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A New Synchronization Method for Three-phase Grid-tied LC-Filtered Voltage Source Inverters

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ABSTRACT

In order to identify and to track the phase angle and magnitude of the grid voltage, several synchronization methods exist, among which the phase-locked loop (PLL) algorithm is the most popular. This paper presents a new synchronization method for grid-tied voltage source inverters (VSIs) based on the intrinsic inverter synchronous reference frame. The absolute phase angle of the grid voltage is not required but its voltage direct and quadrature components into the well-known inverter frame. The advantages of this method is its low computational load with a reduced number of control parameters, as well as its robustness and effectiveness. This property makes it very convenient for embedded control systems with limited computing resources. Simulations and experimental test results are presented to prove the performance of the proposed method.

Keywords: *Grid synchronization, Grid-tied inverters, Smart grids, Phase-locked loop*

INTRODUCTION

Due to the increasing integration of electrical power from renewable energy sources (RES), the world steady trend toward decentralized power generation boosts the use of VSIs in the interconnected micro grids. In 2014, the world electricity production from photovoltaic (PV) and wind power plants was about 900 TWh. This is a bit more than 10 times the energy production ten years before in 2004[1][2]. This provides a good overview of the number and the size of the power inverters installed since the energy transfer chain of the PV plants as well as the wind farms mostly depends on the capacity of the dedicated power converters. From 2005 to 2014, the average rated power of wind turbines increased from 1.4 MW to 2.2 MW[3] allowing a total installed power of wind turbines of 300 GW in 2013 [4]. In 2014 only, the installed PV systems had a total power of nearly 40 GW, where China, Japan and the USA accounting for 62.5% of the total installed power [5]. Almost all the installed PV plants are connected to a larger utility power grid. The off-grid system market can hardly compete with the grid-tied one. Only 1 to 2% of the 2014 installation were off-grid. They represent only 5% of the total installations between 2000 and 2014 [5].

In order to achieve an optimal distribution of the electrical power, all these decentralized and independent micro grids, supplied by PV or wind turbines as well as other renewable energy sources, must be synchronized and have to work together in a robust and stable way. Synchronizing two voltage sources means achieving the minimum possible voltage parameters difference between them. This state should not be punctual but a fully steady state for a given long time. Therefore, the synchronization of two direct current (DC) voltage sources is easier compared to that of two alternating voltage (AC) sources. The AC voltages are identified by three variables, which are the magnitude, the frequency and the phase angle, whereas DC sources are characterised only by the magnitude. Unbalance and harmonics distortion that can occur in three-phase AC voltage sources represent additional parameters that needs to be taken into consideration during the synchronisation that must be done prior to the connection of the two voltages sources. An inaccurate synchronisation can generate high current draw that might cause grid protection equipment to trip decreasing the reliability of the whole power grid. For grid-tied VSIs, since the modulated output voltage first needs to be filtered by a passive LC circuit, the final sinusoidal output voltage is different (mainly the phase-angle, the voltage drop by the LC filter is generally negligible) from the reference controlled signal applied in the inverter. That is why actually two signal identifying systems have to be implemented: One for the grid voltage and the second for the LC-filter output voltage. The latter is controlled so that it is synchronised with the grid voltage.

Over the years, several synchronisation methods have been proposed for AC voltage sources. Synchronism measurement equipment as the synchroscope and the synchronism-check relay have been developed [6][7][8][9]. However, no standard recommendation on the synchronisation precision exists. The main synchronisation focus point has always been the fast detection and tracking of the grid voltage phase-angle since matching the magnitude is less challenging. The difference among the different methods was based on the phase tracking precision of the method in presence of grid disturbance such as harmonics, unbalance and frequency change.

The goal of this paper is to present a new synchronisation method that requires less computational resources with a reduced number of control steps. The proposed method remains very stable with an improved dynamics while being very efficient in term on harmonics rejection. First, a brief review of the existing synchronisation methods is done. Then the proposed method is presented followed by the results from practical lab experiments.

