 doi:10.20944/preprints201705.0136.v1

Article

Instantaneous Symmetrical Component Estimator Using Second Order Generalized Integrator under Distorted Voltage Conditions

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Abstract: Frequency, amplitude and phase information of the grid voltage are of great importance in constructing a robust controller structure for grid connected inverter systems. This paper presents a simple and robust approach for the instantaneous estimation of positive and negative sequence voltage components under distorted voltage conditions. A second order generalized integrator (SOGI) is used to filter the distorted voltage and to generate orthogonal voltage components for each of the three phases. These filtered and orthogonal components are used for instantaneous calculation of symmetrical components. The implemented method is frequency adaptive; the method is demonstrated and compared to a conventional phase locked loop (PLL) technique with both MATLAB/Simulink simulations and experiments utilizing the dSPACE ds1103 digital controller.

Keywords: generalized integrator; grid connected inverters; phase locked loops; renewable energy; symmetrical components; unbalanced voltage

1. Introduction

Utilization of renewable energy sources has been increasing recent years due to limited source of fossil fuels and environmental issues. The popularity of grid connected inverter structures in the industry such as uninterruptable power supplies (UPS); active front ends (AFE), flexible alternating current transmission systems (FACTs) etc. and their essentiality in solar and wind energy conversion systems increase the importance of inverter controller structures. Due to this fact, power systems of the future will contain more grid connected power converters, and the reliability of the control system against voltage distortions and unbalances will be more critical due to strict grid standards [1, 2].

Amplitude, phase and frequency information of grid voltage are very critical parameters for grid connected inverter structures. In addition, doubly fed induction generator (DFIG) based wind turbines which are very cost effective and energy efficient due to lower rated inverter structure and direct stator connection requires accurate knowledge of voltage parameters to become robust against voltage unbalances and distortions.

Phase-Lock-Loop (PLL) techniques [3] are the most popular techniques for detection of critical voltage parameters due to their robustness and ease of implementation. However, the performance of PLL may become deficient under unbalanced and distorted voltage conditions with conventional methods. Different types of PLL structures can be formulated to deal with grid voltage problems. One example is the decoupled double synchronous reference frame PLL (DDSRF-PLL) which constructs two synchronous frames to isolate the effects of positive and negative components [4]. Another important method in [5] uses single-phase enhanced PLL (EPLL) for each phase. The comparative survey given in [6] may be studied for further analysis and comparison for different types of PLL.

Analysis of symmetrical components [7] is a very important task in detecting unbalanced voltage conditions of electrical networks. It decomposes unbalanced voltage components into a set of balanced positive, negative and zero sequence voltage components by using 120^0 phase shift operators in the frequency domain. This method is also widely used for constructing robust controller structures for grid connected inverters under unbalanced voltage conditions. A simple and robust real time calculation of symmetrical components by allowing the use of the orthogonal component of the original voltage signal is given in [8]. A different symmetrical component generation technique is given in [9] which directly shift the voltage 120^0 in time domain.

This study implements a simple and robust algorithm for the estimation of symmetrical components under distorted voltage conditions. The implemented structure filters the distorted voltage and constructs orthogonal components of the voltages by using the second order generalized integrator (SOGI) given in [15]. These filtered and 90^0 leading orthogonal signals are used for the online estimation of symmetrical components under distorted voltage conditions as given in [8]. The implemented method combines both methods and is demonstrated both in MATLAB/Simulink simulation platform and in experiments by using dSPACE ds1103 digital controller. In addition, the implemented method is compared to a conventional PLL algorithm and the results show that oscillations on frequency and synchronously rotating dq-axis voltage components are minimized with the method presented.

The rest of the paper is organized as follows. Single and three-phase PLL structures by using SOGI are explained in section 2. Section 3 explains the concept of implemented instantaneous symmetrical components. Section 4 demonstrates results from simulations and experiments. Finally, section 5 gives the conclusion and proposes the future work.

