Novel Flux Weakening Control for Improving Current Response and Stability of EV Motor

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ABSTRACT: The response and stability of flux weakening control in the high-speed range of IPMSMs is one of the most important factors for EV and industrial applications. Conventional flux weakening control based on the voltage reference feedback method is highly stable against fluctuations motor parameters but has a problem that the current response is low compared to the control in the constant torque region. Therefore, this paper proposes a novel flux weakening controller that combines feedforward and feedback control to improve response and stability of current control in the flux weakening region.

KEY WORDS: electric vehicle, IPMSM, motor drive, vector control, flux weakening

1. INTRODUCTION

IPMSMs used in electric vehicles are required to have a wide range of output characteristics such as high torque and high speed(1). Also, high response and stability are required to realize the 'Electric Stability Control' function, etc(2).

To achieve high-speed motors, flux weakening control is necessary to suppress voltage saturation that accompanies the increase in the motor's back EMF. Flux weakening control is a method in which a negative d-axis current (flux weakening current) is applied to the motor to counteract the increase in the motor's back EMF(3) (4).

Conventional flux weakening control used in industrial applications adjusts the flux weakening current by the current or voltage reference feedback(5) (6). However, this method has the disadvantage that it does not allow for a high response of the flux weakening control.

The other method uses motor parameters to calculate feedforward the flux weakening current was also proposed(7) (8). This method allows for a higher response of the flux weakening current. However, since motor parameters are used in the calculation, there is a concern that the stability of the flux weakening control will be reduced when parameter fluctuations occur.

These problems can be solved by implementing a current command lookup table(9), but this method requires table creation work and implementation costs.

To solve the above problem, we propose a novel flux weakening controller that combines feedforward and feedback control. By applying this method, it is possible to easily improve the response and stability current control in the flux weakening region.

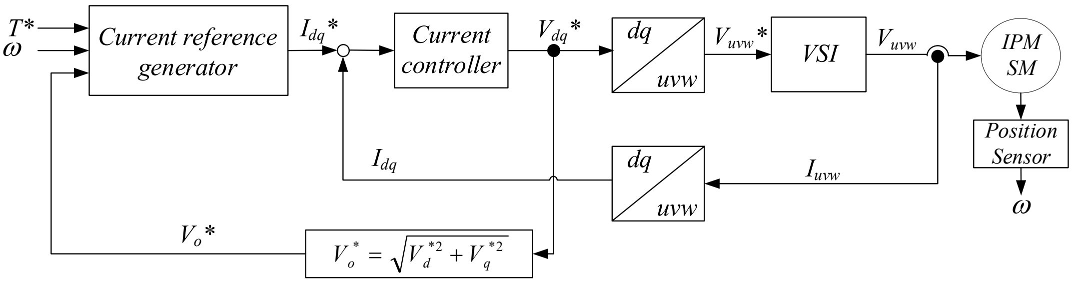

Fig. 1. Block diagram of the proposed method

2. PROPOSED ALGORITHM

2.1. Structure of the Proposed Algorithm

The overview of proposed method is shown in Fig.1. This control system is configured as a torque control system using vector control. Proposed flux weakening control is included in the current reference generator in the same figure.

2.2. Proposed Flux Weakening Control

In general, the flux weakening current calculation method used in flux weakening control is based on observing the amount voltage saturation due to voltage command and bus voltage. The flux-weakening current is determined by a feedback (FB) flux-weakening regulator based on the amount of voltage saturation. Alternately, there is a feedforward (FF) flux weakening controller calculates flux weakening current at each operating point by using motor parameters.

