Maximum Torque Control of an Induction Machine in the Field Weakening Region

Sang-Hoon Kim, Seung-Ki Sul, Min-Ho Park
Dept. of Electrical Engineering
Seoul National University
Shilim-Dong Kwang-Ku Seoul Korea, 151-742
TEL : Korea)-2-880-7243 FAX : Korea)-2-871-5974

Abstract - In this paper, a new approach for the induction machine control which ensures producing maximum torque per ampere over the entire field weakening region is presented. In addition, the relation of the output torque capability with the leakage inductance of the machine is examined. Also by adjusting the base speed for the field weakening operation according to the flux level, the current limit and the voltage limit, the smooth and precise transition into the field weakening operation can be achieved. The proposed scheme is verified through simulation and experiment for a 5 hp laboratory induction motor drive system.

1. Introduction

The availability of the constant power operation is very important in applications such as spindle, traction and electric vehicle drives. The field-oriented induction machine drive is a desirable candidate for such applications because the field of the induction machine can be easily weakened by reducing the flux component current as the rotor speed increases[1]. The maximum output torque developed by the machine is dependent on the allowable inverter current rating and the maximum voltage which the inverter can apply to the machine[2]. Therefore, considering the limited voltage and current capacities, it is desirable to use the control scheme which yields the maximum torque per ampere over the entire speed range.

In general, the voltage rating of the machine equals that of the inverter, while the current rating of the inverter is usually 150~200% of the machine to provide higher acceleration torque during transient. In this paper, it is assumed that the inverter current rating, in other word, the current limit of the drive system is 1.5 times rated current of the machine and that the voltage limit is the rated voltage of the machine.

In high speed range, the output torque capability of the induction machine quite depends on the field weakening strategy. The conventional method for the field weakening is to vary the rotor flux reference in proportion to the inverse of the rotor speed \( \psi_r \)[3]. In this method, because the reference flux is too high, the voltage margin enough to regulate current is not maintained. As a result, by the '1/\( \psi_r \)' method the torque capability of the machine can't be maximized within given limited conditions. Recently, Xu, et al. derived the rotor flux reference for the maximum torque from the stator flux limit[4]. However, by this method, there exist some speed ranges where the maximum torque can't be obtained.

This paper presents a novel field weakening approach for the induction machine drive system which ensures the maximum torque operation over the entire high speed range under the voltage limit and the current limit. In addition, the relation of the output torque capability with the leakage inductance of the machine is examined. Also, the base speed for the transition into the field weakening operation is adjusted according to the flux level, the current limit and the voltage limit. As a result, the smooth and precise transition into the field weakening operation can be possible.

The output torque capability of the proposed scheme is compared with that of the '1/\( \psi_r \)' method. The whole control algorithm with the proposed scheme is fully implemented in the digital control system based on a TMS320C30 DSP.

II. The voltage limit and the current limit

The condition of \( i_{d}^* \) and \( i_{q}^* \) in order to satisfy the given voltage and current limits, can be determined as follows.

A. Voltage limit

The steady-state equations of the rotor flux-oriented induction machine in the synchronous frame are given as[5]

\[
V_{d}^* = R_{i}i_{d}^* + \omega_{s}L_{i}i_{q}^* \\
V_{q}^* = R_{i}i_{q}^* - \omega_{s}L_{i}i_{d}^* \\
T_{e} = \frac{3}{2} \frac{P}{2} \frac{L_{i}}{L_{s}} i_{d}^* i_{q}^* \tag{3}
\]

where, \( V_{d}^* \), \( V_{q}^* \) : \( d \)- and \( q \)-axis stator voltages
\( i_{d}^* \), \( i_{q}^* \) : \( d \)- and \( q \)-axis stator currents
\( \omega_{s} \) : excitation angular frequency
\( L_{i} = L_{s} - \frac{L_{i}^{2}}{L_{s}} \) : stator transient inductance
The maximum stator voltage, $V_{\text{max}}$, is determined by the available DC link voltage and the PWM strategy. The $V_{\text{m}}$ and $V_{\text{d}}$ should satisfy the following equation.

