Instantaneous grid voltage estimation based on the Newton-Raphson optimization for grid connected VSC applications

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Abstract—**This paper presents a proportional-resonant current control scheme for three-phase grid connected voltage source converters (VSCs) which does not require ac side voltage sensors. In the proposed method, a non-linear model is derived for the grid connected converter which relates the instantaneous grid voltage value to the filter parameters and the generated converter voltage in each switching period. The non-linear model is solved in each period using the Newton-Raphson optimization; then the reference current for the current control loop is generated from the estimated grid voltages. Using an estimator instead of voltage sensors not only reduces the size and cost but also improves the reliability of the converter system and protects it from grid voltage disturbances and noises.**

Keywords- Voltage source converter (VSC); sensorless control; propotional-resonant controller (PR); voltage estimation, Newton-Raphson algorithm

I. INTRODUCTION

Nowadays, pulse-width modulated (PWM) voltage source converters (VSCs) have become of great interest due to various advantages they offer. The main advantages include the ability to use advanced modulation techniques, bi-directional power flow, fast and accurate current regulation with low total harmonic distortion (THD), and adjustment of input power factor and DC link voltage. In order to regulate the power exchange between the grid and VSC in grid connected mode of operation, and simultaneously provide the sinusoidal current with minimum distortions in the ac side, various control strategies have been reported. Recently the idea of using proportional-resonant (PR) controllers to regulate the sinusoidal currents with zero steady-state error has attracted considerable attention. The PR based current control is implemented in the stationary reference frame and provides a very high gain at its resonant frequency (grid fundamental frequency). Therefore, in this method, tracking of sinusoidal signals with zero steady-state error is achieved simply [1-5].

To reduce the cost of grid connected converters, the grid voltage sensors can be eliminated and using the model parameters and other measured quantities, these voltages can be estimated. The most simple voltage estimation method consists of adding the converter output voltage to the voltage drop on the filter inductance. Despite its simplicity, the differentiation of current is a serious drawback of this method. Furthermore, the neutral point variations of the converter must be considered in the calculations [6].

In voltage estimations based on instantaneous powers [6-7], firstly instantaneous active and reactive powers are estimated using the measured currents, DC link voltage, switching state, and the filter inductance. Afterwards, voltages are calculated based on estimated powers and measured currents. Similar to the pervious method, high frequency noises owning to the differentiation operation are amplified. Therefore, to achieve a good estimation performance a high sampling frequency and a large inductance are required.

Virtual flux (VF) is one of the most commonly used methods in applications of grid connected VSCs [8-14]. In according to the intrinsic integration existed in this method, the effect of distorted grid voltage on control system is reduced. Practical implementation of a perfect VF estimator is based on an ideal integrator and is not possible. Noises and DC offset in the measured currents cause drift and saturation. To overcome these problems, solutions such as low-pass filtering [8-11], band-pass filtering [11-12] and frequency-adaptive band-pass filtering [13-14] are proposed. The steady-state error in estimated voltages, sensitivity to frequency variations, complicated structure and necessity of using a PLL are considered as main shortcomings associated to these methods.

Adaptive observers like Kalman filter and Luenberger observer could attract many attentions due to good dynamic and accuracy. Complexity of control algorithm and high computational burden are some of their disadvantages [15].

In this paper, a PR based current control without any AC side voltage sensors for the grid connected VSC is presented. In the proposed method, the grid voltage is estimated using the converter system equations in the time domain. The Newton-Raphson optimization is employed to solve the non-linear equations. In the following sections, details of the proposed method will be presented. Afterwards, the proper operation of the proposed method is confirmed through extensive simulations.

