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Smart Inverter with Active Power Control and Reactive Power Compensation

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Abstract: Conventional grid-tied single phase inverters of renewable power generators (solar PV systems typical) have limited reactive power compensation capability and do not have active power control. This paper presents a novel control strategy which provides active power control with reactive power compensation for a DC/AC inverter connected to a single-phase AC grid, which supplies electricity to local loads. By sampling the instantaneous current on the grid at the local load side, which represents the domestic load current, an orthogonal signal is constructed using second order generalised integrator. The active and reactive current of the local loads are then rapidly detached from the orthogonal signal through specific trigonometric calculation. The reference current for the inverter output are produced by combining the active current and the reactive current which is detached from the domestic load current. Comparing the reference current with the inverter output current generates the PWM signals which are used to control the IGBT devices of the inverter bridge with capacitive impedance output to achieve domestic reactive compensation for inductive loads. The output current remarkably improves the load capacity of the grid and reduces the demand of reactive power from the gerid.

Keywords: Grid-Connected, Inverter, Active, Reactive, SOGI

1. Introduction

The power grid provides both active power and reactive power to satisfy the requirement of application of non-linear loads, such as induction motors driving domestic appliances, which require a large amount of reactive power. Therefore the fluctuation of reactive power demand impacts the balance of grid voltage. With high penetration of distributed power sources such as grid-tied single-phase photovoltaic power generation system, unbalanced voltage can easily go beyond the limit which forces the inverter stop injecting power into the grid even with strong solar irradiation [1] [2]. The feeder randomly and geographically extends out that brings huge challenge to find an appropriate approach to achieve reactive power compensation to stabilise the voltage of local electricity grid. Static compensators installed at the residential terminals will bring extra costs to the residents. Utilities are considering charging reactive power demand. For example, Italy's leading power distributor has decided to install more than 20 million household electricity meters with active and reactive power measurement [3]. For the safe operation of the power grid and improving power quality, the grid infrastructure must be configured reasonably, and also have optimal control methodologies, which can smoothly adjust the amplitude, current, frequency and phase angle. Secure and economic operation of power grid depends largely on its controllability, i.e. the power control, including active and reactive power control. Electromechanical oscillations have been observed widely in many power systems worldwide[4]. There are a number of situations which could cause the power system oscillation, such as a fast exciter for a wind turbine generator, fluctuation of the loads and intermittence of distributed power generation, such as fluctuated renewable power generation. The problems of oscillation may lead to power system blackout or power interruption [5]. The loadability of a power grid depends on the demands of active and reactive power that is received from distributed lines. As the capacity of electricity system load approaches its maximum critical point, the demands of both active and reactive power increase rapidly. Therefore, the reactive power supports have to be locally available [6].

The current mainstream approach to solve reactive power compensation is to connect a Flexible AC Transmission System (FACTS) device in parallel with the power line. There are a number of FACTS controllers [7], which are developed by engineers to damp the power oscillation [4] [8], such as Static Var Compensators (SVC), Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSC), Unified Power Flow Controller (UPFC), and Static Synchronous Compensator (STATCOM). Among the available FACTS devices, the STATCOM is a good one to be introduced in renewable generation to improve dynamic stability, steady state stability and transient stability [9] [10].

Micro renewable power generation interfaces with the power grid by inverters, which inject power to the grid as much as it can. Sometimes the loads of the micro-grid may require a sinusoidal current which is not in phase with the micro-grid voltage [11]. Conventional inverter rather considers how to inject the maximum power to the grid as much as it can whatever circumstance, even operating in the situation of the voltage magnitude of grid approaches collapse due to a plenty of renewable power generation is installed in the community. As the result of that the inverter stops output in order to meet the standard of Engineering Recommendation G83 [2].

The second order generalised integrators (SOGI) based on Phase Locked Loop (PLL) are well-known. Several researchers have successfully extended application in various purpose, such as synchronous signal with grid-converted in the application of active rectifier, active filters, uninterruptible power supplies and distributed generation etc.[12].

