, this method is sensitive to imbalance and harmonic distortion.

For these reasons, many researchers have proposed several improvements like DSRF-PLL [1], DDSRF-PLL [12]... In this paper, we have adopted the double second-order generalized integrator PLL (DSOGI-PLL) which adopts the instantaneous symmetrical component method on the stationary reference frame and provides an effective solution for grid synchronization of power converters under grid faulty conditions.

B. Comparative Study of Control Strategies

During voltage dips, continuous power delivery from distributed generation systems is suitable to support the network. For this, the control of power electronic interfaces must be adapted to the ongoing evolution of network requirements. In this section, a comparative study has focused on the control of the network-side converter, regardless of upstream sources and their controls. The instantaneous powers delivered to the grid were established according to the instantaneous power theory based on symmetric sequences [12], [13] as follows:

$$p_g = v_g \cdot i_g = \begin{pmatrix} v_a^p \\ v_b^p \\ v_c^p \end{pmatrix} + \begin{pmatrix} v_a^N \\ v_b^N \\ v_c^N \end{pmatrix} + \begin{pmatrix} v_a^Z \\ v_b^Z \\ v_c^Z \end{pmatrix} \cdot \left(\begin{pmatrix} i_a^p \\ i_b^p \\ i_c^p \end{pmatrix} + \begin{pmatrix} i_a^N \\ i_b^N \\ i_c^N \end{pmatrix} + \begin{pmatrix} i_a^Z \\ i_b^Z \\ i_c^Z \end{pmatrix} \right) \quad (3)$$

$$q_g = (v_{g\perp}) \cdot i_g = \left\{ \frac{1}{\sqrt{3}} \cdot \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix} \cdot \begin{pmatrix} v_a^p \\ v_b^p \\ v_c^p \end{pmatrix} + \begin{pmatrix} v_a^N \\ v_b^N \\ v_c^N \end{pmatrix} + \begin{pmatrix} v_a^Z \\ v_b^Z \\ v_c^Z \end{pmatrix} \right\} \cdot \left(\begin{pmatrix} i_a^p \\ i_b^p \\ i_c^p \end{pmatrix} + \begin{pmatrix} i_a^N \\ i_b^N \\ i_c^N \end{pmatrix} + \begin{pmatrix} i_a^Z \\ i_b^Z \\ i_c^Z \end{pmatrix} \right)$$

The objectives of the control strategies that will be checked will be focused on the control of active and reactive powers while paying particular attention to the generation of balanced three-phase injected current, the elimination of second harmonic oscillations in active and reactive power flow. Herein, we talk about the instantaneous active reactive control method (IARC), the instantaneously controlled positive-sequence method (ICPS), the average active reactive control method (AARC) and the balanced positive-sequence control method (BPSC) [12], [13]. For each of the studied methods, the generation of the reference currents is established taking into account the various compromises and constraints of the power electronic converter. The calculation of reference currents is based only on positive and negative sequence instantaneous components.

III. SIMULATION RESULTS & DISCUSSIONS

The response of the for control strategies during a voltage sag type C engaged at t=0.1seconds. The voltages at the PCC point terminals are behaving as Fig. 3 shows.

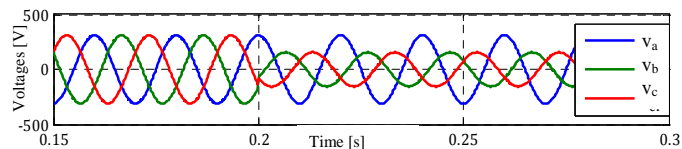


Fig. 3. Unbalanced grid voltages.

The application of the IARC control technique shows that, although the active and reactive powers are kept constant even in case of fault, the currents injected to the grid are unbalanced and very harmonic polluted currents (Fig. 4).

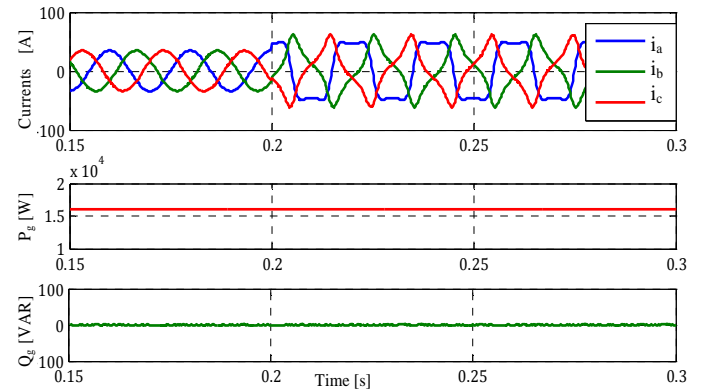


Fig. 4. Grid currents and active and reactive powers using IARC control.

