한국산학기술학회논문지
Vol. 10, No. 12, pp. 3587-3593, 2009

PR Controller Based Current Control Scheme for Single-Phase Inter-Connected PV Inverter

Trung-Kien Vu[1] and Se-Jin Seong[1*]
[1]Chungnam National University, Division of Information Communication

PR제어기를 이용한 단상 계통 연계형 태양광 인버터 설계

부우충기엔[1], 성세진[1*]
[1]충남대학교 정보통신공학부

Abstract Nowadays, the PV systems have been focused on the interconnection between the power source and the grid. The PV inverter, either single-phase or three-phase, can be considered as the core of the whole system because of an important role in the grid-interconnecting operation. An important issue in the inverter control is the load current regulation. In the literature, the Proportional+Integral (PI) controller, normally used in the current-controlled Voltage Source Inverter (VSI), cannot be a satisfactory controller for an ac system because of the steady-sate error and the poor disturbance rejection, especially in high-frequency range. By comparison with the PI controller, the Proportional+Resonant (PR) controller can introduce an infinite gain at the fundamental ac frequency; hence can achieve the zero steady-state error without requiring the complex transformation and the dq-coupling technique. In this paper, a PR controller is designed and adopted for replacing the PI controller. Based on the theoretical analyses, the PR controller based control strategy is implemented in a 32-bit fixed-point TMS320F2812 DSP and evaluated in a 3kW experimental prototype Photovoltaic (PV) power conditioning system (PCS). Simulation and experimental results are shown to verify the performance of implemented control scheme in PV PCS.

요 약 최근 태양광 시스템에서는 기존의 태양광 시스템을 계통과 전원으로 상호 접속하는 것에 대한 연구에 관심이 모아지고 있다. 단상, 삼상 시스템에 관계없이 태양광 시스템에서 태양광 인버터는 계통연계 동작에 중요한 역할을 하기 때문에 전체 시스템에서 핵심요소로 고려된다. 태양광 인버터를 제어하기 위해서는 부하 전류 조절이 핵심요소 중 하나이다. 일반적으로 태양광 인버터에서 이용되는 PI 제어기는 정상상태 오차와 왜란에 취약하다는 단점을 가지고 있기 때문에 실제 시스템에 완벽하게 적용하기에는 무리가 있다. 특히, 이는 고주파영역에서의 PI와 PR 제어기의 성능을 비교해보면 알 수 있다. 이 논문에서 제시된 PR 제어기는 무한 이득을 교류 기본파 성분에 넣을 수 있기 때문에 PR 제어기는 회전좌표계의 PI 제어기에서 사용되는 디커플링 기법과 복잡한 변환 없이 제로 정상상태오차에 도달할 수 있다. 그렇기 때문에 이 논문에서는 PI 제어기를 대체하는 이론적 분석을 통해 PR 제어기를 설계하였다. 논문에 제시되어 있는 이론을 바탕으로 한 PR 제어기를 고정 소수점 연산방식의 32비트 마이크로컨트롤러 DSP320F2812를 기반으로 한 3kW 프로토타입 태양광 인버터에 적용, 평가하였다. 또한 태양광 인버터의 제어 성능을 시뮬레이션과 실험결과를 통하여 보여주고 검증하였다.

Key Words : Inter-connected, Inverter, PR controller, Photovoltaic, Single-phase

1. Introduction

Nowadays, the concern of Photovoltaic (PV) system has been focused on the interconnection between the PV power source and the grid. The dc/ac inverter, either single-phase or three-phase design, can be considered as

*Corresponding : Se-Jin Seong(vukien@gmail.com)
Received August 10, 2009 Revised (1st November 24, 2009, 2nd December 14, 2009) Accepted December 16, 2009

the core of the whole system because of an important role in inter-connected operation.

Several methods have been proposed in the literature for the control such inverters[1-5].

As for predictive control, it depends on the accuracy of both the system model and the reference current prediction[1,2]. A hysteresis controller can control the ac input current accurately without knowledge of the supply voltage and the grid side circuit parameters. But it has major drawbacks in variable switching rate, current error of twice the hysteresis band, and high frequency limited cycle operation, especially for high-power applications[3].

