11th International Conference on Power Electronics-ECCE Asia
May 22 - 25, 2023 / ICC Jeju, Jeju, Korea

Active Discharging Method of PMSM Using Flux Map-based Torque Control

Youngeun Oh[1] and Jongwon Choi[1]
[1] Dept. of Electrical and Electronic Engineering, Hannam University

***Abstract*-- A dc-link voltage control algorithm is developed using the flux-based torque control method and the flux controller. Using negative dq-axes currents, the DC-link voltage can be controlled regardless of the motor operation state. The power flow of the electric-drive vehicle is modeled, and the voltage controller is analyzed. Due to the copper loss of the motor, the nonlinear function, square, is included in the voltage control loop. Using the linear approximation, the control loop is approximated as a linear system. The variable gain, which depends on the current and dc-link voltage, was derived straightforwardly. The compensation gain is proposed to maintain the performance of the voltage controller regardless of the operating point. The performance is experimentally demonstrated under different operation conditions such as 500rev/min and 1000rev/min.**

***Index Terms*—active discharging, electric vehicle, linear approximation, voltage control**

I. Introduction

Due to the global climate crisis, the companies and governments are mandating a transition to electrification vehicle. The interior permanent magnet synchronous motor (IPMSM) has an excellent efficiency and energy density and is widely used as a traction motor in electric vehicles (EV). Also, for reducing the high battery current, the main battery is becoming higher, and the battery voltage is applied from 400V to 800V in passenger car. But the high voltage of the electric drive system poses a risk of electric shock to the driver or auto mechanic. According to the United Nations Vehicle Regulations ECE R94 [1], the dc-link voltage must be reduced to a safe voltage when a serious problem occurs in the vehicle. The safe voltage is defined as DC voltage lower than 60V or AC voltage lower than 30V within 5s.

One of the active discharge methods is a bleeder resistor which is connected in parallel with dc-link capacitor [2]. To step down a high voltage to a safe voltage in a second, the external bleed resistor with a very high-power rating is required. It causes that the power density of the power conversion system is reduced. Therefore, this method is not suitable for electric drive systems. An active discharge control algorithm was proposed to regulate the dc-link voltage using both d-axis and q-axis current [3], [4]. A new safe state transition method using voltage vector selection according to the location of the current vector was proposed. In the induction motor, the charging and discharging of the capacitor was controlled while selecting the voltage according to the position of the current vector [5].

In this work, an active discharge voltage control method is proposed using the flux map-based torque control with the flux controller, which are widely used in EV inverter. The regenerative torque was adjusted using the output value of the voltage controller and flux-map. Using the d-axis command from the flux map and the output of the voltage controller, the capacitor discharge was controlled. The voltage controller is analyzed through linear approximation. The variation loop gains are calculated according to the inverter operating point and is compensated.

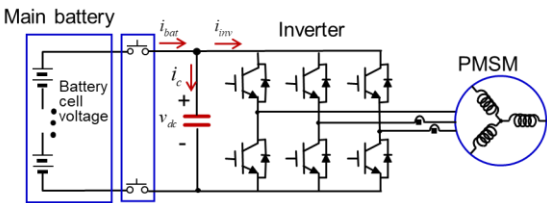


Fig. 1 The inverter system for battery based electric drive vehicle.

II. MATHEMATICAL MODELIG

The voltage equations of IPMSM are given as,

$$\begin{aligned} v_d &= R_s i_d + L_d \frac{di_d}{dt} - L_q i_q \omega_e \\ v_q &= R_s i_q + L_q \frac{di_q}{dt} + L_d i_d \omega_e + \omega_e \psi_m, \end{aligned} \qquad (1)$$

where R_s is stator resistor, i_d and i_q are d, q axis currents L_d and L_q are d, q axis inductance, and ω_e is electric motor speed, and ψ_m is the flux linkage constant. Substituting (1) into $p_{mot} = \frac{3}{2}(v_d i_d + v_q i_q)$, the input electrical power of motor is derived as

$$p_{mot} = R_s \frac{3}{2}(i_d{}^2 + i_q{}^2) + \frac{3}{2}(L_d \frac{di_d}{dt} i_d + L_q \frac{di_q}{dt} i_q) + \omega_r T_e,$$
(2)

where p_{mot} is the input instantaneous power of motor, ω_r is the mechanical speed, and T_e is the production torque of the IPMSM. The torque equation is defined as

$$T_e = \frac{P}{2}\frac{3}{2}(\psi_m i_q + \left(L_d - L_q\right) i_d i_q), \qquad (3)$$

