Control of Single Phase PWM Converter for Renewable Energy System Using Active and Reactive Current Components

S. Wangsathitwong, S. Sirisumrannukul, S. Chatratana and W. Deleroi

Abstract— *This paper presents a control of single-phase PWM power converter based on active and reactive current components. In this control scheme, the active power and reactive power can be directly and independently controlled. The line current phasor is decomposed into active and reactive current components, which are in phase and quadrate to the system voltage phasor, respectively. Therefore, two control loops, one for the dc link voltage or active power control and the other for reactive power control, can be formed. Feed forward technique is employed to decouple two control loops and a standard PI controller can be used in each loop effectively. With reactive power control the proposed system can be used to perform as voltage regulation. The performances of the proposed control were simulated and illustrated for rectifying mode, inverting mode and load voltage regulation mode.*

Keywords— **Single-phase PWM converter, Active current and reactive current components, Decoupled control, PI controller.**

1. INTRODUCTION

Renewable energy sources such as wind energy (WE) and photovoltaic (PV) system are widely used and their installed capacities are dramatically increased every year. These systems require power electronic converter to control the energy transfer, whether they are isolated or grid connected. Both WE and PV can be operated as an individual system or a hybrid system. When a system is connected to the electric supply, the converter must be able to handle bi-directional flow of the active and reactive power of the converter, i.e. the rectifying and inverting modes of operation.

For three-phase system, the model of the converter is based on d-q synchronously rotating reference frame [1], [2]. In this frame, the three-phase ac voltages and currents are transferred onto the d-q axis, which is oriented along the supply voltage vector. The active power and reactive power are decoupled and the power flow between ac supply and the dc link can be independently controlled to flow in both directions.

For small renewable energy systems that are installed in rural or remote areas, the supply side converter may be of single-phase type. The supply side converter is controlled to maintain constant dc link voltage and to produce ac sinusoidal current waveform at the point of common coupling (PCC). The ac current reference is derived from 50 Hz sinusoidal voltage waveform and a current controller is required to track the reference waveform. Normally, the current control scheme is based on hysteresis control [3]. This controller is simple and robust but there are several disadvantages such as variable switching frequency, current error band and high frequency limit [4]. Furthermore, due to the ac sinusoidal reference current waveform, the design of the PI controller for this signal is not as simple as the design with dc constant reference signal.

This paper proposes a control method for a single phase PWM converter. The method is based on active current and reactive current components. These two components are derived from the ac line current. The active current component is a sinusoidal ac current which is in phase with the supply voltage. The reactive current component is a sinusoidal ac current which is in quadrature with the supply voltage. At steady state, the magnitudes of these current components are constant. Consequently, the single phase PWM converter can be controlled in the similar fashion to the control of three-phase PWM converter system based on the d-q axis. The operation with this control scheme leads to a linear control design technique and a simple design of input filter with a specified high switching frequency.

With reactive power control, the proposed control technique can be used as a voltage sag compensator. If the voltage at the point of common coupling (PCC) drops below a specified value, the reactive power flow into the ac system will be increased and the PCC voltage will be restored.

This paper is organized in four parts. The mathematical model of a single phase PWM converter based on active and reactive current components is described in Section 2.1. In Section 2.2, the linearized model is analyzed to determine system stability. The method to compensate voltage sag is described in Section 2.3. The simulation results are shown in Section 3 for rectifying mode, inverting mode and voltage sag compensation mode. The conclusion is given in Section 4.

S. Wangsathitwong (corresponding author) and S. Sirisumrannukul are with King Mongkut's Institute of Technology North Bangkok (KMITNB), Bangkok, Thailand. Phone: +66-2-9132500 ext. 6304; Fax: +66-2-5874356; E-mail: ssww@kmitnb.ac.th.

S. Chatratana is with Technology Management Center, National Science and Technology Development Agency (NSTDA), 111 Thailand Science Park, Paholyothin Rd., Patumthani, Thailand. e-mail: somchaich@nstda.or.th.