Three major classes of Voltage Source Inverter (VSI) based current controllers have evolved in the load current regulation, being hysteresis controller, predict deadbeat controller and Proportional+Integral (PI) controller, where the PI controller is normally used.

The stationary frame PI controller is conventionally regarded as unsatisfactory for ac system because of the supposedly unavoidable steady-state errors in amplitude and phase. But the synchronous frame PI controller acts on dc signal and can achieve the zero steady-state error with the integral part of controller. However, the reference frame transformation leads to a complex synchronous frame controller implementation. Hence, a controller with zero steady-state error in the synchronous frame would have advantages in the implementation.

In order to achieve zero steady-state error, a Proportional-Resonant (PR) controller based current control scheme has been used. Due to an infinite gain at the fundamental frequency, PR controller can achieve the high performance in both the sinusoidal reference tracking and the disturbance rejection.

2. PR controller analysis and design

In single-phase system, the popularly reference frame transformation cannot be applied directly. Therefore, an alternative approach of transforming the controller in dc quantities from synchronous to stationary frame is the frequency modulated method. This process can be mathematically expressed as a low-pass to band-pass or a frequency shifting transformation[6][7]:

$$G_R(s)= G_I^{ac}(s)= \frac{1}{2}\left[G_I(s+j\omega_0)+ G_I(s-j\omega_0)\right] \qquad (1)$$

where ω0 is the ac frequency and GI(s) is a low-pass transfer block By using the first-order low-pass filter or the PI controller in the synchronous frame, but centered around frequency ω_0, we can get:

$$G_R(s)= G_I^{ac}(s)= \frac{1}{2}\left[K_p+K_i\frac{1}{s+j\omega_0}+K_p+K_i\frac{1}{s-j\omega_0}\right]$$

$$=K_p+K_i\frac{s}{s^2+\omega_0^2} \qquad (2)$$

Equation (2) can be seen to be an ideal PR controller which achieves infinite gain at the ac frequency ω_0.

However, the ideal PR controller is hard to implement in reality because of the following reasons:

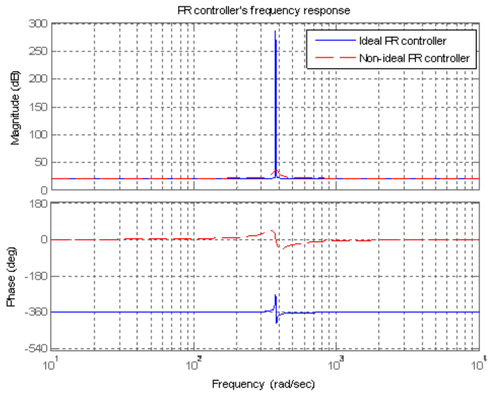
- First, the introduced infinite gain leads to an infinite quality factor which cannot be achieved in either analog or digital system.
- Second, the gains of PR controller are much reduced at other frequencies and they are no introduced adequate to eliminate harmonic influence caused by ac voltage.

To avoid stability problem associated with an infinite gain, as shown in (3), a non-ideal PR controller using a high gain low-pass filter is used:

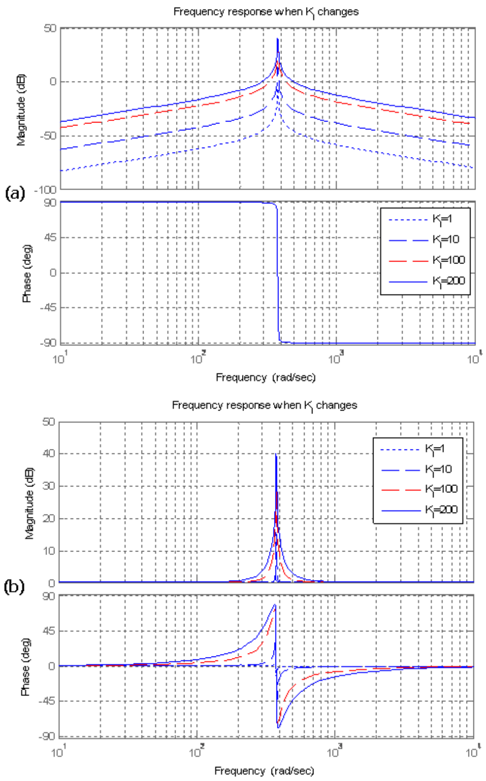
$$G_R(s)= K_p+K_i\frac{(\omega_c s+\omega_c^2)}{s^2+2\omega_c s+\omega_c^2+\omega_0^2} \qquad (3)$$