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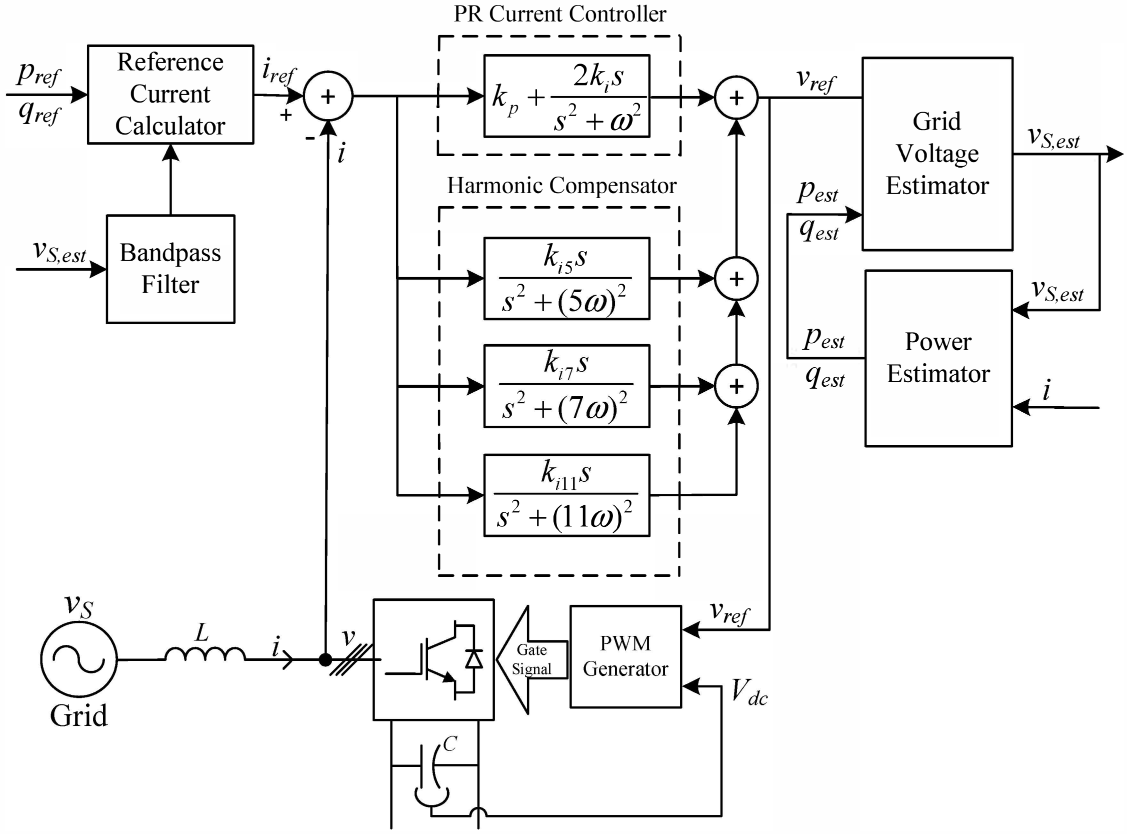


Figure 1. Proposed control method for the grid connected VSC

II. PROPOSED CONTROL METHOD

The block diagram of the proposed control method is shown in Fig. 1, which consists of the current control loop and the voltage estimator. The current control loop uses PR controllers and harmonic compensators (HCs) to regulate the grid current and eliminate the low order harmonic components [1-5]. As it can be seen, the HC network includes resonators at the desired harmonic frequencies to be attenuated (here 5th, 7th, and 11th).

At the first stage of block diagram of Fig. 1, the reference converter currents for the PR regulator are generated from the estimated grid voltages and the reference powers, in accordance with (1):

$$\begin{bmatrix} i_{\alpha,ref} \\ i_{\beta,ref} \end{bmatrix} = \frac{1}{(v_{S\alpha,est}{}^2 + v_{S\beta,est}{}^2)} \begin{bmatrix} v_{S\alpha,est} & v_{S\beta,est} \\ v_{S\beta,est} & -v_{S\alpha,est} \end{bmatrix} \begin{bmatrix} p_{ref} \\ q_{ref} \end{bmatrix} \quad (1)$$

In (1), $i_{\alpha,ref}$ and $i_{\beta,ref}$ are the converter reference currents, and $v_{S\alpha,est}$ and $v_{S\beta,est}$ are the estimated grid voltages in the stationary ($\alpha\beta$) reference frame.

