# Maximum Torque Control in Overmodulation Region for Vector Controlled Induction Machine

Dae-Woong Chung and Seung-Ki Sul
Dept. of Electrical Engineering
Seoul National University, Seoul, Korea
Phone: +82-2-880-7243 Fax: +82-2-878-1452
E-Mail: cdw@plaza1.snu.ac.kr Web: http://eepel.snu.ac.kr

***Abstract*** - In this paper, a new dynamic overmodulation strategy is proposed for vector-controlled induction motor drive, and a comparison experiment with conventional schemes are also performed. In overmodulation region, the proposed overmodulation scheme allocates the output voltage of inverter so that synchronous d-axis voltage is diminished in proportion as reference voltage exceeds hexagon boundary. As a result, d-axis current is decreased in the overmodulation region, which improves the dynamic performance of torque control considering the current dynamics of induction motor. The conspicuous improvement of the proposed scheme over conventional ones is observed in experimental results.

## I. INTRODUCTION

Due to the improvement of fast-switching power semiconductor devices and machine control algorithms, high performance PWM method of dc-ac inverter finds a growing interest. Among requirements of PWM method, full utilization of the dc bus voltage is extremely important to achieve the maximum output torque under all operating conditions for induction motor drive applications. With voltage source inverter, the output voltage is bounded by dc link voltage in the form of hexagon. When the reference voltage vector exceeds the hexagon region, the reference voltage can not be applied to the motor. When inverter enters overmodulation for a long time, inverter output voltage contains substantial subcarrier frequency harmonics and drive performance degrades considerably. Though fundamental component voltage gain and current waveform characteristics in overmodulation range are well improved in [1~3], these schemes are suitable for only open loop(volts-per-hertz) controlled induction motor drive, not vector-controlled one.

Vector controlled induction motor drive requires closed loop current control with fast dynamic characteristics. Although the performance of current regulator meets the requirement within voltage boundary, in overmodulation region the drive performance significantly degrades and the bandwidth of the regulator is shrunk[4]. Therefore, the designed performance of current regulator is guaranteed only in the linear modulation region. When inverter enters overmodulation for a long time, the rotor flux should be weakened to reduce induced back-emf voltage. It is, however, difficult to weaken rotor flux sufficiently in the transient state such as reference change, load disturbance, and sudden drop of utility voltage because this transient state is much shorter than the rotor time constant in general. Therefore, in this case, a proper dynamic overmodulation scheme should be implemented because it determines the dynamic performance of the induction motor drive. Therefore, many research results on the dynamic overmodulation scheme have been developed[5~8]. In [5~7], inverter output voltage is determined in the geometrical sense such as same angle and closest magnitude. In [8], the longer switching state is kept and the other is reduced so that the output voltage is located on the voltage boundary. But all of them have not considered the dynamic characteristics of vector-controlled induction motor. Therefore, even though these schemes are adopted in dynamic overmodulation period, the improvement of dynamic performance is not guaranteed.

In this paper, a new dynamic overmodulation strategy is proposed for vector-controlled induction motor drive. By considering voltage boundary of inverter and current dynamics of induction motor simultaneously, the proposed overmodulation scheme allocates the output voltage of inverter so that d-axis voltage in the synchronous frame is diminished in proportion as reference voltage exceeds hexagon boundary in the dynamic overmodulation region. As a result, d-axis current is decreased, which improves the dynamic performance of torque control in the overmodulation region. As well as a detailed explanation of the new overmodulation strategy, the experimental results are presented to verify the performance of proposed scheme.

## II. NEW OVERMODULATION STRATEGY

### A. Dynamics of Vector-Controlled Induction Motor

The voltage equation of vector controlled induction motor in the synchronous d-q frame are

$$V_d^e = (R_s + R_r \frac{L_m^2}{L_r^2}) i_d^e + p\sigma L_s i_d^e - \omega_e \sigma L_s i_q^e - R_r \frac{L_m}{L_r^2} \lambda_{dr}^e$$
$$V_q^e = (R_s + R_r \frac{L_m^2}{L_r^2}) i_q^e + p\sigma L_s i_q^e + \omega_e \sigma L_s i_d^e + \omega_r \frac{L_m}{L_r} \lambda_{dr}^e \quad (1)$$

where $p$ denotes derivative operator, $R_s$, stator resistance, $R_r$, rotor resistance, $L_s$, stator self inductance, $L_r$, rotor self inductance, $L_m$, mutual inductance, $\omega_e$, electrical angular frequency, $\omega_r$, electrical rotor angular frequency, $\sigma$, leakage coefficient, $\lambda_{dr}^e$, d-axis rotor flux respectively.

