Control Mode Switching of Induction Machine Drives between Vector Control and $V/f$ Control in Overmodulation Range

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Abstract

This paper proposes a control mode switching scheme between vector control and constant $V/f$ control for induction machine (IM) drives for maximum torque utilization in a higher speed region. For the constant $V/f$ scheme, a smooth transition method from the linear range of PWM up to the six-step mode is applied, by which the machine flux and torque can be kept constant in a high-speed range. Also, a careful consideration of the initial phase angle of the voltage in the transient state of the control mode change between the vector control and $V/f$ schemes is described. The validity of the proposed strategy is verified by the experiment result for a 3-kW induction motor drives.

Key Words: Induction machine drives, Overmodulation, $V/f$, Vector control

I. INTRODUCTION

Recently, variable-speed machine drive applications have come to play an important role in industry. The induction machine fed by a three-phase voltage-source inverter (VSI) with a front-end diode rectifier, shown in Fig. 1, is often used for these applications due to its high performance, low cost, and low maintenance requirements [1]–[3]. In high-performance machine drive systems, fast torque control is an essential requirement. A vector control employing a fast current control of induction machines is usually used for these applications. The role of the current controllers is to generate a voltage reference for the inverter modulation, which makes the machine currents follow a command value. However, the vector control applied to the machine drive system, shown in Fig. 1, with a fixed DC-link voltage, $V_{dc}$, has drawbacks due to the input voltage limitations of the DC-link voltage. The maximum output voltage, $V_{max}$ of a space vector PWM (SVPWM) inverter is $V_{dc}/\sqrt{3}$ [4], [5]. When a machine operates in high speed ranges, the induced back-electromotive force (EMF) of the induction machine may exceed the limitation of the stator voltage. Hence, the machine output torque capability is reduced since the magnetic flux is decreased in the field weakening region [6]–[9].

To improve machine torque capability, the full voltage utilization of the PWM VSI by applying overmodulation techniques has been presented [4], [5], [10], [11], in which the operating range of the PWM inverter can be extended from a modulation index (MI) of 0.906 up to the six-step mode. The maximum output voltage can be increased up to $2V_{dc}/\pi$ [2], [3]. For overmodulation operation, the reference voltage vector is boosted beyond the inscribed circle of the hexagon, which causes the motor current to be distorted [4], [5], [12]. Hence, the performance of vector control-based machine drives in the overmodulation range is deteriorated since the harmonic components of the machine current severely deteriorate the current control performance.

Several previous studies have been presented to improve the performance of current controllers in overmodulation operation. A control algorithm which compensates for the effect of the harmonic components in feedback current has been introduced, where a first-order model is used to estimate the harmonic components [12]. This method offers good performance for vector control in the overmodulation range up to the six-step mode. Also, other studies have been presented...
in which SVPWM based on the stator flux is used considering the flux error. The torque control in the OVM is satisfactory in the transient state as well as in the steady state. However, these methods are dependent on the machine parameters for estimating the harmonic currents and the magnetic flux.

On the other hand, constant V/f control methods for induction machine drives have been used in the overmodulation range for high speed operation [5], [16]. By increasing the output voltage limit of the PWM inverter, the machine flux can be kept constant, even when the machine speed increases higher than the based speed, \( \omega_{\text{base}} \), which is decided from the voltage and the current constraints of the PWM inverter. Hence, the machine can provide maximum torque during OVM operation.

In this paper, a new method which combines the vector control and the constant V/f scheme is proposed for the wide speed range operation of induction machines. The vector control is applied in a speed range lower than \( \omega_{\text{base}} \), where it provides good performance of the current and torque control. On the other hand, the operation mode of an induction machine drive is changed to the constant V/f control with a slip regulator if the machine speed increases higher than \( \omega_{\text{base}} \), where the PWM inverter operates in the OVM range. Hence, the constant V/f scheme is able to keep the machine flux constant up to the six-step output voltage and to provide maximum torque capability in high-speed range operation. The phase angle of the output voltage is adjusted to be consistent in the transient state when the control mode changes between the vector control and the constant V/f method. The slip regulator in the speed control loop improves the speed oscillation under load variation and supply voltage fluctuation conditions. The validity of the proposed control scheme has been proven through experimental results with 3-kW induction motor drives.