GRID SYNCHRONISATION METHODS

The rapid progress made in the power electronics, as well as in fields such as sensors and microcontrollers, has triggered the proposal of multiple grid synchronisation methods. [10] gives a comprehensive review of different synchronisation methods. These methods can firstly be classified based on the voltage system, which is single-phase or three phase. Identifying single-phase signals has been proven more challenging compared to three-phase signal where the same information is encapsulated in three simultaneous values instead of only one. That is why all the methods applied for single-phase systems are also used, with improved efficiency, for three-phase systems. A second classification criterion is the structure of the phase-angle detection system, either open loop or closed loop. On the one hand, the open-loop systems are generally simple as they identify the input signal properties directly. On the other hand, the closed-loop methods generate a virtual frame, where a given controlled value offset or variation indicates the detection precision of the measured input signal.

Among the open loop systems, the zero-crossing detection represents one of the simplest [11][12]. The discrete Fourier transform method DFT, with all his derivate methods like the recursive DFT or the sliding window DFT, were primarily developed for the harmonics and frequency detection [13][14][15]. The Kalman filter [16] as well as multiple variants of adaptive notch filter are also proposed in [17][18][19].

The closed-loop systems, essentially the PLL, are by far the most used synchronisation methods. The PLL is a very old basic concept, known for its effectiveness and robustness in various grid conditions. For this reason, it is used in different applications such as telecommunication & signal processing and more [20]. The PLL can be defined as a closed-loop feedback control system, which synchronises its output signal with the reference input signal in frequency, and phase [10]. For three-phase voltages, it can be considered as a system observer with a virtual rotating orthogonal frame that modifies its internal angular frequency in order to match not only the frequency but also the phase angle of the input voltage. For three-phase systems, the synchronous reference frame PLL (SFR-PLL) and the power PLL (p-PLL) are the basic structures [21]. The SFR-PLL is the most used since it additionally delivers the input voltage components in an orthogonal direct & quadrature (dq)-frame. Numerous modified structures have been proposed in order to improve its efficiency in cases of disturbances on the input voltage signal [22][23][24][25].

Mainly designed for three-phase voltage systems, the SFR-PLL has several structures developed for single-phase voltage systems such as the inverse-Park PLL or the delay PLL [26]. The main difference lies in how the αβ-components of the input voltage are calculated [27][28]. Other single-phase PLL methods exist such as the enhanced PLL (ePLL) [29][30]and the single-phase power PLL [31] as well as the quadrature PLL (QPLL)[32].Further but complex single-phase PLL structures are well presented in [21].

All the above-mentioned synchronisation methods might be different in their structure but share the same critical synchronisation control parameter, which is the delivered phase-angle of the tracked voltage. A good tracking of the phase-angle means that the frequency is also well determined. A second controller is generally used to ensure the voltage magnitude match.

Synchronisation Based on the VSI Internal Reference Frame

The main characteristic of the proposed synchronisation method is the utilisation of the intrinsic, well-known and controlled inverter orthogonal frame (dq-frame). As depicted in Figure 1, the output voltage of a controlled VSI is filtered using a passive low-pass filter (LPF). The filtered voltage nearly harmonics free is to be synchronised with the grid voltage at the point of common coupling (PCC). The coupling breaker ensures the interconnection. The grid voltage as well as the filtered VSI voltage are transformed into the rotating orthogonal frame of the inverter. It is assumed that the reference signal frame is aligned with that of the inverter, so that its direct component $U_{d_{inv}}$ equals zero while its quadrature component $U_{q_{inv}}$ represents its magnitude. U_{d_f} and U_{d_g} are the direct components of the filtered inverter voltage and the grid voltage respectively as U_{q_f} and U_{q_g} represent the respective quadrature components. This configuration allows the direct components to be perfect indicators of the phase-shift between the filtered & grid voltages and the inverter reference signal. The first and preliminary step of the synchronisation is achieved by controlling the magnitude of the inverter voltage, so that it matches that of the grid. The second and most critical step is the phase-angle matching process. The VSI output and grid voltages dq components in the inverter reference frame are expressed in (1) where: $\widehat{U}_f$ and $\widehat{U}_g$ are the inverter filtered and grid voltage magnitude. θ_{inv}, θ_f and θ_g are the phase-angle of the inverter reference signal, the filtered VSI voltage and the grid voltage respectively.