Grid voltages are estimated from the converter system equations with the Newton-Raphson iterative algorithm. Newton-Raphson algorithm is the most widely utilized method in power system applications due to its fast convergence characteristic in offline solving of non-linear mathematical problems such as power flow equations. Considerable improvements in signal processors in recent years have led to use of this powerful mathematical tool for solving various online optimization problems [16]. The next section shows how the converter equations are derived and the Newton-Raphson is adopted to our specific problem.

The most important features of the proposed control method are:

• simple structure and concepts and ease of implementation;

• no need for coordinate transformations and a PLL;

• reduced cost, size and improved reliability of the system, which are consequences of eliminating the voltage sensors;

• full benefits of the PR current controller and harmonic compensators;

• instantaneous voltage estimation with all harmonic contents

III. PROPOSED VOLTAGE ESTIMATION ALGORITHM

Fig. 2 depicts the power stage of the grid connected three-phase VSC. Based on this figure, the active and reactive power exchanges with the grid can be written as shown in (2), where

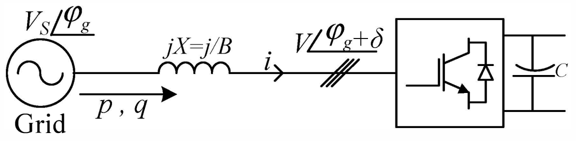


Figure 2. Single line representation of the grid connected VSC

p and q are active and reactive powers, B is the susceptance of the filter inductor, V_S and V are the amplitudes of grid and converter voltages, respectively, and δ is the power angle (phase-angle difference between the grid and converter voltages).

$$\begin{cases} p = BV_S V\sin(-\delta) \\ q = BV_S[V_S - Vcos(\delta)] \end{cases} \quad (2)$$

In (2) it is assumed that p, q, V and B are known and V_S and δ must be calculated in each sampling period.

Phase-angle of the grid voltage (φ_g) is simply obtained from the phase-angle of the converter voltage ($\varphi_C = \varphi_g + \delta$) which is known, and the power angle (δ), which is obtained from (2):

$$\varphi_g = \varphi_C - \delta \quad (3)$$

As mentioned before, φ_C is phase-angle of the converter voltage which can be easily calculated from the reference converter voltages as shown in (4).

$$\varphi_C = \arctan\left(\frac{V_{\beta,ref}}{V_{\alpha,ref}}\right) \quad (4)$$

In summary, to evaluate the instantaneous grid voltage in each sampling period, one can solve, by any means, (2) for V_S and δ (and consequently (φ_g)). Now, components of the grid voltage in the stationary reference frame can be readily calculated as:

$$\begin{cases} v_{S\alpha,est} = V_S\sin(\varphi_g) \\ v_{S\beta,est} = -V_S\cos(\varphi_g) \end{cases} \quad (5)$$

A. Numerical solution based on Newton-Raphson method:

Assuming that V_S and δ must be evaluated, (2) is apparently a system of two non-linear interconnected equations which is complicated enough to preclude an analytical solution; instead, numerical techniques must be used, which is the topic of this subsection.

In this paper, (2) is solved with acceptable accuracy and reasonable effort based on the Newton-Raphson iterative method, the principles of which will now be explained.

To formulate the Newton-Raphson optimization problem in terms of the unknowns V_S and δ, the system of equations (2) can be rewritten as:

$$\begin{cases} f(\delta,V_S) = p - BVV_S\sin(-\delta) = 0 \\ g(\delta,V_S) = q - BV_S[V_S - Vcos(\delta)] = 0 \end{cases} \quad (6)$$

In (6), $f(\delta,V_S)$ and $g(\delta,V_S)$ are the mismatches between the real and calculated active and reactive powers, respectively. To evaluate (6), p and q can be computed using the estimated voltages and measured currents, in accordance to (7), or simply be replaced by the reference values for the active and reactive powers (p_{ref},q_{ref}).