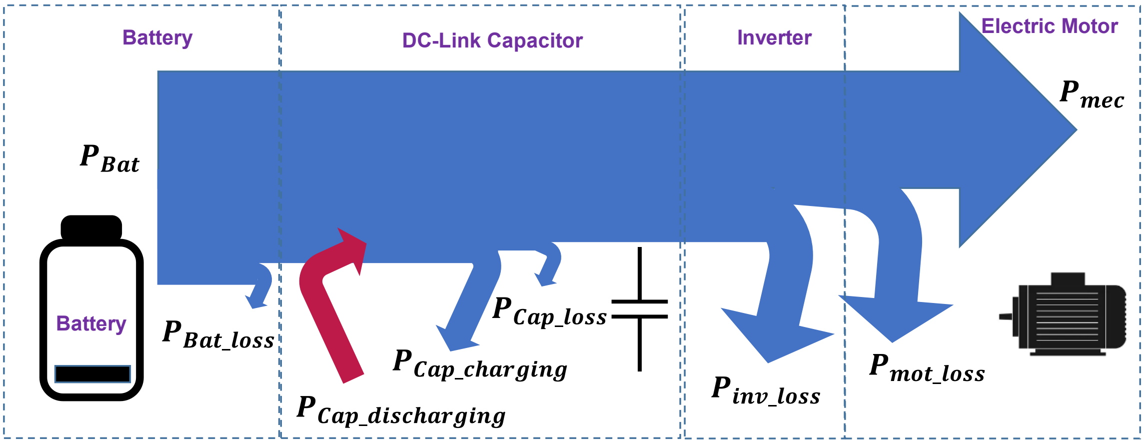


Fig. 2 Sankey Diagram in battery based electric drive vehicle.

where P is the number of poles. Assuming that d-q axis currents are not changed, the average input power of the motor is defined as

$$P_{mot} = R_s \frac{3}{2}(i_d{}^2 + i_q{}^2) + \omega_r T_e, \qquad (4)$$

where P_{mot} is the average input power of the motor. Note that P_{mot} is composed of copper loss and mechanical power. The copper losses are only used for power dissipation. However, the direction of mechanical power can be either motoring or regenerative depending on the speed or torque direction of the motor. Thus, the dc-link voltage can be controlled by adjusting the direction and amount of torque when the motor rotates in the same direction. But, when positive torque is used for discharging the capacitor, an unintended acceleration of the electric vehicle occurs. This violates the functional safety goal of electric vehicles. Consequently, discharging of the capacitor should be achieved using the copper losses and the capacitor is charged using the regenerative torque of the motor. Therefore, the capacitor charging and discharging should be achieved through different power components.

Fig.1 shows the inverter system for electric traction system and dc-link capacitor. The capacitor voltage can be calculated as

$$\frac{dv_{dc}}{dt} = \frac{1}{C_{dc}} I_c = \frac{1}{C_{dc}}(I_{bat} - I_{inv}), \qquad (5)$$

where I_c, I_{bat}, and I_{inv} are the capacitor, and battery, and inverter input average current, respectively. For the sake of simplicity, PWM ripple current from the power converter is not considered. Fig. 2 shows a Sankey diagram to depict a power flow from battery to inverter and motor in electric vehicle. Note that the DC-link capacitor performs charging and discharging according to the voltage of the battery and capacitor. The power from the main battery is stored as a DC-link capacitor or supplied to an inverter. The inverter converts dc power into AC voltage and current and supplies it to the AC motor. Then, the mechanical power is transferred except inverter and motor loss. From Sankey diagram in Fig.2 and (4), the inverter power is defined as,

