The Utility Power Factor Control system of Photovoltaic Power Generation System

Kang-Hoon Koh[1] Hyun-Woo Lee[1] Ki-Young Suh[1] Katsunori Taniguchi[2]

1 : Division of electrical and electronic engineering
Kyungnam University 449, Wolyoung-Dong,
Masan, Kyungnam, 631-701 Korea
Fax: 82-551-248-2228 Tel: 82-551-249-2635
e-mail:lhwoo@kyungnam.ac.kr
http://lhwlab.kyungnam.ac.kr

2: Department of Electrical Engineering
Faculty of Engineering, Osaka Institute of
Technology, Omiya 5-16-1, Asahi-ku,
OSAKA 535-8585 JAPAN
Fax:81-6-6957-2133 Tel:81-6-6954-423
e-mail:taniguchi@ee.oit.ac.jp

ABSTRACT

The photovoltaic power generation system has a great future as clean energy instead of fossil fuel, which has many environmental problems such as exhausted gas or air pollution. In a utility interactive photovoltaic generation system, a three phase inverter is used for the connection between the photovoltaic array and the utility. This paper presents a three phase inverter for photovoltaic power system with current controller, voltage controller, PLL control system and the phase detector of interactive voltage by using dq transformation. The proposed inverter system provides a sinusoidal ac current for domestic loads and the utility line with unity power factor.

KEYWORD : photovoltaic power generation system, PLL, unity power factor

1. INTRODUCTION

For a future energy source, the photovoltaic power generation has been staged as the most ideal energy source due to a possibility of unlimited generation and the side of environment. According to link methods toward a utility power, the photovoltaic power generating system is classified in two systems. The one is utility interactive system which is always connected electrically, and the other is utility backed-up system that is always separated electrically except the case of insufficiency of solar generating power; in this case, the utility backed-up system is linked with the photovoltaic power system. It is possible for the former to transmit surplus power of photovoltaic power generation into utility line by means of reverse power transmission, and the latter doesn't possibly transmit reverse power transmission but simply supplies power to load [1][2]

The solar cell used in photovoltaic power generating system shows constant current source characteristic in a high output current area and, according to photovoltaic quantity, has less output than short circuit current even for a moment. It means that the solar cell itself has current-limitation function. These characters make the solar cell suitable for current-fed inverter property. However, the inverter needs big reactor for smoothing in output terminal and reverse blocking property. Thus, voltage-fed inverter is used for practical usage. The voltage-fed inverter can be classified voltage control method, whose control target is output voltage, and current control method, whose control target is output current. Because of a problem at accurate power failure detecting in voltage control, compared to the current control, and a defect of big interactive reactor, the current control method is mainly used. [3-6]

For convenience of easy analysis of three phase utility interactive photovoltaic generating system, this paper shows transformed three phase power to two phase coordinate system by dq. Coordinates transformation, each derived state variable in the system, and, finally, analysis about control variable by defining relationship among state variables.

2. CONTROL ALGORITHM

2.1 Single phase PWM converter

Figure 1 shows single phase PWM converter circuit in order to analyses three phase PWM converter.

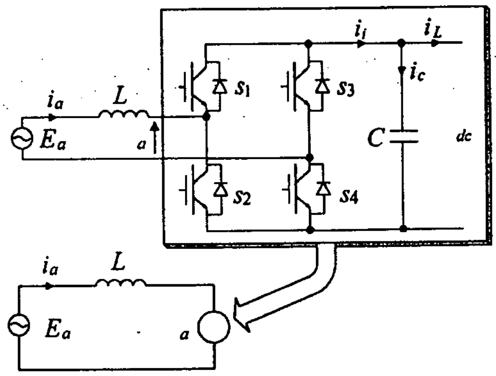


Fig. 1 Configuration and equivalent circuit of single phase PWM converter

When switching periods is Ts and continuity time of $S1$ is Ton, average voltage at a is shown below. (1) (2) (3)At the above formula

$$V_a = \frac{T_{on}}{T_s} V_{dc} + V_{dc}\left(\frac{T_{on}}{T_s} - 1\right) = V_{dc}\left(2\frac{T_{on}}{T_s} - 1\right) \quad (1)$$

