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# CONTROL AND GRID SYNCHRONIZATION OF TWO LEVEL VOLTAGE SOURCE INVERTER UNDER TEMPORARY VOLTAGE UNBALANCE

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***Abstract**. This paper presents the operation of grid tied, two level voltage source inverter (VSI) during network voltage unbalance. The control system was implemented in synchronous rotating reference frame dq0 (SRF). Two types of control structures were investigated herein. First utilizes the Double Decoupled SRF Phase-locked loop (DDSRF-PLL) synchronisation with positive and negative sequence currents control. Second one is simplified system that does not provide symmetrical components decomposition and decoupling for synchronisation. Simulation results exhibited a superior performance of the DDSRF-PLL control system under grid voltage unbalance.*

**Keywords**: control, PLL, unbalance, synchronisation

## STEROWANIE ORAZ SYNCHRONIZACJA DWUPOZIOMOWEGO FALOWNIKA NAPIĘCIA W WARUNKACH PRZEJŚCIOWEJ ASYMETRII NAPIĘĆ SIECI

***Streszczenie:** Niniejszy artykuł przedstawia pracę dwupoziomowego falownika napięcia współpracującego z siecią, podczas przejściowej asymetrii napięć. System sterowania został zaimplementowany w wirującym układzie synchronicznym dq0. Przeanalizowano dwa typy sterowania. W pierwszym zastosowano metodę synchronizacji z odprzęganiem DDSRF-PLL wraz z możliwością kontroli prądów składowej zgodnej i przeciwnej. Drugi natomiast w swoje uproszczeni formie nie pozwalała na sterowanie obu składowych symetrycznych, zabrakło również odprzęgania podczas synchronizacji z siecią. Wyniki symulacji pokazały o wiele lepsze działanie pierwszej metody sterowania.*

**Słowa kluczowe**: sterowanie, PLL, asymetria, synchronizacja

## Introduction

The semiconductor based power converters are commonly used in order to provide the desired supply conditions for a given application. This can be for example a motor drive which requires a specific functions that could not be provided by means of any other equipment. Another application are renewable energy sources [34]. Typically the transmission system operator (TSO) defines the requirements for grid connected converters operation (grid codes). The increasing demand of grid code compliance require a sophisticated power converters topologies and control [33]. Due to unpredictable nature of energy carriers such as wind, sun radiation or sea waves, not only the network operator's requirements are the challenge, but also a robust and economical operation of such power sources are at stake [35]. Three phase electrical utility grid is subjected to various disturbances such as faults, harmonics, transients, it is crucial that the converter is able to withstand such conditions. One of the most common disturbance occurring in three phase network is voltage unbalance. It may be caused by variety of factors such as faults, unsymmetrical load, system overloading [30].

The main scope of this paper is the investigation of control method that ensure stable operation of power converter and maintain the reference tracking during AC grid unbalance. Moreover, the author presents a comprehensive literature review which resulted in clear classification of available methods applied for control of grid connected power converters. The following sections of this paper present the comparison of highly complex control scheme that is able to fulfil abovementioned requirements and the simplified algorithm with limited controllability of power converter output during voltage asymmetry. Both of control schemes are based on voltage oriented (VOC) approach with PI regulators operating in synchronous rotating reference frame *dq0* (SRF). The simulation results obtained using Simulink software are followed by their interpretation and conclusions.

## 1. Voltage unbalances in three phase grids

In certain conditions the three phase grid voltage can become either unbalanced or distorted. The unbalance may take a various form but generally it concerns voltage magnitude, phase or both. In order to simplify the analysis of such unbalanced systems the decomposition into symmetrical components is applied. It allows one to represent the unbalanced system by means of three symmetrical balanced components namely: positive, negative and zero sequence. Positive and negative sequences are three phase symmetrical, 120 degrees shifted systems that rotate with the same frequency but in opposite directions. Whilst zero sequence components are all in phase. When considered as vectors the original voltage vector is essentially a geometrical sum of corresponding positive, negative and zero sequence components.

Due to the fact that the voltage unbalances may have a various nature, it is convenient to have some kind of classification that would at least give an idea which parameters of the supply are affected the most. The general classification of disturbances in power systems is for example provided by the IEC 61000-2-5:1995 standard [30]. It addresses the number of phenomena and classify them in the frequency domain (Table 1). As can be observed the low frequency conducted phenomena is one of the largest group. It is also a crucial range from the point of view of power converters control. This is due to the fact that high frequency phenomena are hard to be affected by the control that is coupled with a power converter which operates at switching frequency in range of couple of kHz.