II. OVERMODULATION METHOD

The maximum output voltage of a PWM inverter is obtained at the six-step operation in which the fundamental voltage component is \( 2V_{\text{dc}}/\pi \). In SVPWM, the three-phase voltage reference is given as a voltage reference vector \( V_{\text{ref}} \). The modulation index is defined as the ratio of the peak value of the fundamental of the modulated output voltage to that in six-step mode operation, which is expressed as:

\[
MI = \frac{V_{\text{ref}}}{(2/\pi)V_{\text{dc}}} \tag{1}
\]

where \( V_{\text{ref}} \) is the magnitude of the phase voltage reference and \( V_{\text{dc}} \) is the inverter input voltage.

In the linear control range of the SVPWM inverter, the maximum value of the fundamental component is \( V_{\text{dc}}/\sqrt{3} \), in which the modulation index is 0.906. The overmodulation range refers to the operation regions of the pulse-width modulator beyond the linear range, which is the inscribed circle of the hexagon with a radius of \( V_{\text{dc}}/\sqrt{3} \). According to the modulation index, the PWM range is divided into three regions, as shown in Fig. 2 and described in detail in [5].

A. Linear Modulation \((0 \leq MI \leq 0.906)\)

If the magnitude of the voltage reference vector is lower than \( V_{\text{dc}}/\sqrt{3} \) (MI0.906), the space-vector modulator produces sinusoidal output voltages. The space voltage vectors consist of the six effective vectors and the two zero vectors, which are shown in Fig. 2. If \( V_{\text{ref}} \) is located in sector I, the effective vectors \( V_1, V_2 \) and the zero vector \( V_0 \) are used to determine the switching pulse durations. It is similar when \( V_{\text{ref}} \) is in the other sectors. The voltage reference vectors, their phase angles, and their switching times are described in detail in [5].

B. Overmodulation Zone I \((0.906 < MI \leq 0.952)\)

In zone I of the overmodulation range, the trajectory of the reference voltage vectors is partly outside the hexagon. As a result, the PWM inverter is not able to generate the desired fundamental voltage reference. Hence, the magnitude of the compensated voltage is boosted to produce the desired fundamental voltage reference. The modified voltage reference vector is derived from the reference voltage vector by changing the magnitude of the reference voltage vector only, while the angle is kept at the uniform angular velocity.

The new reference voltage vector is shown in Fig. 3, the details of which have been described in [5].
C. Overmodulation Zone II ($0.952 < MI \leq 1$)

To increase the MI further, an actual voltage reference vector is kept at the vertex of the hexagon for a particular time and a change in the angle of the modified reference vector is required. Hence, its angular velocity is changed discontinuously, as seen in Fig. 4, the details of which have been described in [5]. When the modulation index increases to 1, the modulator operates in the six-step mode.

III. MODELING AND CONTROL OF INDUCTION MACHINES

A. Modeling of Induction Machines

The d-q voltage equations expressed in the stationary reference frame are written as [17]-[18]:

$$
\begin{align*}
V_d^s &= R_s i_{ds} + \frac{d}{dt} \lambda_d^s + L_{ds} i_{ds} \\
V_q^s &= R_s i_{qs} + \frac{d}{dt} \lambda_q^s + L_{qs} i_{qs} \\
0 &= R_s i_{ds} + \frac{d}{dt} \lambda_d^s + \omega_s \lambda_{qr} \\
0 &= R_s i_{qs} + \frac{d}{dt} \lambda_q^s + \omega_s \lambda_{dr}
\end{align*}
$$