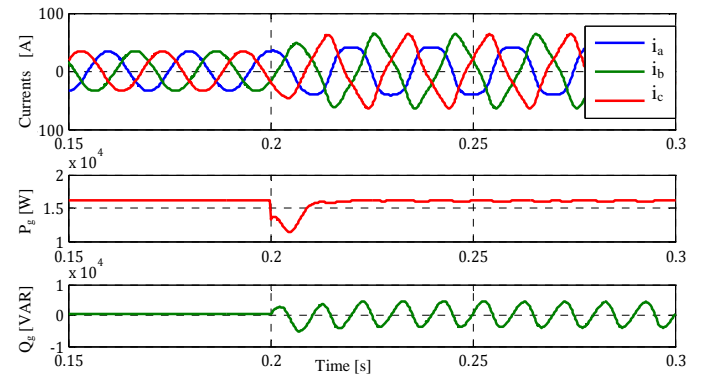


Fig. 5. Grid currents and active and reactive powers using ICPS control.

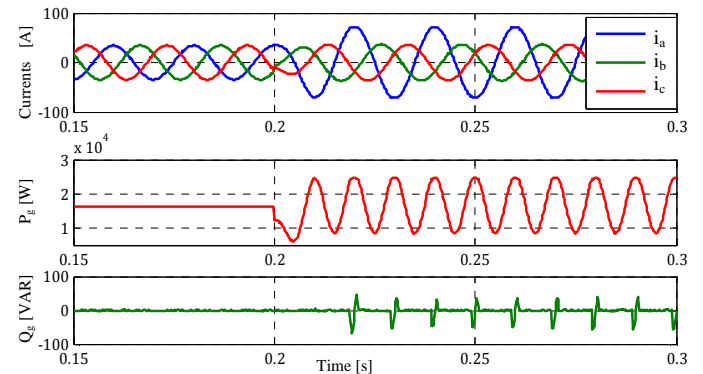


Fig. 6. Grid currents and active and reactive powers using AARC control.

In case of the ICPS strategy and facing the same fault, Figure 13 shows the appearance of reactive power oscillations at twice the fundamental frequency. However, the injected currents are less distorted than in the case of the previous control strategy, but they are still far from sinusoidal. Regarding the active power P_g , it is shown that it is well controlled.

For the AARC method, the active power reference is maintained equal to its reference P_g^* and that of the reactive power is kept at zero. It can be proven that the injected currents are assumed sinusoidal unbalanced in amplitude when imbalance occurs (Fig. 6). These currents are proportional to

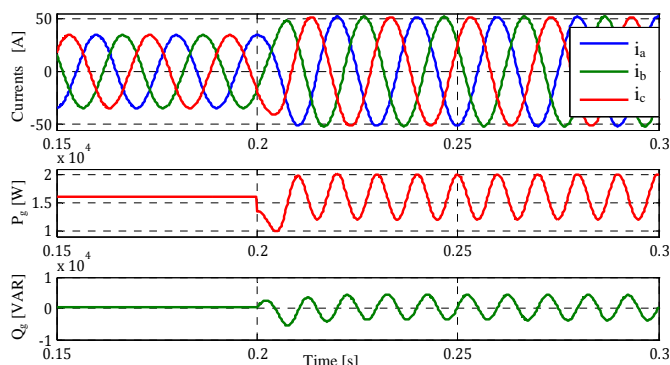


Fig. 7. Grid currents and active and reactive powers using BPSC control.

the point of common coupling voltages. However, the active power reveals significant oscillations at twice the fundamental frequency ($\tilde{p}_{2\omega} \approx 50\%$ of P_g^*). Moreover, this technique is able to eliminate the reactive power oscillations.

In the presence of the same default, BPSC control allows to have sinusoidal currents, balanced and in-phase with the corresponding voltages (Fig. 3). The current amplitude is increased to maintain the average active power injected to the PCC during the voltage dip. Only, important second harmonic oscillations was superimposed upon both the active and reactive powers; which is detrimental to the stability of the power system (Fig. 7).

IV. CONCLUSIONS

This paper presents and discusses four control strategies dedicated to control a grid-connected inverter under unbalanced operating conditions. Especially, it focuses on the generation of the current references responsible to control the delivered reactive power.

The results have shown that the choice of the suitable strategy for delivering a desired reactive power depends also on another compromise. In fact, the limitation of power oscillations engenders distorted currents however the generation of high-quality currents imposes important power oscillations. This is very useful for analyzing the selection criteria. It proves that such a strategy depends on the utility network needs. Much remains to be done especially if we take account additional complexities of other structures of the GSC converter.