2. Orthogonal Signal Generation

Orthogonal signal generation is an important process for single-phase PLL structures. Different approaches can be formulated for orthogonal system generation, such as Transport Delay [10], Hilbert transform [11], inverse park transformation [12]. The main drawback of the above methods is the frequency dependency. A frequency adaptive kalman filter (KF) technique is proposed in [13]. The problem of KF technique is the computational complexity. Another frequency adaptive method given in [14] uses multiple second order generalized integrators for different dominant frequencies. The method given in [15] proposes a simple and robust structure for orthogonal signal generation by using a second order generalized integrator (SOGI). Generalized integrator using a simplified block transfer function for a sinusoidal signal is given as follows.

$$GI(s) = \frac{2s}{s^2 + \omega^2} \tag{1}$$

Simplified structure of SOGI for a-phase of the grid voltage is given in Fig. 1, and this can be applied to b and c phases.

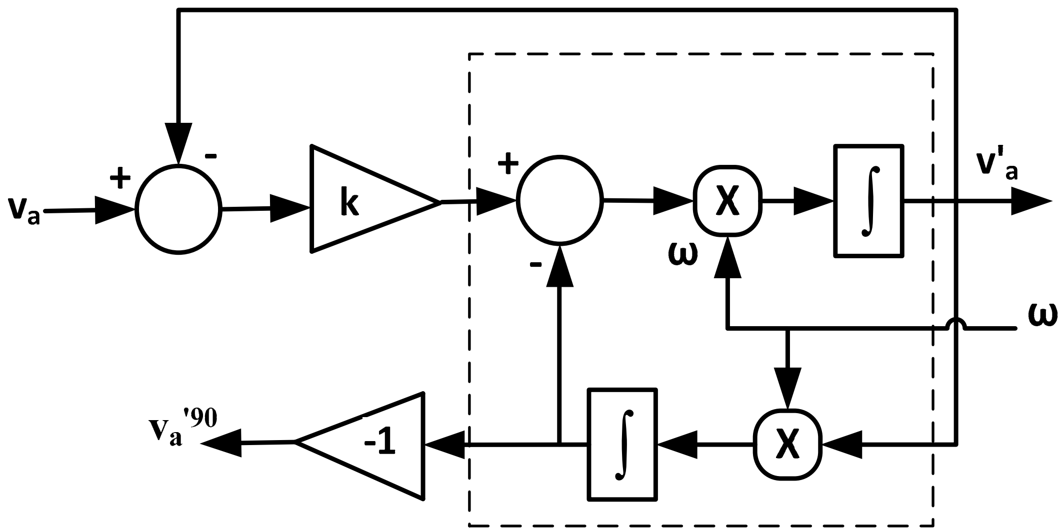

Figure 1. Second Order Generalized Integrator

The terms, v_a, v'_a, $v_a'^{90}$ represent measured, filtered and orthogonal phase signals, respectively. The term k is a constant that changes the bandwidth of the system. Transfer function of the proposed method in [15] can simply be given as;

$$H(s) = \frac{v_a^{'}}{v_a} = \frac{k\omega s}{s^2 + k\omega s + \omega^2} \tag{2}$$

The main advantage of the SOGI method for generating orthogonal voltage is the filtered voltage generation without phase delay, and this can also be applied to distorted voltage waveforms. In addition, the structure has the capability of frequency adaptation, and the step response of this adaptation can be adjusted by tuning the constant k. Thus, PLL structures that are more robust against voltage distortions and frequency variations can be constructed for three phase systems by applying the SOGI method for each phase of the system.

Typical single-phase and three-phase PLL structures utilizing orthogonal components are depicted in Figure 2a and Figure 2b, respectively. These types are commonly used for grid connected inverters.