The d-axis current, $i_d^e$, is normally regulated to be constant in constant torque region and varies very slowly according to speed variation in the field weakening region. Therefore the derivative of d-axis current in (1) can be approximated to near zero. The d-axis back-emf which is the last term of $V_d^e$ is also near to zero. At high speed, which is the case that overmodulation is most likely to occur, the voltage drop across the resistance is much smaller than that across the inductance. Therefore, at high speed region, the voltage equation of (1) can be approximated to

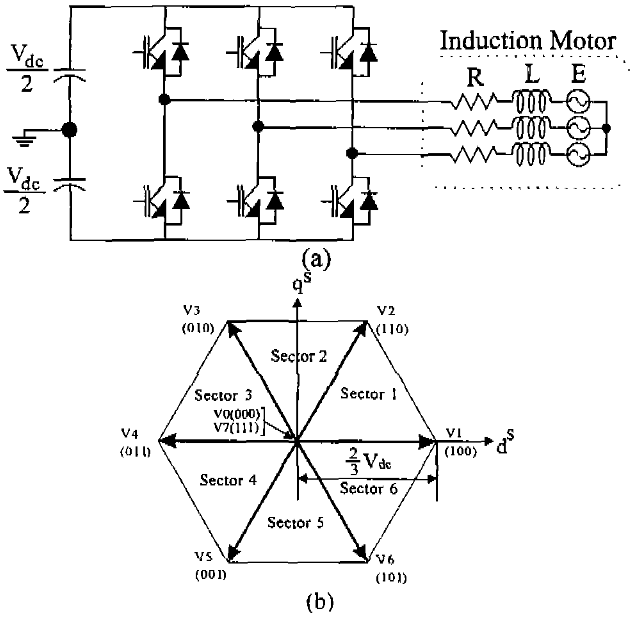
$$V_d^e \approx -\omega_e \sigma L_s i_q^e, \qquad V_q^e \approx p\sigma L_s i_q^e + \omega_e \sigma L_s i_d^e + \omega_r \frac{L_m}{L_r} \lambda_{dr}^e. \quad (2)$$

When inverter enters overmodulation for a long time, the rotor flux should be weakened to reduce q-axis back-emf voltage. It is, however, difficult to weaken rotor flux sufficiently in the transient state such as reference change, load disturbance, and sudden drop of utility voltage because this transient state is generally much shorter than the rotor time constant. Therefore the dynamic performance is deteriorated because the increasing rate of q-axis current should be limited by dc-link voltage of inverter.

To overcome this situation, it is desirable to decrease d-axis current for a while in the overmodulation region, which improves q-axis current control and consequently torque control[9]. Since this transient period is much shorter than rotor time constant, rotor flux $\lambda_{dr}^e$ is nearly not decreased even though d-axis current is decreased for a moment.

### *B. Voltage Boundary*

In Fig.1(a), a typical power stage of the 3-phase inverter and equivalent circuit of induction motor are presented. And, in Fig.1(b), the available eight different switching vectors of the inverter are depicted with space vector concept. The switching state '1' means the firing for upper device of each arm. In this paper, superscript 's' means the value of stationary reference frame, 't', the value of transformed reference frame, and 'e', the value of synchronous reference frame respectively.



(a)

(b)

Fig. 1. 3-pase inverter and its switching vectors.
(a) 3-phase inverter system. (b) Space vector diagram of the available switching vectors.

In the inner region of voltage hexagon, d and q-axis voltage( $V_d^s$, $V_q^s$ ) in the stationary reference frame can be selected independently. But these two voltages become dependent when a voltage vector is located on the hexagon boundary in the overmodulation region. This state constrains $V_d^s$ to be a function of $V_q^s$ according to the sector. Therefore, at overmodulation instant, not two but only one voltage can be selected as an independent variable for d and q-axis current regulation.