$$P_{inv} = \frac{3}{2} R_s (i_d{}^2 + i_q{}^2) + \omega_r T_e + P_{loss-inv}, \qquad (6)$$

where P_{inv} is the power supplied to the inverter and $P_{loss-inv}$ is the dissipated power in the inverter such as switching loss and conduction loss of the power semiconductor. Consequently, the dc-current supplied to the inverter is calculated as follows:

$$I_{inv} = \frac{P_{inv}}{v_{dc}} = \frac{3}{2}\frac{R_s(i_d{}^2 + i_q{}^2)}{v_{dc}} + \frac{\omega_r T_e}{v_{dc}} + \frac{P_{loss-inv}}{v_{dc}}, \qquad (7)$$

Replacing (7) in (5), it follows that

$$\frac{dv_{dc}}{dt} = \frac{1}{C_{dc}}\left(I_{bat} - \frac{3}{2}\frac{R_s(i_d{}^2 + i_q{}^2)}{v_{dc}} - \frac{\omega_r T_e}{v_{dc}} - \frac{P_{loss-inv}}{v_{dc}}\right),$$
(8)

Using (8), Fig. 3 shows the dc-link capacitor model. Note that the mechanical power of the motor and the battery have a bidirectional power flow. But, the motor loss and inverter loss is unidirectional power.

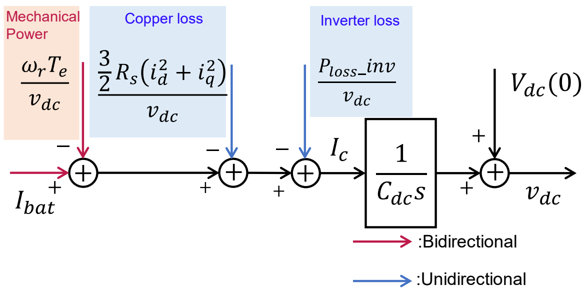


Fig. 3 Block diagram of the dc-link capacitor.

III. PROPOSED DC-LINK VOLTAGE CONTROL METHOD

When the main battery relay is off and active discharge is requested from external control unit in vehicle, the motor control unit (inverter) should perform dc-link voltage control regardless of the operating conditions of the motor such as rotor speed and dc-link voltage. To control the dc-link voltage, there are two methods. When the motor is operated at standstill or low speed, the d-axis current is only used to discharge the capacitor voltage with zero torque generation. In another method, when the motor is rotating at a medium or high speed, the dc-link capacitor can be charged using the regenerative torque of the motor. For the active discharging in high speed, it is necessary to prevent the back EMF voltage of the motor from charging the dc link voltage of the inverter. The flux weakening control is required and it uses significant negative d-axis current. The use of more d-axis current results in a decrease in the faster dc-link voltage. Therefore, it is necessary to compensate for the motor loss by the regenerative torque for the current control.

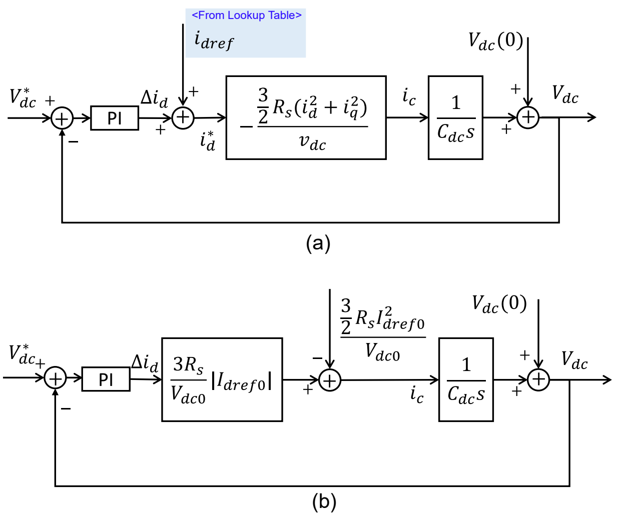


Fig. 4 Capacitor discharge control block using only d-axis current: (a) voltage control loop and (b) modified voltage control loop using linear approximation.

