Digital Current Controller with Smith-Predictor for PWM Converters

Jin-Woo Lee

Abstract - From the cost-effective point of view, it is very important to design a current controller with the highest utilization factor of current capacity of power devices. This can be accomplished by a current controller without overshoot irrespective of the varying bounds of control voltage in PWM converters and the dead time due to the time delay.

This paper suggests a novel decoupled current controller with Smith-predictor which has the fast control response without overshoot and steady state error and also deals with the design method of the controller for PWM converters. The extensive digital simulations done by SIMULINK/MATLAB show that the suggested controller guarantees the full utilization of current capacity of power devices and the decoupled current control behavior.

I. INTRODUCTION

The current and voltage ratings of power devices for PWM converters are generally designed under considerations of source voltage, load capacity, efficiency, safety factor, control characteristics, and so on. From the system design point of view, it is very important to fully utilize the device capacity because the cost of products is directly affected. Especially, the current utilization factor strongly depends on the control characteristics because the current overshoot over the maximum current rating of device due to the controller results in severe faults or in the design of low current utilization of devices. However, many papers focus on the fastest control response, current harmonics and no steady state error [1]~[4], not on the current overshoot.

The conventional PI controller is widely adopted in various industrial fields due to its simplicity and effectiveness as well as in PWM converters and PWM inverters. But under the saturation of control input, it shows the deterioration of control performance, such as overshoot due to the windup phenomenon of integrator. As a solution, a conditional integrator, a limited integrator, a tracking anti-windup controller and etc. are suggested.[5],[6]

Additionally the ideal decoupled current control characteristic is necessary to independently control the active and reactive input power in all operating conditions, especially under the over-modulation region in the given PWM method.[7]

The author suggested the current controller without overshoot irrespective of the varying bounds of control voltage in PWM converters.[9],[10] But the computational delay was not treated, which deteriorates the control behaviors.

This paper suggests a digital current controller with Smith-predictor in order to cope with the time delay, which has reasonable control bandwidth, no steady state error, and no current overshoot. First, this paper deals with modeling and analysis of PWM converters to get the very simple model and to fully understand the inherent behaviors of PWM converters from the control point of view. Then the design method of a novel controller is presented and also the control system is modeled and simulated by SIMULINK/MATLAB for convenience. Simulation results are shown to verify the validity of the proposed controller.

II. MODELING AND ANYALYSIS OF PWM CONVERTERS

The circuit of PWM converter with typical variables is shown in Fig. 1 and can be modeled as follows.

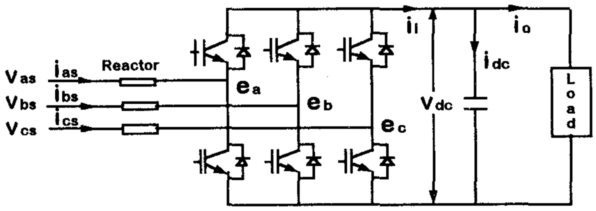


Fig. 1. Power circuit of PWM converter

$$\frac{dV_{dc}}{dt} = \frac{1}{C}(i_i - i_o) \tag{1}$$

$$\begin{aligned} \frac{di_d}{dt} &= -\frac{R}{L}i_d + \omega \cdot i_q + \frac{v_{ds}}{L} - \frac{e_d}{L} \\ \frac{di_q}{dt} &= -\frac{R}{L}i_q - \omega \cdot i_d + \frac{v_{qs}}{L} - \frac{e_q}{L} \end{aligned} \tag{2}$$

From the control point of view, each component of Eq.(2) can be classified as follows. The converter output voltages, e_d & e_q, are control inputs, the source voltages, v_{ds} & v_{qs}, are disturbances, and the terms, $-\omega L \cdot i_d$ & $\omega L \cdot i_q$, are coupling terms between two current components.