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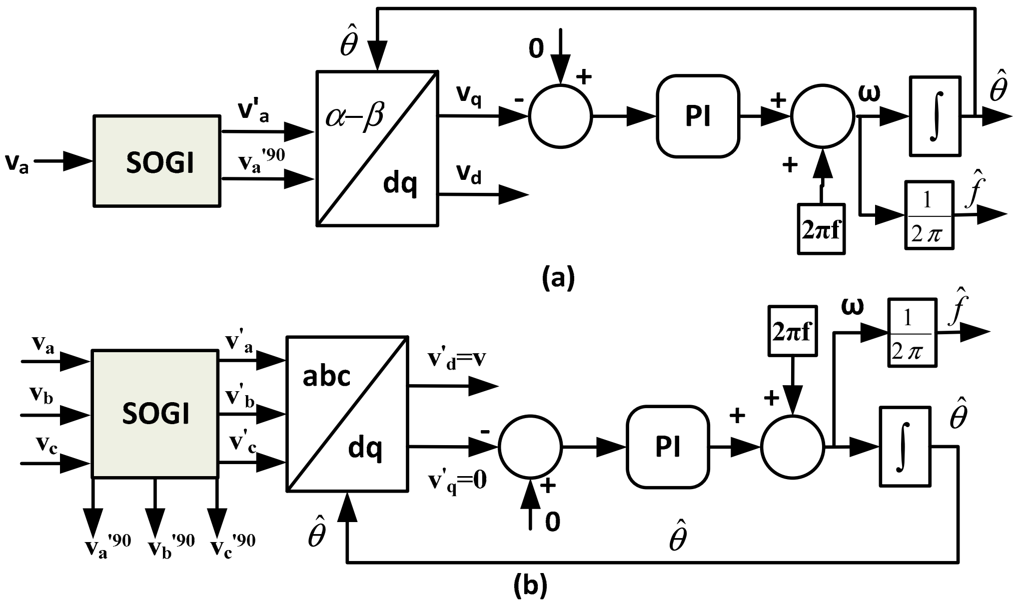

Figure 2. Typical Single-Phase (a) Three-Phase PLL (b) with SOGI

The terms, v_a-v_b-v_c, v'_a-v'_b-v'_c, $va^{'90}$-$vb^{'90}$-$vc^{'90}$ represent measured, filtered and 90° leading orthogonal phase signals, respectively. The terms, $\hat{\theta}$ and $\hat{f}$ represent the estimated phase angle and frequency of voltage signal, respectively

3. Instantaneous Signal Generation

The concept of symmetrical components first appeared in [7] to be primarily used for analysis of asymmetrical voltages for polyphase networks and for protection purposes. Symmetrical voltage components can mathematically be shown in the following form [8].

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} v_a^+ \\ v_b^+ \\ v_c^+ \end{pmatrix} + \begin{pmatrix} v_a^- \\ v_b^- \\ v_c^- \end{pmatrix} + \begin{pmatrix} v_a^0 \\ v_b^0 \\ v_c^0 \end{pmatrix} \tag{3}$$

Where superscripts +, -, 0 represent positive, negative and zero sequence components, respectively. Instantaneous set of positive, negative and zero sequence components are shown as given below [16].

$$\begin{pmatrix} v_a^+ \\ v_b^+ \\ v_c^+ \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & \alpha & \alpha^2 \\ \alpha^2 & 1 & \alpha \\ \alpha & \alpha^2 & 1 \end{pmatrix}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \quad \begin{pmatrix} v_a^- \\ v_b^- \\ v_c^- \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & \alpha^2 & \alpha \\ \alpha & 1 & \alpha^2 \\ \alpha^2 & \alpha & 1 \end{pmatrix}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \tag{4}$$

$$V_{abc}^0 = \frac{1}{3}\left(V_a + V_b + V_c\right) \tag{5}$$

Where $\alpha = e^{j120}$ is the 120^0 phase shift operator, $v_a(t)$, $v_b(t)$, $v_c(t)$ are instantaneous voltage signals. The main difficulty in the digital implementation of symmetrical component generation is the 120^0 phase-shifting of sinusoidal signals in the discrete domain. To simplify this task, e^{j120} can be rewritten in the following form [8].

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$$e^{\pm j120} = e^{\pm j(90+30)} = -\frac{1}{2} \pm \frac{\sqrt{3}}{2} e^{j90} \tag{6}$$

Therefore, symmetrical voltage components can be defined solely with 90 degrees leading signals of instantaneous voltages as described in Fig. 2. If (6) is substituted within (4) as $\alpha = e^{j120}$, the revised symmetrical components can be defined as follows [8];

$$\begin{pmatrix} v_a^+ \\ v_b^+ \\ v_c^+ \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & -0.5 & -0.5 \\ -0.5 & 1 & -0.5 \\ -0.5 & -0.5 & 1 \end{pmatrix}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} - \frac{\sqrt{3}}{6}\begin{pmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{pmatrix}\begin{pmatrix} v_a^{90} \\ v_b^{90} \\ v_c^{90} \end{pmatrix} \tag{7}$$

$$\begin{pmatrix} v_a^- \\ v_b^- \\ v_c^- \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & -0.5 & -0.5 \\ -0.5 & 1 & -0.5 \\ -0.5 & -0.5 & 1 \end{pmatrix}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} + \frac{\sqrt{3}}{6}\begin{pmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{pmatrix}\begin{pmatrix} v_a^{90} \\ v_b^{90} \\ v_c^{90} \end{pmatrix} \tag{8}$$