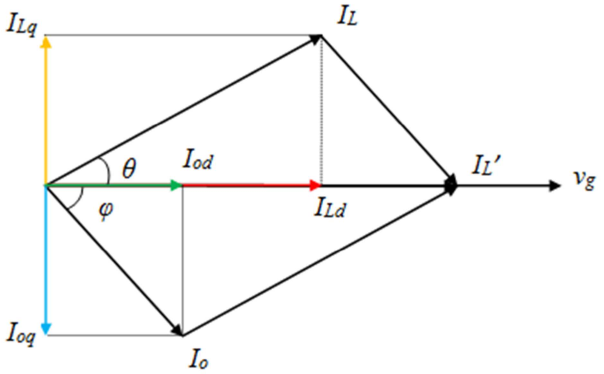


Figure 1. *Envisaged the vector relationships between currents and voltage.*

Figure 1 illustrates the vector relationships between the inverter output current, the load current I_L and the grid voltage v_g. The load current I_L can be decomposed into active current I_{Ld} and reactive current I_{Lq} respectively. As shown in Figure 2, the inverter output current I_o is decomposed by an active component I_{od} and a reactive component I_{oq}. If I_{oq} has the same magnitude of the load current's reactive component I_{Lq} and opposite direction, the whole system reactive power can be completely compensated by the inverter, then it can inject active power to the grid with reactive power compensation.

2. Control Strategies

2.1. Overall of Control Methodology

Through the above analysis, the domestic reactive power compensation of single phase grid can be achieved by adjusting instantaneous reactive current which is decomposed out from the output current of single phase inverter according to the instantaneous active and reactive power theory.

The instantaneous active and reactive power theory well-known as d-q theory is the mostly widely used time reference current generation technique[13]. The second order generalised integrator (SOGI) is widely exploited to achieve Phase Locked Loop (PLL) [13] [14] [15] and to eliminate or reduce the instantaneous noise level in many fields, such as control theory, relaying protection, signal processing, radio frequency, power systems, etc. [15]. The present strategy is shown in Figure 2, SOGI is used to construct a pair of the orthogonal trigonometric function for the current of loads which is sampled from the grid. Afterwards yielding the reactive current of loads i_q through decomposes load's active and reactive current by means of d-q theory, which is combined with the active current of demand to produce an instantaneous expected reference current compares with the actual output current of inverter i_o. The comparative error is exploited to generate PWM signal that is applied to control the inverter bridge.

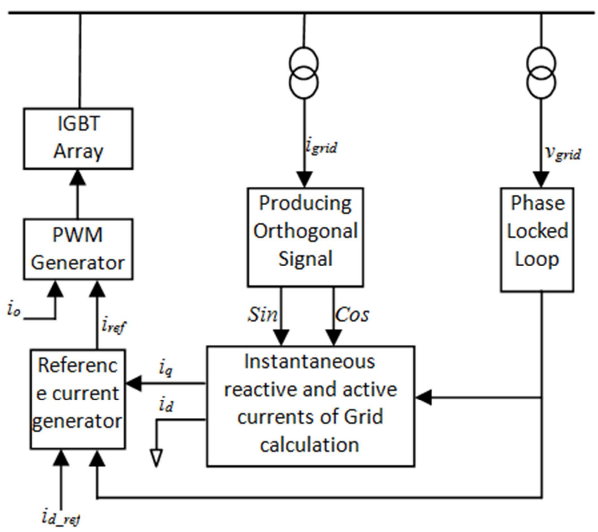


Figure 2. *Method of reactive power compensation.*

The single phase instantaneous voltage of the power grid and the load current are given by:

$$U_g = U_A \cos \omega t \tag{1}$$

$$I_\alpha = I_A \cos(\omega t - \theta) \tag{2}$$

Where

U_A is the root mean square (rms) value of the grid voltage,

I_A is the rms value of the load current,

I_α is the instantaneous current of the grid, and

θ is the phase angle.