(2)

where $V_d^s$, $V_q^s$, $i_{ds}$, and $i_{qs}$ are the $dq$-axis stator voltage and current components, respectively, $R_s$ and $R_r$ are the stator and rotor resistances, respectively, $\omega_s$ is the rotor speed, and $\lambda_d^s$, $\lambda_q^s$, $\lambda_{dr}$, and $\lambda_{qr}$ are the $dq$-axis stator and rotor fluxes, respectively. The stator and rotor fluxes are expressed as:

$$
\begin{align*}
\lambda_d^s &= L_s i_{ds}^s + L_{m} i_{ds} \\
\lambda_q^s &= L_s i_{qs} + L_{m} i_{qs} \\
\lambda_d^r &= L_r i_{dr} + L_{m} i_{dr} \\
\lambda_q^r &= L_r i_{qr} + L_{m} i_{qr}
\end{align*}
$$

(3)

where $L_s=L_{sl}+L_m$ and $L_r=L_{rl}+L_m$, where $L_{sl}$ and $L_{rl}$ are the stator and rotor leakage inductances, $L_m$ is the magnetizing inductance, and $i_{ds}^s$ and $i_{qs}^s$ are the $dq$-axis rotor current components, respectively.

The machine torque, $T_e$, can be expressed from the rotor flux linkage and the stator current as:

$$
T_e = \frac{3}{2} P \frac{L_m}{L_r} (\lambda_{dr} i_{qs}^* - \lambda_{qr} i_{ds}^*)
$$

(4)

where $P$ is the number of poles.

B. Vector Control Method

By applying the rotor flux-oriented control ($\lambda_{qr} = 0$), the rotor flux linkage exists on the d-axis only. Hence, the magnitude of the rotor flux, $\lambda_{r-mag}$, can be expressed as:

$$
\lambda_{r-mag} = \lambda_{dr} = L_m i_{ds}
$$

(5)

where $\lambda_{dr}$, $\lambda_{qr}$ and $i_{ds}$ are the $dq$-axis components of the rotor flux and stator current expressed in synchronous rotating reference frame.

The machine torque can be rewritten as:

$$
T_e = \frac{3}{2} P \frac{L_m}{L_r} L_{dr} i_{qs}
$$

(6)

where $i_{qs}$ is the q-axis stator current in the synchronous $d$-q reference frame.

Therefore, it can be seen from (5) and (6) that the rotor flux linkage can be adjusted by controlling the $d$-axis stator current, and that the machine torque can be controlled by regulating the q-axis stator current.

A control block diagram of the vector control method using synchronous $d$-$q$ current regulators is shown in Fig. 5. The feed-forward terms, $V_{df}^f$ and $V_{qf}^f$, in Fig. 5, for the decoupling control can be expressed as:

$$
\begin{align*}
V_{df}^f &= -\omega_s \sigma L_m i_{qs} \\
V_{qf}^f &= \omega_s L_r i_{ds}
\end{align*}
$$

where $\omega_s$ is the synchronous angular frequency, $\sigma = 1 - \frac{L_m^2}{L_r L_s}$ is the leakage factor.

C. Flux Weakening Control

In a PWM inverter with a front-end diode rectifier, the DC-link voltage is constant. Hence, the vector control of the induction machine is no longer performed properly in the high speed range [10]. The field weakening control of induction machines is a well-known method to overcome this difficulty [9], [17], [18]. In this case, however, the output torque capability is decreased.

The well-known field weakening strategy is to vary the rotor flux reference in proportion to the inverse of the rotor speed [17]-[19]. Hence, the rotor flux is decreased as the d-axis current is decreased. In order to fully utilize the current rating of the inverter and the machine, the q-axis current reference is increased within the allowable stator current. The
IV. Control Mode Change between Vector Control and V/f Scheme in the OVM Range

A. Constant V/f Control with a Slip Regulator in the OVM Range

As mentioned before, the flux weakening control of a vector-controlled IM for high speed operation limits the torque capability due to a reduction of the rotor flux. Further, operation in the OVM range gives high ripples in the currents and torque due to a deterioration of the PI current control performance.