A. Capacitor discharging method using d-axis current and zero torque.

The d-axis current and zero q-axis current is used to discharge the voltage of the dc-link capacitor. We assume the inverter loss is neglected. Substituting T_e=0, I_{bat}= 0, and $P_{loss-inv}$= 0 into (8), the capacitor current is obtained as $I_c = -\frac{3}{2}\frac{R_s({i_d}^2+{i_q}^2)}{v_{dc}}$. Using this equation, the voltage control block is drawn in Fig. 4 (a). But, the nonlinear function, square, is included in the voltage control loop. Thus, the performance of the controller can be affected depending on the operating point and it is difficult to analyze the controller. Using linear approximation, the capacitor current at the certain operation point (i_{d0}, V_{dc0}, $i_{q0}=0$) can be approximated as

$$I_c \simeq I_c(i_{d0},V_{dc0}) + \left.\frac{\partial I_c}{\partial i_d}\right|_{(i_{d0},V_{dc0})} \Delta i_d \qquad (9)$$
$$\simeq -\frac{3}{2}\frac{R_s {i_{d0}}^2}{V_{dc0}} - \frac{3R_s i_{d0}}{V_{dc0}}\Delta i_d,$$

where Δi_d is additional d-axis current to control the voltage and i_{d0} is calculated from d-axis look-up table to control the flux magnitude. Because d-axis current is negative value, the following equation is modified from (9)

$$I_c \simeq K_{t1}\Delta i_d - \frac{3}{2}\frac{R_s {i_{d0}}^2}{V_{dc0}}, \qquad (10)$$

where $K_{t1} = \frac{3R_s|i_{d0}|}{V_{dc0}}$ is variation gain in the control loop. Using (9), Fig. 4 (a) can be modified to Fig. 4 (b). where I_{dref} is d-axis current control reference value calculated from d-axis look-up table. Note that the variation gain is changed depending on dc-link voltage, the magnitude of the d-axis current, and resistance. The voltage and current always change according to the operating point, which is a burden on the performance of the voltage controller.

B. Capacitor charging method using the regeneration torque

Substituting I_{bat}= 0, and $P_{loss-inv}$= 0 into (7) the capacitor current is obtained as

$$I_c = -\frac{3}{2}\frac{R_s({i_d}^2+{i_q}^2)}{v_{dc}} - \frac{\omega_r}{v_{dc}}\Delta T_e, \qquad (11)$$

where ΔT_e is the addition regenerative torque for dc-link voltage regulation, $\Delta T_e < 0$. The variation gain in voltage control loop is defined as $K_{t2} = -\frac{\omega_r}{V_{dc}}$. The variation gain in the control loop causes the performance of the voltage controller and affects the stability of the voltage controller. Using the regeneration torque, the block diagram of the voltage control is shown in Fig. 5.

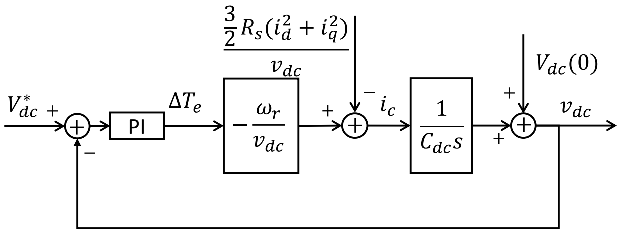


Fig. 5 Capacitor charging method using the regeneration torque.