$(0 \le T_{on} \le T_s)$

$$i_a = \frac{1}{L}\int (E_a - V_a)dt \quad (2)$$

$$V_{dc} = \frac{1}{C}\int (i_i - i_L)dt \quad (3)$$

where is $i_i = \frac{T_{on}}{T_s} i_a$ and $V_{dc} i_i = E_a i_a$

Once Va is bigger than Ea, the current, ia, is decreased, and, on the other hand, when Va is smaller than Ea, the current, ia, is increased. A condition that the current is not decreased or increased is $Va = Ea$ and, therefore, the continuity time of $S1$ can be shown as below.

$$T_{on} = \frac{E_a}{V_{dc}} T_s \le T_s \quad (4)$$

2.2 Three phase system modeling

An advantage of PWM converter is that the size of DC link condenser can be reduced due to the power factor is controlled 1 and DC link voltage is controlled constantly and rapidly in any case, such as operating of a motor, regenerative, etc.
These PWM converter models are shown figure 2 and formula modeling is shown below.

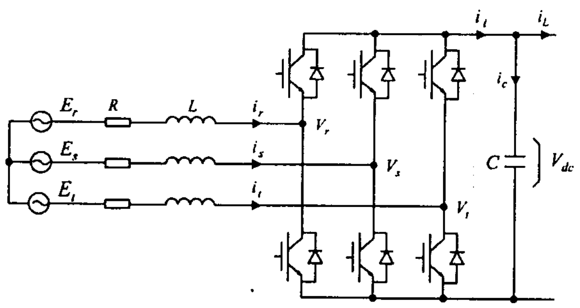


Fig. 2 Model of three-phase PWM converter

$$E_r = L\frac{di_r}{dt} + i_r R + V_r \quad (5)$$

$$E_s = L\frac{di_s}{dt} + i_s R + V_s \quad (6)$$

$$E_t = L\frac{di_t}{dt} + i_t R + V_t \quad (7)$$

When the formulas, (5), (6), (7), with three phase are expressed in two phase coordinate system which has rotating source angular frequency, ω, each state variable is expressed in DC quantity, so it is easy to handle them. And, in this case, matrix, $C1$, which converses three phase to two phase static coordinate system is shown below.

$$\begin{bmatrix} i_{qs} & i_{ds} & i_{dqos} \end{bmatrix}^T = C1 \begin{bmatrix} i_{rs} & i_{ss} & i_{ts} \end{bmatrix}^T \quad (8)$$

$$C1 = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (9)$$

From the above formulas, i_{dqos} equals zero when three phase balance is assumed. In order to derive system modeling of rotating coordinate system, static coordinate system formula can be described as below.

$$E^s_{dq} = L\frac{d i^s_{dq}}{dt} + R i^s_{dq} + V^s_{dq} \quad (10)$$

A matrix, T, which converts dq variable in static coordinate system to dq variable in rotating coordinate system is defined as below.

$$\begin{pmatrix} f^e_d \\ f^e_q \end{pmatrix} = T \begin{pmatrix} f^s_d \\ f^s_q \end{pmatrix}, \qquad T = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad (11)$$

Characteristic of the T is

$$\frac{dT}{dt} = \frac{dT}{d\theta}\frac{d\theta}{dt} = \omega_e \begin{pmatrix} -\sin\theta & \cos\theta \\ -\cos\theta & -\sin\theta \end{pmatrix} = -\omega_e \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} T \quad (12)$$

$$T\frac{d f^s_{dq}}{dt} = \frac{d}{dt}\left(T \cdot f^s_{dq}\right) - \frac{dT}{dt} f^s_{dq} = \frac{d f^e_{dq}}{dt} + \omega_e \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} f^e_{dq} \quad (13)$$

At the formula (10), by multiplying both sides by T, rotating coordinate system formula is derived as below.

$$TE^s_{dq} = LT\frac{d i^s_{dq}}{dt} + RT i^s_{dq} + TV^s_{dq} \quad (14)$$

$$\therefore E^e_{dq} = L\frac{d i^e_{dq}}{dt} + \omega_e L \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} i^e_{dq} + R i^e_{dq} + V^e_{dq} \quad (15)$$

A formula, that is expressed in three phase static coordinate system, is converted into that of two phase static coordinate system and, again, converted into that of two phase rotating coordinate system, then, the formula is described as below.

In this case, the part that includes ωL is defined by velocity voltage, which appears when the coordinate axis is rotating.

$$\begin{bmatrix} E_q \\ E_d \end{bmatrix} = \begin{bmatrix} Ls+R & \omega L \\ -\omega L & Ls+R \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} V_q \\ V_d \end{bmatrix} \qquad (16)$$

Figure 3 is a equivalence circuit of converter circuit of formula (16). And, figure 4 is phasor diagram of voltage and current. In addition, (a) has 1 with power factor and (b) shows that power factor is not 1.

