Rapid and Stable Speed Response Based on Current Differential Signal and Priority Amplitude Method of SVM in Flux-Weakening Region of SPMSM

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In the AC servo system, the output voltage is restricted by inverter output limitations. Voltage saturation occurs as a result of these limitations. The settling time of the current and speed increases because of voltage saturation. This paper proposes a new control system for improving the transient response of the surface permanent magnet synchronous motor (SPMSM) by using the proposed flux-weakening control based on the current differential signal. Because the current differential signal is taken into consideration, the suppression of voltage saturation is achieved with a smaller d-axis current in a transient state. Finally, this paper proposes a new combination method of flux-weakening control and an inverter modulation scheme, which makes it possible to improve the voltage utilization on condition of flux-weakening region. The proposed speed control system achieves a quick and stable speed and current response. The effectiveness of the proposed control methods is confirmed by both the numerical simulation results and the experimental results.

Keywords: flux-weakening control, voltage saturation, space vector modulation, spmsm

1. Introduction

AC servo motors, which are used in industrial applications, are required to have a quick and stable response of speed and torque. Generally, a speed servo system based on vector control of AC servo motor consists of several PI controllers, and these outputs are restricted by a current limiter and an inverter voltage output limitation. Voltage saturation occurs because of existence of the inverter voltage output limitation. In voltage saturation region, control performance is often degraded for a quick speed reference.

In order to overcome these problems caused by voltage saturation, the inverter voltage utilization needs to increase. Various inverter modulation schemes are used to improve the voltage utilization of a three-phase PWM inverter. For example, two phase modulation, third harmonics injection and space vector pulse width modulation (SVPWM). Inverters using SVPWM output voltage as the linear region inside of the inverter voltage limitation hexagon (1)(2). A stable speed and current responses are obtained as a result of the inverter operating in the linear region. The SVPWM based inverter has the large voltage region of the precise sinusoidal phase voltage in the linear region. However, SVPWM based inverter also has voltage saturation for large quick speed and current reference. It often has some problems because of voltage saturation. For example, the settling time of the speed response becomes longer, and the current response doesn’t coincide with its reference.

A flux-weakening control has often been used to suppress voltage saturation (3)(7). However, the conventional flux-weakening control outputs excessive d-axis current reference in transient state. Because the conventional flux-weakening control is based on steady state motor voltage equation. This paper proposes a new flux-weakening control method with smaller d-axis current, which improves the transient response. It is achieved by using the current differential signal included transient state motor voltage equation. However, in the conventional and proposed flux-weakening control, the voltage utilization is low. Because, an inscribed circle of inverter voltage limitation hexagon is used as voltage restriction for flux-weakening control. In order to improve this problem, this paper proposes a new inverter modulation using the extended inverter voltage limitation circle.

Finally, this paper proposes a new combination method of flux-weakening control and inverter modulation scheme to improve the voltage utilization on condition of flux-weakening region.

The effectiveness of proposed method is confirmed by the numerical simulation results and the experimental results.

2. Suppression Method for Voltage Saturation by Conventional Flux-Weakening Control

2.1 Control Scheme When voltage saturation occurs, flux-weakening control is operated by using the d-axis current and suppresses the voltage saturation. If the voltage vector exceeds the inscribed circle of the inverter output limitation hexagon, voltage saturation occurs as shown in Fig. 1(a). In flux-weakening control, in order to keep the inverter voltage vector on the inscribed circle as shown in Fig. 1(b), the
inverter control system determines the desired d-axis current reference. The d-axis current reference is determined by an equation that is derived from the motor voltage equation. On d-q axes, SPMSM voltage equations are expressed as Eq. (1).

\[
\begin{bmatrix}
    v_d \\
    v_q
\end{bmatrix} = 
\begin{bmatrix}
    R_a + P L_a & -\omega L_a \\
    \omega L_a & R_a + P L_a
\end{bmatrix} \begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} + 
\begin{bmatrix}
    0 \\
    \omega_b \Phi_a
\end{bmatrix} \tag{1}
\]

where, \(v_d\): d-axis current, \(i_d\); q-axis current, \(v_q\): d-axis voltage, \(v_q\): q-axis voltage, \(\Phi_a\): linkage flux of permanent magnet, \(R_a\): winding resistance, \(L_a\): winding inductance, \(\omega_b\): electrical angular speed, \(P = d/dt\). The supplied motor voltage is restricted by the inverter output limitation. Eq. (2) shows the limitation of motor voltage.

\[
\frac{V_{DC}}{\sqrt{2}} \geq v_d^2 + v_q^2 \tag{2}
\]