A constant V/f control scheme with a slip regulator can enhance the output torque capability in OVM mode. Due to the machine inertial effect, the high-frequency ripple components in the rotor speed do not appear, even though the machine torque ripples exist in the OVM range. The ripple components of the stator voltages, the currents and the torque due to the OVM operation do not affect the performance of the speed control loop. Hence, the slip regulator with the closed speed control loop offers good performance in the OVM range of the PWM inverter.

B. Control Mode Change between Vector Control and V/f Control

Fig. 8 shows a control block diagram of the IM drive using the control mode change between vector control and the constant V/f scheme. When the machine speed is lower than \( \omega_{\text{base}} \), the vector control is applied and the machine torque can be controlled at the rated value. As the machine speed increases higher than \( \omega_{\text{base}} \), the control mode is changed to the constant V/f control with a slip regulator. This mode can keep the rotor flux constant by increasing the output voltage capability of the PWM inverter in OVM operation. Hence, the machine torque capability can be kept constant in a higher speed range operation.

In the inverse case, when the machine speed decreases to less than \( k \cdot \omega_{\text{base}} \), the control mode is changed to the vector control, in which the \( k \) is a hysteresis factor to prevent frequent changing of the control modes for a small speed variation near the base speed. In this paper, \( k \) is chosen as 0.9.

In the vector control mode, the constant parameter \( K_{T1} \) in Fig. 8 indicates the relationship between the machine torque and the q-axis current expressed from (5) and (6) as:

\[
K_{T1} = \left( \frac{3 P L_m}{L_q^2} \right)^{-1}. \tag{10}\]

Similarly, the constant parameter \( K_{T2} \) in Fig. 8 for the slip regulator control describes the relationship of the machine torque and the slip. For a low-slip region, \( K_{T2} \) can be expressed as [19]:

\[
K_{T2} = \left( \frac{3 P}{2 R_s} \right)^{-1}. \tag{11}\]

The PI control loops are used in both of the control modes. Hence, an error accumulation in the integral regulator for the speed and current controllers should be considered for fast transition between the two control modes. The PI regulators...
are implemented in the discrete time domain. The accumulative error of the integral regulator in the speed control loop for the vector control mode is kept as an initial value in the case of the constant \( V/f \) control and vice versa. Meanwhile, PI current controllers are used in the vector control only. So, the accumulative error of the \( I \)-regulator is considered only when the constant \( V/f \) mode is changed to the vector control mode. The actual currents are able to track their references immediately due to the good performance of the slip regulator as the control mode changes. Hence, the initial accumulative error of the \( I \)-regulator of the current control is set as zero.

In addition, the phase angle of the reference voltage in SVPWM should change continuously in the two control modes. The phase angle of the reference voltage in the vector control mode is based on the rotor flux angle. Hence, when the control mode changes from the vector control to the \( V/f \) mode, the last value of the phase angle for the vector control is set as the initial phase angle of the reference voltage in the case of the constant \( V/f \) scheme. For indirect vector control, the phase angle should be considered similarly when the operating mode changes from the \( V/f \) scheme to the vector control.

Fig. 9 shows the torque-speed characteristics of IM drives with the control mode change applied. When the PWM inverter operates in the six-step mode, the \( V_{\text{dc}} / \pi \) is increased up to \( 2V_{\text{dc}} / \pi \). From (9), the machine speed can be increased up to \( 1.1\omega_{\text{base}} \), at which the machine torque and the flux can be kept at the rated value.