Assuming $\omega_c \ll \omega_0$, a simpler approximation is:

$$G_R(s)= K_p+\frac{K_i\omega_c s}{s^2+2\omega_c s+\omega_0^2} \qquad (4)$$

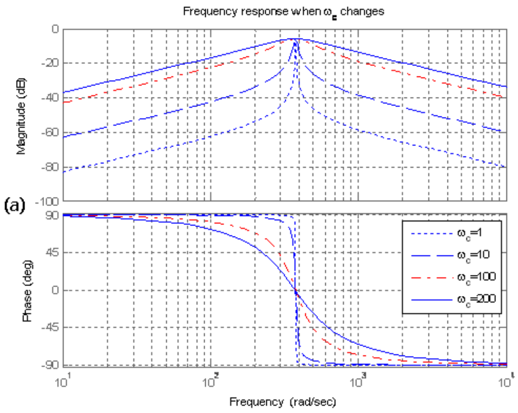


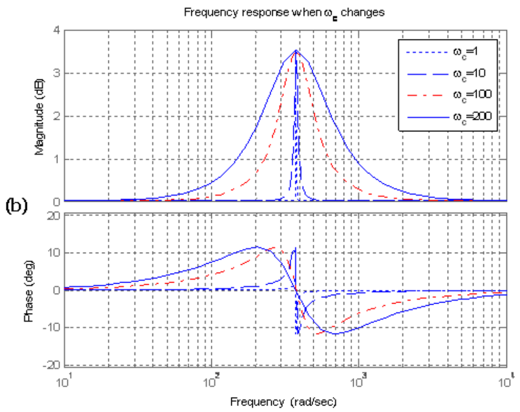
[Fig. 1] Frequency responses of ideal and non-ideal PR controller (K_p=10, K_i=100, ω_c=10rad/s, ω_0=377rad/s)



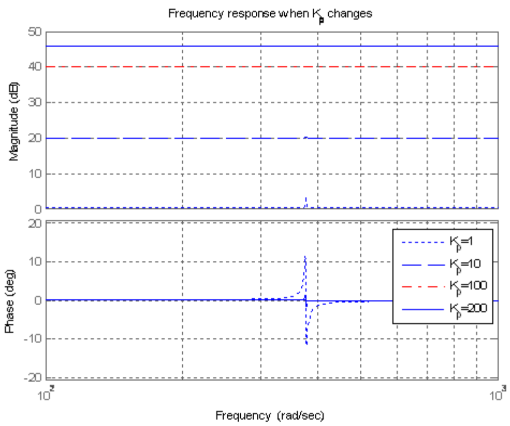
[Fig. 2] Frequency response of non-ideal PR controller when Ki changes with (a) K_p=0, ω_c=1rad/s, ω_0 =377rad/s and (b) K_p=1, ω_c=1rad/s, ω_0 =377rad/s

The frequency responses of ideal and non-ideal PR controllers are depicted in Fig. 1. The PR controller achieves an infinite gain at the ac frequency (f_0=60Hz) to force the steady-state voltage error to zero, and no phase shift and gain at other frequencies.





[Fig. 3] Frequency response of non-ideal PR controller when ω_c changes with (a) K_p=0, K_i=1, ω_0 =377rad/s and (b) K_p=1, K_i=1, ω_0=377rad/s



[Fig. 4] Frequency response of non-ideal PR controller when K_p changes with K_i=1, ω_c=1rad/s, ω_0 =377rad/s

In (4), there are three parameters affect to the PR controller operation, or three-degree of freedom in PR controller design.