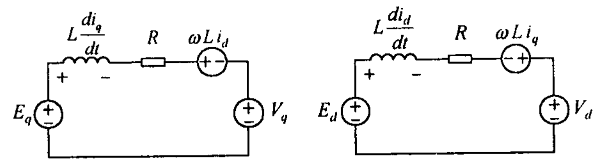


Fig. 3 $d.q$ -axis equivalent circuit of converter system

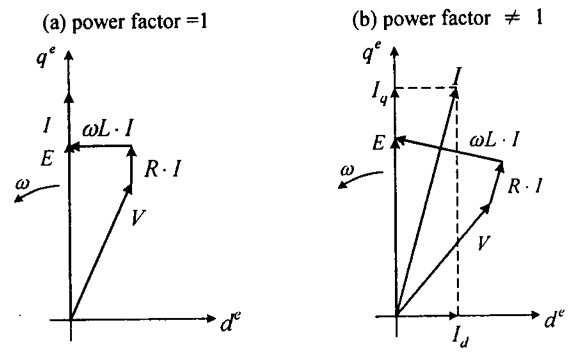


Fig. 4 Phasor diagram of voltage, current

A formula about voltage change of DC link condenser and relationship between input and output power converter can be described as below.

$$C\frac{dV_{dc}}{dt} = i_i - i_L \qquad (17)$$

$$V_{dc}\, i_i = \frac{3}{2}(V_d i_d + V_q i_q) \qquad (18)$$

Use of PWM converter is aimed for DC link voltage control and power factor 1 control. In order to make power factor 1, rotational angle, $\theta(=\omega t)$, in rotating coordinate system should be controlled under a condition of $Ed = 0$ and $id = 0$.

In other words, by controlling coordinate axis to make $Ed = 0$, $Eq = Em$ (Em is peak value of phase voltage), then, to make $id = 0$, power is existed preponderantly on q -axis. Also, DC link voltage can be controlled with controlling input current of converter, iq.

3. CONSTRUCT OF CONTROLLER

The construct of PWM converter and controller is shown figure 5. They consist of power circuit part, that consists of reactor, DC link condenser, and IGBT for power device, detect device of source phase for synchronizing phase with source voltage, voltage controller for constant DC link voltage control, current controller, two phase – three phase and static-rotating coordinate converter, and gate driver circuit that drives power driver as PWM type. Zero point of source voltage in r, s, t phase is detected with three phase transformer.

From the Zero point of three phase, direction of phase rotation (positive or negative order) is detected, and from zero point of t phase, rotating angular velocity and rotating angle in rotating coordinate system are decided in order to match voltage vector of source to q -axis of rotating coordinate axis.

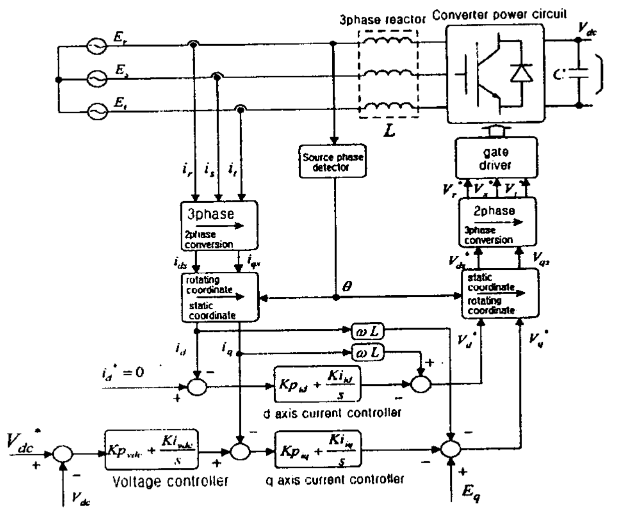


Fig. 5 Configuration of PWM converter

In view of current, Hall CT output of r and s phase is converted with A/D conversion, and t phase is calculated while it is assumed as three phase balance. Through three phase – two phase conversion and static coordinate - rotating coordinate conversion, the three phase current is described to d, q in rotating coordinate system.

In order to control current of d -axis to zero, PI current control is used, and by compensating interaction component of q -axis in PI current controller, voltage command of d -axis is made. At this point, when increased current is required, switching voltage of converter should be smaller. Thus PI current controller output is changed to minus.