REFERENCES

[1] R. Abbassi, S. Chebbi, "Energy Management Strategy for a Grid-Connected Wind-Solar Hybrid System with Battery Storage: Policy for Optimizing Conventional Energy Generation", *International Review of Electrical Engineering*, Vol. 7, N° 2, pp. 3979-3990, April 2012.

[2] Balaguer, I.J. Qin Lei ; Shuitao Yang ; Supatti, U.; Fang Zheng Peng, Control for Grid-Connected and Intentional Islanding Operations of Distributed Power Generation, *Industrial Electronics, IEEE Transactions on*, Vol. 58, n° 1, pp. 147 - 157, 2011.

[3] R. Abbassi, S. Chebbi, "Optimal Energy Management Strategy for Wind Photovoltaic Hybrid System with Battery Storage", 16th IEEE Mediterranean Electrotechnical Conference (MELECON), pp. 810–813, Mars 2012.

[4] F. Blaabjerg, Z. Chen, and S. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184–1194, Sep. 2004.

[5] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, 2006.

[6] R. Abbassi, S. Saidi, M. Hamami, S. Chebbi, "Analysis and Operation of Renewable Energy Power Generation Systems: The Key to Optimizing Power System Reliability and Flexibility During Unbalanced Network Fault", *Handbook of Research on Advanced Intelligent Control Engineering and Automation: Pennsylvania (USA)*, November 2014, Chapter 24.

[7] Wei, Mu; Chen, Zhe, "Study of Distributed Generation System Characteristics and Protective Load Control Strategy", *Universities' Power Engineering Conference (UPEC), Proceedings of 2011 46th International*, vol., no., pp.1,6, 5-8 Sept. 2011.

[8] S. Saidi, R. Abbassi and S. Chebbi, "Virtual ux based direct power control of shunt active filter," *Scientia Iranica D*, vol. 21, n° 6, pp. 2165-2176, 2014.

[9] Gonzalez Normiella, J. Cano, J.M. ; Orcajo, G.A. ; Rojas, C.H. ; Pedrayes, J.F. ; Cabanas, M.F. ; Melero, M.G. "Improving The Dynamics Of Virtual-Flux-Based Control Of Three-Phase Active Rectifiers," *IEEE Trans. on Industrial Electronics*, Vol. 61, n° 1, pp. 177 - 187, Jan. 2014.

[10] Cirrincione, M. ; Pucci, M. ; Vitale, G., "New Direct Power Control Strategies of Three-Phase VSIs for the Minimization of Common-Mode Emissions in Distributed Generation Systems," *Industry Applications IEEE Conference, 42nd IAS Annual Meeting.*, pp. 1962-1973, 2007.

[11] A. Bouafia, J. P. Gaubert, and F. Krim, "Predictive direct power control of three-phase pulsewidth modulation (PWM) rectifier using space-vector modulation (SVM)," *IEEE Trans. Power Electron.*, vol. 25, no. 1, pp. 228–236, Jan. 2010.

[12] J. A. Suul, A. Luna, P. Rodriguez, and T. Undeland, "Virtual-Flux-Based Voltage-Sensor-Less Power Control for Unbalanced Grid Conditions", *IEEE Trans. Power Electron*, vol. 27, pp. 4071-4087, 2012.

[13] F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Pliant Active and Reactive Power Control for Grid-Interactive Converters Under Unbalanced Voltage Dips", *IEEE Trans. Power Electronics*, Vol. 26, No. 5, pp. 1511-1521, May 2011.

[14] Hasan, H., "Improved voltage disturbance rejection of grid-connected VSC under unbalanced voltage sag based on grid dynamic model". 3rd International Conference on Instrumentation Control and Automation (ICA), 2013 , 28-30 Aug. 2013. Ungasan. pp. 92-97. DOI:10.1109/ICA.2013.6734070

[15] Jiabing Hu; Zhu, Z. Q., "Improved Voltage-Vector Sequences on Dead-Beat Predictive Direct Power Control of Reversible Three-Phase Grid-Connected Voltage-Source Converters," *Power Electronics, IEEE Transactions on*, vol.28, no.1, pp.254,267, Jan. 2013. doi: 10.1109/TPEL.2012.2194512

[16] Remus Teodorescu, Marco Liserre and Pedro Rodríguez, "Grid Converters for Photovoltaic and Wind Power Systems", 2011, John Wiley & Sons, Ltd. ISBN: 978-0-470-05751-3.

[17] de Souza, H.E.P.; Bradaschia, F.; Neves, F.A.S.; Cavalcanti, M.C.; Azevedo, G.M.S.; de Arruda, J.P., "A Method for Extracting the Fundamental-Frequency Positive-Sequence Voltage Vector Based on Simple Mathematical Transformations," *Industrial Electronics, IEEE Transactions on*, vol.56, no.5, pp.1539,1547, May 2009.