One of the simplest parameter that expresses the severity of unbalance is expressed by the equation (1). It shows the ratio of negative sequence to positive sequence voltage average value [31].

$$\%Imbalance = \frac{|V_{neg}|}{|V_{pos}|} \times 100\%$$

More complex view on the type of voltage unbalance is so called ABC notation which is strictly related with a fault type that can cause such voltage conditions. This kind of classification precisely specifies how the fault has affected the symmetrical components of the voltage. Knowing that one may easily distinguish the disturbance and possibly apply certain countermeasures [6, 7]. Only type A voltage sag is a symmetrical disturbance that appears only in amplitude. This kind of disturbance can be caused for example by 3-phase fault or symmetrical overload. Type B can be easily projected to e.g. single phase fault which is one of the most common short circuits in power systems (around 70% of all faults [37]). Type E can be a consequence of two phase to ground fault. Whereas types C, D, F and G are the consequences of either B or E. There are also other classification schemes that may be applied for a description of voltage unbalance. In [32] author proposes the classification that is based on space vector methodology. This method utilizes the fact that in balanced conditions the rotating space vector on the complex plane that represents the voltage creates the perfect circle. Unlike when the unbalance occurs, during which this shape becomes elliptic. This deformation is defined by the severity of magnitude and phase unbalance.

*Table 1. The classification of network disturbances [30]*

| *Group* | *Examples* |
|---|---|
| Conducted low-frequency phenomena | Harmonics, interharmonics<br>Signal systems (power line carrier)<br>Voltage fluctuations<br>Voltage dips and interruptions<br>Voltage imbalance<br>Power-frequency variations<br>Induced low-frequency voltages<br>DC in AC networks |
| Radiated low-frequency phenomena | Magnetic fields<br>Electric fields |
| Induced continuous wave (CW) voltages or currents | Unidirectional transients<br>Conducted high-frequency phenomena<br>Oscillatory transients |
| Radiated high-frequency phenomena | Magnetic fields<br>Electric fields<br>Electromagnetic fields<br>Continuous waves<br>Transients |
| Electrostatic discharge phenomena (ESD) | - |
| Nuclear electromagnetic pulse (NEMP) | - |

## 2. Power converters control methods

The topic of grid connected power electronic control has been elaborated in number of papers [25, 38, 45, 63, 75, 76]. The variety both methods makes it possible to find the optimal solution for nearly every application. A universal control scheme that would satisfy all requirements does not exists and there are always certain constraints to every single method. The choice of the control technique should be made mainly based on the application. Factors such as power, voltage level, space constraints also play a significant role in choosing the control or modulation type. This chapter provides a comprehensive view on available control methods that can be applied for grid connected converters. Although, the primary goal of each method is to robustly track the desired reference their performance and complexity may differ significantly. Table 2 presents control methods that are categorized based on relevant references.

The most common control methods are voltage or virtual flux oriented control methods based on proportional-integral (PI) or proportional resonant (PR) controllers. The topology presented herein is the state-of-the art approach. Implementation in *dq0* SRF with axis decoupling and separate controllers for positive and negative components is a robust and well known solution. Predictive methods such as DB or FCS-MPC provide superior performance in terms of dynamics but are fairly complex and require a good knowledge about the system under control. Likewise the State Feedback control requires accurate model of the system as well as increased number of measurements (which can be in some cases replaced with observers). DPC offers a high dynamic and reference tracking. On a downside it requires high sampling rates and is characterized with variable switching frequency when applied with use of LUT. Sliding Mode Control operation principle consists in modification of a control structure that maintains the output within predefined range (sliding surface). Fuzzy logic control on the other hand allow to control the system even in case of limited knowledge about it structure (i.e. does not require exact model of the controlled structure). It is based on set of fuzzy logic rules that assign the input value to a specific membership function defined by the designer. Finally the hysteresis controllers track the control single with respect to the reference value in order to keep it within specified limits (hysteresis band). Hysteresis band may be constant or adaptive which results in either variable or constant switching frequency.