In order to get the very simple model, lets design control inputs such as shown in Eq.(3) which consists of feedforward compensation terms to disturbances and

$$\begin{aligned} e_d &= \omega L \cdot i_q + v_{ds} - u_d \\ e_q &= -\omega L \cdot i_d + v_{qs} - u_q \end{aligned} \tag{3}$$

coupling terms, and feedback control terms of u_d & u_q.

By substituting Eq.(3) into Eq.(2), the following very simple system of Eq.(4) is obtained.

$$\begin{aligned} \frac{di_d}{dt} &= -\frac{R}{L} i_d + \frac{1}{L} u_d \\ \frac{di_q}{dt} &= -\frac{R}{L} i_q + \frac{1}{L} u_q \end{aligned} \tag{4}$$

The system of Eq.(4) may be the simplest. If the compensations could be done ideally, then two currents can be independently controlled by two feedback control voltages.

However, in the over-modulation region of the space vector PWM method, which is adopted in this paper, the feedforward compensation voltage vector, V_2, can not be ideally compensated by the vector, E_{2b}^*, which is obtained by the conventional over-modulation method. But it can be ideally done by the other vector, E_{2a}^*, as shown in Fig. 2.[7] On the other hand, the admissible range of control inputs is the hexagonal area which is made of the available output voltage vectors in PWM converters as shown in Fig. 2.

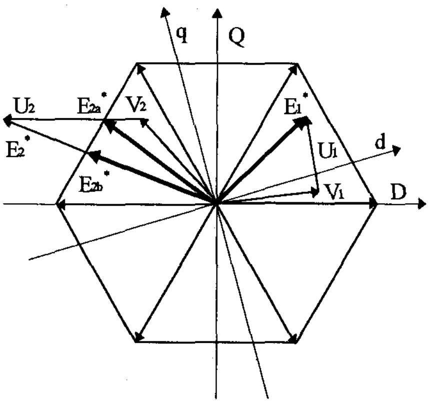


Fig. 2. An admissible control area in PWM converters

From Eq.(3) and Fig. 2, it is clear that the bounds of control inputs vary as a function of position of the output voltage vector and also the bounds of the feedback control voltage vector vary. In addition, the PWM method generates only the equivalent average voltage vector during a sampling period to the reference one. Therefore there always exists a little mismatch between the command and the output. However, the control voltage is generated by only switching operations of PWM converter with the dc-link voltage, so that there is no disadvantage to fully utilize the control inputs under the given switching frequency. This means that the available maximum inputs should be applied to the system to obtain the fastest current control response.

From the above mentioned, it is indispensable to consider these facts carefully in order to design a new current controller with superior performance.

Ⅲ. A NOVEL FEEDBACK CURRENT CONTROLLER WITH SMITH-PREDICTOR

Let's apply the conventional PI control law as a feedback controller to Eq.(4). Then the differential equation of Eq.(5) is obtained as follows.

$$\begin{aligned} L\frac{d^2 i_d}{dt^2} &= -R\frac{di_d}{dt} + K_p\frac{d}{dt}(i_{d\_ref} - i_d) + K_i \cdot (i_{d\_ref} - i_d) \\ L\frac{d^2 i_q}{dt^2} &= -R\frac{di_q}{dt} + K_p\frac{d}{dt}(i_{q\_ref} - i_q) + K_i \cdot (i_{q\_ref} - i_q) \end{aligned} \tag{5}$$

First, let's design a proportional gain, Kp. In case of a proportional controller only, the transfer function to Eq.(5) reduces to the first order low pass system as follows, where for simplification the subscript 'd & q' is omitted.

$$\frac{I}{I_{\_ref}} = \frac{K_p/L}{S + (R/L + K_p/L)} \tag{6}$$

From the continuous system point of view, we can design the gain, Kp, as large as possible to obtain a wide current control bandwidth and to reduce a steady state error. But, as analyzed in the previous chapter, the PWM converter is a discrete system due to its switching operations with a limited switching frequency. Thus, it is reasonable to design the gain in the discrete control sense. In addition, the only proportional control system from Eq.(5) without reference input is the same as that of a state feedback control system, and then the reference input to that is equivalent to changing an initial state in state feedback control systems. Therefore lets design a proportional gain in accordance with a discrete state deadbeat controller[8] because it has the fastest control response. The gain, Kp, is represented as follows.

$$K_p = L/T_s - R \tag{7}$$

where Ts is one half of the switching period.