To clarify this situation, rotational transformation from stationary to transformed reference frame can be adopted as follows.

$$\begin{bmatrix} V_d^t \\ V_q^t \end{bmatrix} = T(\Phi) \begin{bmatrix} V_d^s \\ V_q^s \end{bmatrix}$$
$$where\ T(\Phi) = \begin{bmatrix} \cos\Phi & \sin\Phi \\ -\sin\Phi & \cos\Phi \end{bmatrix}, \quad (3)$$
$$\Phi = \frac{\pi}{3}(\mathrm{m}-1) + \frac{\pi}{6}, \mathrm{m} = \text{sector number}$$

After the transformation, the sector where the reference voltage is located can be depicted as deep-colored region as shown in Fig. 2 and voltage boundary in the transformed reference frame becomes

$$V_d^t = \frac{V_{dc}}{\sqrt{3}}, \quad \left|V_q^t\right| \le \frac{V_{dc}}{3}. \tag{4}$$

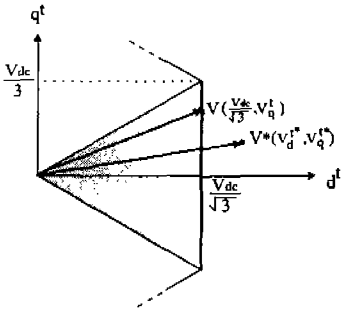


Fig. 2. Rotationally transformed voltage boundary.

### C. Proposed Overmodulation Strategy

In vector-controlled induction motor drive, all physical quantities including voltage are handled in the synchronous reference frame(superscript 'e'). Therefore, the voltage distortion in the synchronous reference frame is of prime concern in the overmodulation region. The voltage relationship between synchronous and transformed reference frame is as follows:

$$\begin{aligned}\begin{pmatrix} V_d^e \\ V_q^e \end{pmatrix} &= T(\theta)\begin{pmatrix} V_d^s \\ V_q^s \end{pmatrix} = T(\theta)T(-\Phi)\begin{pmatrix} V_d^t \\ V_q^t \end{pmatrix} \\ &= \begin{pmatrix} \cos(\theta-\Phi) + \sin(\theta-\Phi) \\ -\sin(\theta-\Phi) + \cos(\theta-\Phi) \end{pmatrix}\begin{pmatrix} V_d^t \\ V_q^t \end{pmatrix}\end{aligned} \tag{5}$$

Since the d-axis voltage in the transformed reference frame is fixed to $V_{dc}/\sqrt{3}$ in the overmodulation region as shown in Fig. 2, the voltage distortions in synchronous frame become

$$\begin{aligned}\begin{pmatrix} \Delta V_d^e \\ \Delta V_q^e \end{pmatrix} &= \begin{pmatrix} V_d^{e*} - V_d^e \\ V_q^{e*} - V_q^e \end{pmatrix} \\ &= \begin{pmatrix} \cos(\theta-\Phi) + \sin(\theta-\Phi) \\ -\sin(\theta-\Phi) + \cos(\theta-\Phi) \end{pmatrix}\begin{pmatrix} \Delta V_d^t \\ \Delta V_q^t \end{pmatrix}\end{aligned} \tag{6}$$

$$where\ \Delta V_d^t = V_d^{t*} - \frac{V_{dc}}{\sqrt{3}}, \Delta V_q^t = V_q^{t*} - V_q^t.$$

By considering the dynamics of induction motor, it is desirable to decrease d-axis current more as reference voltage gets farther away from the voltage boundary. For this purpose, $\Delta V_d^e$ is set to $\Delta V_d^t$ in the proposed overmodulation scheme because $\Delta V_d^t$ is the distance between voltage boundary and reference voltage.

$$\Delta V_d^e \equiv \Delta V_d^t. \tag{7}$$

From (6) and (7), q-axis voltage in the transformed reference frame is determined as follows.

$$V_q^t = \frac{1-\cos(\theta-\Phi)}{\sin(\theta-\Phi)}\left(\frac{V_{dc}}{\sqrt{3}} - V_d^{t*}\right) + V_q^{t*}. \tag{8}$$

The proposed scheme can be implemented as shown in the block diagram of Fig.3.