*Table 2. The classification of grid connected power converters control methods*

| |
|---|
| Voltage/Virtual flux Oriented Control (VOC/VFOC) |
| • PI-VOC/VFOC [16, 22, 47, 61, 66, 73] |
| • PR-VOC/VFOC [4, 27, 41, 69] |
| • Integral Resonant [42, 43] |
| Dead-beat control (DB) |
| • DB-DPC [56, 57] |
| • DB current control [5, 11, 24, 48, 79] |
| Finite Control Set Model Predictive Control (FCS-MPC) |
| • DPC [70] |
| • VF-DPC [3, 51] |
| • Current control [71] |
| • MP3C [23] |
| • Hysteresis [81] |
| State Feedback Control |
| • Full State Feedback [10, 18, 20, 67] |
| • Partial State Feedback [21, 58] |
| Direct Power Control (DPC) |
| • Look-up Table Based (LUT-DPC) [15, 29, 52, 60] |
| • Space Vector Modulation Based (SVM-DPC) [50, 82] |
| • ORS concept [19] |
| Sliding Mode Control |
| • Hysteresis based [1, 2, 13, 39, 40, 74] |
| • PWM based [14, 26, 36, 44, 46, 77, 78] |
| • DPC [28] |
| Fuzzy Logic Control |
| • DPC [8, 9] |
| • PID or PR [12, 62, 65, 72] |
| • Adaptive [64] |
| Hystersis Control |
| • Constant hysteresis band [17, 49, 53, 54] |
| • Variable hysteresis band [55, 59] |

Most of existing current and power control methods were verified or adopted for operation under voltage unbalance. The main reason for making the converter control immune to disturbances such as voltage unbalance are network stability requirements. Namely, the converter should not trip which could lead (especially in high power applications) to load rejection or generation loss. This in turn may cause frequency and voltage variation which are unfavourable in terms of network operation. This paper presents as an example of power converter control under voltage unbalance a widely used VOC technique with a robust DDSRF-PLL synchronisation algorithm

## 3. Control system and network description

The control methods described herein are both voltage oriented (VOC) with PI controllers used for current reference tracking. They differ in control capabilities during voltage unbalances. The most important differences are application of symmetrical components decomposition and Double Decoupled SRF Phase-locked loop (DDSRF-PLL) synchronisation in case of extended VOC control. [47, 68, 80, 83]. It is noteworthy that the gains of the current and PLL PI controllers are the same for basic and extended control algorithms.

### 3.1. Basic VOC-SRF control algorithm

Basic control algorithm implemented in SRF is a VOC with feedforward and PI regulators and simple phase-locked loop (PLL). This particular control system lacks function of symmetrical components decomposition. Both the control structure and PLL are shown in figures below (Fig. 1 and Fig. 2 respectively).

The reference values of direct and quadrature components of currents (proportional respectively to active and reactive powers) are calculated based on equations (1) – (4) setting the negative sequence components of currents of voltages and currents to zero.

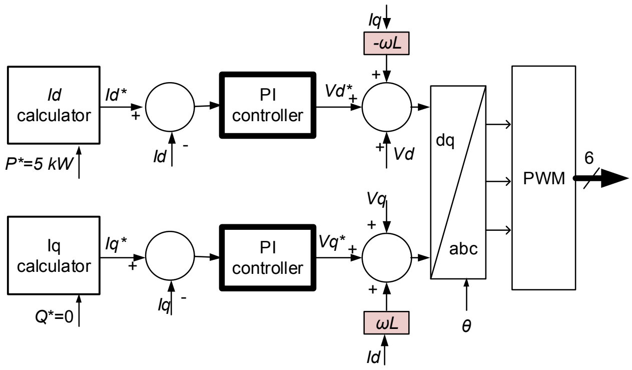


*Fig. 1. Basic VOC-SRF control*

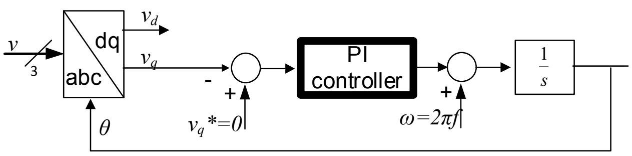


*Fig. 2. Basic PLL grid voltage synchronisation*

## 3.2. Extended VOC-SRF control

The extended control structure is depicted in Fig.3. Compared to basic algorithm it provides robust operation during voltage asymmetry due to utilization of DDSRF-PLL (Fig. 4) and sequence components decomposition. Because of abovementioned features current and resulting power controllability are greatly improved.