$$\begin{cases} U_{d_f} = -\widehat{U}_f \sin(\theta_{inv} - \theta_f) \\ U_{d_g} = -\widehat{U}_g \sin(\theta_{inv} - \theta_g) \\ U_{q_f} = \widehat{U}_f \cos(\theta_{inv} - \theta_f) \\ U_{q_g} = \widehat{U}_g \cos(\theta_{inv} - \theta_g) \end{cases} \qquad (1)$$

As the goal is to reach a zero phase-shift between the voltages, the inverter frequency is controlled so that the grid and the inverter direct components are equal, using the phase-shift representative value given by (2).

$$e_\theta = \left(U_{d_f} \times U_{q_g} - U_{q_f} \times U_{d_g}\right) \qquad (2)$$

(1) into (2) leads to,

$$e_\theta = \widehat{U}_f \cdot \widehat{U}_g \sin(\theta_f - \theta_g) \qquad (3)$$

Equation (3) will be zero only when the VSI voltage phase-angle θ_f is equal to that of the grid voltage θ_g. This leads to $U_{d_f} = U_{d_g}$ when both voltage magnitudes are equal. For small phase-shift values, (3) can be linearized to (4).

$$e_\theta = \widehat{U}_f \cdot \widehat{U}_g (\theta_f - \theta_g) \qquad (4)$$

This is similar to the controlled voltage value in the SFR-PLL [26]. The difference here is that the computed phase-shift is not between one measured signal and the internal PLL frame but between two measured voltages to be synchronised.

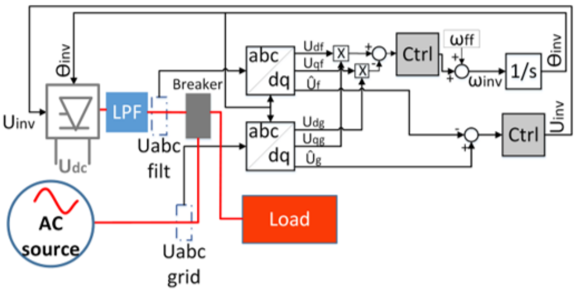

Figure1. *Working Principle of the Synchronisation Based on the VSI's Frame*

e_θ represents the value that has to be regulated to zero in order to ensure a zero phase-shift between the voltages. It is important to start the control of the voltage magnitude before that of the phase because the phase control is strictly dependent on the stability of the voltages magnitudes.

Any disturbance or oscillatory or linear transient caused by the magnitude control strongly affects the phase control since it is based on real voltages values.

Experiments and Results

Simulations

A MATLAB/SIMULINK model has been designed. A three-phase IGBT-based power inverter, fed by a 600V DC source, generates voltages that are filtered using a big low-pass LC circuit with 1.62Ω, 1.56mH and 1.5mF as respectively the resistance and inductance value of the inductor and the capacitance of the capacitor. This makes a LPF with a very low cut-off frequency at 103Hz that eliminates all the high frequency voltages induced by the PWM. The grid, modelled as a 50Hz three-phase power source, generates a 230V RMS phase voltage.

Undistorted grid voltage

The proposed method has been implemented and the results of its behaviour in steady state conditions are depicted in the *Figure2*. It shows comparative graphs of the grid and the filtered inverter voltage. The magnitude control as well as the measured phase-shift $\Delta\theta$ converge to their final steady state value as the inverter voltage is being superimposed on that of the grid.

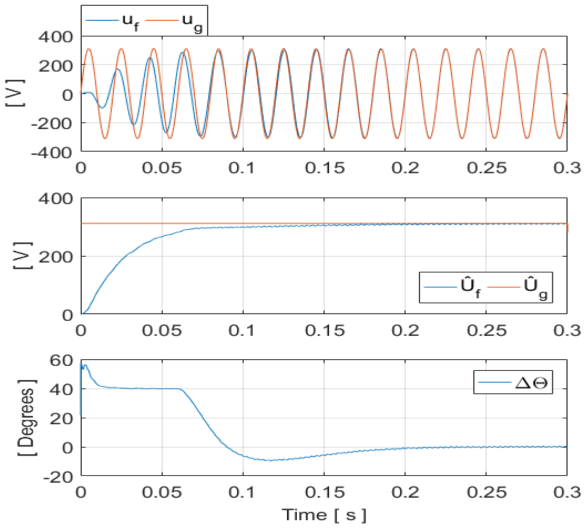

Figure2. *Simulation results of the synchronisation in the inverter frame. Top: comparison of the measured voltages. Middle: Comparison of measured voltages magnitudes. Bottom: Phase shift between measured voltages.*

In this scenario, the phase shift control starts when the voltages magnitude difference is lower than 30 Volts in order to limit the impact of the magnitude control on the calculation of the phase-shift. More interesting is the dynamic behaviour of the method, when the tracked voltage experiences some disturbances. The grid voltage drops by 10% at time 0.3 sec, then a phase jump of 20 degrees occurs at 0.5 sec and finally the grid frequency increases by 5% at 0.7 sec. The performance of the system is depicted in the Figure3.