$$V_{\text{m}}^2 + V_{\text{d}}^2 \leq V_{\text{max}}^2 \quad (4)$$

In this paper, the PWM strategy based on the voltage space vector is used, and then $V_{\text{max}}$ is $V_{\text{dc}}\sqrt{3}$ [6]. For high speed operation, the stator resistance effect is negligible in above (1) and (2). Then, the maximum limit for the steady-state currents $i_{\text{d}}$ and $i_{\text{q}}$ available from $V_{\text{max}}$ can be obtained by combining (1), (2) and (4) as

$$(u_s L_{d} i_{\text{d}})^2 + (u_s L_{q} i_{\text{q}})^2 \leq V_{\text{max}}^2 \quad (5)$$

Eq. (5) means the voltage-limit boundary that sets the limit of controllable currents $i_{\text{d}}$ and $i_{\text{q}}$ under given voltage limit and speed. Eq. (5) can be also expressed as

$$\frac{i_{\text{d}}^2}{a^2} + \frac{i_{\text{q}}^2}{b^2} \leq 1 \quad (6)$$

where, $a = \frac{V_{\text{max}}}{u_s L_{d}}$ and $b = \frac{V_{\text{max}}}{u_s L_{q}}$.

Eq. (6) means the ellipse, of which the radii become small as the rotor speed increases. In general, the shape of the ellipse is determined by the eccentricity $e$. The eccentricity $e$ of (6) is defined as follows

$$e = \frac{\sqrt{b^2 - a^2}}{b} = \sqrt{1 - \frac{L_{q}^2}{L_{d}}} \quad (7)$$

The shape of the voltage-limit ellipse depends on the eccentricity $e$, that is, the leakage inductance of the machine at a given speed. Fig. 1(a) and (b) show the voltage-limit ellipses in the $d^*-q^*$ axis current plane for several speeds.

Fig. 1. Voltage-limit ellipse and current-limit circle
(a) In case of large leakage inductance
(b) In case of small leakage inductance

For satisfying the voltage-limit constraint (5), the current reference vector $i_{\text{d}}^*$ (comprising $i_{\text{d}}^*$ and $i_{\text{q}}^*$) should remain inside the ellipse for each speed. The inside area of ellipse is different according to the speed and the leakage inductance. That is, the area of the controllable reference current varies. As a result, the maximum torque is not a negligible factor in the voltage limit.

B. Current limit

The maximum stator current $I_{\text{max}}$ is limited by the inverter current rating and the machine thermal rating. The $i_{\text{d}}$ and $i_{\text{q}}$ should satisfy $I_{\text{max}}$ as below

$$i_{\text{d}}^2 + i_{\text{q}}^2 \leq I_{\text{max}}^2 \quad (8)$$

Eq. (8) represents a circle that means the boundary of the controllable reference current at given current limit, $I_{\text{max}}$. For satisfying the constraint of (8), the reference currents $i_{\text{d}}^*$ and $i_{\text{q}}^*$ must be inside of this circle. The current-limit circle is kept constant regardless of the speed, whereas the voltage-limit ellipse becomes small as the rotor speed increases, as shown in Fig. 1.