$$\begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} p_{est}(k) \\ q_{est}(k) \end{pmatrix} = \begin{pmatrix} v_{S\alpha,est}(k) & v_{S\beta,est}(k) \\ v_{S\beta,est}(k) & -v_{S\alpha,est}(k) \end{pmatrix}\begin{pmatrix} i_\alpha(k) \\ i_\beta(k) \end{pmatrix} \quad (7)$$

The Jacobian J_{est} matrix for (6) is obtained as:

$$J_{est} = \begin{bmatrix} \frac{\partial f}{\partial \delta} & \frac{\partial f}{\partial V_S} \\ \frac{\partial g}{\partial \delta} & \frac{\partial g}{\partial V_S} \end{bmatrix} \quad (8)$$

Where

$$\begin{cases} \frac{\partial f}{\partial \delta} = BV_S Vcos(\delta) \\ \frac{\partial f}{\partial V_S} = BV\sin(\delta) \\ \frac{\partial g}{\partial \delta} = -BV_S V\sin(\delta) \\ \frac{\partial g}{\partial V_S} = BVcos(\delta) - 2BV_S \end{cases} \quad (9)$$

Given initial values V_{S0} and δ_0, the iterations of the Newton-Raphson algorithm are performed through evaluating the following equations:

$$\begin{bmatrix} \Delta\delta_k \\ \Delta V_{S,k} \end{bmatrix} = J_{est,k}^{-1}\begin{bmatrix} f(\delta_k,V_{S,k}) \\ g(\delta_k,V_{S,k}) \end{bmatrix} \quad (10)$$

$$\begin{cases} \delta_{k+1} = \delta_k + \Delta\delta_k \\ V_{S,k+1} = V_{S,k} + \Delta V_{S,k} \end{cases} \quad (11)$$

Iterations are terminated once the changes (Δ values) are small enough.

In engineering problems the Newton–Raphson method has proved most successful thanks to its fast and strong convergence characteristics. However, if a given problem has saddles or multiple roots, the algorithm may get trap in a suboptimal solution or even become unstable. Therefore, it is very important that the convergence condition of the algorithm is investigated, before it is implemented. Equation (9) shows that all four elements of the Jacobian matrix are monotonous and do not have saddles or multiple roots. Therefore, this problem will always convergence to the right solution and will yield to a close approximation of V_S and δ.

It is clear that proper initial values speed up the Newton-Raphson process. In the current problem, it is convenient to select the initial guesses as the nominal grid voltage value for V_S and zero for δ. Also, once V_S and δ are updated successfully, they will not experience a considerable change until the system conditions (grid voltages or exchanged powers) change remarkably.

IV. PERFORMANCE EVALUATION

In order to evaluate the performance of the proposed control strategy, a digital computer simulation model has been established in Matlab/Simulink. The main parameters of the simulated platform are listed in Table I.

Several tests have been conducted to verify the effectiveness and feasibility of the voltage sensorless control strategy. The steady-state and the transient responses of the proposed method are investigated in various conditions.

The steady-state waveforms under various grid conditions, such as pure sinusoidal, highly distorted (5% of 5^{th} and 7^{th} harmonics), and imbalanced voltages (5%) are presented in Figs. 3-6. The steady-state waveforms confirm the excellent performance of the proposed voltage estimation method, even when the grid is highly polluted and imbalanced. Fig. 4 shows that the voltage estimator can successfully estimate the actual voltage with all harmonics contents. The grid current harmonic spectrums are shown in Figs. 5 and 6. As it can be seen, the total harmonic distortion (THD) is found to be 2.96% and 3.37% for ideal and non-ideal grid voltages, respectively, which meets the IEEE Std 519 recommendation.

Finally, the transient performance of the proposed control method as well as the voltage estimator is presented in Fig. 7. It confirms a fast and decoupled transient response to various step changes in the reference active and reactive powers.