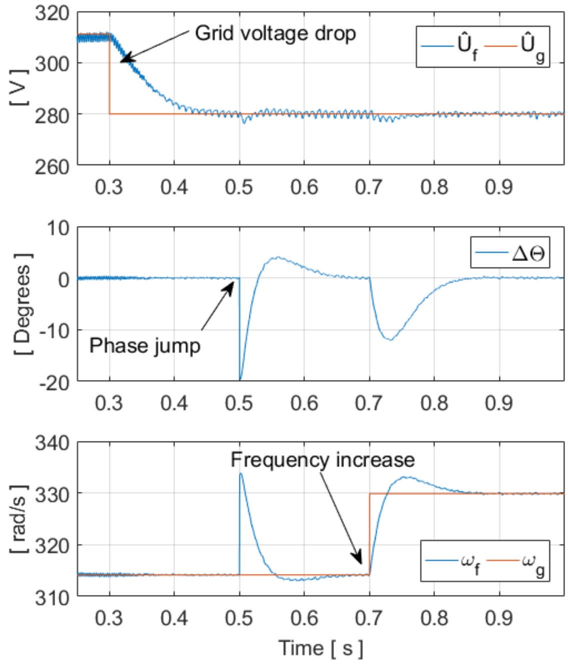

Figure3. *Synchronisation performance by grid voltage magnitude drop, phase jump and frequency deviation*

The system shows convincing reactions to the fundamental voltage disturbances. The magnitude drop of the grid does not affect the phase-control. As the phase jump and later on the frequency variation occur, the magnitude control remains stable. The 20° sudden phase jump, which is immediately and precisely detected, is then corrected within the next 200ms. The system also successfully controls its angular speed to correct the phase-shift caused by the frequency variation and then remain stable at the new frequency. The observed oscillations are the residual high frequency voltages from the PWM.

Harmonics rejection

The harmonics rejection performance of the tracking system is shown on Figure4. The grid voltage is distorted with the 5th, 7th and 11th harmonic with 25V, 20V and 15V respectively. This leads to a total harmonic distortion of 14.5%. The frequency of the grid increases by 5% at 0.4 sec. It can be observed that the presence of harmonics slightly modifies the dynamic of the system. The highest error value nears 32° (only 13° with non-distorted grid voltages) that decays with oscillations.

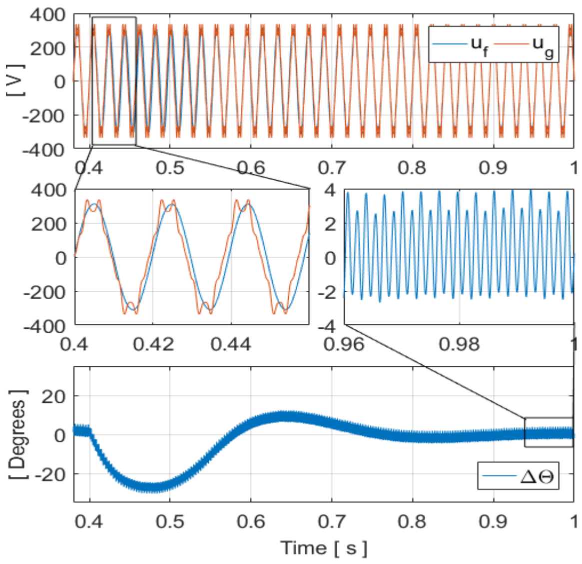

Figure4. *System performance in case ofa distorted grid voltage with THD=14.5%.*

The achieved phase angle error is oscillating with an average value near to zero. Similar to the study in [26], the error peak value increases with the peak value of the sum of the harmonics content. In this case, with a 14.5% THD (almost the double of the European standard EN50160 limit [33]), the punctual peak error is 4°. This remains, in the domain of electrical energy transmission and distribution, a very acceptable error.