W. Deleroi was with Delft University of technology, Delft, Netherlands. E-mail: werner.deleroi@skynet.be.

2. SYSTEM CONFIGURATION AND MODELING

2.1 Nonlinear Model Analysis

The single phase PWM converter is a H-bridge converter connected to the electric supply with a dc capacitor on the dc side. The simplified model is depicted in Figure 1. The supply voltage and dc power equations for the PWM converter are given in (1) and (2).

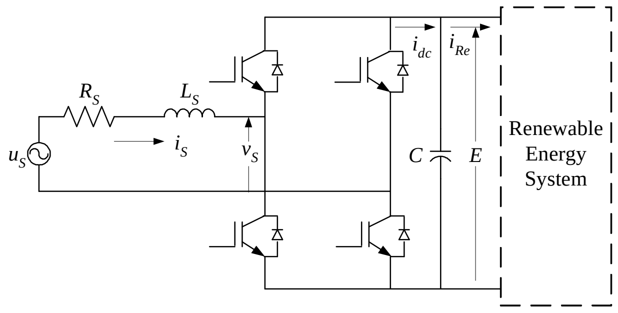

Fig.1. Single-Phase PWM Converter

$$u_S = R_S i_S + L_S \frac{di_S}{dt} + v_S \tag{1}$$

$$Ei_{Re} + EC\frac{dE}{dt} = Ei_{dc} = P_{dc} \tag{2}$$

By assigning the supply voltage, u_S, as a reference, the instantaneous values of u_S , i_S and v_S can be expressed as

$$u_S = U_S \sin(wt) \tag{3}$$

$$i_S = I_S \sin(wt - q) \tag{4}$$

$$v_S = V_S \sin(wt - d) \tag{5}$$

The expressions for, i_S and v_S, can be expanded into two terms as

$$i_S = I_{Sp}\sin(wt) + I_{Sq}\cos(wt) \tag{6}$$

$$v_S = V_{Sp}\sin(wt) + V_{Sq}\cos(wt) \tag{7}$$

where the active and reactive components of the currents (I_{sp}, I_{sq}) and voltages (V_{sp}, V_{sq}) are

$$I_{Sp} = I_S\cos(q), \quad I_{Sq} = -I_S\sin(q)$$

$$V_{Sp} = V_S\cos(d), \quad V_{Sq} = -V_S\sin(d)$$

The average single phase ac active power and reactive power flow are

$$P = \frac{1}{2}U_S I_{Sp} \tag{8}$$

$$Q = -\frac{1}{2}U_S I_{Sq} \tag{9}$$

Substituting (6) and (7) in (1) and separating the coefficient of $\sin(\omega t)$ into one equation and the coefficient of $\cos(\omega t)$ into another equation, the two equations can then be expressed as

$$R_S I_{Sp} + L_S\frac{dI_{Sp}}{dt} = U_S + wL_S I_{Sq} - V_{Sp} \tag{10}$$

$$R_S I_{Sq} + L_S\frac{dI_{Sq}}{dt} = -wL_S I_{Sp} - V_{Sq} \tag{11}$$

If the power loss in the converter is small and can be neglected, the dc power in (2) is equal to the ac active power in (8), i.e.

$$Ei_{Re} + EC\frac{dE}{dt} = \frac{1}{2}U_S I_{Sp} \tag{12}$$

Apparently, the active current component can be used to regulate dc voltage and the reactive current component can be used to regulate the reactive power.

The block diagram of the proposed PWM converter control is shown in Figure 2, with the selection of V_{PCC} control and reactive current control. The control objective in Figure 2 is to maintain the dc link voltage (E) at a desired value and the reactive current (I_{sq}^*) at a reference either positive, negative or unity power factor. Some important characteristics of the control loop in Figure 2 are as follows.

1) The voltage of the line is measured and the magnitude U_s and the reference angle ωt are derived.