III. Optimal control for the maximum torque capability in the field weakening region

A. The conventional method ('1/1/r' law)

For the field weakening operation, a commonly used method is to vary the rotor flux reference in proportion to $1/\nu_r$. Usually, the $d$-axis reference current $i_{\text{d}}^*$ is decreased in order to reduce the rotor flux. And the $q$-axis reference current $i_{\text{q}}^*$ is increased according to the decrease of the $d$-axis reference current to use the current rating fully. In such case, $i_{\text{d}}$ and $i_{\text{q}}$ are related with $I_{\text{max}}$ as follows

$$i_{\text{d}}^* = \frac{I_{\text{max}}}{\nu_r} \quad (9)$$

$$i_{\text{q}}^* = \frac{\sqrt{i_{\text{d}}^2 - i_{\text{d}}^2}}{\nu_r} \quad (10)$$

where, $I_{\text{max}}$ is the rated $d$-axis current. By combining (9) and (10), the relation of $i_{\text{d}}^*$ and $i_{\text{q}}^*$ is also given as

$$\left(\frac{I_{\text{max}}}{\nu_r}\right)^2 + i_{\text{q}}^* = I_{\text{max}}^2 \quad (11)$$

Eq. (11) describes that when the rotor flux is reduced according to $1/\nu_r$, the trajectory of the reference current vector...
increases. Therefore, the voltage limit is not considered in this method. As a result, the voltage margin enough to regulate the current reference can't be maintained. Fig. 2 shows that at a specific speed, the current reference vector \( \mathbf{i}_{\text{ref}} \) becomes A point from (11).

![Fig. 2. Current reference vector in \( 1/\omega_r \) method](image)

(a) In case of large leakage inductance
(b) In case of small leakage inductance

The point A satisfies the current-limit constraint (8). But since it is located at outside of the ellipse, the voltage-limit constraint (5) is not satisfied. Consequently, the resultant current vector \( \mathbf{i}_{\text{rms}} \) is forced to diverge from the reference current vector \( \mathbf{i}_{\text{rms}} \) in order to remain within the voltage-limit ellipse. In the long run, the resultant current vector \( \mathbf{i}_{\text{rms}} \) moves to point B as shown in Fig. 2. As a result, the developed torque is dropped below the desired value. This phenomenon is dependant on the leakage inductance. In case of small eccentricity \( e \), that is, large leakage inductance, since the current reference vector is extended further outside the ellipse, this phenomenon is obvious as shown in Fig. 2(a). On the other hand, Fig. 2(b) shows that in case of large eccentricity \( e \), that is, small leakage inductance, this phenomenon is somewhat obscure. However in the very high speed region, this phenomenon is more obvious regardless of the leakage inductance. As a result, the regulation of the current is no longer possible.

B. The proposed scheme for the maximum torque capability

As stated above, in the \( 1/\omega_r \) method, the maximum output torque can't be obtained because only the current limit is considered. Therefore, considering both the current limit and the voltage limit, this paper presents a method such that the output torque is maximized for each rotor speed. The optimal current vector for the maximum torque can be determined as follows.

To satisfy both the voltage-limit constraint (5) and the current-limit constraint (8), the current reference vector \( \mathbf{i}_{\text{rms}} \) must remain inside the common area of the voltage-limit ellipse and the current-limit circle for a given speed (hatching area in Fig. 3). There are numerous combinations of \( \mathbf{i}_{\text{rms}} \) and \( \mathbf{i}_{\text{rms}} \) in meeting this requirement. Among these, a combination to maximize the following function \( F \) becomes a optimal combination for maximizing the output torque. The function \( F \) is defined from (3) as below:

\[
F = \frac{P_L}{k_1} = \mathbf{i}_{\text{rms}} \cdot \mathbf{i}_{\text{rms}}
\]

where, \( k_1 = \frac{3}{2} \frac{P}{2} \frac{i_{\text{rms}}}{L} \).

![Fig. 3. Current reference in proposed scheme](image)

These optimal currents can be determined from (5), (8) and (12) as follows.

The whole field-weakening region can be divided into two subregion. In each subregion, the output torque is affected by the voltage limit \( \alpha \) and the current limit. Thus the optimal current condition for yielding the maximum torque is different in each subregion.