\(V_{DC}\) is DC link voltage. The left side of Eq. (2) describes an inscribed circle of the inverter output limitation hexagon. Eq. (2) is transformed into Eq. (3) by substituting each axis voltage from Eq. (1). When the current differential terms in Eq. (3) are omitted, the simple voltage limitation equation is induced in Eq. (4). The d-axis current reference equation, that outputs d-axis current reference during voltage saturation period, is derived by solving Eq. (4) for \(i_d^*\). The equation determining the d-axis current reference is expressed as Eq. (5).

\[
\frac{V_{DC}}{\sqrt{2}} \geq \left( R_a i_d^* - \omega L_a i_q^* \right)^2 + \left( \omega_b \Phi_a \left( i_d^* + \Phi_a \right) \right)^2 \tag{4}
\]

\[
i_d^* = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{5}
\]

\[
A = R_a^2 + \omega_b^2 L_a^2
\]

\[
B = 2\omega_b^2 L_a \Phi_a
\]

\[
C = \Phi_a^2 (R_a^2 + \omega_b^2 L_a^2)
\]

\[
+ \omega_b \Phi_a (2R_a i_q^* + \omega_b \Phi_a) - \left( \frac{V_{DC}}{\sqrt{2}} \right)^2 \tag{3}
\]

\[2.2 \text{ System Structure} \]

Figure 3 shows the block diagram of PI controller considering output variable saturation, which is the anti-windup control. Where, \(K_p\): proportional gain, \(K_i\): integral gain, \(F(s)\): conditioning gain. The anti-windup control is not applied to the d-axis current controller.
Fig. 3. Block diagram of PI controller considering output variable saturation

because, when the voltage saturation value is fed back to the d-axis current controller, decoupling control is disturbed by the feedback at the control with \(i_d = 0\). However, d-axis current controller is compensated from voltage saturation, because flux-weakening control works as one kind of anti-windup control. The d-axis current reference is calculated by Eq. (5) using \(\omega_e\) and \(i^*_q\). On condition that the calculated value of \(i^*_q\) is negative, it is used as the d-axis current reference. Its upper limit of \(i^*_d\) is set as operating control with \(i_d = 0\) when the calculated value is positive. Additionally, the d-axis current is almost transformed into the power loss because the d-axis current does not contribute to the torque and the output in the SPMSM. Permanent magnets have a risk of permanent demagnetization due to heating. Thus, the flux-weakening control has a lower limiter of the rated value (−2.42 A) because of permanent demagnetization occurs when d-axis current becomes less than −2.42 A. The decoupling control is applied to the system. The q-axis current response \(i_q\), the d-axis current response \(i_d\) and the electrical angular speed \(\omega_e\) are used in the decoupling control.

2.3 Numerical Simulation Results Figure 4 shows the numerical simulation results on condition of \(i_d = 0\).

Figure 5 shows the numerical simulation results of the conventional method for the system shown in Fig. 2. In Fig. 4, voltage saturation occurs in the transient state. In this case, the q-axis current cannot track its reference, and the settling time of the speed response becomes longer than Fig. 5. In contrast, in Fig. 5, voltage saturation is suppressed by outputting the d-axis current and operating the flux-weakening control in the transient state. As a result of the suppressed voltage saturation, the q-axis current can track its reference, and a fast settling time of the speed response is obtained. The current vector includes the d-axis current component when flux-weakening control is operated. When the d-axis current occupy the current vector component, power factor is reduced. In the conventional method, flux-weakening control works to make a voltage vector move to on voltage restriction circle. As a result, maximum voltage vector is not used in voltage saturation region and voltage utilization is low.

3. New Flux-Weakening Control

3.1 Control Scheme On condition of the conventional flux-weakening control, excessive d-axis current reference is calculated. For a new flux-weakening control considering a current differential signal, it is possible to calculate the smaller d-axis current reference in a transient state. Eq. (6) is derived by considering q-axis current differential term in Eq. (3).

\[
\left(\frac{V_{DC}}{\sqrt{2}}\right)^2 = \left(R_di_d^* - \omega_e L_ai_q^*\right)^2 + \left[R_di_q^* + \frac{di_q^*}{dt} + \omega_e (L_ai_d^* + \Phi_a)\right]^2 \quad \cdots \cdots \quad (6)
\]
In Eq. (6), d-axis current differential term is omitted to prevent oscillation of calculated d-axis current reference. If d-axis current differential term is included in Eq. (6), large d-axis current reference is calculated in next sampling when d-axis current reference change largely. And, the amount of d-axis current reference change become zero when the d-axis current reference is restricted by d-axis current limiter. The d-axis current differential signal becomes zero and the calculated d-axis current reference becomes small. As a result of such calculations are done repeatedly, the d-axis current reference becomes oscillated. Eventually, flux-weakening control doesn’t not work properly. Therefore, d-axis current differential term is not included in Eq. (6). The d-axis current reference as shown in Eq. (7) is obtained by solving Eq. (6) for $i_d^*$:

$$\frac{di_d}{dt} = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{7}$$

$$A = R_d^2 + \omega_e L_d^2$$

$$B = 2\omega_e L_d \Phi_0$$

$$C = \frac{i_q^* (R_d^2 + \omega_e^2 L_d^2) + 2R_d L_d i_q^*}{\omega_e L_d} \frac{di_d}{dt} + \left( L_d \frac{di_d}{dt} \right)^2$$

$$+ \omega_e \Phi_0 \left( 2R_d i_q^* + \omega_e \Phi_0 + 2L_d \frac{di_d}{dt} \right) - \left( \frac{V_{DC}}{\sqrt{2}} \right)^2$$

$$\frac{di_d}{dt} = \frac{i_q^{(n-1)} - i_q^{(n-2)}}{T}$$

Where, T is sampling period.

### 3.2 System Structure

Figure 6 shows the block diagram having the d-axis current reference calculation considering the differential current signal. In the calculation of this method, $i_d^*$ is determined by using $i_q^*$, $\omega_e$ and q-axis current differential signal $di_q^*/dt$. However, the $i_d^*$ often has the noisy value because of the current differential signal. Hence, $i_d^*$ often oscillates because of the noisy value of $i_d^*$. Moreover, the voltage saturation occurs by the oscillated current response. In this method, a moving average filter is used for $i_d^*$ to suppress the oscillation phenomenon. The system structure is the same in Fig. 2, except the part of the d-axis current reference calculation.

### 3.3 Numerical Simulation Results

Figure 7 shows the numerical simulation results of a new flux-weakening control considering a current differential signal. As a result of operating flux-weakening control, voltage saturation is suppressed, the q-axis current response tracks its reference and a settling time of the speed response is faster than the control with $i_d = 0$ (Fig. 4). Moreover, this method considering the differential signal suppresses voltage saturation with a smaller d-axis current in comparison with the conventional method omitting a current differential signal.

### 4. Proposed Combination Method of Inverter Voltage Utilization on Flux-Weakening Control

In the conventional flux-weakening control, voltage restriction is set to an inscribed circle of the inverter voltage limitation. Therefore, the flux-weakening control makes voltage vector move on the inscribed circle. As a result, inverter voltage utilization becomes low on flux-weakening control. This paper finally proposes a new combination method of inverter voltage utilization on flux-weakening control. It is achieved by combine a flux-weakening control and inverter modulation scheme.

#### 4.1 Control Scheme

In the proposed combination method, voltage restriction is expanded as shown in Fig. 8. However, voltage saturation region exist because of expanding voltage restriction circle. In the proposed combination method, priority amplitude method (13) is used as inverter modulation scheme on voltage saturation region. Voltage restriction circle is set as saturation phase occupy half of the restriction circle. Voltage restriction circle is expressed in Eq. (8) by using cyclotomic equation and one side of voltage limitation hexagon is expressed in Eq. (9) as linear equation.

$$x^2 + y^2 = \frac{V_{DC} M}{\sqrt{2}} \tag{8}$$

$$y = -\sqrt{3}x + \sqrt{2}V_{DC} \tag{9}$$

Where, M is a ratio of voltage restriction circle based on inscribed circle. Intersections of voltage restriction circle and one side of hexagon are expressed as Eqs. (10)–(13).

$$x_1 = \frac{\sqrt{6} + \sqrt{2(M^2 - 1)}}{4} V_{DC} \tag{10}$$
Angles $\theta_1$, $\theta_2$ are expressed as Eq. (14) and Eq. (15).

$$
\theta_1 = \tan^{-1}\left(\frac{y_1}{x_1}\right) \quad (14)
$$

$$
\theta_2 = \tan^{-1}\left(\frac{y_2}{x_2}\right) \quad (15)
$$

$\theta_{sat}$ is expressed as (16). $M$ is decided as $\theta_{sat}$ is equal to 30°. Here, $M$ is equal to 1.03.

$$
\theta_{sat} = \theta_2 - \theta_1 \quad (16)
$$

4.2 Numerical Simulation Results

Figure 9 shows the Numerical simulation results of the proposed combination method of inverter voltage utilization on flux-weakening control. In these results, voltage saturation occurs due to expanding voltage restriction. However, speed response is improved because of combining with priority amplitude method. In addition, d-axis current is reduced due to improving voltage utilization and including differential signal. In the proposed method, d-axis current is reduced in voltage saturation region. The power factor is maintained high value. The voltage utilization is also improved due to expanding voltage restriction. Table 1 shows THD of the three phase current in steady state (0.2–0.25 s). The THD are almost same value in each method. Therefore, there is no negative effect by implementing the proposed method in steady state. Figure 10 shows a speed servo system considering the new combination method.