First, assuming the proportional gain K_p and the cutoff frequency ω_c have no change. Fig. 2(a) shows that without K_p, the variation of K_i has effect on the gain of the controller. The gain increases as K_i is added.

With K_p, the K_i variation has effects on both bandwidth and gain of PR controller, as shown in Fig. 2(b). PR controller can achieve a very high gain in a narrow frequency band centered around the resonant frequency. A low K_i value leads to a very narrow resonant frequency band while a high K_i leads to a wider one.

Second, assuming the proportional gain K_p and integral gain K_i are constant, the cutoff frequency ω_c has effect on the bandwidth and small effect on the gain of the PR controller. As shown in Fig. 3(a) and (b), the PR controller bandwidth increases as ω_c added, but there is only a small change in the controller gain. Hence we can say the same controller gain can be achieved at the resonant frequency when ω_c changes. Using a smaller ω_c will make the controller more sensitive to the variation of frequency, this leads to a slower transient response and more difficult in DSP implementation. In practical, ω_c can be chosen at 5-15(rad/s) for a good response[8].

Finally, as shown in Fig. 4, when K_p is added, the PR controller gain increases. But a high K_p value will decrease the bandwidth of the PR controller. It means that the harmonic impedance increases as K_p added, and then the higher K_p value can lead to a relatively low harmonic component.

In conclusion, the PR controller gains can be designed following a step-by-step procedure:

- First, choose the value of ω_c to meet the system bandwidth requirement.
- Second, choose the integral gain K_i for a suitable controller gain.
- Finally, the proportional gain K_p can be selected to make sure that the system can achieve high performances in sinusoidal signal tracking and disturbance rejection.

Based on the theory analysis, in this paper, PR controller gains are chosen as: K_p=15, K_i=200 and ω_c=15(rad/s).

3. Single-phase inter-connected PV inverter control technique

A single-phase inter-connected PV PCS has been built where its circuit block diagram of current control scheme is depicted in Fig. 5[9].

The equivalent representation of the current regulation based single-phase inter-connected inverter system can be obtained as shown in Fig. 6, where the relationship between input and output of current control system can be obtained as:

$$I_g = H_i(s) I_g^* - H_g(s) V_g \tag{9}$$

$$H_i(s) = \frac{I_g}{I_g^*} = \frac{G_c(s) G_i(s) G_f(s)}{1 + G_c(s) G_i(s) G_f(s)} \tag{10}$$

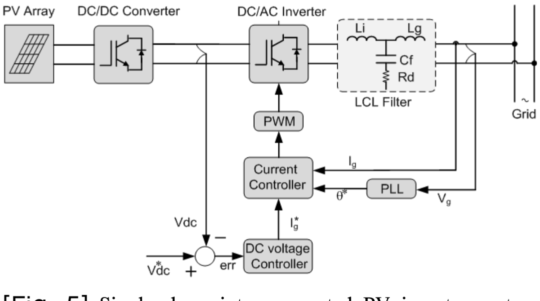
$$H_g(s) = \frac{I_g}{V_g} = \frac{G_f(s)}{1 + G_c(s) G_i(s) G_f(s)} \tag{11}$$

where $G_c(s)$ is PR controller transfer function as shown in (4);

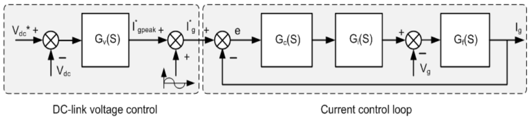
$G_i(s)=K$ is the inverter transfer function. Assuming the switching frequency is high enough to neglect the inverter dynamics, the PWM inverter can be represented by a gain for a simplicity of analysis due to the relatively high switching frequency;

$G_f(s) = \dfrac{R_d C_f s + 1}{L_i L_g C_f s^3 + (L_i + L_g) R_d C_f s^2 + (L_i + L_g) s}$ is the LCL-filter transfer function with damping resistor (the resonant frequency can be calculated as $\omega_{res} = \sqrt{\dfrac{L_i + L_g}{L_i L_g C_f}}$).