2) The line current I_s is measured with the help of ωt to obtain active current component I_{sp} and reactive current component I_{sq}. I_{sp} and I_{sq} will be used as feedback signal for current control and as feedforward signal for decoupling process.

3) In the dc voltage control loop, the dc voltage of the capacitor E is measured and fed back for comparison. A PI controller is used to regulate the dc voltage. The active power command P^* from the controller is multiplied by a factor of $2/U_S$ to obtain the active current command I_{sp}^*. The error of the active current command and the actual active current is the input of another PI controller. The feed forward signal of $\omega L_s I_{sq}$ is added to the output of the controller to decouple the reactive component from the active equation. The supply voltage is then added to obtain the active voltage component command V_{sq}^*.

4) Similar reasoning can be used to describe the signal flow in the reactive current loop.

5) The active voltage command, reactive voltage command and the reference angle of the voltage from the measurement are the inputs for the PWM controller.

6) The PWM controller generates switching signals for the converter.

2.2 Linearized Model and Stability Analysis

The nonlinear equation in (9)-(12) can be linearized [5] and the linear control analysis such as stability and design technique can be directly applied. The linear relation between converter terminal voltage, v_S, and dc bus voltage, E, is expressed as

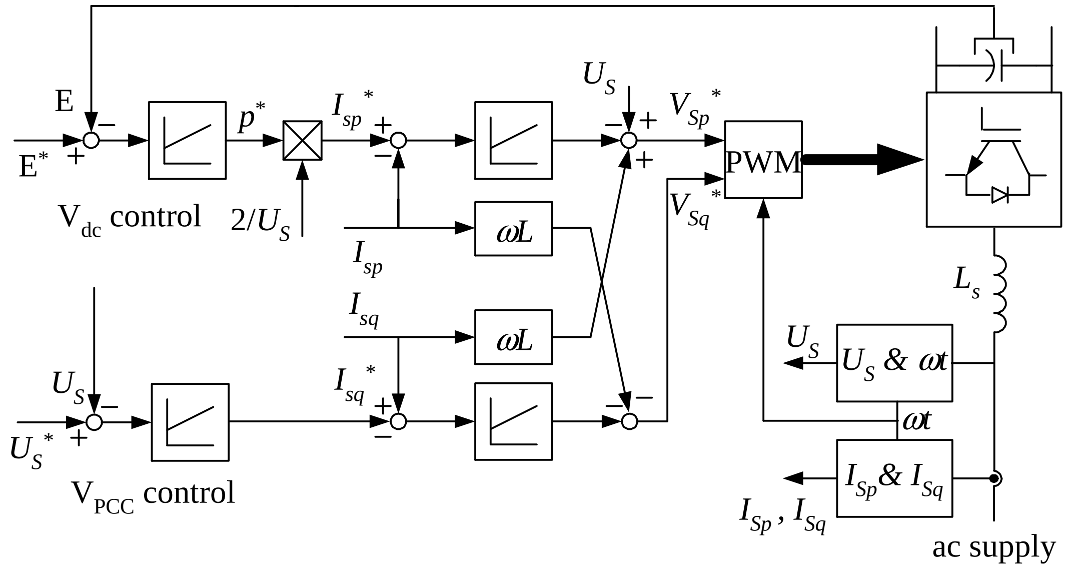

Fig.2. Control Block Diagram of Active and Reactive Current Component of PWM Converter