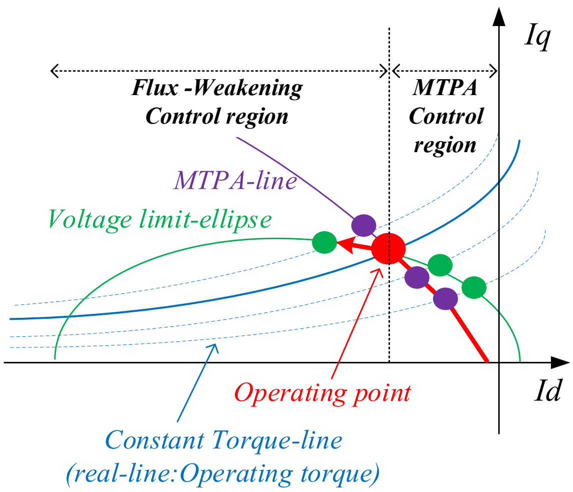

Fig. 2. Comparison of each driving pattern in i_d - i_q coordinates

The output of the latter feedforward (FF) flux weakening controller can be calculated by finding the combination of current components i_d and i_q at the intersection of the constant torque-line and the voltage limit-ellipse in i_d - i_q coordinates as shown in Fig. 2. The i_d (flux weakening current) at the intersection can be expressed as shown in equation (1).

$$i_d = \frac{-\varphi_m + \sqrt{\left(\frac{V_{\lim}}{\omega}\right)^2 - \left(L_q i_q\right)^2}}{L_d} \tag{1}$$

φ_m : magnetic flux, i_q: q axis current, L_d, L_q: dq axis inductance respectively, ω: rotational speed, V_{lim} : variable voltage limit that depend on DC link voltage.

In this controller, the current command value when flux weakening control is not necessary is calculated by MTPA trajectory is shown in Fig 2. This trajectory minimizes the distance between the constant torque-line and the origin. By selecting a current command on this locus, it is possible to output the desired torque with less current.

During actual operation, it is necessary to switch between MTPA and flux weakening region. Specifically, based on MTPA operation, when the operating point in MTPA control is outside the voltage limit-ellipse, it switches to flux-weakening control. Comparing the d-axis components of the MTPA current and the flux-weakening current for the same torque in Fig. 2, it can be seen that the MTPA current is larger in the MTPA region and the flux-weakening current is larger in the flux-weakening region. Therefore, it can be seen that switching between MTPA and flux weakening can be done by comparing the magnitude of both respective current commands and then adopting the larger value. This current selection method makes it possible to switch between an appropriate current command simply by comparing it's magnitude without performing complicated calculations.

Based on this concept the current reference generator including the proposed flux weakening controller is shown in Fig.3. The current command I_{d_temp1} and I_{d_temp2} are compared. Based on magnitude of these respective current values, selection between MTPA controller and feedforward flux weakening control is decided.

The proposed flux weakening controller consists of a Feedback (FB) flux weakening controller and Feedforward (FF) flux weakening controller. FB flux weakening controller adopts a general method of adjusting the flux weakening current by using voltage reference feedback. The FF flux weakening controller consists of a calculation part based on equation (1) and a filter part. This filter part reduces the interference caused by the q-axis current reference forming a loop inside the current reference generator. By adopting this configuration that