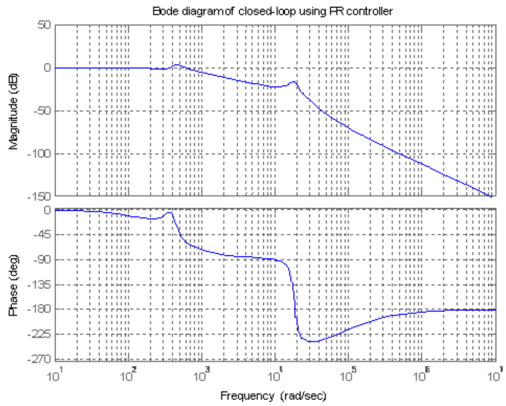
Because PR controller introduces an infinite gain, then the first term of (9) approaches the inverter current reference and the second term approaches zero. Hence, PR controller can achieve the zero steady-state error.



[Fig. 5] Single-phase inter-connected PV inverter system



[Fig. 6] Current-controlled single-phase inter-connected PV inverter system



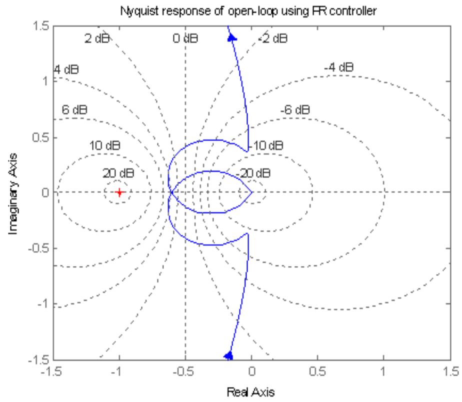
[Fig. 7] Bode diagram of closed-loop transfer function using PR controller (K_p=15, K_i=200, ω_c =15rad/s)

The closed-loop transfer function of current control loop shown in Fig. 6 can be obtained:

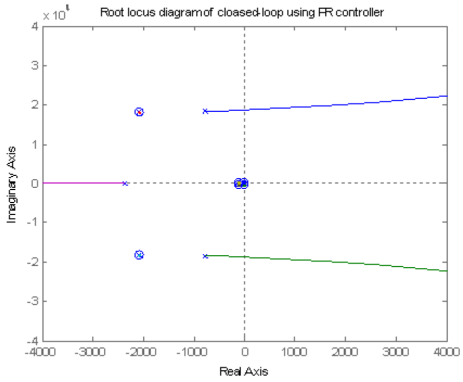
$$H_{i_R}(s)=\frac{A_3s^3+A_2s^2+A_1s+A_0}{B_5s^5+B_4s^4+B_3s^3+B_2s^2+B_1s+B_0} \tag{26}$$

where

$$A_3=R_dC_fK_pK$$
$$A_2=K\left[K_p+(2K_p+K_i)\omega_cR_dC_f\right]$$
$$A_1=K\left[(2K_p+K_i)\omega_c+K_pR_dC_f\omega_0^2\right]$$
$$A_0=KK_p\omega_0^2$$
$$B_5=L_iL_gC_f$$
$$B_4=(L_i+L_g)C_fR_d+2L_iL_gC_f\omega_c$$
$$B_3=(L_i+L_g)(1+2\omega_cC_fR_d)+L_iL_gC_f\omega_0^2+KK_pC_fR_d$$



(a)



(b)

[Fig. 8] (a) Nyquist and (b) root locus diagrams of system using PR controller

$$B_2=(L_i+L_g)(2\omega_c+C_fR_d\omega_0^2)+KK_p+(K_i+2K_p)KC_fR_d\omega_c$$
$$B_1=(L_i+L_g)\omega_0^2+KK_pC_fR_d\omega_0^2+(K_i+2K_p)K\omega_c$$
$$B_0=KK_p\omega_0^2$$

Fig. 7 shows the bode diagram of closed-loop system using PR controller, where the PR controller can introduce an infinite gain at the fundamental frequency.

For stability analysis, because the VSI switching frequency is higher than power system frequency, the inverter will have negligible impact on the control loop dynamics and assuming a sinusoidal supply voltage, the current closed-loop control stability can be analyzed with classical methods such as Nyquist, root locus ...