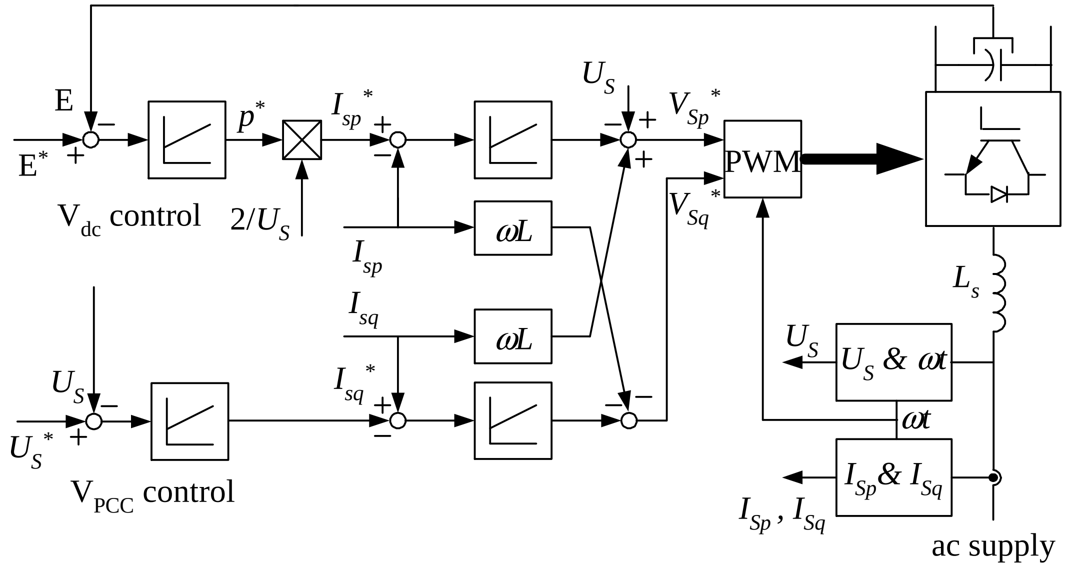

Fig.2. Control Block Diagram of Active and Reactive Current Component of PWM Converter

$$v_S = mE \tag{13}$$

Equations (10)-(12) can then be rewritten in state equation form as follows.

$$L_S \frac{dI_{Sp}}{dt} = -R_S I_{Sp} + wL_S I_{Sq} + (U_S - V_{Sp}) \tag{14}$$

$$L_S \frac{dI_{Sq}}{dt} = -R_S I_{Sq} - wL_S I_{Sp} - V_{Sq} \tag{15}$$

$$C \frac{dE}{dt} = i_{dc} - \frac{E}{R_{dc}} \tag{16}$$

If it is assumed that the dc power is equal to converter terminal active power, the expression for the dc power is

$$P_{dc} = Ei_{dc} = \frac{1}{2}(V_{Sp}I_{Sp} + V_{Sq}I_{Sq})$$

$$P_{dc} = \frac{1}{2}V_S(I_{Sp}\cos d - I_{Sq}\sin d) \tag{17}$$

$$\frac{v_S}{m}i_{dc} = \frac{1}{2}V_S(I_{Sp}\cos d - I_{Sq}\sin d)$$

$$i_{dc} = \frac{1}{2}m(I_{Sp}\cos d - I_{Sq}\sin d) \tag{18}$$

Substituting (18) in (16), and rearranging (14) – (16) in the standard form results in

$$\frac{d}{dt}\begin{bmatrix} I_{Sp} \\ I_{Sq} \\ E \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_S} & \omega & -\frac{m}{L_S}\cos\delta \\ -\omega & -\frac{1}{T_S} & \frac{m}{L_S}\sin\delta \\ \frac{m}{2C}\cos\delta & -\frac{m}{2C}\sin\delta & -\frac{1}{T_{dc}} \end{bmatrix} \begin{bmatrix} I_{Sp} \\ I_{Sq} \\ E \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} U_S \\ 0 \end{bmatrix} \tag{19}$$