The positive and negative sequence components given in (7) and (8) which use orthogonal voltage components can easily be used for the digital implementation of grid connected inverter structures. The block diagram given in Fig.3 can be constructed with this information at hand.

4. Simulation and Experimental Results

4.1. Third Order Integrator

Discretization is another important task for practical implementation in digital controllers. Forward or backward Euler methods can be applied for integral operations in SOGI as given in Fig. 1.

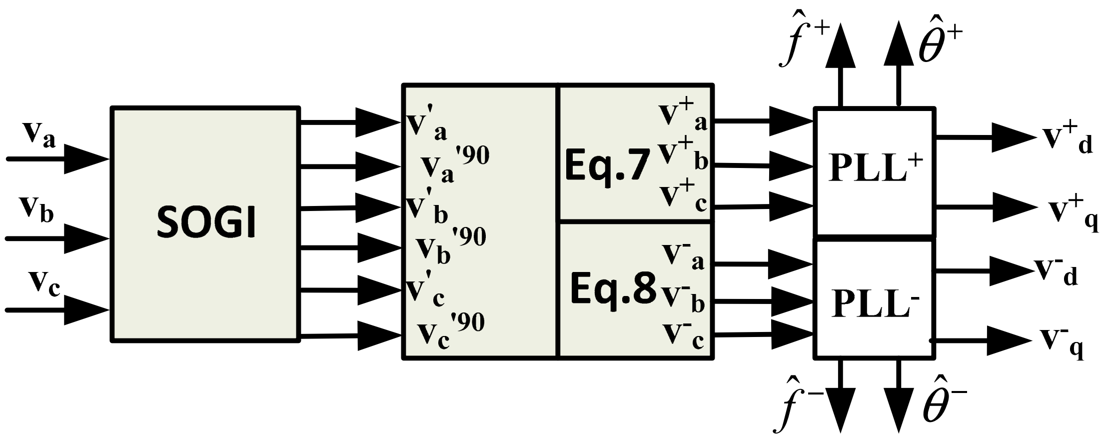

Figure 3. Generation of Symmetrical Components

However, it is known that first order discrete time integrators using Euler methods cannot realize 900 phase shift. Different types of advanced discrete integrator types can be applied to overcome this problem, such as the trapezoidal, second or third order integrators. In this study, the third order integrator given in [15] is implemented as given in the following form:

$$y(k) = y(k-1) + \frac{T_s}{12}\left[23u(k-1) - 16u(k-2) + 5u(k-3)\right] \tag{9}$$

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Simplified block diagram of the third order integrator is given in Fig. 4. The term T_s represents the sampling time of the digital controller. Third order type integrators are used for integration in all simulations and experiments to guarantee the orthogonal transformation of the voltage signal.