V. EXPERIMENTAL RESULTS

To verify the validity of the proposed scheme, experimental tests have been performed with a 3 kW squirrel-cage induction motor (SCIM). The overall experimental setup is shown in Fig. 10. A permanent-synchronous generator (PMSG) driven...
Fig. 11. Performance of IM drive using the constant V/f scheme with slip regulator in OVM range. (Case A: zone I (MI=0.915), Case B: zone II (MI=0.958), Case C: Six-step operation (MI=1)) (a) Machine speed, (b) Stator voltage, (c) Stator current, (d) Machine torque, (e) Spectrum of (b), (f) Spectrum of (c), (g) Spectrum of (d)

by back-to-back converters is used as the load of the IM. The IM is driven by a PWM inverter with a front-end diode rectifier with two parallel 2,300µF DC-link capacitors. The IM parameters are listed in Table I. The switching frequency of the converters is 5 kHz. The AC source is 220V/60Hz.

A. Investigation of the Constant V/f Control with a Slip Regulator

Fig. 11 shows the performance of the IM drives with the constant V/f scheme in the cases of OVM zone I, zone II and the six-step operation, respectively. In Case A for OVM zone I (MI=0.915), the performance of the speed controller is shown in (a), in which the actual speed follows its reference well at 1,510 rpm. A stator phase voltage is shown in (b), which is distorted. Hence, the stator current and the machine torque are also distorted as shown in (c) and (d), respectively. The harmonic spectra by the fast Fourier transform (FFT) of the stator voltage, the current, and the machine torque are shown in (e)-(g), respectively. It can be seen that the the 5th- and 7th-order harmonic components of the voltage and current
and consequently the 6th- and 7th-order harmonic components of torque are low in OVM zone I. For investigating the OVM zone II operation, the machine speed is increased up to 1,600 rpm. The machine speed tracks its reference well as shown in (a) of Case B. The stator voltage and its spectrum are shown in (b) and (e), respectively, in which the harmonic components are higher than those of Case A. Due to the higher ripples of the stator voltage, the current and the machine torque have high ripples as shown in (c) and (d), respectively, in which their spectra are shown in (f) and (g), respectively. The torque ripple is about 13.1% of the average value in the case of MI = 0.958. Similarly, the machine operates at 1,650 rpm for an investigation of the six-step mode (MI=1) as shown in Case C of Fig. 11. The speed control performance is shown in (a). It can be seen in (b) that the stator voltage is a six-step wave.

The current and the torque have much higher ripples compared with the two cases mentioned above as shown in (c) and (d), respectively. The spectra of the stator voltage, the current and the torque are shown in (e)-(g), respectively. It is obvious that, odd harmonic components appear such as the 5th, 7th, etc.

Fig. 12 shows the stator voltage and the rotor flux in the linear range of the PWM. The dq-axis stator voltages are shown in Fig. 12(a) without distortion. The circular trajectory of the dq-axis stator voltage shown in Fig. 12(c) also proves this aspect. The dq-axis rotor fluxes and its trajectory are shown in Fig. 12(b) and (d), respectively, in which it is kept at the rated value of 0.425 Wb. In addition, the stator voltages and the rotor fluxes are shown in Fig. 13 for the six-step operation. Fig. 13(a) shows the dq-axis stator voltages and their hexagonal trajectory is shown in Fig. 13(c). It can be seen from the dq-axis rotor fluxes and its trajectory in Fig. 13(b) and (d) that the rotor flux is kept at the rated value in the six-step operation.

Fig. 14 shows the line-to-line stator voltage, which is measured by a differential probe. The line-to-line voltage from OVM zone I (MI=0.911) to zone II (MI=0.958) is shown in Fig. 14(a), whereas Fig. 14(b) shows the value from OVM zone II (MI=0.978) to the six-step operation.