$$\frac{d}{dt}\begin{bmatrix} \Delta I_{Sp} \\ \Delta I_{Sq} \\ \Delta E \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_S} & \omega & -\frac{m_0}{L_S}\cos\delta_0 \\ -\omega & -\frac{1}{T_S} & \frac{m}{L_S}\sin\delta_0 \\ \frac{1}{2}\frac{m_0}{C}\cos\delta_0 & -\frac{1}{2}\frac{m_0}{C}\sin\delta_0 & -\frac{1}{T_{dc}} \end{bmatrix} \begin{bmatrix} \Delta I_{Sp} \\ \Delta I_{Sq} \\ \Delta E \end{bmatrix}$$
$$+ \begin{bmatrix} \frac{m_0 E_0}{L_S}\sin\delta_0 & -\frac{E_0}{L_S}\cos\delta_0 \\ \frac{m_0 E_0}{L_S}\cos\delta_0 & \frac{E_0}{L_S}\sin\delta_0 \\ -\frac{1}{2}\frac{m_0}{C}\left(I_{Sp0}\cos\delta_0 + I_{Sq0}\sin\delta_0\right) & \frac{1}{2C}\left(I_{Sp0}\cos\delta_0 - I_{Sq0}\sin\delta_0\right) \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta m \end{bmatrix} \tag{20}$$

where

$$T_S = \frac{L_S}{R_S} \text{ and } T_{dc} = R_{dc}C$$

The linearization for small perturbation is represented by the first order terms of Taylor's expansion given in (19). The linear difference equations are given in (20). Therefore, the characteristic equation is

$$\lambda^3 + \left(\frac{2}{T_S} + \frac{1}{T_{dc}}\right)\lambda^2 + \left(\frac{2}{T_S T_{dc}} + \frac{1}{T_S^2} + K + \omega^2\right)\lambda + \left(\frac{2}{T_S^2 T_{dc}} + \frac{K}{T_S} + \frac{\omega^2}{T_{dc}}\right) = 0 \tag{21}$$

where $K = \frac{1}{2}\frac{m_0^2}{L_S C}$.

In (21), there is no δ term in the characteristic equation. Thus, switching angle does not affect the position of characteristic roots. Reassigning the coefficients of the polynomial in terms of a_0, a_1 an a_2, (21) can be rewritten as

$$l^3 + a_2 l^2 + a_1 l + a_0 = 0$$

The Routh-Hurwitz criterion can be used to determine stability analysis of this system.

$$\begin{array}{c|cc} l^3 & 1 & a_1 \\ l^2 & a_2 & a_0 \\ l^1 & a_1 - \frac{a_0}{a_2} & \\ l^0 & a_0 & \end{array}$$

For the system to be stable, the component of Routh array in the λ^1 row must be greater than 0, which results in

$$\frac{4}{T_S} + \frac{2}{T_{dc}} + \frac{2T_{dc}}{T_S^2} + KT_{dc} + KT_S + 2\omega^2 T_{dc} \geq 0 \tag{22}$$

Obviously, for all positive values of system parameters the system is stable.

2.3 Voltage Sag Compensation

Voltage sag is a reduction of the voltage magnitude from its nominal value. A PWM converter can be used to reduce the influence of the sag. If the voltage at the point of coupling drops, it can be restored by injecting reactive power into the ac system. The PCC voltage magnitude is

$$|u_S| = U_S \tag{23}$$

The reactive power injected by the PWM converter is given in (9). Therefore, if the PCC voltage is too low, the reactive power should be injected and also the reactive current component should be compensated.

The block diagram of PCC voltage control is shown in Figure 2 with a selection switch that receives an input from the output of the first PI controller (PCC voltage control loop) instead of I_{sq}^*. The reference PCC voltage is compared with the actual line voltage and the error is used as the input of the second PI controller (reactive current control loop). The output of this PI controller is the desired reactive current component, which is fed to the reactive current controller, to restore the PCC voltage back to the reference value.

3. SIMULATION RESULTS

From the control block diagram in Figure 2, the proposed method has been verified by computer simulation for three modes of operation: rectifying mode, inverting mode and voltage sag compensation mode.

3.1 Rectifying Mode

In this operation, the converter is operated in order to regulate the dc link voltage at a fixed value in conjunction with a reactive power control. The results are shown in Figures 3, 4 and 5. The converter was initially operated at zero reactive power or unity power factor. It can be seen in Figure 3 that the line current is in phase with the supply voltage. At time = 2 s, the reactive current component reference was decreased in step from 0 to –1500 var. Apparently, the supply current changed from in phase with the supply voltage to leading position. The active power is rather constant, due to the decoupling control, as shown in Figure 4. In Figure 5, the dc link voltage is oscillated in a narrow range of ±3 V but the average voltage is the same as before at 400 V.