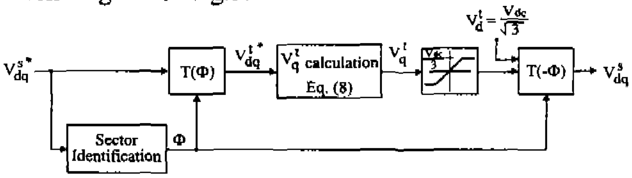


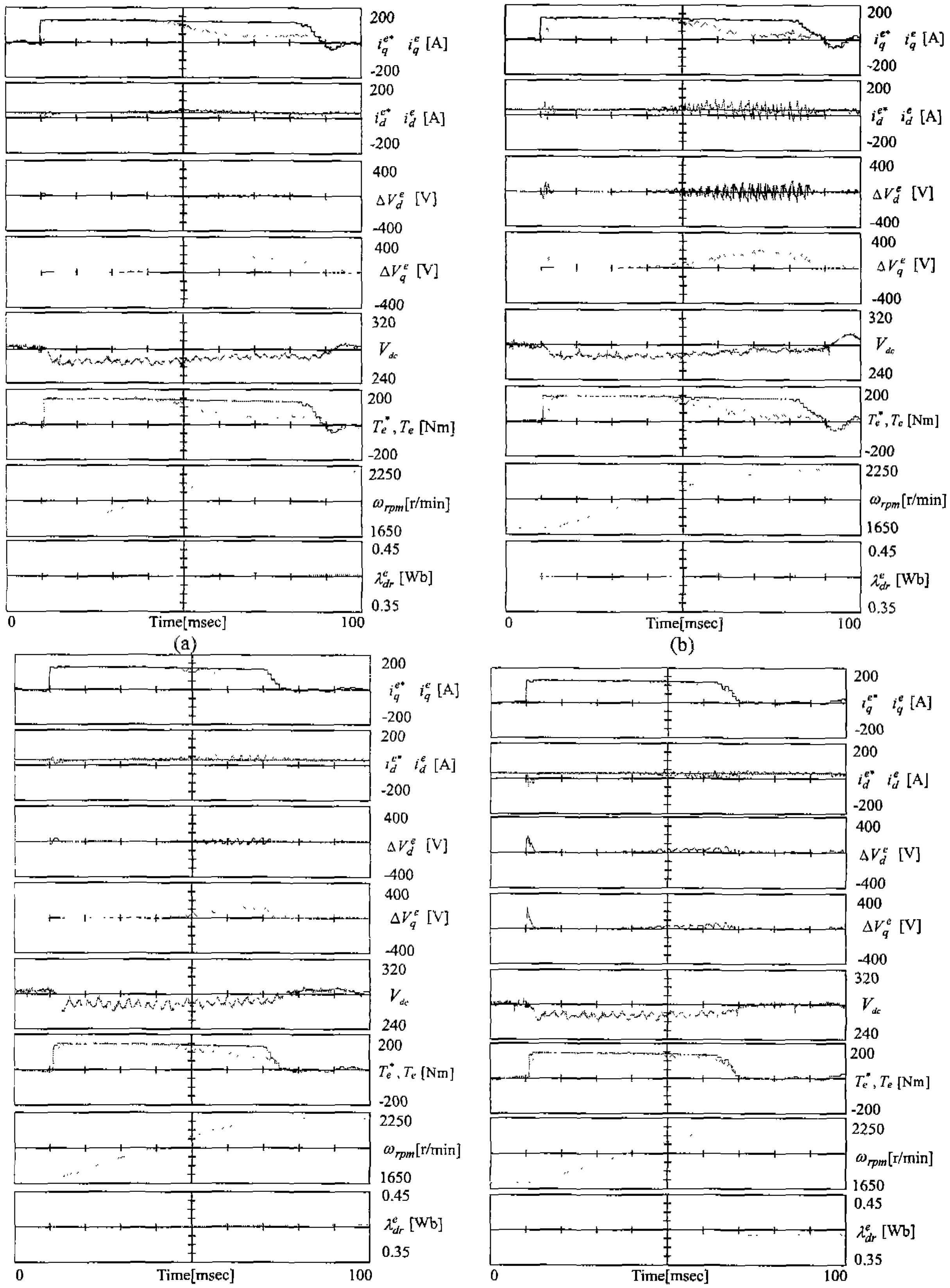
Fig. 3. Sequence of output voltage generation in proposed overmodulation scheme.

## III. EXPERIMENTAL RESULTS

In order to demonstrate the superiority of the proposed overmodulation scheme, an experiment with test set-up was carried out. The VSI utilizes a diode rectifier front end with a DC bus voltage of 280V. Switching frequency is 3kHz and sampling time is 167μsec. And an indirect vector-controlled 22kW induction motor is used whose parameters are represented in the table 1.