By using a proportional controller with gain of Eq.(7), i.e., a digital state deadbeat controller, it's possible to get the fastest control response without overshoot in switching systems such as PWM converters.

Then, lets design the integral gain, Ki, based on the proportional gain of Eq.(7) by comparing the characteristic equation to Eq.(5) with that of a second order system.

$$K_i = L \cdot (2 \cdot \zeta \cdot T_s)^{-2} \tag{8}$$

By using the Bode plot of transfer function with gains of Eq.(7) and Eq.(8), the damping factor can be designed.

However, because of the varying control bounds of PWM converters, this PI controller shows overshoot behavior due to windup phenomenon of integrator. Therefore some variations are required in order to get the current controller without overshoot and steady state error.

Based on the above observations, the novel feedback current controller as shown in Fig. 3 was proposed.[9] The block of Mag_BPW in Fig.3 functions as a band pass window with limit to the input.

This controller changes its structure from a digital state deadbeat controller of Eq.(7) to a digital state

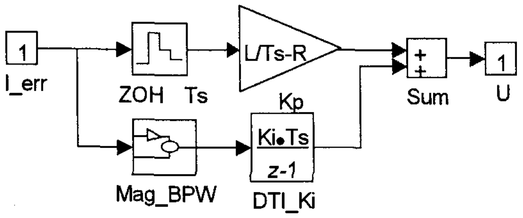


Fig. 3. SIMULINK block diagram of a novel feedback current controller

deadbeat controller with a conditional integrator based on Eq.(8) and vise versa, according to the absolute magnitude of its state error. It has a deadbeat control response without steady state error. The magnitude of error as a change condition of structure can be easily tuned by trial and error.

From the practical implementation point of view, the computational delay should be properly considered in order to obtain the desirable control performance. This paper suggests a current controller with the Smith-predictor[5] to cope with the delay of one sampling time. Even though the system of Eq.(2) has two inputs and two outputs, the system can be treated as a single input and single output(SISO) system as long as the compensations are done ideally. Therefore the Smith-predictor for SISO system can be easily applied to Fig. 3 as shown in Fig. 4. And the initial conditions of the controller are deliberately set to the proper values to obtain better control performance at the initial start.

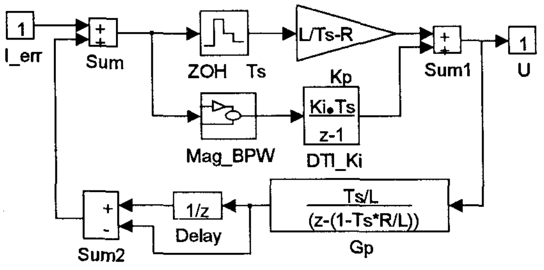


Fig. 4. SIMULINK block diagram of a feedback current controller with Smith-predictor

IV. SIMULATION RESULTS AND DISCUSSIONS

For the purpose of examining current control responses, the control system is modeled and simulated by SIMULINK/MATLAB for convenience. The SIMULINK block diagram of the whole control system is shown in Fig. 5, where there are three main parts; a current controller, a space vector PWM modulator with the modified over-modulation scheme, and a current dynamic system. But the dc-link part is modeled to be an ideal dc source in order to focus on the current control performance.