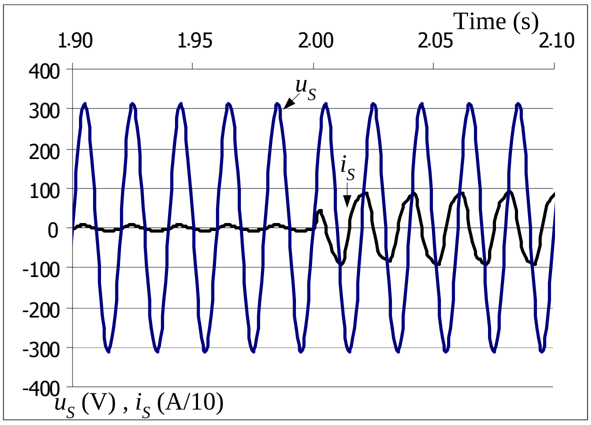

Fig. 3. Supply Voltage and Current

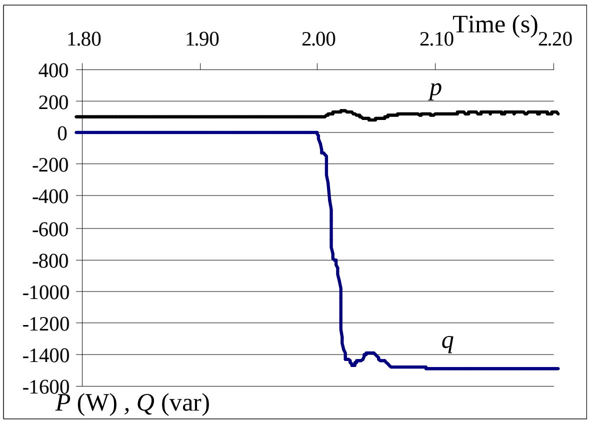

Fig. 4. Active and Reactive Power

3.2 Inverting Mode

When the power flow from the renewable energy system to the dc bus increases, the dc capacitor voltage increases to a value higher than the reference value. The dc voltage controller must regulate the dc voltage by injecting active power to the ac supply network.

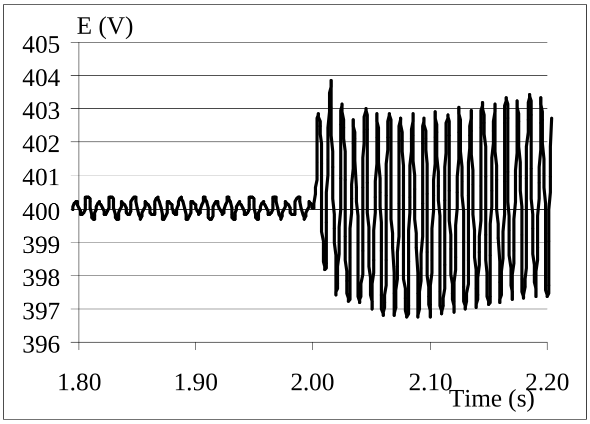

Fig. 5. DC Link Voltage

In Figure 6, the dc voltage was increased from the reference value of 400 V to 402 V at time = 2 s. The dc voltage controller regulated this voltage back to the setting value at 2.3 s.