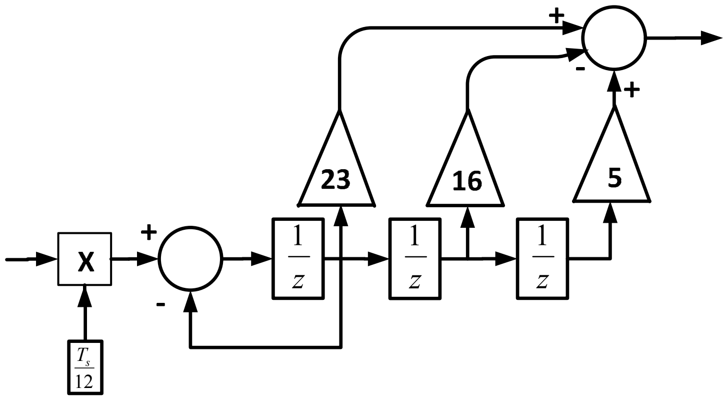

Figure 4. Third Order Integrator Block Diagram

4.2. Simulation Results

Simulation of the instantaneous symmetrical components is carried out in the MATLAB/ Simulink environment. Distorted grid voltage samples were measured in an industrial steel plant for 10 seconds, and the measured data was inserted into the Simulink workspace. The industrial steel plant where the measurements were taken has high voltage total harmonic distortion (THD) value, and suffers from voltage quality problems. Implemented block diagram given in Fig.3 are tested by using measured samples. Sample time of the measurements and simulations are 80μs. Measured, filtered and leading 3-phase line voltages are given in Fig. 5. It is shown from Fig. 5 that distorted voltage is filtered without phase delay, and orthogonal components are successfully generated. THD of voltage measurement is 8%, and harmonic spectrum of voltages is given in Fig. 6. It is shown from Fig.6 that the voltage components have high frequency harmonics generated by high power commercial inverters.

50% of unbalance voltage is generated on a-phase of the grid voltage as seen in Fig.7. Positive sequence transient voltage components with v^+_q are shown in Fig. 8. It is shown that the balanced set of positive sequence voltages is generated. Fig. 9 shows the negative sequence voltage generation.

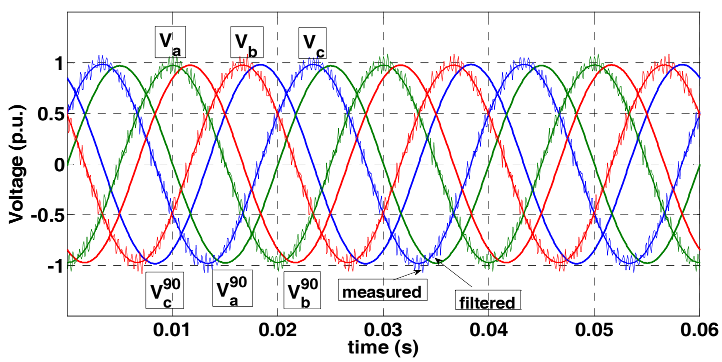

Figure 5. Measured, filtered and leaded voltages in p.u. (*V_{LL}=34.5kV*)

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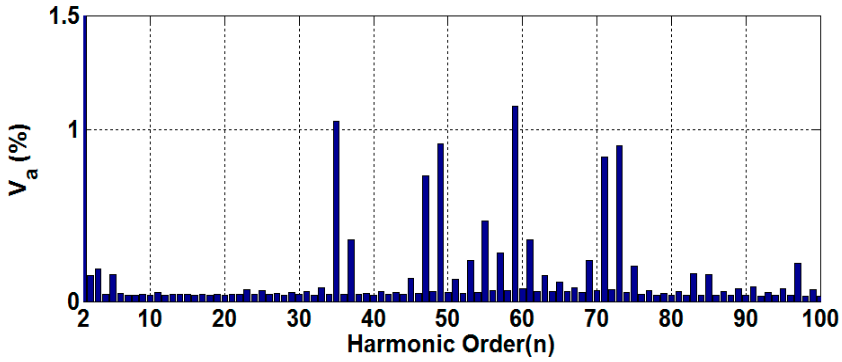

Figure 6. Harmonic Spectrum of v_a signal (THD=8%)