C. Proposed voltage control method for the active discharging.

Fig.6 shows the overall control block diagram. The proposed voltage control is added to the torque control based on flux map. To solve the variation control loop gains, K_{t1} and K_{t2}, in the voltage control loop, the compensation gain $\frac{1}{K_t(V_{dc},\omega_r,I_{dref})}$ is multiplied by the output of dc-link voltage controller. The compensation gain is continuously updated according to the motor operating point. In general, torque control is performed by receiving a torque command from the vehicle control unit (VCU). The active discharge is operated by the discharge request flag, $Flag_{dis}$, which can be requested by external control unit such as airbag control unit. The voltage control methods are determined according to the direction of the voltage controller output, T^*_{dis}. When the output of the voltage controller is negative, the capacitor voltage is discharged and regulated using only d-axis current. On the

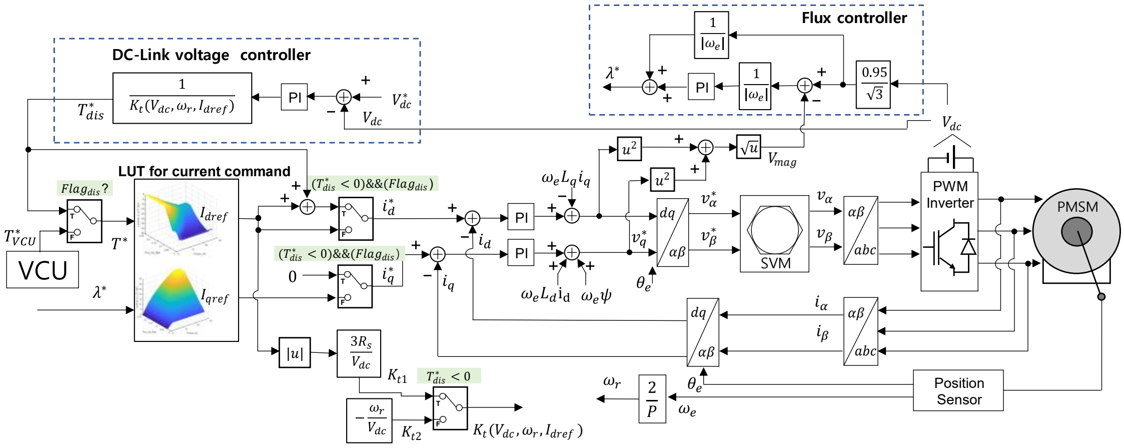


Fig. 6 Overall control block diagram

other hands, the capacitor voltage is regulated by the regeneration torque when the output of the voltage controller is positive.

IV. SIMULATION RESULT

The proposed control method was simulated in a MATLAB/Simulink with PMSM model. The PMSM model and inverter parameters are in Table 1. Active discharging request flag turn on at 0.5 second. Fig.7 (a) and Fig. 8 (a) are used constant d-axis current injection for discharging.

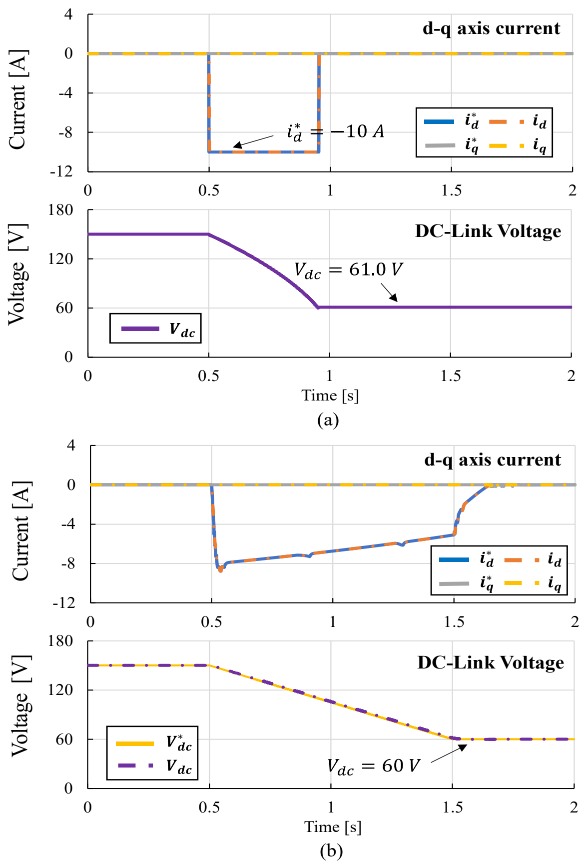


Fig. 7 DC-link voltage and dq axes current characteristics in active discharge at $\boldsymbol{\omega_r} = \mathbf{500rev/min}$: (a) constant d-axis current injection (b) proposed control method.