In experiment, the reference speed of the motor is abruptly changed from 1700r/min to 2200r/min at no load. At the moment, the q-axis reference current in the synchronous frame becomes positive maximum. The transient responses of three conventional schemes and proposed one are compared to demonstrate the fast and stable torque regulation of the proposed overmodulation scheme under identical speed and current controller. The overmodulation scheme of [5,6] is called scheme-I, scheme of [7], scheme-II, scheme of [8], scheme-III respectively. The sampling period and regulation bandwidth of current control are 167μsec and 2000rad/s respectively and those of speed control are 1msec and 210rad/s. All the current controllers fully use their control voltage in the transient state, which means that this performance difference is caused by only the adopted overmodulation scheme.

Fig. 4 shows that the current regulators with conventional overmodulation schemes(scheme-I,II,III) have the slow transient response though they use all the available output voltage during the transient region. Non-zero voltage distortion in synchronous frame means the overmodulation region. Compared to the conventional schemes, the proposed scheme has the fast and stable torque regulation. The most distinguished difference is the d-axis current in overmodulation region. Since the proposed scheme decreases the d-axis voltage in proportion as reference voltage exceeds hexagon boundary, d-axis current is consequently decreased and the control voltage margin is secured. It makes fast and stable regulation of q-axis current possible. Since the rotor time constant of this motor is about 0.57sec, rotor flux does not significantly vary in transient region. So, the fast and stable q-axis regulation of proposed scheme agrees with torque regulation. The presented experimental results show that the proposed overmodulation strategy outdistances conventional ones in torque regulation capability.



(a) (b)

(c) (d)

Fig. 4. Torque regulation characteristics of over-modulation schemes.
(a) scheme-I. (b) scheme-II.
(c) scheme-III. (d) proposed scheme.

Table 1. Parameters of induction machine

| 22kW, 220V, 4pole, 60Hz, 1765rpm |
|---|
| $R_S$ : 0.041Ω $R_r$ : 0.024Ω $L_S$ :13.35mH $L_r$ :13.65mH<br>$L_m$ :13.25mH $J_m$:0.12Kg-m$^2$ |

## IV. CONCLUSION

By considering the current dynamics of vector controlled induction motor and voltage boundary of 3-phase inverter simultaneously, a new dynamic overmodulation strategy is developed. Synchronous d-axis voltage is diminished in proportion as reference voltage exceeds hexagon boundary to obtain fast and stable response of torque regulation. The presented experiment shows that the proposed overmodulation strategy outdistances conventional ones in torque regulation capability.

## REFERENCES

[1] J. Holtz, W. Lotzkat and A.M. Khambadkone, "On continuous control of PWM inverters in the overmodulation range including the six-step mode," *IEEE Trans. on Power Elect.. vol.8, no.4, Oct., pp.546-553, 1993.*

[2] V. Kaura and V. Blasko, "A new method to improve linearity of a sinusoidal PWM in the overmodulation region," *IEEE Trans. on Ind. Appl., vol.32, pp.1115-1121, Sep./Oct., 1996.*

S. Bolognani and M. Zigliotto, "Novel digital continuous control of SVM Inverters in the overmodulation range," *IEEE Trans. on Ind. Appl., vol.33, no.2, pp.525-530, 1997.*

[3] T.M. Rowan and R.J. Kerkman, "A new synchronous current regulator and an analysis of current-regulated PWM inverters," *IEEE Trans. on Ind. Appl., vol.22, no.4, pp.678-690, Jul./Aug., 1986.*

[4] H. Mochikawa, T. Hirose and T. Umemoto, "Overmodulation of voltage source PWM inverter," JIEE Ind. Soc. Ann. Conf. Rec., 1991, pp.466-471.

[5] T.G. Habetler, F. Profumo, M. Pastorelli, and L.M. Tolbert, "Direct torque control of induction machines using space vector modulation," *IEEE Trans. on Ind. Appl., vol.28, no.5, pp.1045-1053, 1991.*

[6] D. R. Seidl, D. A. Kaiser and R. D. Lorentz, "One-step optimal space vector PWM current regulation using a neural network", in Conf. Rec. of IAS'92, pp.570-577, 1992.

[7] L. Rossetto, P. Tenti and A. Zuccato, "Integrated optimum control of quasi-direct converters," *IEEE Trans. on Power Elect., vol.12, no.6, Nov., pp.993-999, 1997*

[8] J.W. Choi, H.W. Kim and S.K. Sul, "New current control concept : Minimum time current control in induction machine drive", in Conf. Rec. of IECON'95, pp.311~316, 1995