TABLE I. **SIMULATION PARAMETERS**

Grid Voltage	50 Vrms
DC Link Voltage	200 V
Filter Inductance	3.5 mH
Filter Resistance	0.02 Ω
Grid Frequency	50 Hz
Sampling and Switching Frequency	5 kHz

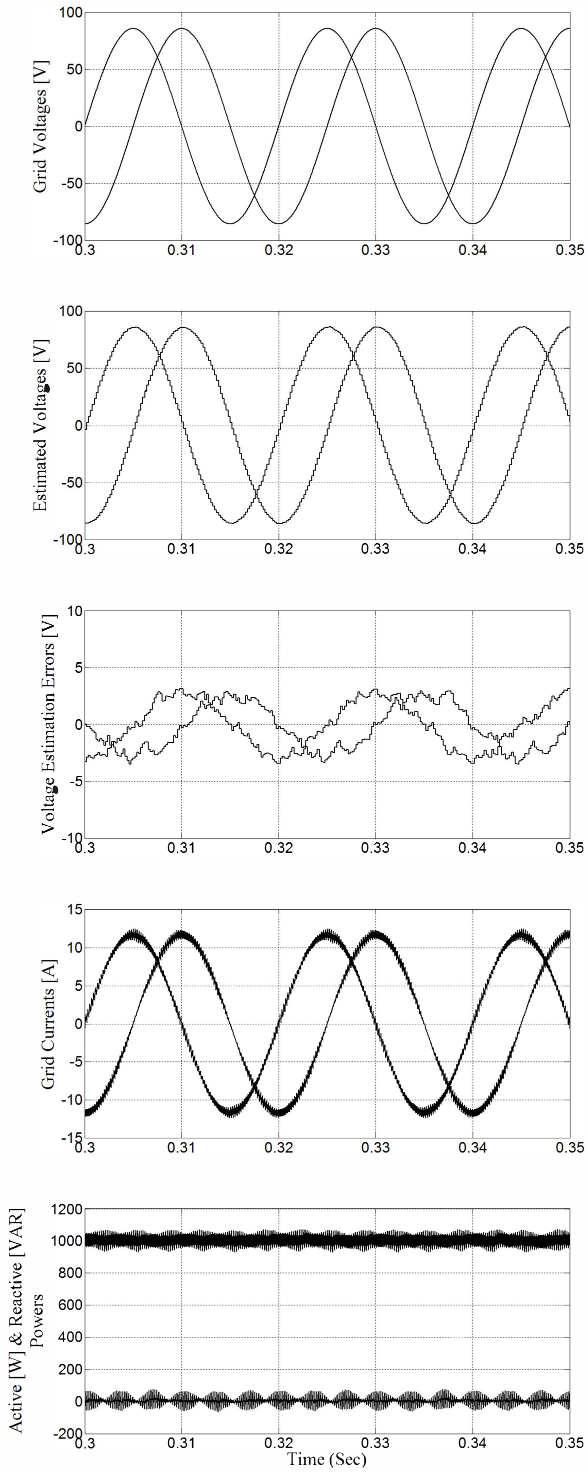


Figure 3. Steady-state performance under ideal grid voltages (all simulated waveforms are in the stationary reference frame (αβ));