In constant d-axis current injection, when active discharging request flag turn on, d-axis and q-axis current set as -10A and 0. When DC-link voltage arrives 60V, d-axis current(i_d) and q-axis current(i_q) set as 0. Fig.7 (b) and Fig. 8 (b) are used proposed voltage control method. In voltage control method, when active discharging request flag turn on, the voltage reference(V_{dc}^*) decrease from 150V to 60V during the 1.0 second.

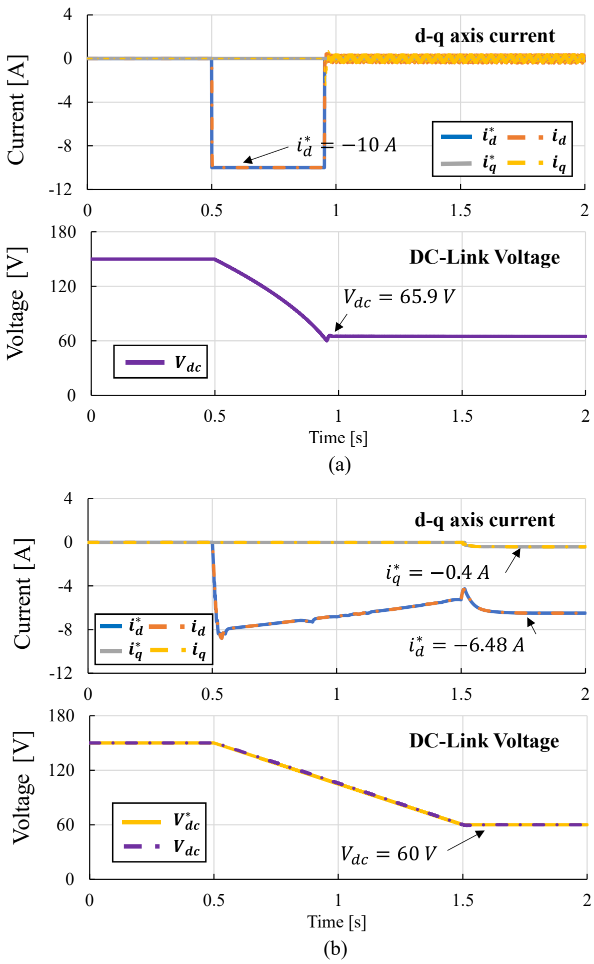


Fig. 8 DC-link voltage and dq axes current characteristics in active discharge at $\boldsymbol{\omega_r} = \mathbf{1000rev/min:}$ (a) constant d-axis current injection (b) proposed control method.

The controller gains are fixed at $K_{Pv} = 0.12$, $K_{iv} = 3.2$ to verify the effect of the compensation gain.

Fig.7 and Fig.8 show DC-link voltage and dq-axes current characteristics in active discharge at each $\omega_r = 500\text{rev/min}$ and $\omega_r = 1000\text{rev/min}$. Using constant d-axis current can decreases dc-link voltage faster than 1.0 second. However, the voltage cannot be maintained 60V after discharging because of back EMF voltage. Fig.7 (a) and Fig. 8 (a) shown the dc-link voltages rising each 61.0V and 65.9V after decreasing to 60V.

Compared to constant d-axis injection, Fig.7(b) and Fig. 8 (b) illustrate that the DC-link voltage decreases stable as operating voltage control. After voltage regulation, each result show DC-link voltage stabilizing at 60V. After 1.5 second, Fig. 8 (b) d-axis current(i_d) and q-axis current(i_q) set as -6.48A and -0.4A, because i_d is required value for flux weakening control and i_q creates regenerative torque to compensate motor loss caused i_d. Voltage controller in Fig. 8 (b) operate discharging method at from 0.5 second to 1.5 second and charging method after 1.5second.