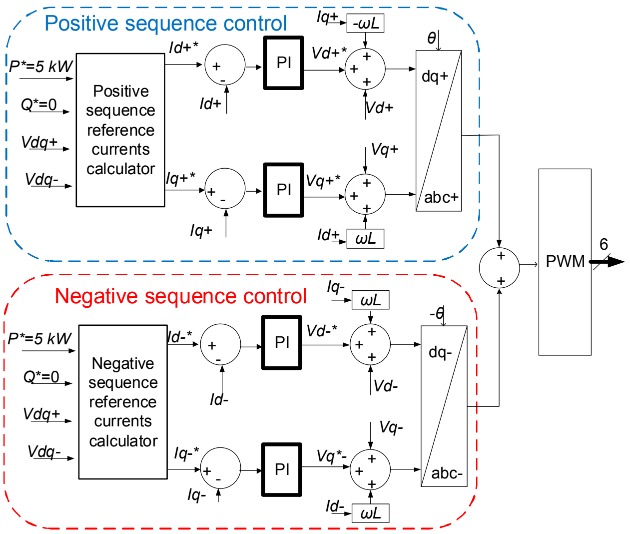


*Fig. 3. Extended VOC-SRF control*

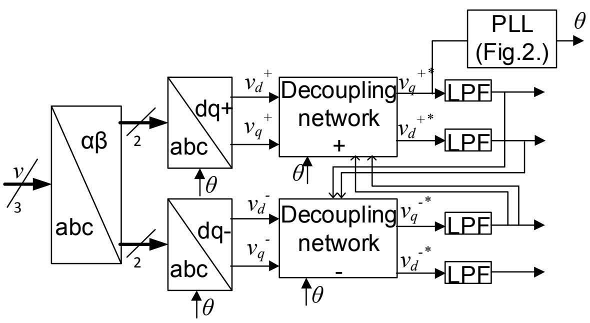


*Fig. 4. DDSRF-PLL grid voltage synchronisation*

The reference currents in direct and quadrature axes are calculated based on the power reference and voltage measurements. As it can be observed in Fig. 3 and Fig. 4 the control system requires also a decomposition into symmetrical components which are then decoupled and controlled independently. The control uses the DDSRF decoupling network and output low pass filters both in case of measured voltages and currents. The most essential block for the control objective determination is the reference current calculator which determines the currents in current supply voltage conditions that will result in desired power flow (in this particular case 5 kW).

$$\begin{bmatrix} I_{dref}^{+} \\ I_{qref}^{+} \\ I_{dref}^{-} \\ I_{qref}^{-} \end{bmatrix} = \begin{bmatrix} V_d^{+} & V_q^{+} & V_d^{-} & V_q^{-} \\ V_q^{+} & -V_d^{+} & V_q^{-} & -V_d^{-} \\ V_q^{-} & -V_d^{-} & -V_q^{+} & V_d^{+} \\ V_d^{-} & V_q^{+} & V_q^{+} & V_q^{+} \end{bmatrix}^{-1} \begin{bmatrix} \frac{2}{3}P_{ref} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_{dref}^{+} \\ I_{qref}^{+} \\ I_{dref}^{-} \\ I_{qref}^{-} \end{bmatrix} = \frac{2}{3D} P_{ref} \begin{bmatrix} V_d^{+} \\ V_q^{+} \\ -V_d^{-} \\ -V_q^{-} \end{bmatrix} \tag{2}$$

$$D \equiv \left[ (V_d^{+})^2 + \left(V_q^{+}\right)^2 \right] - \left[ (V_d^{-})^2 + \left(V_q^{-}\right)^2 \right] \tag{3}$$

$$D \neq 0 \tag{4}$$

The equations (1) – (4) represent the operations done for reference currents calculations [9].

## 3.3. Network under study

The network under study is depicted in Fig. 5 and Fig. 6. Two level inverter comprises ideal switches (losses are neglected). It is coupled to the external network modelled as an infinite bus via current filter of 10 mH. Sinusoidal pulse with modulation (PWM) is used for gating. The frequency of a triangular carrier wave was set to 16 kHz. The measurements of three phase voltages and currents are taken behind the filter (at grid connection) where the reference conditions should be achieved.