Table 1 shows system parameters of a 185kW PWM converter which is under development as a part of ac

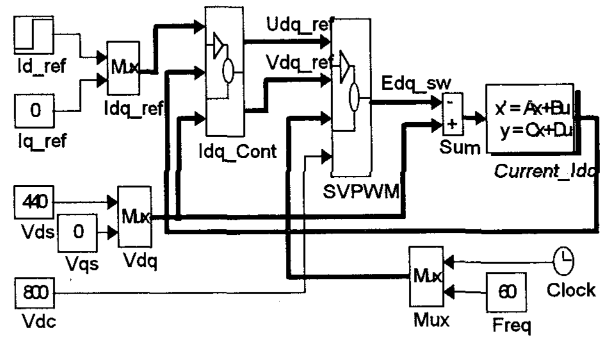


Fig. 5. SIMULINK block diagram of control system

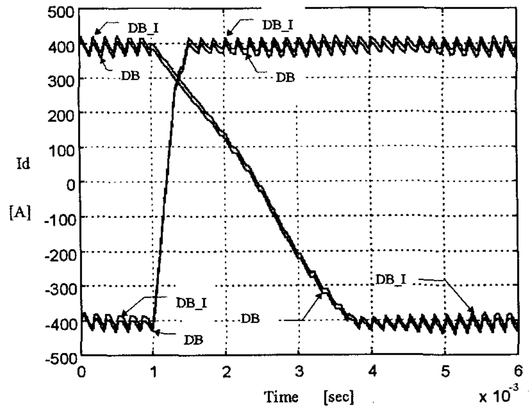
TABLE 1. SYSTEM PARAMETERS

L = 0.5 [mH]	Vdc = 800 [V]	fsw = 3 [kHz]
R = 2 [m]	Vll = 440 [V]	Kp = 2.998
C = 27.2 [mF]	Pout = 185 [kW]	Ki = 2250($\zeta=\sqrt{2}$)

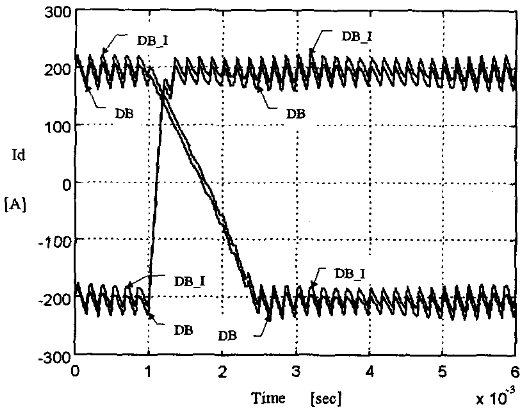
motor drive for commercialization. And 1.1 times the rated voltage is assumed as an parameter uncertainty of source voltage.

In case of no time delay, the simulation results of the proposed controller using the novel feedback contrller are compared with those of the state deadbeat controller which has an ideal control response except the steady state error only. First, the difference between the rising time and the falling time for the same magnitude of reference change implies the varying control bounds in PWM converters as shown in Fig. 2. And Fig. 6 shows that the proposed controller has nearly the same respose time and the better steady state perfomance irrespective of the varying bounds of control inputs. Fig. 7 shows the identical control response of d-component current and a good decoupled control characteristic even in transien period by the modified over-modulation scheme.[10]

In case of one sampling time delay(166.7[μsec]), Fig. and Fig. 9 show the comparative simulation results of th proposed controller with and without delay tim compensation. It is shown that the proposed controlle without deay time compensation reveals the deteriorated



(a) step reference change: 400A ↔ -400A



(b) step reference change: 200A ↔ -200A

Fig. 6. Simulation results of a d-component current (DB: deadbeat controller, DB_I: proposed controller, I_BPW = 50[A])