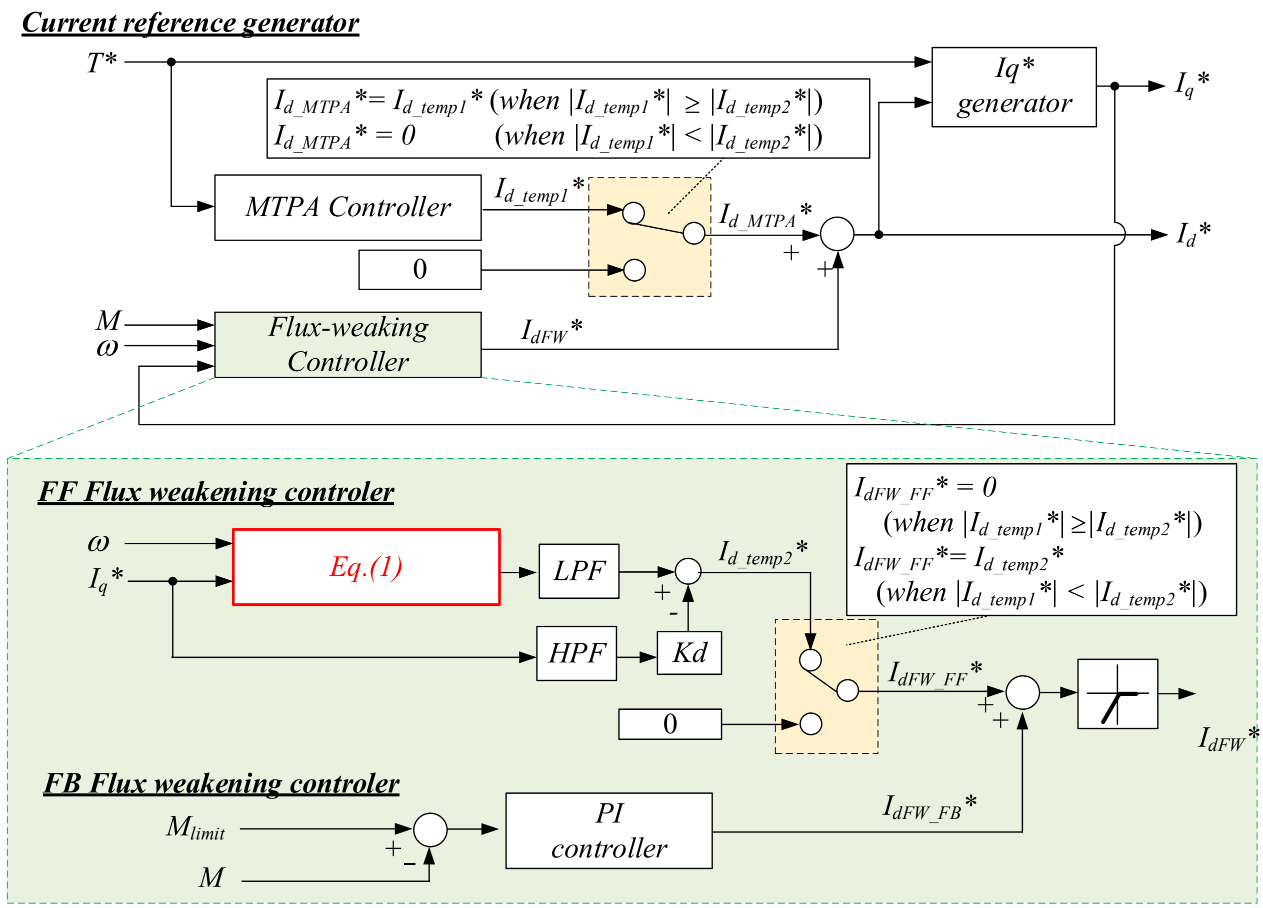

Fig. 3. Current reference generator and proposed Flux weakening controller

combines LPF and HPF, it is possible to set a higher response than the configuration with only LPF.

In addition, the proposed flux weakening controller is configured to add the output of the FB flux weakening controller I_{dFW_FB}* and the FF flux weakening controller I_{dFW_FF}*. By adopting this configuration, even if an inappropriate I_{dFW_FF}* is calculated due to a motor parameter error, etc., I_{dFW_FB}* compensates the flux weakening current I_{dFW}* to an appropriate value.

For example, when performing flux weakening control only with the FF flux weakening controller to improve response, parameter errors occur, and if the value is larger than the ideal value is calculated and the voltage is excessively limited. This leads to problems such as limitations on the output power range. Therefore, by using both FF control and FB control as mentioned in the proposed method, it is possible to improve the stability against variations in motor parameters while at the same time improving the response.

3. EXPERIMENTAL RESULT

3.1. Experimental Setup

Specification of test motor is listed in Table 1, whereas the parameter of proposed function is shown in Table 2. The parameters shown in Table 2 are optimized by preliminary tests on the same machine on which the experiment is to be conducted.

Table 1 Specification of tested motor

Parameter	Value
Rated Voltage	350[V]
Rated Output	40[kW]
Maximum Output	130[kW]
Rated Torque	120[Nm]
Maximum Torque	280[Nm]
Rated Speed	4092[min^{-1}]
Maximum Speed	12500[min^{-1}]

Table 2 Parameter of proposed function

Parameter	Value
LPF Cutoff frequency	500[Hz]
HPF Cutoff frequency	50[Hz]
K_d (Proportional Gain)	1.0[-]
PI controller Gain	0.8[-]
PI controller Integrate time	5.0[ms]

3.2. Torque Step Response

In this section, the torque step response in the flux weakening region is verified. Here, the proposed flux weakening control is compared with the conventional FB flux weakening method, i.e., without FF flux weakening controller.