The orthogonal equation of (2) the instantaneous current of loads can be obtained as:

$$I_\beta = I_A \sin(\omega t - \theta) \quad (3)$$

Applying trigonometric calculation for equation (2) and (3) yields:

$$I_\alpha = I_A \cos\omega t \cos\theta + I_A \sin\omega t \sin\theta \quad (4)$$

$$I_\beta = I_A \cos\omega t \sin\theta - I_A \sin\omega t \cos\theta \quad (5)$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} I_A \cos\theta \\ I_A \sin\theta \end{bmatrix} \quad (6)$$

To obtain the active and reactive current of the load by multiplying matrix $\begin{bmatrix} \cos\omega t & -\sin\omega t \\ \sin\omega t & \cos\omega t \end{bmatrix}$ at both side of the equation (6)

$$\begin{bmatrix} I_A \cos\theta \\ I_A \sin\theta \end{bmatrix} = \begin{bmatrix} \cos\omega t & -\sin\omega t \\ \sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (7)$$

Obviously the active and reactive current I_d, I_q have been apart from the sampling load current by equation (7), which are $I_A cos\theta$, $I_A sin\theta$ respectively.

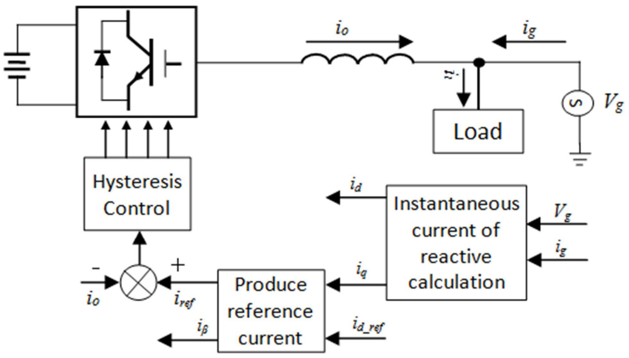


Figure 3. *Decomposes reactive and active load current.*

In the equation 7, sine and cosine functions can be acquired by a phase-locked loop.

Figure 3 is a module of to obtain instantaneous active and reactive current from electric utility.

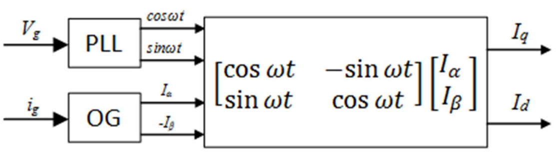


Figure 4. *Equation of obtaining active and reactive current.*

The system samples the voltage of grid to ensure the output power from inverter is completely synchronous with the grid in the term of frequency, phase and the room mean square (RMS) voltage.

Figure 4 implements equation (7), which illustrates that the module produces the output reference current of the inverter according to the demanded reactive power of the grid, the ability of inverter provides active power and PLL signals.

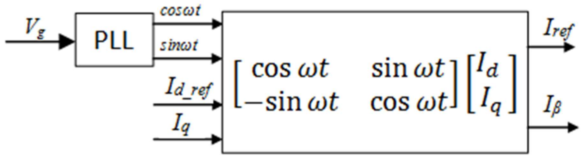


Figure 5. *Producing the reference current.*

2.2. Orthogonal System Generation

Assuming that an input signal is a sinusoidal signal v_i=$sin\omega t$, the orthogonal function of sinusoidal function is cosine function that can be obtained by generalized integration as the following equation:

$$y = \int_{-\infty}^{+\infty} \sin\omega t\, dt = -\frac{1}{\omega}.\cos\omega t + C \quad (8)$$

And the input signal can be retrieved by means of derivative of above equation as below.

$$\frac{dy}{dt} = \sin\omega t = v_i \quad (9)$$

If only considers that the input signal v_i start from time 0, which means the function $sin\omega t$ is defined for all t ≥ 0, then Laplace transfer of sine trigonometric function is:

$$F(s)= \mathcal{L}(y) = \frac{\omega}{s^2+\omega^2} \quad (10)$$

And the Laplace transfer of the derivative of function *y'* can be granted as:

$$\mathcal{L}(y') = \frac{s\omega}{s^2+\omega^2} \quad (11)$$

So the equation above is the response function of system H_s that needs to be constructed.