Voltage controller PI gains(K_{Pv}, K_{iv}) are affected depending on the operating point. As using compensation gain to voltage control, simulation result shows relatively stable voltage control performance at different speed condition.

V. EXPERIMENTAL RESULT

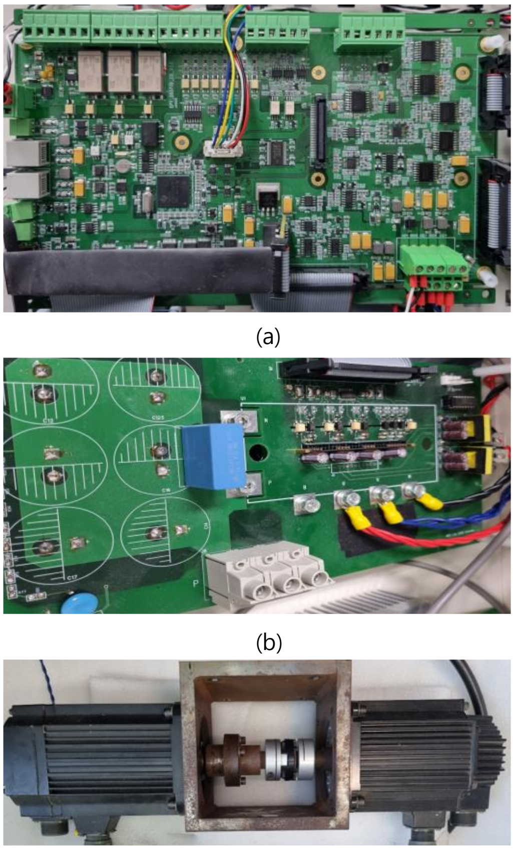
The experimental setup consists of a PMSM coupled to an AC machine, and the inverter unit. Modeled Case circuit breaker (MCCB) is used as the connection part to supply dc-link voltage. The PMSM parameters and inverter are listed in Table 1. Fig. 9 shows the experimental environment such as control board, inverter, and dynamo set. A TMS320F28377 was used, and the pulse-width modulation (PWM) frequency was set 5 kHz. And the double sampling mode was utilized.

Table 1
PRAMETERS OF PMSM AND INVERTER

Rated Power	P_{mot}	1.9 kW
Number of pole pairs	p	4
Rated Torque	T_e	8.34 N.m
Rated Speed	ω_r	1500 rev/min
Armature resistance	R_s	0.39 Ω
Magnet flux linkage	ψ_m	0.095 Wb
d/q-axis inductance	L_d, L_q	2.5 mH
DC-link capacitance	C_{dc}	2.82 mF

The dc-link voltage was set to 150V and the threshold voltage for starting voltage control was set 147V. When MCCB passively turn off, voltage disconnect from dc power supply to inverter unit and the dc-link voltage begins to decline. If dc-link voltage reaches the threshold voltage, the proposed voltage control working.

Figs. 10 show the discharge performance compared to constant d-axis current and proposed method at 500rev/min. Fig. 10 (a) shows the discharge curve of DC-link voltage using constant d-axis current. The DC-link capacitor is discharged by copper loss of the motor using d-axis current. When the voltage is reached at 60V, the d-axis command is changed to 0A.



(a) (b) (c)

Fig. 9 Experimental environment: (a) Control board, (b) inverter, and (c) dynamo set.

Fig. 9 (b) the voltage control performance using proposed method. After 1 second, the voltage control mode is performed, and the motor is rotating at 500 rev/min. During 1sec, the discharge is performed using only the negative d-axis current. After discharging, a slightly negative q-axis current is used to compensate for inverter losses. Therefore, the dc-link voltage can be regulated.