Because the goal is to synchronise only the fundamental voltages with one another, a perfect harmonic rejection system is performed by using band-pass filters to extract only the fundamental 50Hz signal from the measured voltages as depicted in Figure 5. Finite impulse response (FIR) filters are used for their stability and their linear phase delay.

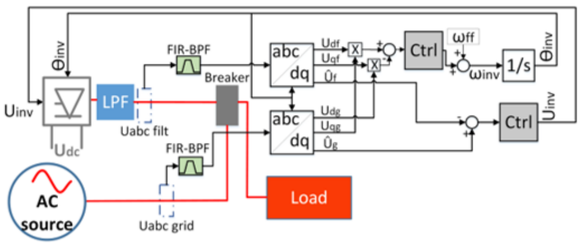

Figure5. *Synchronisation system including FIR filters for harmonics rejection*

The results shown on Figure 6 are obtained using band-pass FIR filters at 50Hz with 400 coefficients for each measured voltage phase. The improved system depicts a better robustness as it reaches the new grid frequency within 200ms with a peak phase error of about 18°. The non-improved system needs a bit more than half a second to stabilize and allows an average phase-error up to 30°.

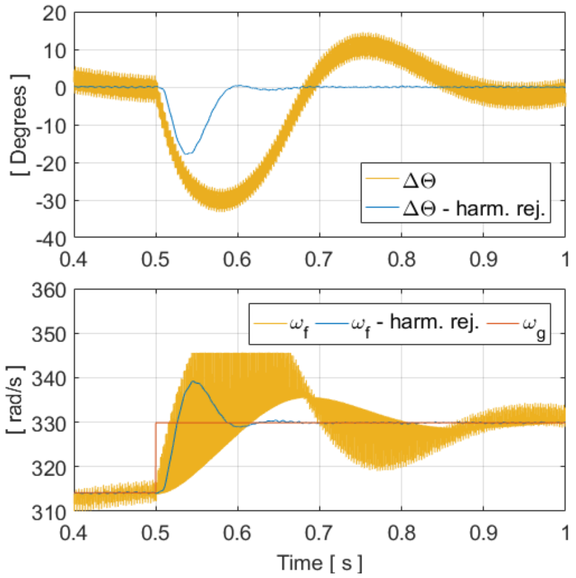

Figure6. *Performance of the synchronization system including the FIR filter-based harmonic rejection*

The proposed harmonics rejection system focuses on the synchronisation of the fundamental voltages. Therefore, it is appropriate for low distorted voltages, otherwise, there might be relatively high harmonics currents right after coupling. Achieving a complete synchronization of the fundamental as well as of the harmonics voltages requires a lot of computing resources because each harmonic frequency has to be controlled in phase and magnitude, so that the distorted grid voltage is perfectly matched by the generated filtered VSI voltage.

Experimental results

Test Rig Setup

The test-rig configuration is shown on **Error! Reference source not found.** 7. The local grid is generated by coupling an asynchronous machine (run by the grid (#9)) to a synchronous generator (#6) that is excited by a DC source (#5). Another DC voltage source (#3) is feeding the IGBT-based power inverter (#2) that is controlled by the microcontroller (#1). The microcontroller is the LABVIEW programmable Compact RIO cRIO-9082 of National Instruments [34]. There is a linear resistive load (#7) along with a non-linear load made of a resistance (#8) fed through a diode rectifier(#4).