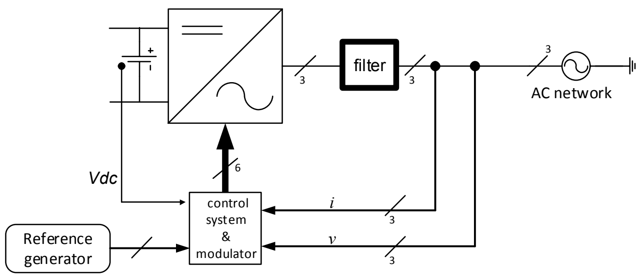


*Fig. 5. Current waveforms for extended control system*

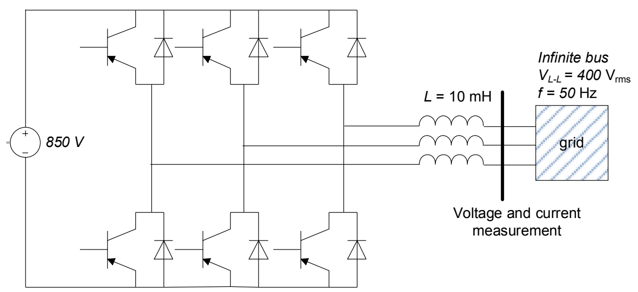


*Fig. 6. Current waveforms for extended control system*

## 3.4. Simulation results

The results presented in this section are the outcome of simulations conducted in Matlab/Simulink for a temporary voltage unbalance in 400 V three phase 50 Hz system.

The occurring unbalance was assumed to have 30% of negative sequence (Fig. 5). The following figures depict the current waveforms and instantaneous power measured for both herein presented control algorithms. Additionally the voltage phase angles theta produced by PLL blocks are presented in Fig. 7 and Fig. 8.

As it can be observed the extended control system was able to maintain controllability and adjust the currents (Fig. 9) to the new grid condition. Basic control algorithm was able only to keep the inverter in operation introducing high deformation of the inverter current (Fig. 11) due to lack of symmetrical components control and advanced synchronisation loop. Despite the same PI controller gains (for making the results comparison possible) the response of the system is different with a visible overshoot in phase currents. This is caused mainly by the modified overall control structure in case of extended control. The main factor that should be also accounted for are filters present in the DDSRF-PLL and most importantly their presence in decomposition of measured currents into symmetrical components. Moreover there is a visible difference in the voltage theta angles of the synchronisation loops (Fig. 7 and Fig. 8). In this case the DDSRF-PLL presents much higher performance with no visible fluctuations, which cannot be said about the simple SRF-PLL. The instantaneous powers traces (Fig. 10 and Fig. 12) exhibit some interesting properties namely, lack of independent positive and negative sequence controllers results in 100 Hz reactive power oscillations. In case of basic control these oscillations are visible for both reactive and active powers whereas the extended control with negative sequence current injection was able to eliminate the active power fluctuations. One should note that in order to eliminate oscillatory terms in both reactive and active powers, the control system should have two more degrees of freedom i.e. inject zero sequence currents. In order to achieve it the inverter would have to operate in four wire topology. Detailed description of such requirements can be found in [68, 80].