Next, from voltage difference between voltage command and A/D converted DC link, PI voltage is controlled, then q - axis current command is made.

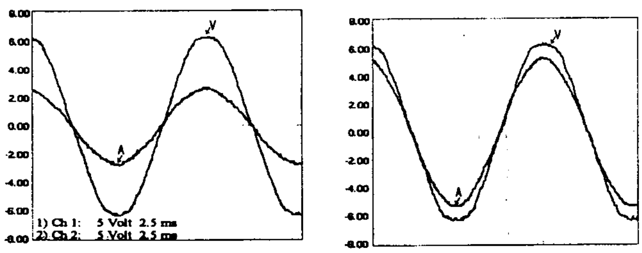
After PI current control for q -axis current control and making up for interaction component of d -axis to PI current controller output, q -axis voltage command is made.

In this case, PI current controller output of q -axis has minus multiply as the case of d-axis. After that, the voltage command of d and q-axis has rotating-static coordinate conversion and 2 phase-3 phase conversion contrarily to what has done until now. And, then, by means of generating PWM signal of chopping wave comparison method, IGBT, which is power device, does switching through gate circuit driver.

4. EXPERIMENTAL RESULTS

The output voltage range of solar cell is DC280 430V in this experimental, and real-time operating of digital controller DSP(TMS320C31), system switching frequency 10kHz, three phase reactor 1mH, capacitor 25uF, and DC capacitor 2200uF are used. The figure 6(a) shows output phase voltage and current waveform at 50% load, (b) is at 100% load.

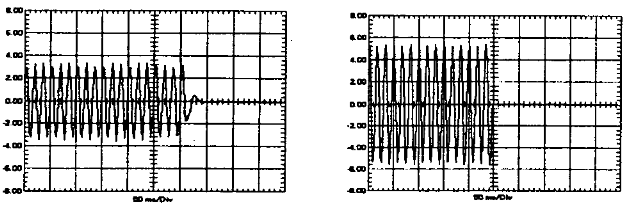
From the figures, some factors are known. These are phase of voltage and current is in-phase controlled and power factor is 1.



(a) 50% load (b) 100% load

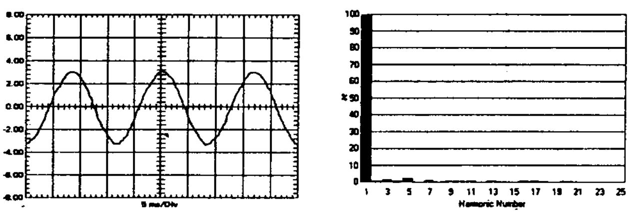
Fig. 6 Output voltage and current of inverter.

The Figure 7 shows inverter response characteristics when utility is shut down, figure (a) is output phase voltage, and (b) is output line-to-line voltage characteristics. The Figure 8 shows output current and THD at 50% load, figure 9 shows output current and THD at 100% load. From the figures, THD of each load conditions are 2.52% at 50% load and 2.03% at 100% load.



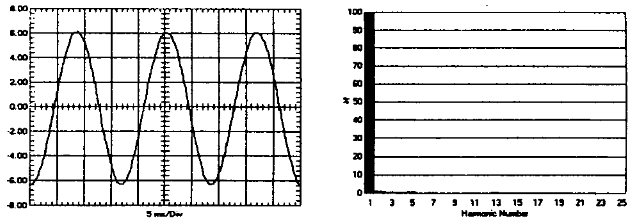
(a) Phase voltage (b) Line voltage

Fig. 7 power failure of interactive line.



(a) Current waveform (b) Harmonic spectrum

Fig. 8 50% load.



(a) Current waveform (b) Harmonic spectrum

Fig. 9 100% load.

5. CONCLUSION

Because the photovoltaic power generating system is affected a lot form environment which surrounds the system, power-conversion-device used in the photovoltaic power generating system must guarantee high confidence in constant voltage and maintain mutual cooperation with utility when they are on interactive.

Consequently, this paper uses dq coordinate conversion analysis method about three-phase-power and, in case of variable input power, through analysis of converter system that maintains DC link voltage constantly, stable power is supplied.

Also, d-axis current and q-axis current are divided through dq conversion, un-interference control is used on interference component, and gain of PI controller is decided to make that transient state characteristic and steady-state characteristic are converged in cut-off frequency range.

By means of utility frequency for inverter control signal, inverter output is supplied to load with in-phase power to utility.

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