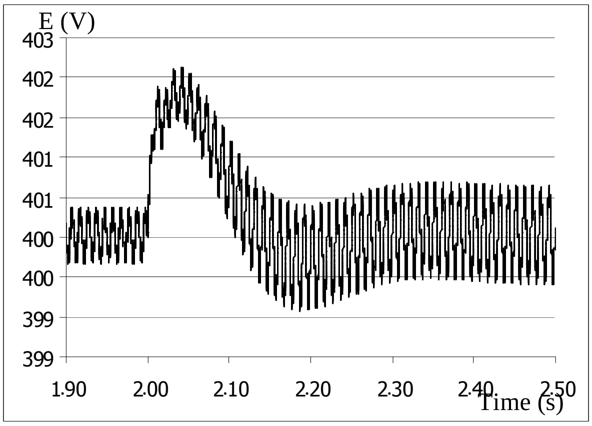

Fig. 6. DC Link Voltage in Inverting Mode

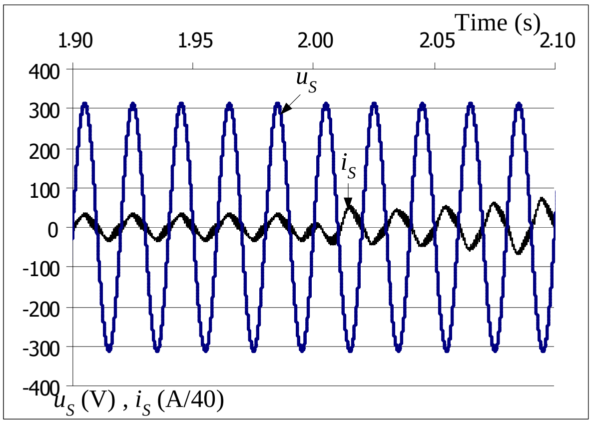

Fig. 7. Supply Voltage and Current in Inverting Mode

In Figure 7, the phase angle difference between the line current and the supply voltage is nearly 180°, which indicates negative power flow. Figure 8 confirms that the active power is negative and energy flows from the converter to the supply while reactive power is still constant.

3.3 Voltage Sag Compensation Mode

In this mode, the reactive current component control loop in Figure 2 is connected to the PCC voltage controller. In Figure 9, when the system voltage was decreased from 1 p.u. to 0.9 p.u. at time = 2 s. The PCC voltage, V_{PCC}, of the system with PCC voltage controlled converter can be restored to a pre-disturbance voltage level of 1 p.u.

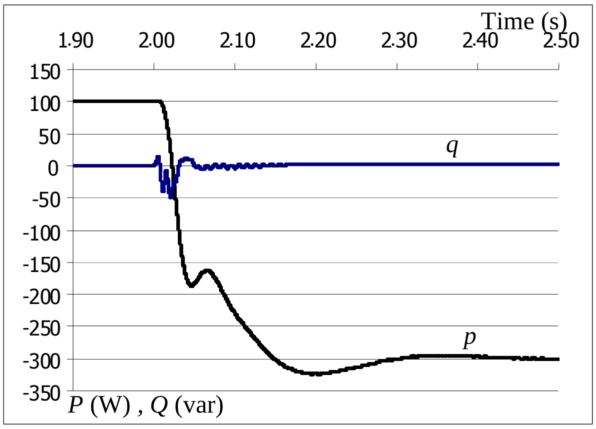

Fig. 8. Active and Reactive Power in Inverting Mode

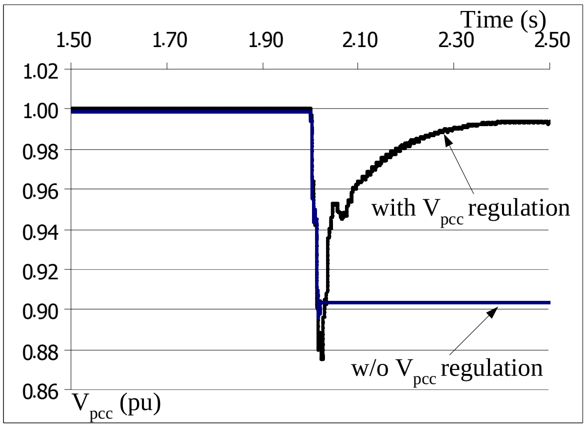

Fig. 9. PCC Voltage in Voltage Sag Compensation Mode

4. CONCLUSION

The control method for single phase PWM converter based on active and reactive current components has been proposed. The active current component is in phase with the supply voltage, while the reactive current component is in quadrature with the voltage.