B. Investigation of the Control Mode Change between the Vector Control and the V/f scheme

The transient performance at the control mode change instant between the vector control and the V/f mode is shown in Fig. 15. First, the IM is controlled by the vector control mode at 1,300 rpm. At 4s, the machine speed is increased. As the speed reaches 1,500 rpm, the control mode is changed to the constant V/f scheme with a slip regulator. It can be seen from Fig. 15(a) that the speed control performance is good for both the vector control and V/f control modes with a low transient speed at the mode change instant. Fig. 15(b) and (c) show the magnitude of the stator voltage and current, respectively, with high ripple during the operation of the V/f mode in the OVM mode. The transient state of the stator current appears at the instance of the mode change, which is about 40% higher than its average. It is obvious from Fig. 15(d) that the rotor flux is kept as the rated value for the two control modes. The average machine torque in the OVM range is kept the same as that of the vector control mode, which is shown in Fig. 15(e).

Fig. 16 shows the transient performance when the control mode changes from the vector control to the V/f mode. In this case, the PWM operation is changed from a linear range to
Control Mode Switching of Induction Machine Drives between OVM operation (OVM zone I). At the mode change instant, as marked in Fig. 16, the transient values of the stator voltages, the currents and the torque appear. Fig. 16(a) and (b) show the magnitude of the stator voltage and its instantaneous waveform, respectively. The transient values of the stator currents are shown in Fig. 16(c) and (d) for its magnitude and instantaneous waveform, respectively. It can be seen in Fig. 16(e) that the transient value of the machine torque also exists at the mode change instant.

Similarly, Fig. 17 shows the transient performance as the control mode is changed from the constant V/f control to the vector control. In this case, the operation of SVPWM is changed from OVM mode (OVM zone I) to the linear range. Hence, the transient values in the stator voltages, the stator currents, and the torque are low, as shown in Fig. 17(a)-(e), respectively.

C. Comparison of Vector Control with the Field Weakening and the Control Mode Changing Scheme in the High Speed Range

A comparison of the torque and flux performances between the vector control method in the field weakening and the control mode change method in the high speed ranges is shown in Fig. 18 and Fig. 19, respectively. The speed range for the test is set from 750 rpm to 1,650 rpm as shown in Fig. 18(a) and Fig. 19(a), in which the base speed is set to 1,500 rpm.
for the field weakening control and the control mode change between the vector control and the $V/f$ mode. For the field weakening control, the magnitude of the rotor flux is reduced according proportionally to an inverse of the rotor speed when the machine speed is higher than the base speed, as shown in Fig. 18(b). It is obvious in Fig. 18(c) that the torque is reduced due to the reduction of the rotor flux. Fig. 18(d) and (e) show a rotor flux-speed plot and the torque-speed characteristics, respectively, in which they consist with the theoretical analysis in Fig. 6. Meanwhile, the rotor flux and torque are kept as constant in the high speed range for the control mode change method, as shown in Fig. 19(b)-(e). The transient states in the rotor speed, the flux, and the torque appear as in Fig. 19. It can also be seen in Fig. 19 that the torque ripple exists in high speed operation due to the OVM mode of the PWM.

VI. CONCLUSIONS

This paper has proposed a strategy to maximally utilize an installed DC-link voltage PWM inverter. In low speed range operation, the vector control method provides a fast torque control. In addition, the constant $V/f$ scheme with a slip regulator has been investigated in high speed operation in the OVM mode. The rotor flux and the torque have been kept at the rated values during a machine speed range that is 10% higher than the based speed. The control mode change method between the vector control and the $V/f$ scheme has been presented with a consideration of the accumulation phenomena of integral regulators and the stator voltage phase angle. Experimental results have been shown to verify the validity of the proposed method.

TABLE I

<table>
<thead>
<tr>
<th>Parameters of Induction Machine</th>
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<tbody>
<tr>
<td>Rated power</td>
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<tr>
<td>Stator voltage/frequency</td>
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<tr>
<td>Rated speed</td>
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<tr>
<td>Stator resistance</td>
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<tr>
<td>Rotor resistance</td>
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<tr>
<td>Stator/rotor inductance</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
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<tr>
<td>Number of poles</td>
</tr>
<tr>
<td>Moment of inertia</td>
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REFERENCES

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