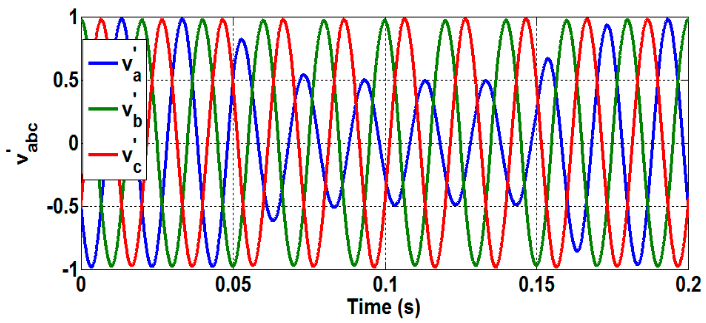

Figure 7. Unbalance Voltage Generation on a-phase

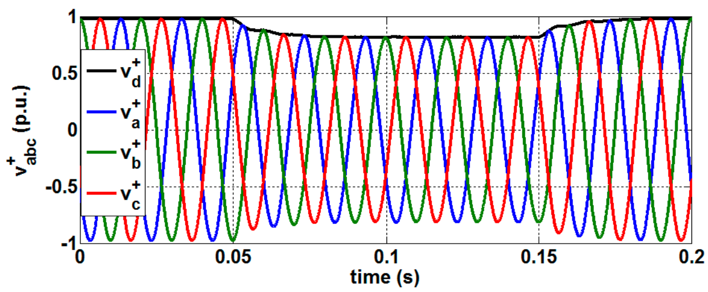

Figure 8. Positive sequence voltages

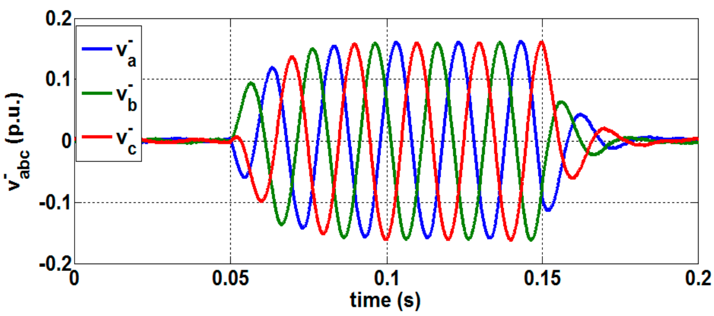

Figure 9. Negative Sequence voltages

Fig. 10 shows the estimated frequency of grid voltage. Performance of conventional PLL method as given in [3] and implemented SOGI based PLL algorithm in Fig. 3 are compared. Fig. 10 compares the estimated frequency of both methods, and it is shown from the figure that frequency of the conventional method has higher oscillation. The term k affects the bandwidth of the SOGI,

 doi:10.20944/preprints201705.0136.v1

and this defects estimated frequency at the instant of unsymmetrical component existence. The constant k=0.6 is used in all simulations. It must be noticed that higher k values increase the amplitude of the oscillation, while lower k values decreases the step response performance.

Fig. 11 shows the comparison of filtered and original d and q-axis voltage component in synchronously rotating frame. It is seen from Fig. 12 that double-frequency 100Hz oscillation exists during network unbalance, and distortions are eliminated with filtered measurements.

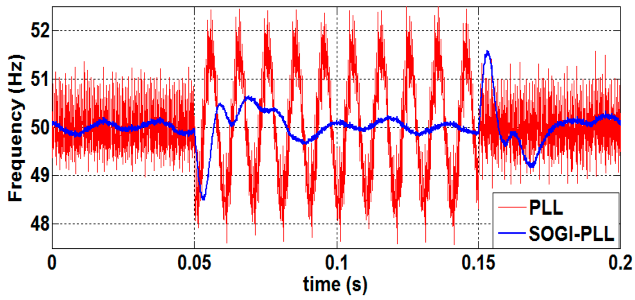

Figure 10. Estimated grid frequency

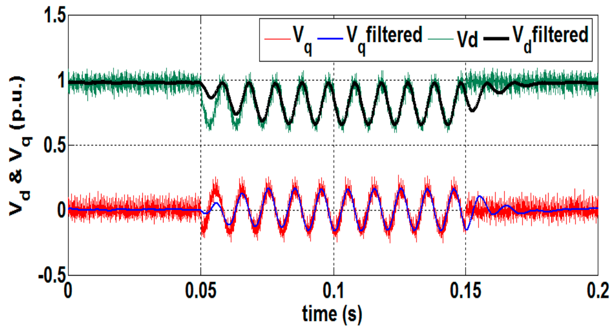

Figure 11. V_d and V_q axis voltages

Fig. 12 and 13 show positive (v^+_d-v^+_q) and negative (v^-_d-v^-_q) sequence synchronously rotating frame dq axis voltages, respectively. It is shown from Fig. 12 that positive sequence components have no oscillation, and at the instant of unbalanced voltage, the amplitude of v_d^+ decreases, while v_q^+ keeps constant at zero. It is shown from Fig. 13 that the negative sequence components exist at the instant of unbalanced voltage.