Fig. 8(a) and (b) show the Nyquist and root locus diagrams of the system using PR controller. As shown in Fig. 8(a), the Nyquist diagram does not contain (-1,j0) and hence, the system stability is verified.

4. Simulation and experimental results

The single-phase inter-connected PV inverter system is simulated by Matlab/Simulink with parameters listed in Table 1.

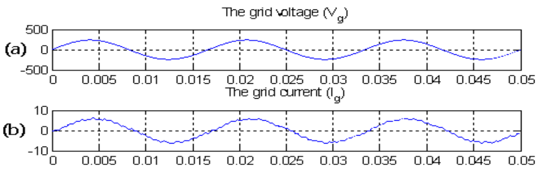
Fig. 9 shows the grid voltage and grid current simulation results by using PR controller, where the FFT analysis and THD value of grid current are shown in Fig. 10, respectively. It is noted that all waveforms are in phase.

The overall system of 3kW single-phase inter-connected PV PCS, as shown in Fig. 11, with PR controller is implemented fully in software adopting a 32-bit fixed-point DSP TMS320F2812 and the PWM pulses are generated through the internal pulse generator of the DSP. The switching frequency of the inverter is chosen to 10 kHz and the dead-time is 3μ s.

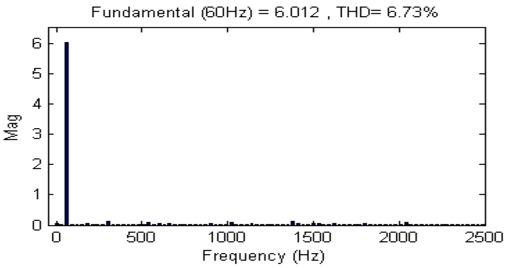
Fig. 12(a) shows the grid voltage in channel 1 (250V/div) and grid current in channel 4 (10A/div), respectively. It can be seen that the grid current waveform is nearly perfect sinusoid. The experimental result shows a good agreement with the simulation result. The harmonic order analysis and THD value of grid current using PR controller are shown in Fig. 12(b). The experimental results show that by using PR controller, the PV inverter current control scheme can achieve steady-state performance.

[Table 1] PV PCS parameters

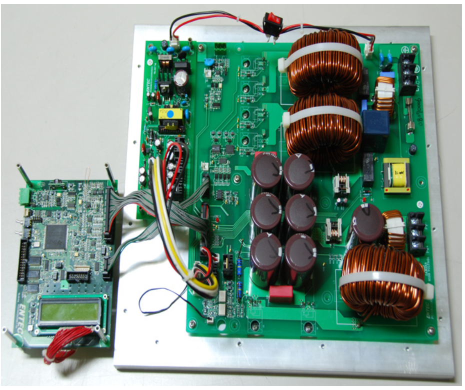
Grid voltage V_g	220V/60Hz
DC voltage V_{dc}	400V
Inverter-side filter inductor L_i	2mH
Grid-side filter inductor L_g	0.86mH
Filter capacitor C_f	5μ F
Filter damping resistor R_d	2.5Ω
Switching frequency f_{sw}	10kHz



[Fig. 9] Grid voltage and current using PR controller



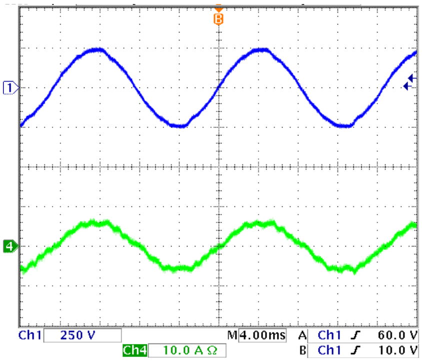
[Fig. 10] FFT analysis and THD value of grid current using PR controller