The control loops for active and reactive currents have been derived and feed forward technique has been employed to decouple two current control loops.

The performances of the system were simulated and illustrated for three modes of operation. In the rectifying mode, the control objectives are to control the dc link voltage at the set value and the reactive current component is regulated according to the reactive power command. In the inverting mode, the active power is controlled to feed power to the ac system when the dc voltage increases to a level higher than the reference value. While in the voltage sag compensation mode, the PCC voltage can be restored back to the reference value, if the voltage drop occurs.

All three modes of the proposed method have been verified by simulations. The results reveal that a single phase PWM converter can effectively control with system operation based on active and reactive current components. With this scheme, both the active power and reactive power can be directly and independently controlled.

NOMENCLATURE

C	DC link capacitor
E	DC link voltage
i_{dc}, i_{Re}	DC current and renewable energy current
i_S, I_S	Supply instantaneous current and amplitude
m	proportional factor
P_{dc}	DC power
R_{dc}	DC equivalent resistance
R_S , L_S	Supply resistance and reactance
u_S, U_S	Supply instantaneous voltage and amplitude
V_{Spq}, I_{Spq}	Active and reactive voltage and current components
v_S, V_S	Fundamental component of converter terminal instantaneous voltage and amplitude
θ	Supply current phase angle
δ	Converter terminal voltage phase angle

REFERENCES

[1] Pena, R. Clare, J.C. and Asher, G.M. 1996. Doubly fed induction generator using back-to-back converter and its application to variable-speed wind-energy generation. *IEE Proc.-Electr. Power Appl.*, vol. 143, no. 3, pp. 231-241.

[2] Leonhard, W. 1996. *Control of Electrical Drive*. Berlin German: Springer.

[3] Bose, B. K. 2002. *Modern Power Electronics and AC Drives*. NJ: Prentice Hall.

[4] Buso, S. Malesani, L. and Mattavelli, P. 1998. Comparison of Current Control Techniques for Active Filter Applications. *IEEE Trans Ind. Electron.*, vol. 45, no. 5, pp. 722-729.

[5] Voraphonpiput, N. and Chatratana, S. 2004. STATCOM Analysis and Controller Deesign for Power System Voltage Regulation. In *Proceedings of Transmission and Distribution Conference*. Dalian, China, 1-6.

[6] Mohan, N. 2003. *Electric Drives an Integrative Approach*. MN: MNPERE.

APPENDIX

In (12), the plant transfer function of dc link voltage can be represented as

$$\frac{E}{I_{Sp}} = \frac{1}{2}U_S \frac{1}{I_{\mathrm{Re}} + sCE}$$

The control block diagram for dc bus voltage controller is shown in Figure A1.

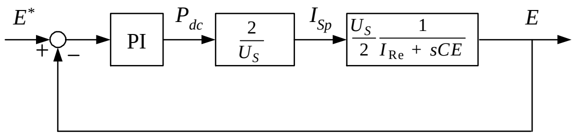

Fig. A1. Block Diagram of dc Voltage Loop Controller

In (10), the active voltage component (V_{Sp}) equation is the functions of I_{Sp} and dI_{Sp}/dt. The terms $-U_S - wL_S I_{Sq}$ in (10) can be treated as disturbances. Equation 10 can be rewritten as

$$-V'_{Sp} = R_S I_{Sp} + L_S \frac{dI_{Sp}}{dt}$$

Therefore, the control block diagram of current loop controller can be shown in Figure A2.

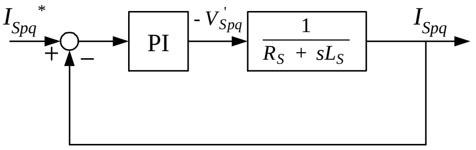

Fig. A2. Block Diagram of Active Current Loop Controller

The reactive current loop controller can be designed in the same manner as the active current loop controller.