$$H_s = \frac{v_o}{v_i} = \frac{s\omega}{s^2+\omega^2} \quad (12)$$

$$=> v_o(s^2+\omega^2) = v_i.s\omega \quad (13)$$

$$=> v_o = \left(v_i - v_o\frac{\omega}{s}\right)\frac{\omega}{s} \quad (14)$$

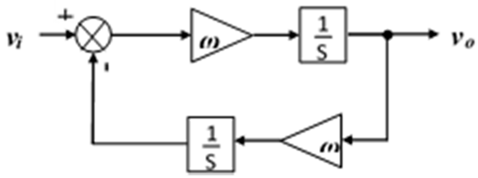


Figure 6. *The response of open-loop system of orthogonal generation.*

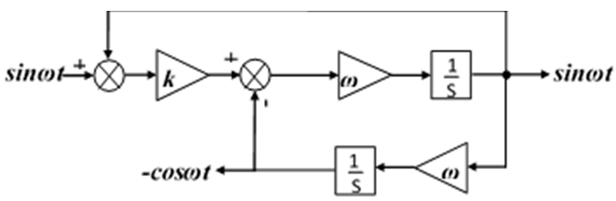


Figure 7. *Closed-loop system of orthogonal generation.*

Figure 6 illustrates the open-loop structure of system response according to Equation 14, and Figure 7 is the structure of closed-loop system. In Figure 7, the gain parameter k affects the bandwidth of the closed-loop system.

3. Simulated Results

Figure 8 illustrates the results of orthogonal system output compare with input signal. As the appearance of figure, the two output signal accurately formed a pair of quadrature. Although there is some unstable at the time starting, the system rapidly operated at steady-state and the produced sinusoidal signal overlaps with input signal.

Obviously, the loads current of the grid leads certain phase angle with respect to the voltage of the grid in Figure 9 (a). There is considerable contrast with Figure 9 (b) which produced by the inverter utilizing the presented method of reactive compensation to coincide with output of active power. The phase angel of loads current perfectly follows the voltage of the grid after delivered reactive power to the grid by the inverter.

The simulation of inverter embedded the presented approach demonstrates that the reactive power supported by the grid significantly fall down as Figure 10 (b) illustrated.