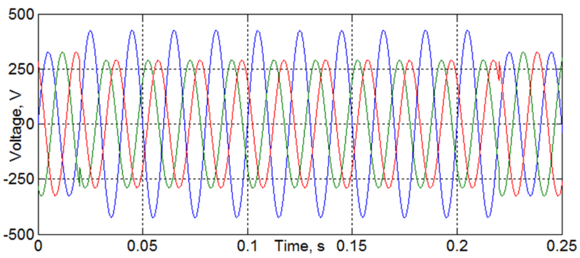


*Fig. 5. Supply voltage unbalance*

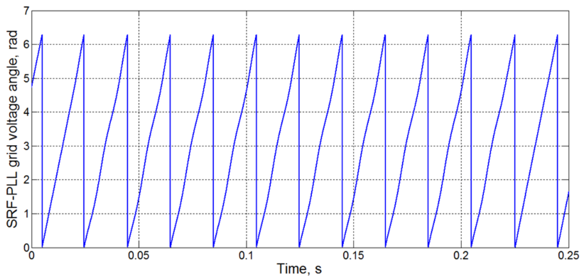


*Fig. 7. Grid voltage angle (theta) for simple synchronisation loop SRF-PLL*

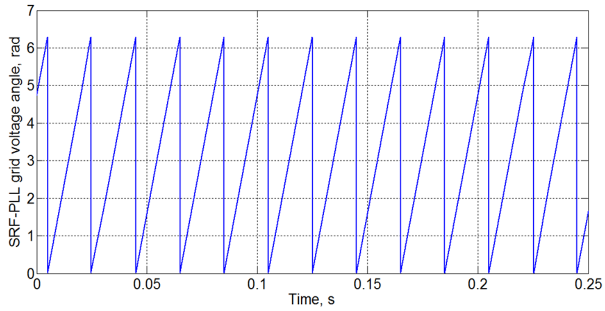


*Fig. 8. Grid voltage angle (theta) for advanced synchronisation loop DDSRF-PLL*

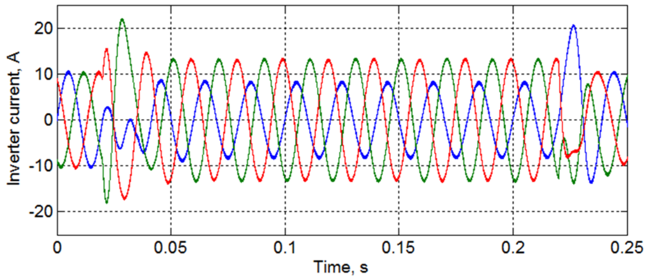


*Fig. 9. Current waveforms for extended control system*

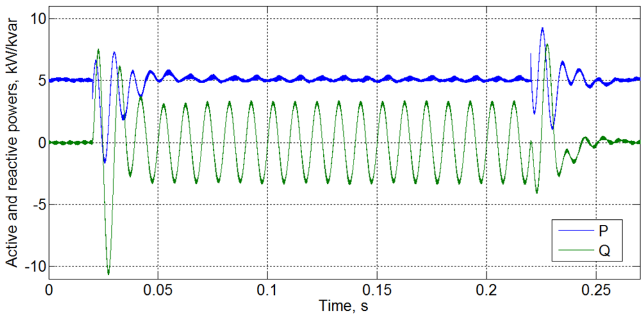


*Fig. 10. Active and reactive powers of the inverter for extended control system*

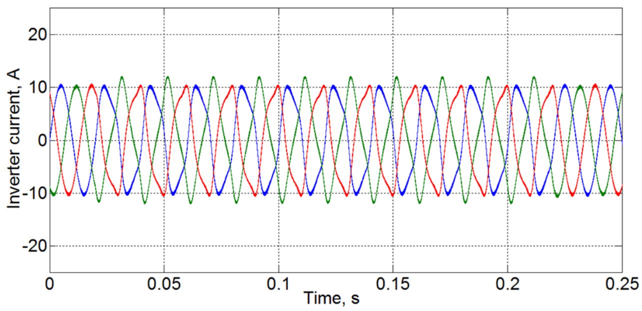


*Fig. 11. Current waveforms for basic control system*

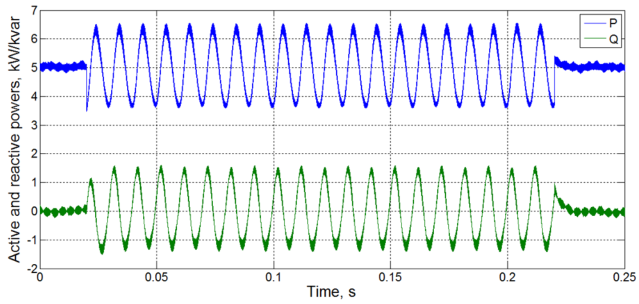


*Fig. 12. Active and reactive powers of the inverter basic control system*

## 4. Summary

Based on the performed simulations it was shown that the control system of a power converter is essential for proper operation of the grid connected power converter. This fact is especially manifested during grid voltage unbalanced. Insufficient control capabilities may result in non-satisfactory output power quality which can even worsen the voltage quality. Only a fully coordinated control, designed for specific system topology is able to provide the reference tracing regardless of an external conditions. Voltage oriented control coupled together with DDSRF-PLL synchronisation has proven to be a good choice for such grid conditions. Basic control system without symmetrical component decomposition and simple PLL was on the other hand maintain the operation of the power converter under the voltage unbalance. This essentially means that it could actually be applied in systems with no strict requirements regarding the power quality or voltage support functionalities.

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