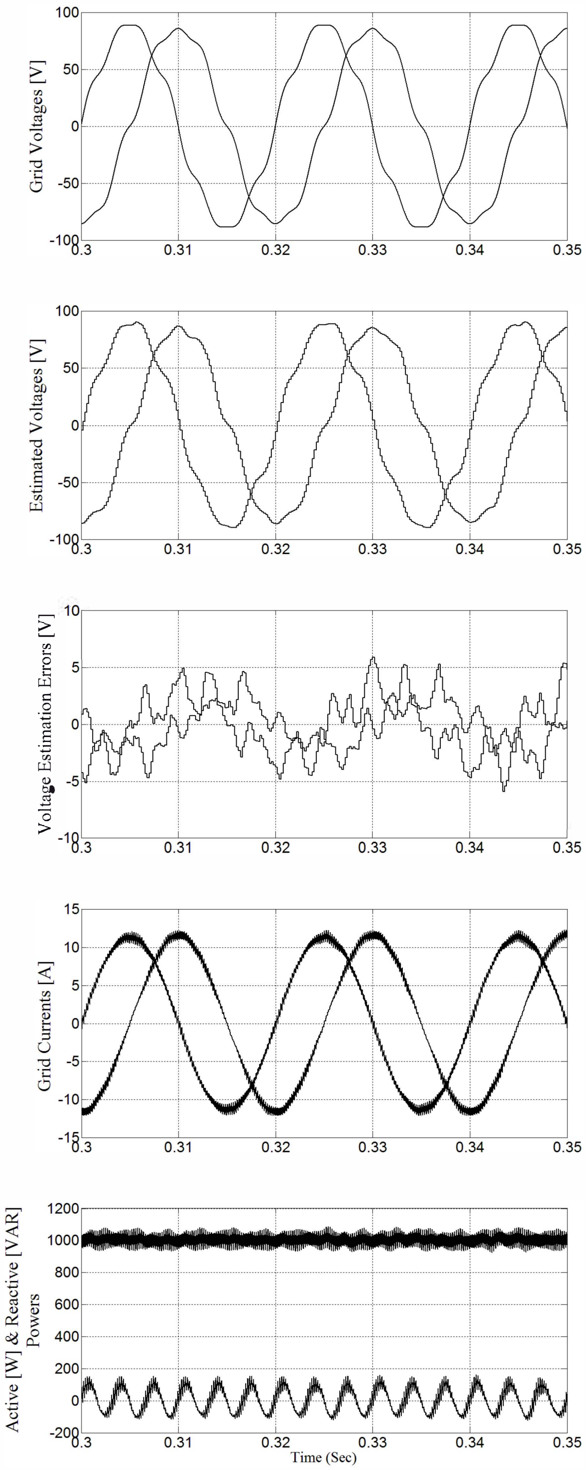


Figure 4. Steady-state performance under distorted and imbalanced grid voltages (5% of 5th and 7th harmonics and 5% imbalance) (all simulated waveforms are in the stationary reference frame (αβ));

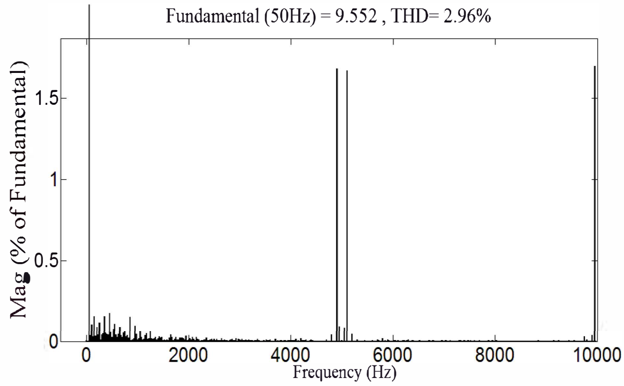


Figure 5. Grid current harmonic specturm under ideal grid voltages (p_{ref}=1000 w, and q_{ref}=0 var)