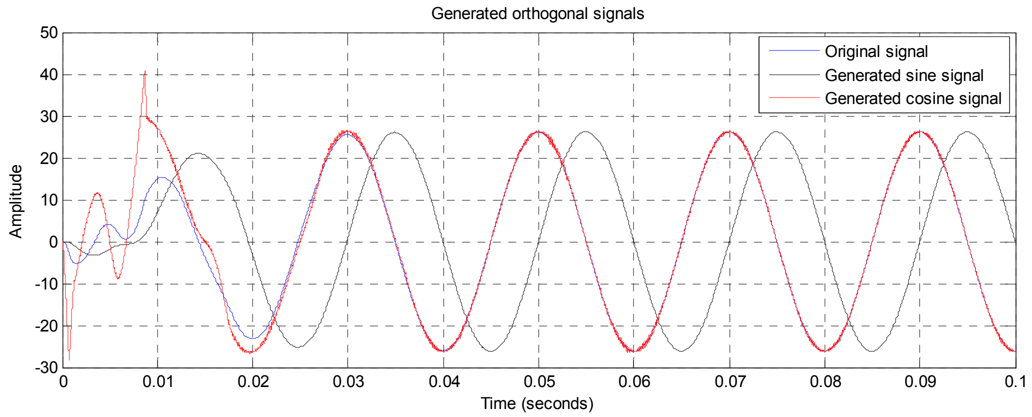
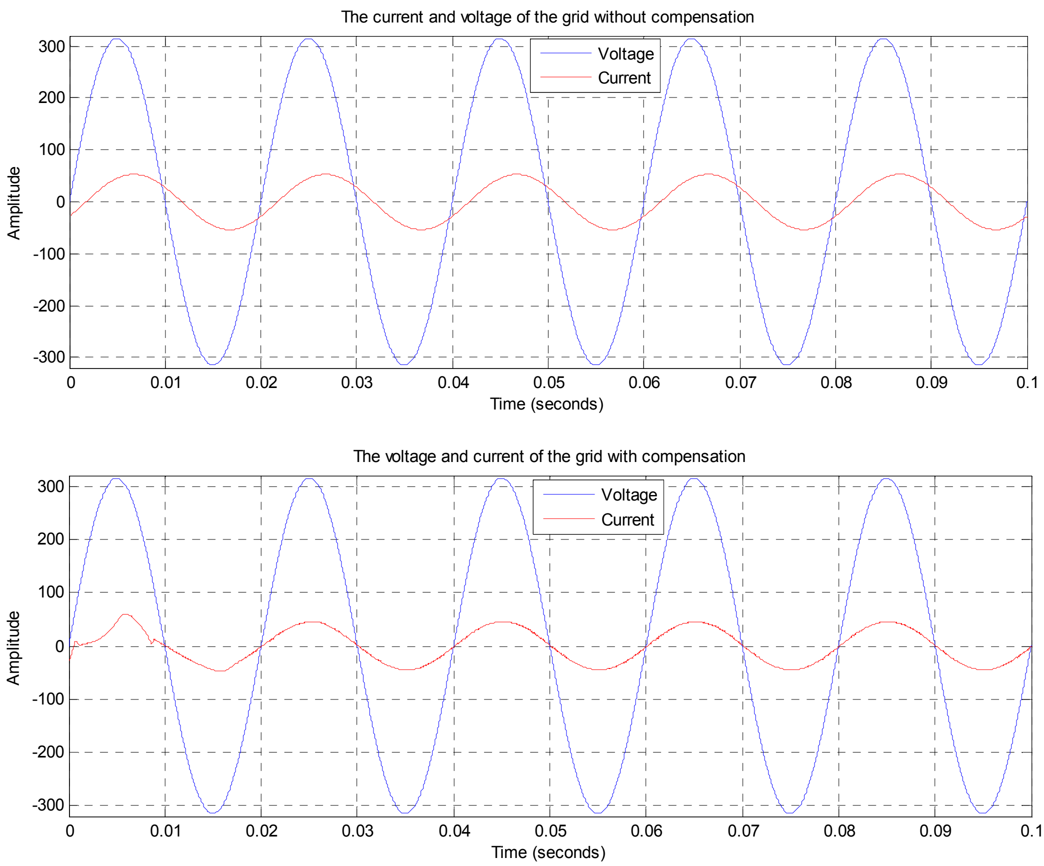