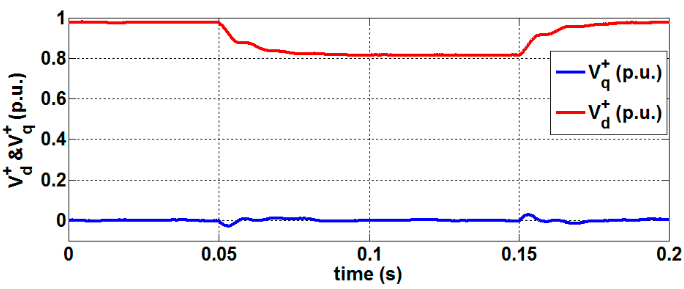

Figure 12. Positive sequence v^+_d-v^+_q voltages (V_{LL}=380V)

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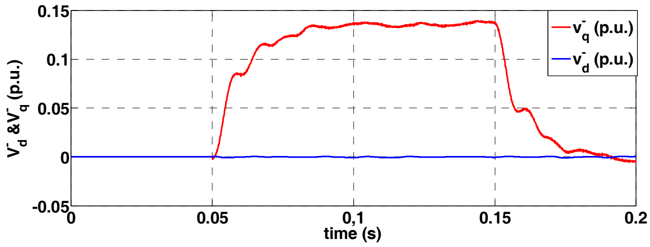

Figure 13. Negative sequence v^-_d-v^-_q voltages

Performance of the implemented algorithm is tested by altering the grid frequency of the applied distorted signal at an arbitrary instant of the simulation. Fig. 14 demonstrates the frequency step response of the distorted voltage signal. It can be observed from Fig. 14 that a quick step response of the frequency is guaranteed under distorted voltage conditions.

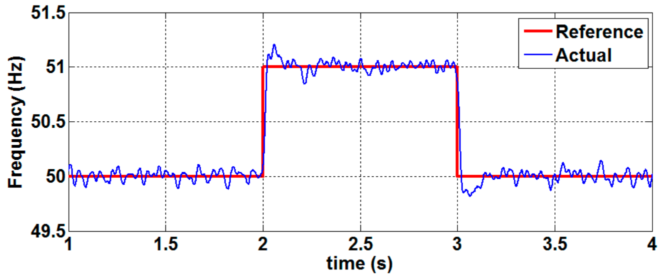

Figure 14. Reference and Estimated Frequency

4.3. Experimental Results

An experimental setup has been built to demonstrate the use of the generated symmetrical components for grid connected inverters. dSPACE ds1103 is used as a digital controller, and the implemented algorithm in Fig.4 was constructed in dSPACE Controldesk platform by using C programming language. Sample Time (T_s) of the controller was selected as 100µs. All voltage measurements were done without additional filters.

A 50% unbalanced voltage was generated on b-phase of the grid voltage at an arbitrary instant of the experiment which lasted 10 seconds. Fig. 15 and Fig. 16 show positive (v^+_d-v^+_q) and negative (v^-_d-v^-_q) sequence synchronously rotating frame dq axis voltages, respectively. Fig.17 shows the applied 50% unbalanced transient on b-phase.

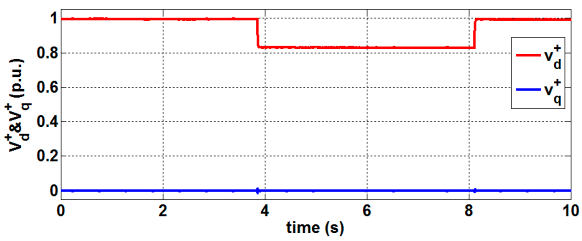

Figure 15. Positive sequence v^+_d-v^+_q voltages

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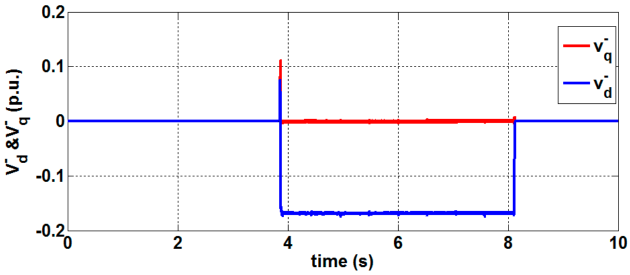