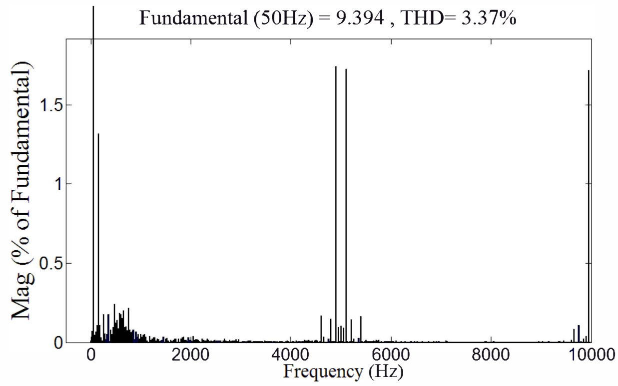
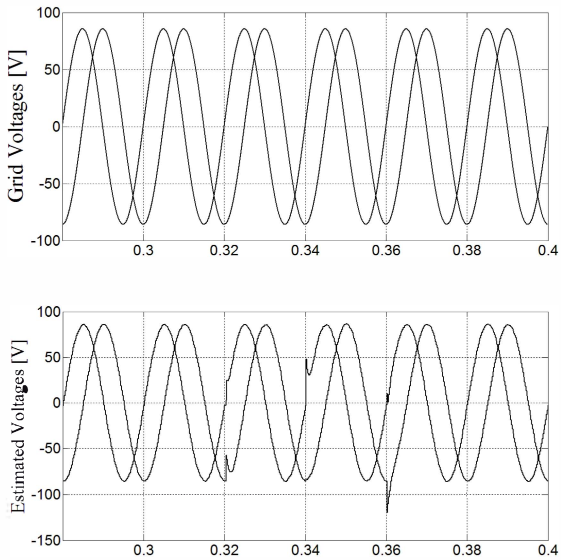


Figure 6. Grid current harmonic specturm under distorted and imbalanced grid voltages (p_{ref}=1000 w, and q_{ref}=0 var)



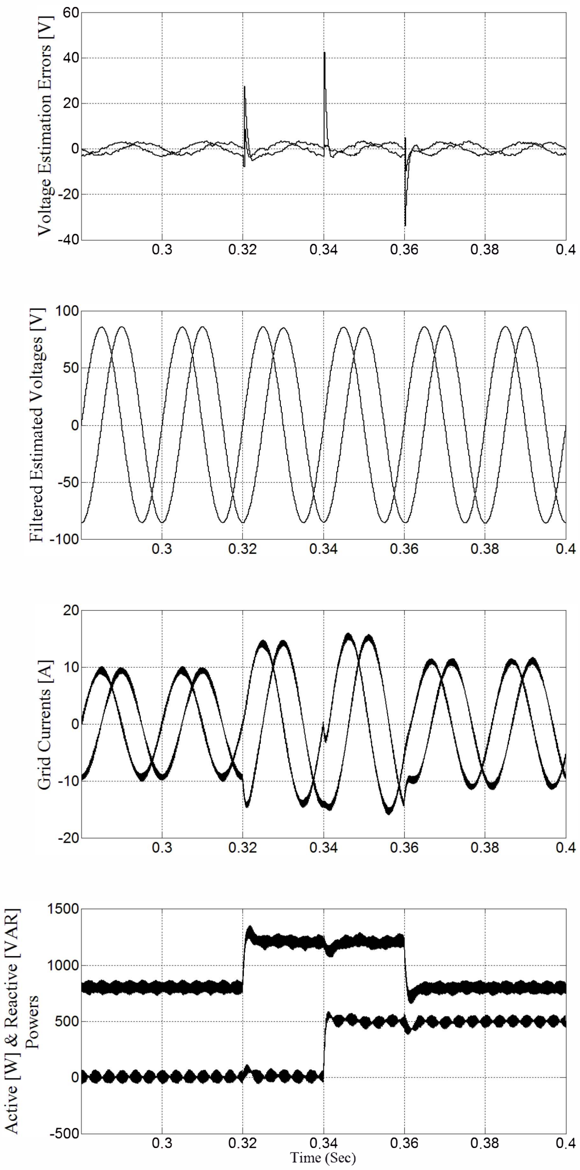


Figure 7. Transient performance for several step changes in active and reactive powers (all simulated waveforms are in the stationary reference frame (αβ));

V. CONCLUSION

The possibility of replacing grid voltage sensors with a voltage estimator scheme in the PR based current control of grid connected VSCs has been examined. The proposed voltage estimator employs the Newton-Raphson algorithm to solve the non-linear equations of the converter system. The excellent performance of the proposed method in steady-state and transients has been confirmed through simulations conducted in MATLAB/Simulink.

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