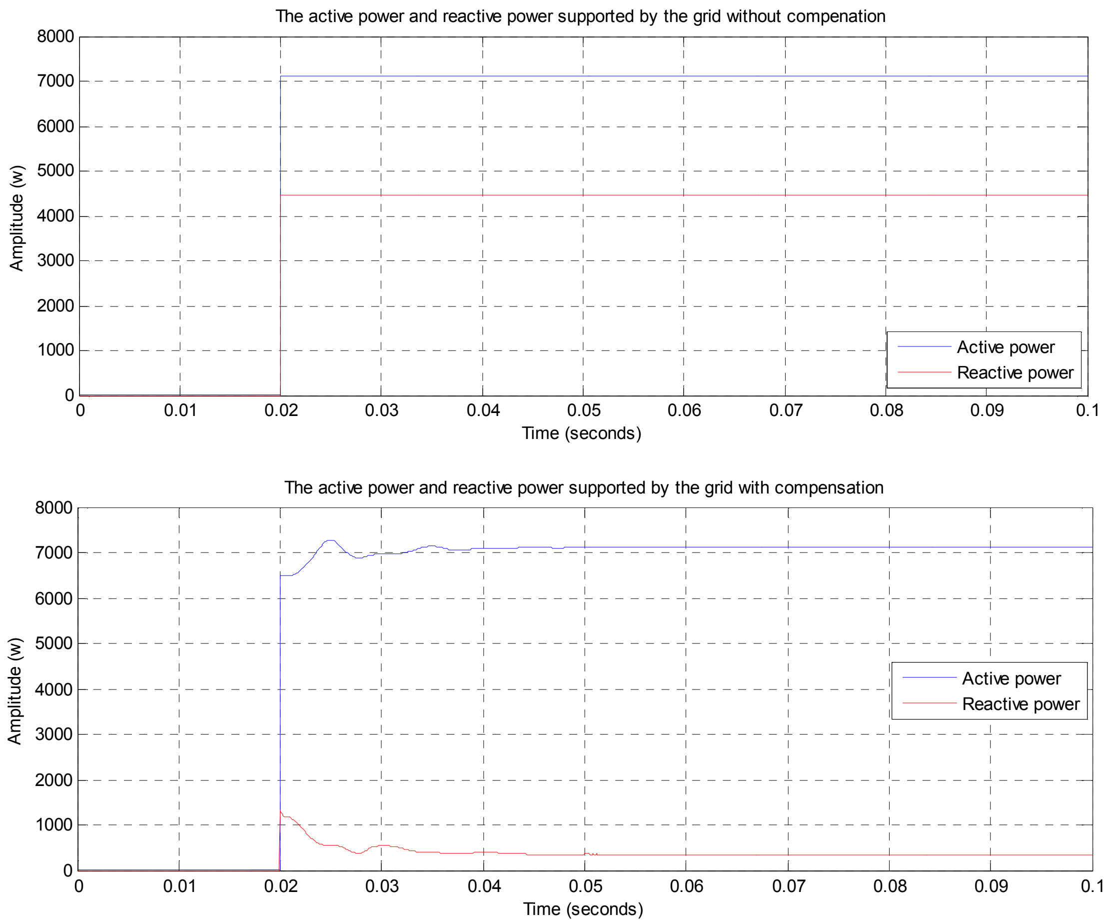