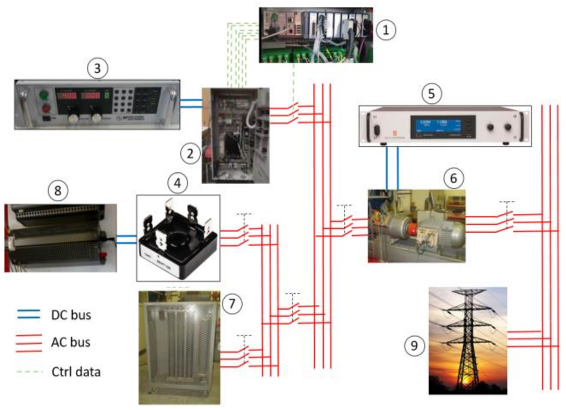

Figure7. *Micro grid test-bench setup in the lab*

Synchronization Performance

The implemented system includes the harmonics rejection function based on the 50Hz band-pass FIR filters (Figure 2). Similar to the simulations, the goal of the experiments is to achieve the smallest possible phase-angle and magnitude difference between the grid voltage and the filtered VSI voltage. The non-linear load generates a harmonic distortion of the grid voltage. Purposely, neither the generator voltage frequency nor its voltage magnitude is controlled. This means that any load connection or disconnection would affect the generator voltage magnitude as well as its frequency. The VSI has to detect and adjust its output voltage, so that the minimal relative voltage difference is achieved.

The following Figure 8 shows the performance achieved by the synchronisation system.

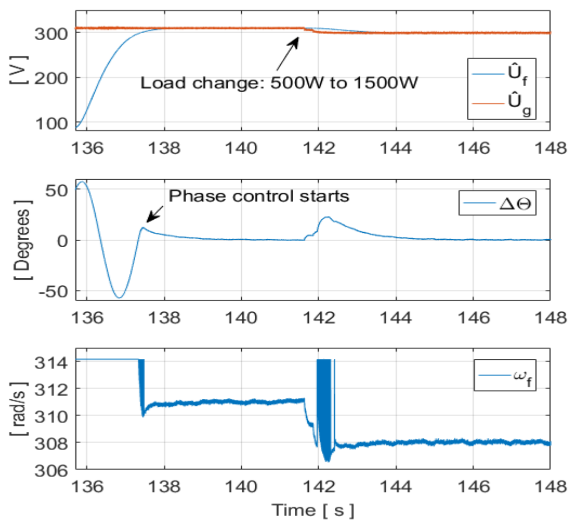

Figure 8. *Experimental synchronization performance with non-distorted grid voltages*

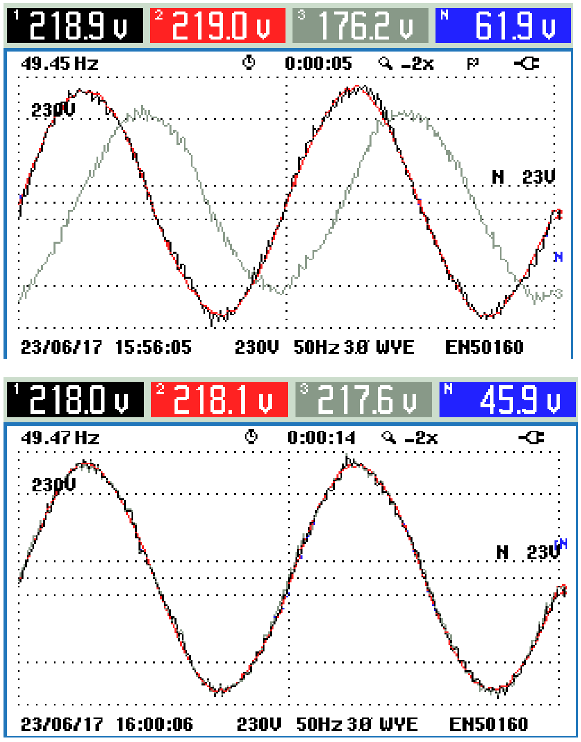

Figure 9. *Real-time oscilloscope screenshots before (top)and after (bottom) the synchronization with non-distorted grid*

As the VSI voltage magnitude is regulated to that of the grid, the phase-shift control starts when the magnitude difference is lower than 10V. The phase-shift then successfully decreases to zero and both voltage sources can be safely coupled. When the generator-fed load increases, it causes a voltage and frequency drop. The magnitude and phase controls react very well as they correct the relative voltage differences to reach the synchronisation few seconds later.

The same good performance is achieved when the generator voltage is distorted due to the 2.2kW non-linear load connected. Figure 10 shows how low the frequency has dropped (because of the higher load compared to the previous scenario in Figure 8). Nevertheless, the VSI is successfully synchronised and reaches the new synchronisation state after the generator voltage magnitude and frequency increased due to the reduction of the load.