Figure 16. Negative sequence v^-_d-v^-_q voltages

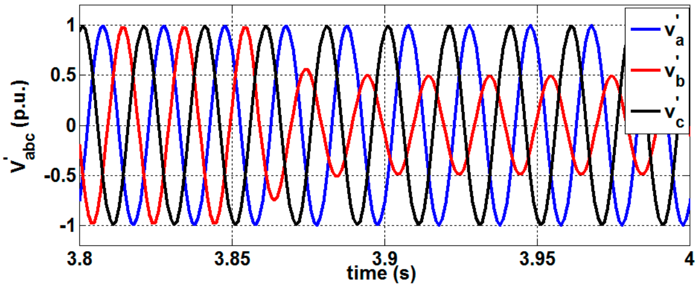

Figure 17. Applied 50% unbalanced transient on b-phase.

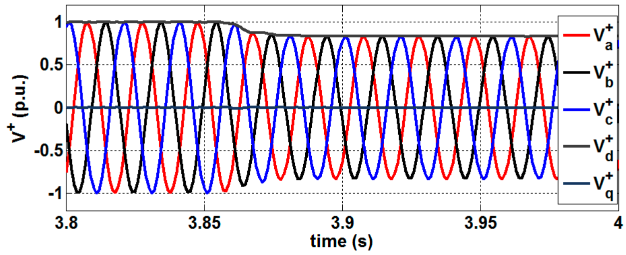

Figure 18. Positive sequence voltage transients with d-q components

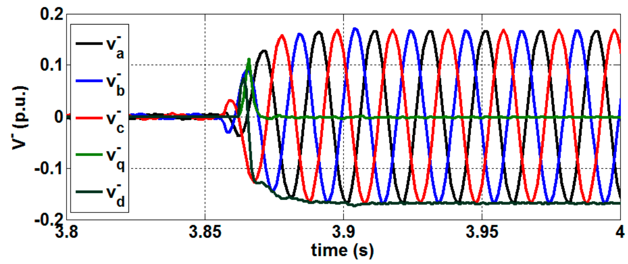

Figure 19. Negative sequence voltage transients with d-q components

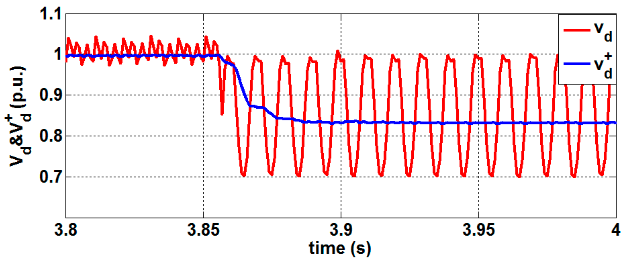

Figure 20. Comparison of d-q axis voltage components

 doi:10.20944/preprints201705.0136.v1

Fig.18 and Fig.19 shows the positive and negative sequence voltage transients with d-q components, respectively. It is shown from Fig. 18 and Fig.19 that the implemented algorithm effectively achieves decomposition of symmetrical components.

The implemented SOGI based PLL algorithm has been compared to the conventional PLL [3] method. The SOGI based PLL algorithm performed better than the conventional PLL method, as shown in Fig. 20. Fig. 20 compares synchronously rotating d-axis component of grid voltage signals. V_d has very high frequency oscillations under distorted and balanced voltage conditions (3.8-3.85 s) and it has a double-frequency 100Hz oscillation under unbalanced and distorted conditions (3.85-4 s). V_d^+ has no oscillation under balanced and unbalanced voltage conditions, and the amplitude of V_d^+ decreases at the instant of unbalance voltage.

5. Conclusion

This investigation articulated simple approach algorithm for the estimation of instantaneous symmetrical components under the distorted voltage conditions. The implemented algorithm filters out the distorted voltage successfully and constructed the symmetrical components under instantaneous unbalanced voltage conditions. A comprehensive comparison was carried out the proposed estimator and the classical PLL estimator, shown that the oscillations in frequency and the dq-axis voltage components are minimized under the distorted voltage conditions using SOGI technique. Complete AC grid system along with the estimators are designed and implemented in the numerical simulation software and corresponding validated with the real time prototype implementation using dSPACE ds1103. Set of numerical and real time results provided in this paper demonstrated the close agreement with the theoretical background of the proposed SOGI estimator method for grid connected inverters.

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