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태양광 전력변환장치의 PI, PR 및 PD 제어기 비교 연구

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Comparative study of proportional-integral, proportional-resonant, and predictive deadbeat controllers in a PV PCS

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Abstract - In industry, there are several different controllers which can be implemented for power conditioning systems (PCS) such as proportional-resonant (PR), predictive deadbeat (PD), or proportional-integral (PI) controller. But there are not any comparison studies about these controllers. To investigate the differences between the three types of the controllers, this paper presents a comparative study of PR, PI, and PD controllers in a photovoltaic (PV) PCS.

These controllers are designed mathematically and simulated for the comparative analysis. The PI controller is designed in the rotating reference (dq) frame. The PR and PD controllers are implemented in the natural (abc) reference frame. The PCS is composed of a DC-DC boost converter and a full bridge inverter. The filter of the PCS is an LCL filter including a passive damping resistor. The parameters of PCS are 3 kW, 25 kHz switching frequency and 220 V-60 Hz grid voltage. The comparison results between these controllers for the grid-connected PCS are clearly shown. The simulation results demonstrate the detailed characteristics of each controller for the PV PCS in order to choose the controller for individual target properly.

1. Introduction

In recent years, distributed generation systems using renewable resource like photovoltaic (PV) generation are attracting more attention. A power conditioning system (PCS) is required to link PV sources to the power grid. The appropriate controller will increase the efficiency, reduce harmonics and the cost of the PCS. To investigate several different controllers in the PCS system, the authors performed a comparative study between proportional-integral (PI), proportional -resonant (PR) and predictive deadbeat (PD) controllers in a PCS.

A PI controller can control active power and reactive power easily in rotating references (dq) frame. And it is a good solution for regulating sinusoidal currents in balanced systems. However, the PI controller in the rotating reference (dq) is complex, and the compensation capability of low harmonics is poor [1]. The PR controller has good output characteristics by high gain of fundamental frequency. It is implemented in natural reference frame (abc). Therefore, the transformation from abc frame to dq frame and reversed transformation are not needed [2-3]. The PD controller is the fastest controller because it can reduce the state variable error to zero in a predictive finite number of sampling. The three controllers are implemented in a PV PCS. The parameters of the PCS are 3 kW, 25 kHz switching frequency and 220 V- 60 Hz grid voltage.

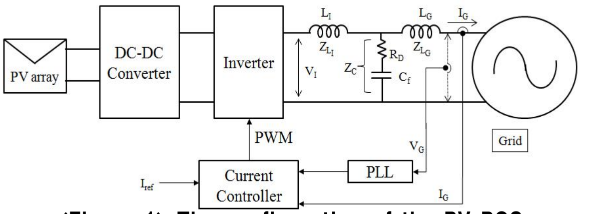
The characteristics of the three controllers were clearly shown. It is useful for choosing proper controller in a individual purpose.

2. Modeling of a PCS

This part is modeled using Kirchhoff's law for the PCS shown in Fig. 1. So we have transfer function between the current into the grid I_G and the voltage in front of the filter V_I as (1)

$$H(s)=\frac{I_G(s)}{V_I(s)}=\frac{Z_C}{Z_{L_G}{*}Z_C+(Z_{L_I}+Z_C){*}Z_{L_1}} \tag{1}$$

where Z_{L_I} is the inverter side impedance, Z_{L_G} is the grid side impedance, Z_C is the impedance of the capacitor C_f with the series damping resistor R_D.



<Figure 1> The configuration of the PV PCS

The requirements of the PCS are 10% of ripple current, 1% of ripple voltage. So we have specific values for the filter of the PCS, $L_I=3\,mH$, $L_G=0.03\,mH$, $C_f=30\,uF$, and the damping resistor $R_D=0.33\,\Omega$.

3. Control strategies for a PCS

3.1 Proportional-Integral controller

The structure of the PI controller for the PCS is shown in Fig. 1. We can write the equation for the PI controller in Laplace domain as:

$$G_C=K_P+\frac{K_I}{s} \tag{2}$$

Using the bode plot for PI controller design, the stability requirements are 120 Hz cut-off frequency and 65 degree phase margin. Therefore, K_P, K_I are 2.283 and 4.79, respectively.