Field-weakening region 1 \( (\alpha_{\text{mmin}} \leq \omega_r \leq \alpha_1) \)

From Fig. 3, it is not difficult to prove that in the hatching area, the optimal current vector maximizing the function \( F \) becomes C point. Thus, the optimal current vector \( \mathbf{i}_{\text{rms}} \) becomes the value at the intersection of the current-limit circle and the voltage-limit ellipse at a given speed. The \( F_1 \) at point C is larger than \( F_2 \) at point B that indicates the current vector by the \( 1/\omega_r \) method. Therefore, it is clear that by \( 1/\omega_r \) method, the maximum torque can't be obtained.

The optimal currents are derived from (5), (8) and (12) as
The trajectory of the optimal current vector for the maximum torque moves along the current-limit boundary as the speed increases.

The base speed \( \omega_{\text{base}} \) for transition into the field weakening region is an important factor to be determined. This speed is usually determined according to flux level. However, since the onset of current regulator saturation is varied according to the allowable current and voltage limits as well as flux level, the base speed \( \omega_{\text{base}} \) must be adjusted. If not, the undesired output torque drop results. The adjusted base speed is derived from (5) as

\[
i_{*} = \sqrt{\frac{(V_{\text{max}}/\omega)^2 - (L_{s} I_{\text{max}})^2}{L_{s}^2 - L_{i}^2}}
\]

The trajectory of the optimal current vector for maximum torque moves along under the voltage-limit constraint as shown in Fig. 4.

\[
i_{*} = \frac{V_{\text{max}}}{\sqrt{2} \omega_{i} L_{r}}
\]

\[
i_{*}^e = \frac{V_{\text{max}}}{\sqrt{2} \omega_{i} L_{r}}
\]

The range of each subregion is very different according to the eccentricity \( e \). In case of the machines with small leakage inductance, the eccentricity \( e \) is large. The eccentricity \( e \) and leakage inductance of the machine A in Table I are 0.9982 and 1.78mH, respectively. In such case, \( \omega_{\text{base}} \) and \( \omega_1 \) are 1663 and 638[rpm], respectively. This machine is the case of machine with large eccentricity. Thus the field-weakening region I is dominant, the speed range of which is extended over almost 3.65 times rated speed. Therefore for yielding maximum torque over the entire high speed region, both the current limit and the voltage limit are important factors to be considered. To the contrary, in case of the machine B in Table II., the eccentricity \( e \) and leakage inductance are 0.9944 and 3.5mH, respectively. And \( \omega_{\text{base}}, \omega_1 \) are 1704, 4290 [rpm], respectively. Thus the machine B corresponds to the case of machine with large leakage inductance and the field-weakening region I is reduced by almost half of the machine A.

IV. Control system Implementation

Fig. 5 shows a block diagram of the proposed scheme applied to an induction machine drive system. The whole system consists of speed regulator, flux regulator, current regulator and indirect rotor flux-oriented controller. The synchronous PI regulator with the voltage space vector PWM is adopted as a current regulation scheme(7). And the feedforward compensation is added in order to decouple the d-q axes interaction(5).
In the flux regulation, the rotor flux reference \( \lambda^* \) is given as (20) from the calculated \( i^*_r \) in each region.

\[
\lambda^* = L_m i^*_r
\]

And the rotor flux is estimated from the terminal quantities \[8\]. The rotor flux estimator can be described by the following equations:

\[
i_r = \int (v_s - r_s i_s) \, dt \quad (21)
\]

\[
i_e = \frac{1}{L_m} (i_r - L_m i_s) \quad (22)
\]

where, \( i_r \) is the estimated stator flux vector,

\( i_e \) is the estimated rotor flux vector,

quantities with \( \bar{\cdot} \) mean estimated quantities.

In practice the original voltage model of (21) is difficult to implement because it requires a pure integrator, which has the initial value and drift problems. To avoid these problems, the pure integrator is replaced by the low pass filter and it produces good performance in high speed region\[8\].