Fig. 4. and Fig. 5. show the torque and d-axis current response waveforms at the maximum torque step at speed of 12000 min^{-1}. Fig. 4. shows the response waveforms of the conventional method whereas Fig. 5. shows the response waveforms of the proposed method. It should be noted that the T_{cal} shows the estimated torque response calculated by using the detected d-q axis currents, and motor parameters.

In case of conventional method, the response is oscillatory and takes a long time to stabilize. The reason for oscillating behavior is that the flux weakening control does not work immediately after the step command is applied (from 0.1 s). Whereas by applying the proposed method, the stabilization time can be shortened without causing excessive overshoot and vibration. Since in proposed method, FF flux weakening control becomes effective when a step command is applied (0.1s~), this adds to the FB flux weakening control command. Due to this modified d-axis current command, the instability of the current control due to voltage saturation is suppressed, and at the same time both current and torque response are improved.

This confirmed the verification and usefulness of the proposed method for improving the response and stability of current control in the flux weakening region.

4. CONCLUSION

In this paper, we proposed a novel flux weakening controller that combines feedforward and feedback control to improve the response and stability of the flux weakening control. By applying this controller, it was shown experimentally that the response and stability of current control in the flux weakening region can be easily improved without implementing a lookup table.

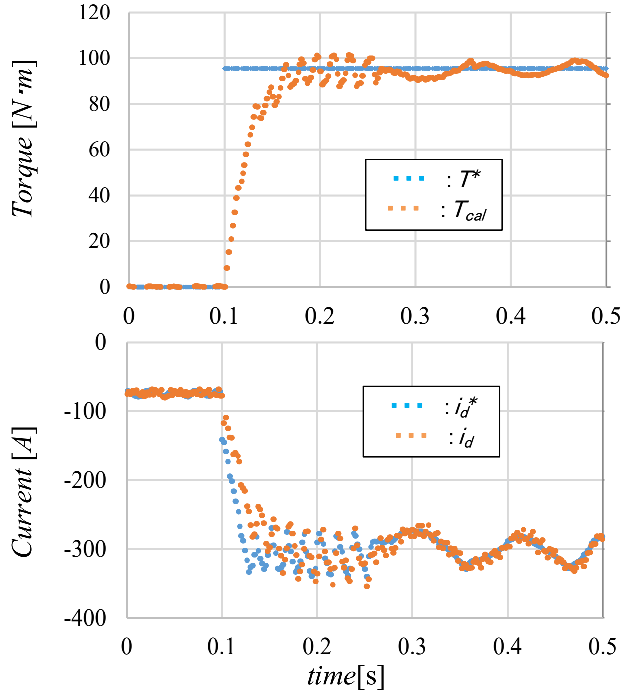

Fig. 4. Torque and d-axis current response

(Conventinal method)

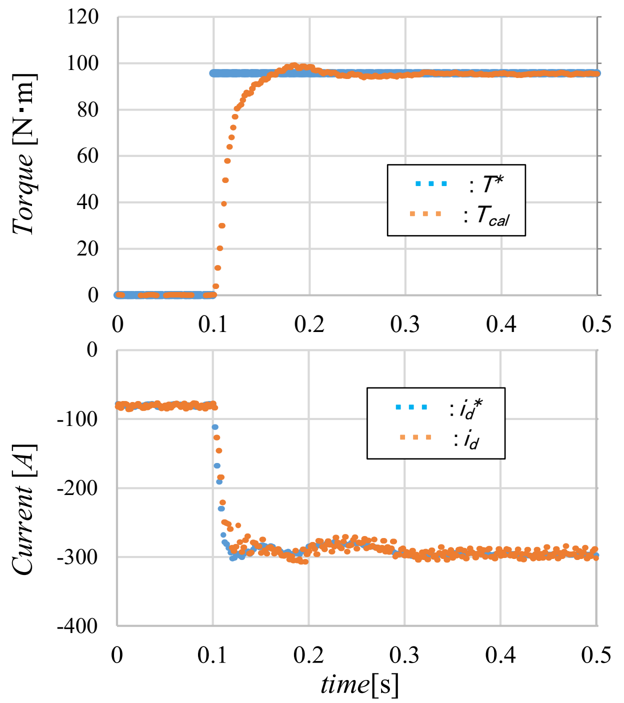

Fig. 5. Torque and d-axis current response

(Proposed method)

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