5. Experimental Results

Table 2 shows the detail description of experimental equipment. Table 3 summarizes the specification of the tested motor. The experiment is applied a speed step reference of 1500 min⁻¹, which is not in the voltage saturation region, to 3000 min⁻¹, which is in the voltage saturation region.

Figure 11 shows the experimental results of the control with $i_d = 0$ and Fig. 12 shows the experimental results of the conventional flux-weakening control, respectively. In Fig. 11, the large voltage saturation occurs in a transient state. $i_q$ cannot track its reference, and the settling time of the speed response becomes long because of the voltage saturation. This settling time is 125 ms. In Fig. 12, the voltage saturation is suppressed by using $i_d$. In the conventional control system, the q-axis current response tracks its reference. It has the fast settling time 108 ms. Compared with the simulation results, voltage saturation slightly occurs around 0.12 s in Fig. 12. The reason is thought to be a reduction in the DC link voltage due to flowing large current and the DC link capacitor discharging when the motor is accelerated.

Figure 13 shows the experimental results of a new flux-weakening control considering a current differential signal. In Fig. 13, voltage saturation is suppressed with smaller d-axis current in comparison with Fig. 12. This method makes 27% reduction of d-axis power loss because of d-axis current reduction. Its settling time of the speed response is 110 ms,
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**Table 2.** Detail of experimental equipment

<table>
<thead>
<tr>
<th>DSP type</th>
<th>PE-Expert3/MyWay Plus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling period (kHz)</td>
<td>10</td>
</tr>
<tr>
<td>Current control bandwidth</td>
<td>6280 rad/sec</td>
</tr>
<tr>
<td>Speed control bandwidth</td>
<td>2000 rad/sec</td>
</tr>
<tr>
<td>Order of the moving average filter</td>
<td>4</td>
</tr>
</tbody>
</table>

**Table 3.** Rated values of tested PMSM

| Rated power (W) | 200 |
| Rated speed (min⁻¹) | 3000 |
| Rated torque (Nm)   | 0.64 |
| Pole pair          | 4   |
| Rated q-axis current (A) | 2.42 |

**Fig. 10.** Total block diagram of speed servo system considering the new combination method

**Fig. 11.** Experimental results of speed step response with voltage saturation on condition of $i_d = 0$ which is similar to that of conventional method.

**Fig. 12.** Experimental results of speed step response with voltage saturation on condition of conventional method

which is similar to that of conventional method.

Figure 14 shows the experimental results of proposed combination method flux-weakening control and inverter modulation scheme. In these results, voltage saturation occurs due to expanding voltage restriction. However speed response is improved because of combining with priority amplitude method and the speed response reaches its reference in 110 ms. Furthermore, d-axis current is reduced due to improving voltage utilization and including differential signal. The d-axis current amplitude is reduced to 0.63 A and the d-axis power loss is reduced by 62%.

Figure 15, Fig. 17 shows the experimental results of the conventional flux-weakening control and Fig. 16, Fig. 18 shows the experimental results of proposed combination method flux-weakening control and inverter modulation scheme, under 25% and 75% load conditions. In these results, d-axis current amplitude is reduced and its settling time...
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Fig. 13. Experimental results of speed step response with voltage saturation on condition of a new flux-weakening control

Fig. 14. Experimental results of speed step response with voltage saturation on condition of proposed combination method with a new flux-weakening control and inverter modulation scheme

Table 4 shows the comparison of settling time of the rotor speed, d-axis power loss and d-axis current amplitude by each method.

Fig. 15. Experimental results of speed step response with voltage saturation on condition of conventional method (under 25% load condition)

Fig. 16. Experimental results of speed step response with voltage saturation on condition of proposed combination method with a new flux-weakening control and inverter modulation scheme (under 25% load condition)
current differential signal is proposed, which improves the transient response. It is possible to suppress voltage saturation with a smaller $i_d$ in the proposed flux-weakening control. It is confirmed that the proposed flux-weakening control achieve good responses according to the numerical simulation and experiment. However, the voltage utilization is low in the conventional and proposed flux-weakening control. Therefore, this paper proposes the combination method of flux-weakening control and inverter modulation scheme. The method reduce d-axis current for flux-weakening control by improving inverter voltage utilization. The proposed combination method makes 0.63 A reduction of d-axis current amplitude under no load condition.

### References

Appendix

App. Fig. 1 shows voltage lissajous diagrams of each method. On the condition of conventional flux-weakening control as shown in app. Fig. 1(a), the lissajous diagram forms an inscribed circle of inverter voltage limitation hexagon. On the condition of a new flux-weakening control with differential signal as shown in app. Fig. 1(b), the lissajous diagram is similar to an inscribed circle. In contrast, on the condition of a proposed combination method as shown in app. Fig. 1(c), the lissajous diagram forms inverter voltage limitation hexagon and it is confirmed that inverter voltage utilization is improved.

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