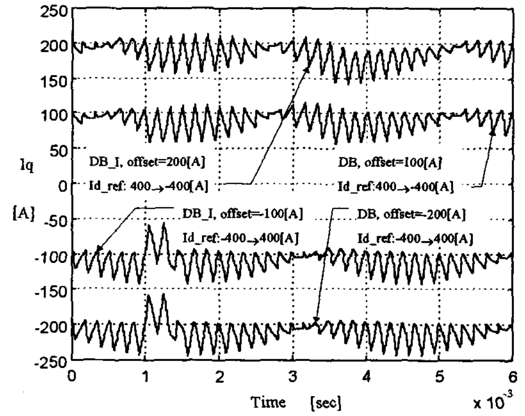
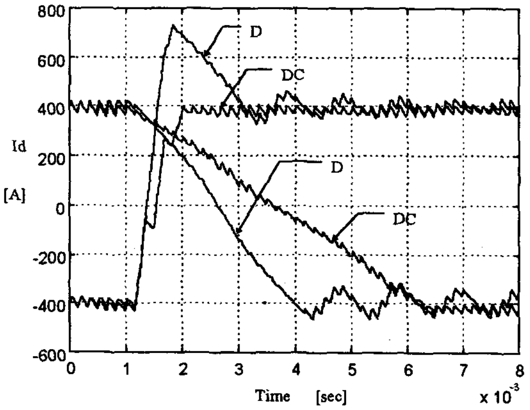


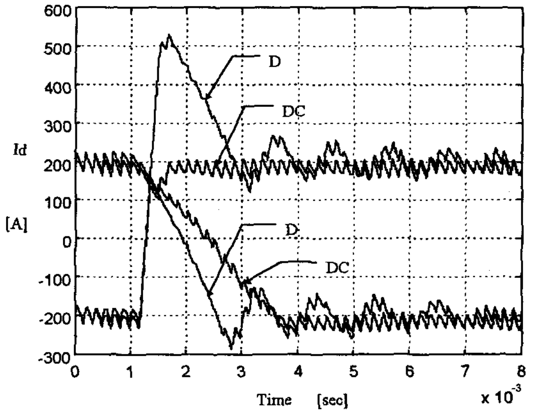
Fig. 7. Simulation results of a q-component current (DB: deadbeat controller, DB_I: proposed controller, Iq_ref = 0[A])

control performances such as overshoot and oscillation due to one sampling time delay. Therefore a proper measure such as tuning the control gain is needed to get the reasonable performance in real applications.

However, the proposed controller with Smith-predictor shows the fast control response without overshoot and steady state error. But the control response gets a little slower due to the Smith-predictor. In addition, the control gain can be designed directly from the system parameters in case of time delay.



(a) step reference change: 400A ↔ -400A



(b) step reference change: 200A ↔ -200A

Fig. 8. Simulation results of a d-component current (D: w/o delay comp., DC: w/t delay comp., I_BPW = 50[A])

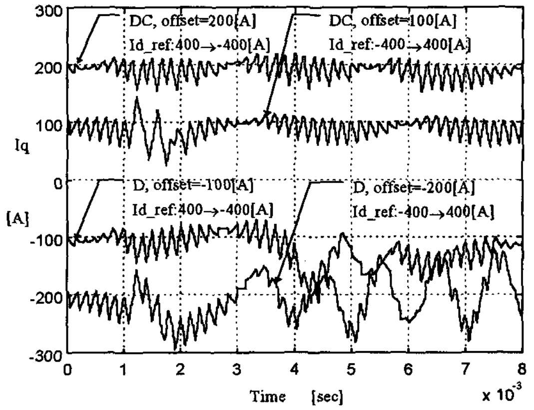


Fig. 9. Simulation results of a q-component current (D: w/o delay comp., DC: w/t delay comp., Iq_ref = 0[A])

From the simulation results, it can be concluded that the proposed controller with Smith-predictor guarantees the full utilization of current capacity of power devices irrespective of the varying control bounds in PWM converters and the computational time delay.

V. CONCLUSIONS

As a solution to fully utilize the current capacity of power devices, this paper proposed a novel decoupled current controller with Smith-predictor which had a fast current control response without overshoot and steady state error and had a good decoupled control response based on the modified over-modulation strategy. And also the design method based on the full analysis of PWM converters was described in detail. The simulation results have shown that the new decoupled controller with

Smith-predictor guarantees the full utilization of current capacity of power devices irrespective of the varying control bounds in PWM converters and the computational time delay.

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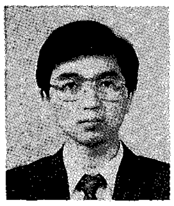

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