3.2 Proportional-Resonant controller

The PR controller has high gain around the resonant frequency and thus, is capable of eliminating the steady-state error when tracking or rejecting a sinusoidal signal. The PR controller is implemented in abc frame. Generally, the equation for an ideal PR controller in frequency domain is:

$$G_{PR}(s)=K_P+K_I\frac{s}{s^2+w_0^2} \tag{3}$$

where the w_0 is the resonant frequency (grid frequency). The equation (3) represents an ideal PR controller which has infinite gain for resonant frequency component. It is impossible in real system and makes stability problems. To avoid these problems, the PR controller can be modified by introducing damping as shown in (4):

$$G_{PR}(s)=K_P+K_R\frac{2w_cs}{s^2+2w_cs+w_0^2} \tag{4}$$

where w_c is the bandwidth around the ac frequency of w_0.

The chosen parameters are: $w_c=1.0\,(rad/s)$, $K_R/K_P=75$, damping ratio $\zeta=0.70$. Therefore, the coefficients K_P and K_R of the PR controller are 20 and 1,500, respectively.

3.3 Predictive deadbeat controller

The PD controller can reduce the state variable error to zero in a predictive finite number of sampling. However, the PD controller only is implemented in digital system. So the transfer function in (1) is digitized by the ZOH method with 25 kHz sampling frequency as:

$$H(z^{-1})=\frac{B(z^{-1})}{A(z^{-1})}=\frac{0.00543z^{-1}+0.01z^{-2}+0.0007z^{-3}}{1-1.394z^{-1}+1.027z^{-2}-0.6362z^{-3}} \tag{5}$$

The number of sampling for transient period is 2 samples. The equation of the PD controller is:

$$G_{DB}(z^{-1}) = \frac{L(z^{-1})B(z^{-1})}{1 - L(z^{-1})A(z^{-1})} \quad (6) \quad \text{where } L(z^{-1}) = l_0 + l_1 z^{-1}$$

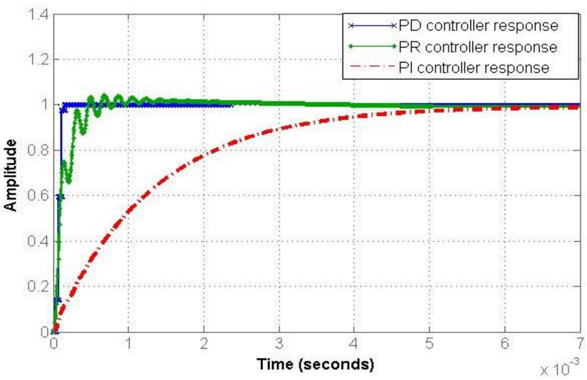
The steady-state error of the system is zero so we have:

$$\lim_{k\to\infty} e_k = \lim_{z\to 1}\left\{(1 - z^{-1})\left[1 - L(z^{-1})B(z^{-1})\right]\frac{1}{1-z^{-1}}\right\} = 0 \qquad (7)$$

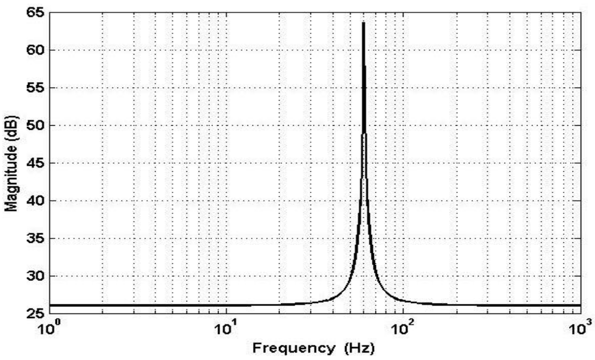
$$\text{and } L(z^{-1}) = 25.8965 + 36.0998z^{-1} \qquad (8)$$

4. Simulation and the results

Based on the mathematical design, the step responses of the system are shown in Fig. 2. The PI controller is implemented in the dq frame. The system has time response of about 4 ms.