In Figure 9 and Figure 11 are depicted the real-time voltages measurements done with the FLUKE 435 Power Quality Analyser. Line 1 (black) is the load voltage, line 2 (red) the generator voltage, line 3 (grey) the inverter voltage and the line N (blue) the neutral voltage.

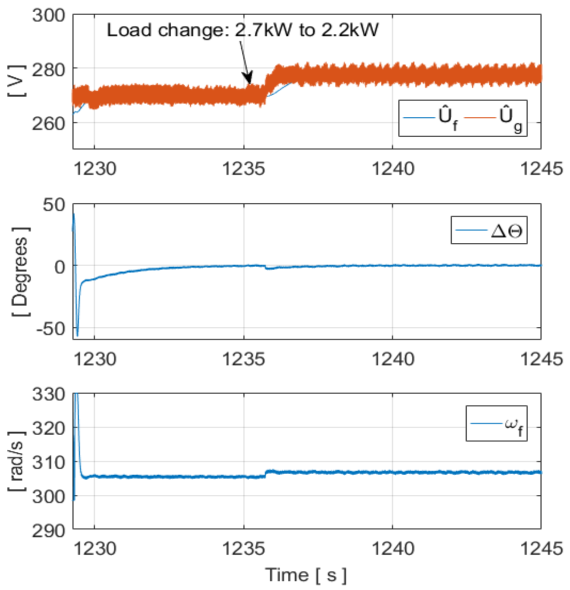

Figure10. *Experimental synchronization performance with distorted grid voltages*

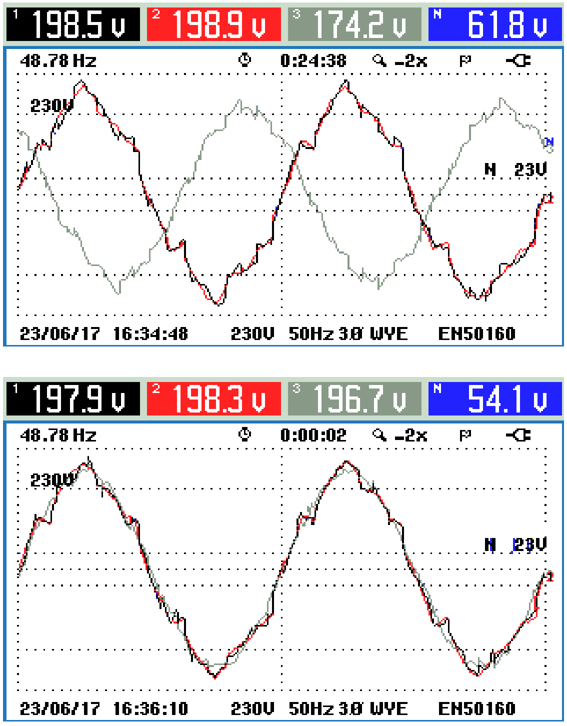

Figure11. *Oscilloscope screenshots before (top) and after (bottom) the synchronization with distorted grid*

The difference between the generator and the VSI voltages is clearly visible before the synchronisation occurs. Due to the non-perfect elimination of the harmonics by the passive filter, the filtered output voltage of the VSI shows some distortion. In addition, the neutral point being common to the generator and the VSI passive filter, the voltages affect each other. Nevertheless, the voltages superimposition is reached, in both cases, even if the generator voltage is distorted or not, thanks to the harmonics rejection effect of the FIR band-pass filters.

Conclusions

This paper presents a new synchronisation method for filtered grid-tied power inverter. The method uses the very accurate internal reference frame of the inverter to compare the VSI filtered output voltage and the grid voltage. The main advantages of the proposed method are: - the reduced computational resources required since phase-shift is not calculated from two separate identification system (generally PLLs); - the improved dynamic due to the direct impact of voltages disturbances on the synchronisation control variables; - the improved stability reached by eliminating the “virtual frames” that have their own dynamic and stability limits. The presented experimental results show the good reliability of the method when a voltage frequency, magnitude and phase-jump occur even simultaneously. Using band-pass filters on the measured voltages bring a very good harmonic rejection property as the synchronisation focuses only on the fundamental frequency. An important future work might be the study and improvement of the method, when the grid voltages are unbalanced. However, this method is developed for three-phase systems, where the frame transformations are simple. It might be interesting to apply the same basic idea for single-phase voltages.

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