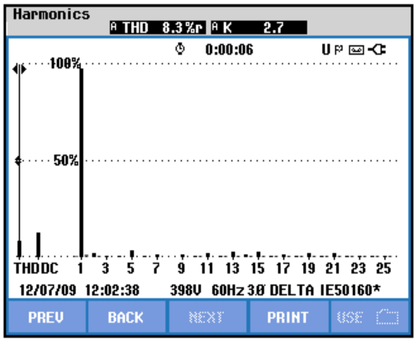
[Fig. 11] 3kW PV PCS experimental prototype

6. Conclusions

In this paper, the theoretical analysis has been performed that the PR controller has some advantages compared with the conventional PI controller and it can enable the implemented control inverter system to achieve the high performance. The simulation and experimental results of 3KW PV PCS prototype system verified the performance of this current control scheme. Furthermore, this control scheme is suitable for single-phase current-controlled VSI of distributed generation units, as well as three-phase systems, and not only photovoltaic but also the other power generation system, such as small wind turbine, fuel-cells, etc...



(a)



(b)

[Fig. 12] (a) Grid voltage and current implementation results and (b) harmonic order and THD value of grid current using PR controller

References

[1] A. Kotsopoulos, J. L Duart, M. A. M Hendrix, "A predictive control scheme for DC voltage and AC current in grid-connected photovoltaic inverters with minimum DC link capacitance", *The 27th Annual Conference of the IEEE Industrial Electronics Society*, Vol.3, pp. 1994-1999, 2001.

[2] D. G. Holmes and D. A. Martin, "Implementation of a direct digital predictive current controller for single- and three-phase voltage source inverters", *Proc. IEEE IAS Annual Meeting*, pp 906-913, 1996.

[3] R. D. Lorenz, T. A. Lipo and D. W. Novotny, "Motion control with induction motors", *Proc. IEEE*, Vol. 82, Issue 8, pp 1215-1240, 1994.

[4] Yong-Seok Lee, Dong-Min Lee and Jun-Keun Ji, "Performance Comparison of Single-Phase PLL Algorithms Using Virtual 2-Phase Strategy", *Journal of the Korean Academic Industrial Society*, Vol.8, No.2, pp.219-225, 2007.

[5] Dae-Seok Rho, Chan-Hyeok Kim, Chang-Hoon Shin and Won-Wook Jeong, "A Study on the Optimal Method for Malfunction of Protection Devices in Distribution Systems Interconnected with Photovoltaic Systems", *Journal of the Korean Academic Industrial Society*, Vol.9, No.6, pp.1599-1606, 2008.

[6] Zmood, D.N., Holmes, D.G. and Bode, G.H., "Frequency-domain analysis of three-phase linear current regulators", *IEEE Transactions on Industry Applications*, Vol. 37, No. 2. pp. 601-610, 2001.

[7] R. Teodorescu, F. Blaabjerg, M. Liserre and P. C. Loh, "Proportional-resonant controllers and filter for grid-connected voltage-source converters", *IEEE Proceeding Electric Power Applications*, Vol. 153, Iss. 5, pp. 750- 762, 2006.

[8] Tan, P.C., Loh, P.C., and Holmes, D.G.,"High performance harmonic extraction algorithm for a 25kV traction power conditioner", *IEEE Proceeding Electronics Power Application*, Vol. 151, No. 5, pp. 505-512, 2004.

[9] Hanju Cha and Sanghoey Lee, "Design and implementation of photovoltaic power conditioning system using a current based maximum power point tracking", 2008 *Industry Application Society Annual Meeting*, pp. 1-5, 2008.

Trung-Kien Vu [Regular member]

- Aug. 2005 : Chungnam National Univ., Electronics Eng., MS
- Aug. 2005 ~ current : Chungnam National Univ., Electrical Eng., Ph.D candidate

<Research Interests>
His research interests are in the areas of power electronics control and renewable energy system.

Se-Jin Seong [Regular member]

- Feb. 1975 : Seoul National Univ., Electrical Engineering, MS
- Feb. 1988 : Tokyo Industrial of Technology, Electrical Eng., PhD
- Feb. 1988 ~ current : Chungnam National Univ., Dept. of Electrical Eng., Professor

<Research Interests>
His research interests include design, modeling and analysis of DC-DC converter, Cycloconverter, Electric machine control and Microprocessor application