V. Simulation and experimental results

A 5kHz IGBT inverter-fed 5hp induction motor drive system was used in the test. The whole control algorithm was fully implemented in software with a digital signal processor(DSP) TMS320C30. The 5hp induction machine listed in Table I as type 'A' was used in the test and simulation.

Fig. 6(a) and 6(b) show simulation results of the reference flux and the torque capability. According to expectation, the reference flux of the \( 1/\alpha \) method is higher than optimal one. As the result, the voltage margin for the current regulation becomes small as the speed increases. Therefore, the output torque capability is reduced. From the comparison of the torque capability, it is apparent that the proposed method provides significantly improved torque production compared with the \( 1/\alpha \) method. The maximum absolute difference of output torque is 3.1 Nt-m(0.15pu). The measured result to verify simulation result is shown in Fig. 7.

Fig. 8(a) and (b) show the output torque characteristics when the machine was accelerated from stall to 4000rpm using \( \omega_{bmax} \) of (15). In \( 1/\alpha \) method, the loss of field orientation results from the failure of accurate current regulation owing to insufficient voltage margin. This results in an oscillating torque at near final velocity as shown in Fig. 8(b). Therefore, to maintain the necessary voltage margin, the flux reference has to be reduced. For this purpose, the base speed is selected at 1480rpm. In such case, at the low speeds, the flux reference will be less than the optimal value, yielding less output torque. Thus, to reach the same speed of the case of Fig. 8(a), more acceleration time is required as shown in Fig. 8(c).

Fig. 9(a) and (b) show the output torque near the onset point of the field weakening. It is seen that the detuning base speed results in the dropping of the output torque. Fig. 9(a) is the case of using the rated speed as base speed and (b) is the case of using the adjusted base speed 1663rpm of (15). Fig. 9(b) shows that, compared with Fig. 9(a), the smooth and
Fig. 8. Output torque characteristic during transient
(a) proposed scheme
(b) 1/ωr method
(c) 1/ωr method (using 1400[rpm] as base speed)

Fig. 9. Detuning effect of base speed
(a) Using rated base speed
(b) Using adjusted base speed

precise transition into field weakening operation can be obtained without dropping the output torque. Fig. 10 (a) and (b) is the experimental result of transient response of the torque as the speed changes from 1500 to 3700[rpm]. It is seen that the drive system by using the 1/ωr method requires more acceleration time to achieve the same speed than by the proposed scheme. This result presents that the 1/ωr method yields less output torque than the proposed method.

Fig. 10. Transient response of the torque
(a) proposed scheme
(b) 1/ωr method

VI. Conclusion

For the field weakening, a commonly used method is to vary the rotor flux reference in proportion to 1/ωr. However in this method, because only the current limit is considered, the maximum torque capability of drive system can’t be fully used.

In this paper, under the voltage limit and the current limit, a new field weakening scheme to maintain the maximum torque capability of an induction machine over the entire high speed range is presented. In addition, it is examined that the output torque capability depends on the leakage inductance of the machine. Also, by using the adjusted base speed for the field weakening operation, the smooth and precise transition into field weakening operation can be obtained.

The proposed scheme is compared with the 1/ωr method through simulations and experiments. And it is verified that the proposed method provides the improved torque capability over the conventional field weakening one.

Table I.
Rating and parameters of induction machine A

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<tr>
<td>Shp. 200V, 4poles 60Hz</td>
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<tr>
<td>Rr : 0.265Ω</td>
<td>Rr : 0.378Ω</td>
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<tr>
<td>Lk : 1.8mH</td>
<td>Lk : 1.8mH</td>
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<td>Lm : 59mH</td>
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Table II
Rating and parameters of induction machine B

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<th>Parameter</th>
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<tr>
<td>$R_s$</td>
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<td>$R_r$</td>
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<tr>
<td>$L_m$</td>
<td>3.5mH</td>
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<tr>
<td>$L_2$</td>
<td>3.5mH</td>
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<tr>
<td>$L_m$</td>
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References

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