Figure 8. *Orthogonal system output.*



(a) The current and voltage of grid without compensation (b) The current and voltage of grid after compensation

Figure 9. *The current and voltage of the grid.*



(a) The results of without compensation (b) The results of after compensation

Figure 10. *The comparison between the inverter with the presented method of compensation and without compensation.*

In Figure 10, the simulated results obtained in the situation of that the inverter only injects reactive power to the power grid. As Figure10 (b) illustrates that the active power supported by the grid maintains at same level contrast with the system without compensation.

Figure 11 shows the simulate model can output active power, and in the meantime also can produce reactive power. Figures 10 and 11 demonstrate that the proposed measure can separately control the active power and reactive power according to the demands of customs.

Figures 12 (a) and (b) elucidate that the power factor has been considerably improved, increased from approximate 0.85 to nearly 1. Improving power factor can reduce power system loses to relatively increase load carrying capabilities in the local power system.

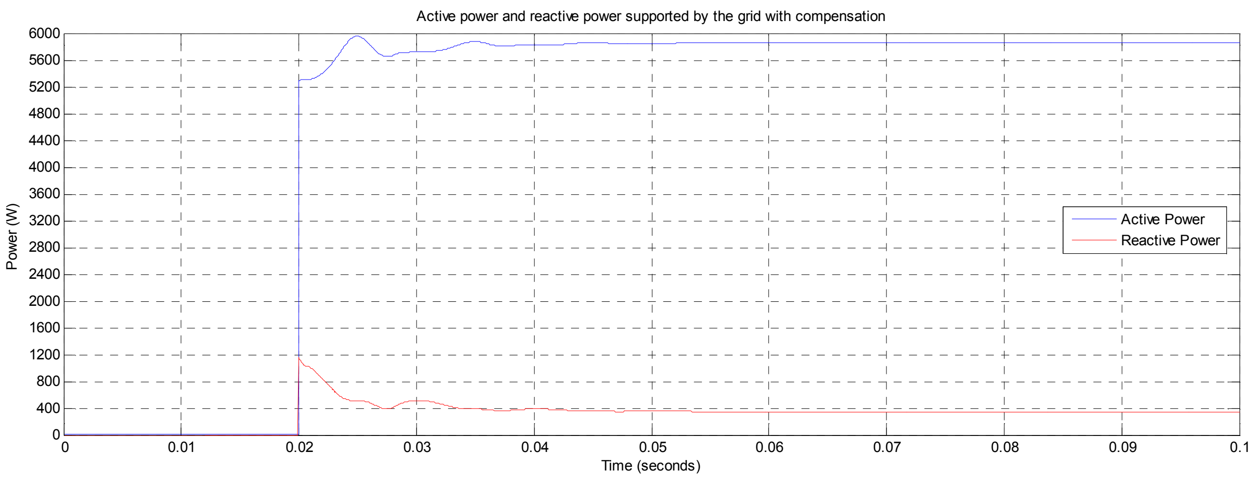
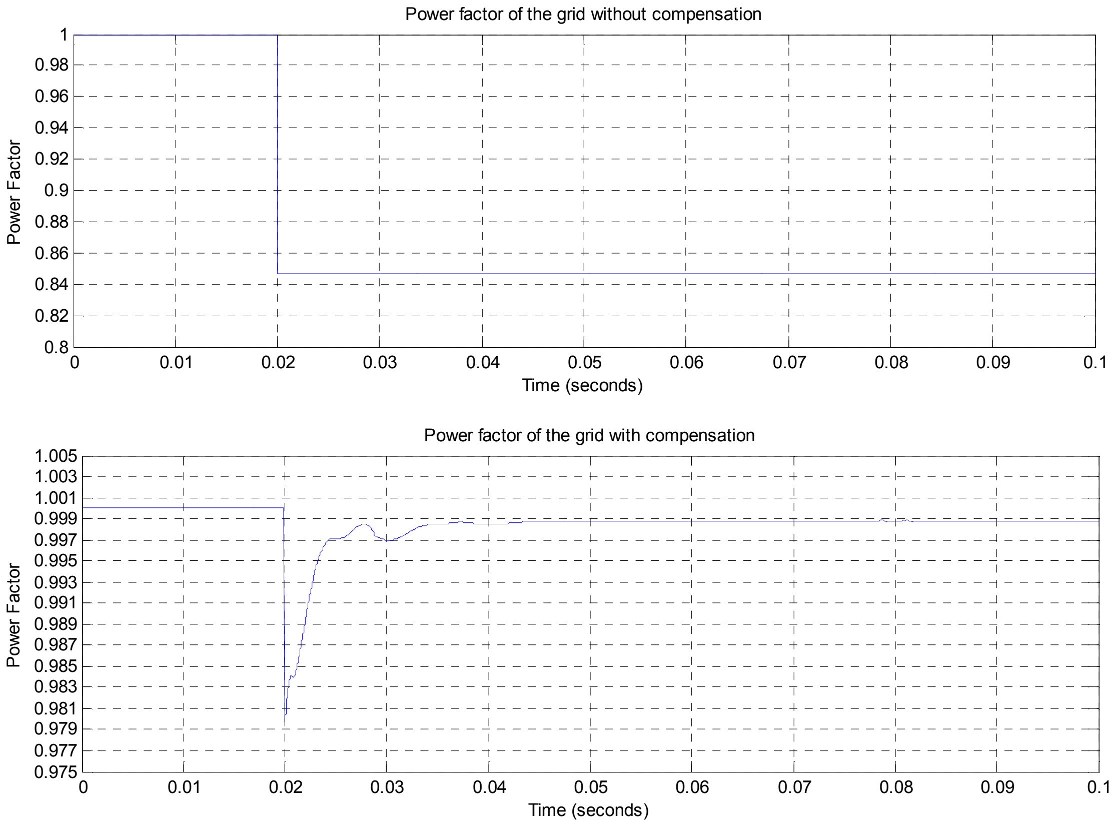


Figure 11. *The results of the inverter model output active and reactive power.*



(a) The power factor of the grid before the model provided compensation (b) The power factor of the grid after compensation

Figure 12. *The comparison of power factor.*

4. Conclusion

The simulation results demonstrate that the proposed method by separating active and reactive current of the grid using SOGI to construct an orthogonal system is successfully approved by means of simulated consequence. It means that the inverter can inject active power into the grid to coincide with certain amount of reactive power compensation.

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