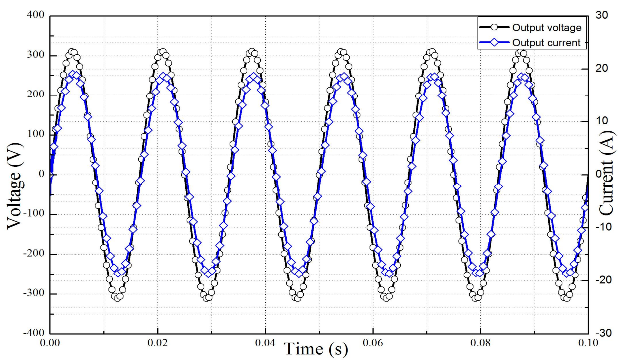


<Figure 2> Step response of the PI, PR, and PD controllers

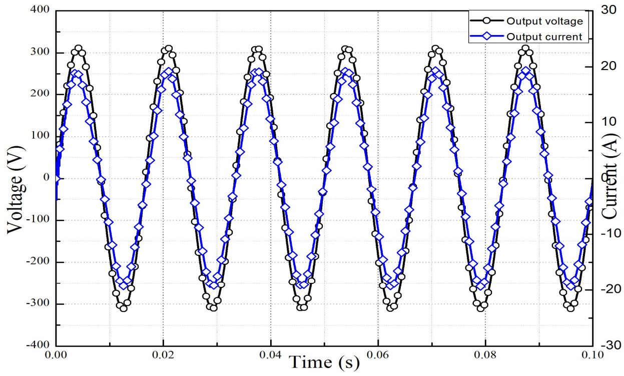


<Figure 3> Bode graph of the PR controllers

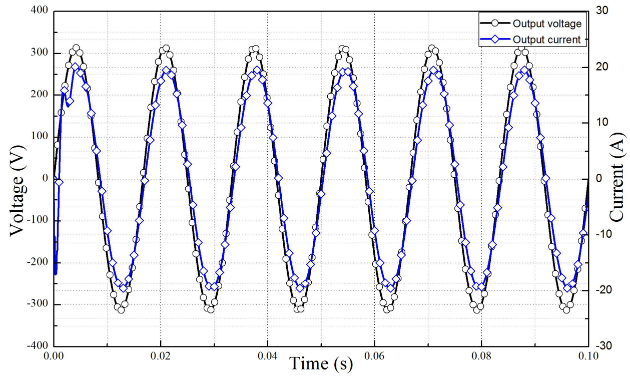
The PR and PD controllers are implemented in the abc frame. The time response of the system is very important because the reference signal is also sinusoidal signal.The response time of the system should be less than 1/10 of the grid period. In Fig. 3, the PR controller has 0.5 ms response time and 64 dB gain values for grid frequency component. The PD controller reaches the reference value after 2 sampling time (0.15 ms).



<Figure 4> The output voltage and current of the PV PCS using PI controllers



<Figure 5> The output voltage and current of the PV PCS using PR controllers



<Figure 6> The output voltage and current of the PV PCS using PD controllers

After the confirmation of the controllers, the simulation circuit is built in PSIM. The simulation results are shown in Fig. 4-6. The simulation results clearly show that the PI controller is a good solution for regulating sinusoidal currents in balanced systems but the compensation capability of low harmonics is poor. The PR and PD controllers are implemented easily in the natural abc frame and reduce computing time in real system because there are no transformations. Both of them are better at disturbance injecting than the PI controller. The PD controller has the best results because it can reduce error signal immediately to zero after 2 sampling time without any overshoot.

5. Conclusions

In this paper, the authors present a comparative study of the PI, PR and PD controller for a PCS. The controllers were investigated in both mathematic model using Matlab and circuit simulation using PSIM, and the detailed characteristics of each controller were demonstrated in order to choose the controller for individual target properly.

Acknowledgement

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