Figs. 10 show the discharge curve and with d-axis current and proposed method at 1000rev/min. Fig. 10 (a) shows the discharging curve using constant negative d-axis current. After the DC-link voltage reached 60V, the d-axis current value is maintained by the flux controller. Due to the voltage limit, the current control cannot be performed well. Fig. 10 (b) shows the voltage control and d-axis and q-axis current. During the discharging, d-axis current is used. After discharge is completed, d-axis and q-axis current are used to maintain 60V. Flux control is performed to ensure the safety of motor current control. Therefore, d-axis current is utilized for handling the magnitude of the motor flux. However, the d-axis current causes loss in the motor and discharges the DC-link capacitor. To maintain the DC-link voltage, the q-axis current is used to compensate the motor and inverter losses using regeneration torque.

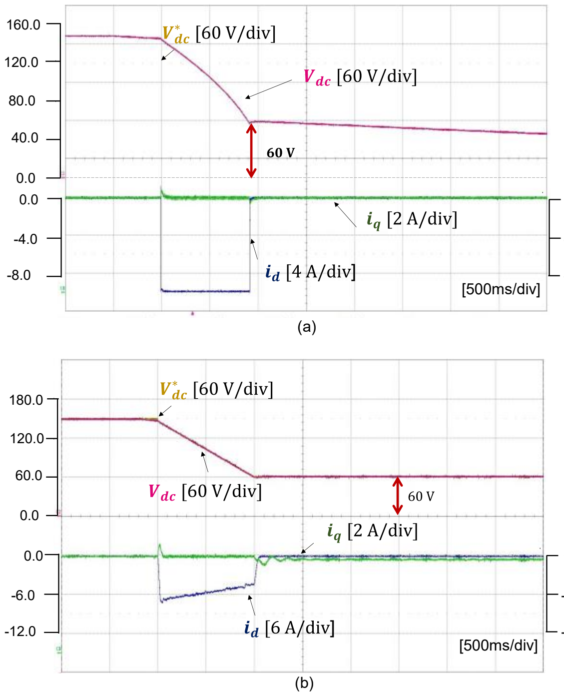


Fig. 10 Discharge performance of the voltage control results at ω_r= **500rev/min** (a) constant d-axis current injection (b) proposed control method.

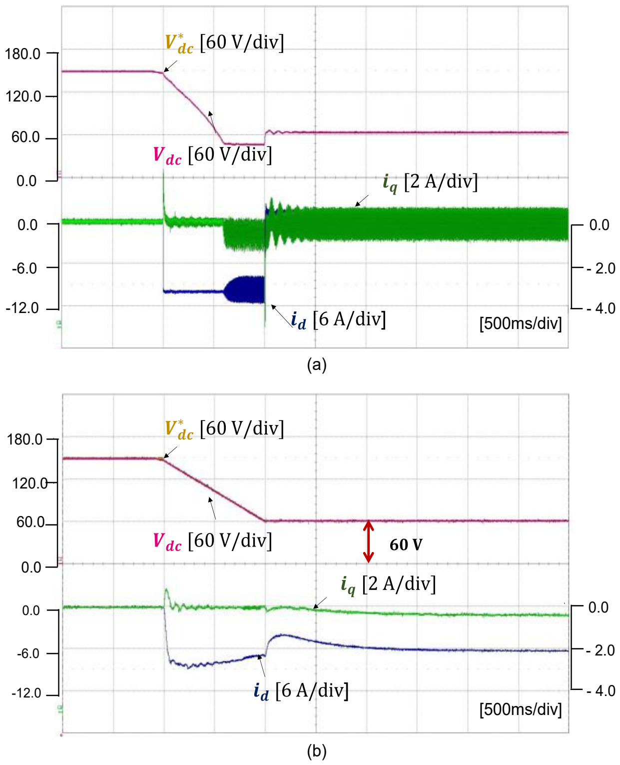


Fig. 11 Discharge performance of the voltage control results at ω_r = **1000rev/min** (a) constant d-axis current injection (b) proposed control method.

VI. CONCLUSION

The proposed voltage control algorithm with the variation gains in the voltage control loop is effective to discharge dc-link voltage. The compensation gain was calculated through the capacitor current and the motor power model. Using the compensation gain, the dc-link voltage was controlled successfully at different speed condition. It was validated through simulation and experiments during rotating the motor.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (NRF-2021R1I1A3059676).

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