Control Scheme for Wide-Speed-Range Operation of Synchronous Reluctance Motor in M–T Frame Synchronized with Stator Flux Linkage

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(Manuscript received March 14, 2012, revised Nov. 9, 2012)

This paper proposes a novel control scheme for wide-speed-range operation of synchronous reluctance motors. The proposed scheme is a combination of maximum torque per ampere control, maximum torque per flux control, flux-weakening control, and torque limiting. These controls are based on a mathematical model in a rotating reference frame that is synchronized with the stator flux-linkage vector. The proposed control scheme is suitable for direct torque control or flux-oriented control. The validity of the control scheme is verified by the experimental results. Influences of parameter variation on the proposed control scheme are discussed. The proposed schemes of flux weakening and torque limiting are insensitive to parameter variation.

Keywords: direct torque control, parameter variation, synchronous reluctance motor drives, wide speed range operation

1. Introduction

Synchronous reluctance motors (SynRMs) are utilized for variable speed electrical drives to reduce costs and achieve maintenance-free operation. Maximum torque per ampere (MTPA) control and flux-weakening (FW) control are applied for wide speed range operation. Many methods of achieving such controls have been reported, and these methods are based mainly on a mathematical model of the rotating $d$–$q$ reference frame that is synchronized with the rotor.

Direct torque control (DTC) can be applied to motor drive systems regardless of the category of motor. The DTC has several advantages: control in a stationary reference frame; torque and flux estimations without inductance; ease of both torque and flux controls. The DTC-based drive system can achieve optimal control by providing reference torque and flux values depending on the operating conditions. Generally, the relationship between torque and flux is determined by the motor model in the $d$–$q$ frame. Motor parameters, such as inductance and magnet flux, are required to calculate the reference torque and the reference flux, even though the DTC works in the stationary $\alpha$–$\beta$ reference frame, and the torque and flux estimations do not require these parameters. On the other hand, several control schemes in a rotating reference frame synchronous to the stator flux-linkage vector were proposed in References (7)–(13).

This paper proposes a novel control scheme for wide-speed-range operation of direct torque controlled SynRMs. The scheme is a combination of MTPA, FW, maximum torque per flux (MTPF) controls, and torque limiting. These controls utilize a mathematical model in the M–T reference frame that is synchronized with the stator flux-linkage vector. A simple expression can be obtained by using the quantities defined in the M–T frame. In the conventional method, the reference values of the torque and the flux are calculated from the $d$- and $q$-axis components, or $\alpha$- and $\beta$-axis components. However, utilization of the $d$- and $q$-axis components is difficult for DTC-based motor drive system because the coordinate transformation requires the rotor position sensor or the position estimation. On the other hand, the DTC works on the $\alpha$–$\beta$ frame, but an AC component is unsuitable for calculation of the reference values. In (13), the inductance variation due to the magnetic saturation is unconsidered, and the inductance is treated as a constant. However, almost SynRMs have non-linear characteristics. In this paper, the influences of the inductance variation on the MTPA and the MTPF controls are discussed. In addition, the FW control, which maintains the armature voltage at its limiting value, uses the voltage equation in the M–T frame, and thus the value of the inductance is not required. Torque limiting is also necessary to maintain the armature current below its limiting value, which is determined by the capabilities of the inverter and motor. The proposed method of torque limiting accomplishes current limitation using a simple equation that does not require the motor parameters. The validity of the proposed scheme is verified through experimental results. Also, characteristics of the proposed control scheme under parameter variation are examined.

2. Control Laws for Wide-speed Range Operation in M–T Frame

2.1 Mathematical Model in M–T Frame Synchro-

ized with Stator Flux-Linkage Vector

In this paper, control laws for wide-speed range operation are derived from mathematical model of SynRM expressed in a rotating reference frame synchronized with the stator flux-linkage vector.
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Fig. 1 illustrates the vector diagram and coordinate axes under a steady-state operating condition. Generally, in SynRMs, the direction of the stator flux-linkage vector $\Psi_s$ disagrees with that of the armature current vector $i_a$ because the values of the $d$- and $q$-axis inductances are different. The $a$–$\beta$ reference frame is a stationary reference frame. The rotating reference frame synchronized with the stator flux-linkage vector $\Psi_s$ is also shown in Fig. 1. This frame is called the M–T reference frame.\(^{(1)}\)

The voltage equation in the M–T frame is given by\(^{(8)–(10)}\)

$$
\begin{bmatrix}
v_M \\
v_T
\end{bmatrix} =
\begin{bmatrix}
R_s & \frac{d}{dt} \\
\frac{d}{dt} & 0
\end{bmatrix}
\begin{bmatrix}
i_M \\
i_T
\end{bmatrix} +
\begin{bmatrix}
0 \\
\omega \Psi_s
\end{bmatrix}
$$

where $v_M$ and $v_T$ are respectively the M- and T-axis components of the armature voltage vector, $i_M$ and $i_T$ are respectively the M- and T-axis components of the armature current vector $i_a$, $\Psi_s$ is the amplitude of the stator flux-linkage vector, and $R_s$ is the armature resistance.

In the steady state, the voltage equation is given by

$$
\begin{bmatrix}
v_M \\
v_T
\end{bmatrix} =
\begin{bmatrix}
R_s & \frac{d}{dt} \\
\frac{d}{dt} & 0
\end{bmatrix}
\begin{bmatrix}
i_M \\
i_T
\end{bmatrix} +
\begin{bmatrix}
0 \\
\omega \Psi_s
\end{bmatrix}
$$

where $\omega$ is the electrical angular velocity.

Since the stator flux-linkage vector has a component only along the M-axis, the electromagnetic torque $T_e$ is calculated by using the orthogonal relationship between the flux and the current, as follows:

$$
T_e = P_n \Psi_s i_T \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \ quad
the tested SynRM.

Assuming (12), the $d$-axis current can be estimated from (16).

$$i_d = \frac{I_a}{\sqrt{2}}$$

where the armature current $I_a$ is given by (17) in the M–T frame.

$$I_a = \sqrt{I_{dM}^2 + I_{fT}^2}$$

Substituting (15) and (16) into (13), $L_{T\text{-MTPA}}$ is also expressed as a function of the armature current.

$$L_{T\text{-MTPA}}(I_a) = \frac{1}{\sqrt{2}} I_a + \frac{L_d}{\sqrt{2} I_a} = \left(\frac{L_d}{2}\right)^2 + L_{qM}^2$$

### 2.4 Maximum Torque per Flux Control

In the case of the SynRM, the torque has a maximum at a torque angle of 45 degrees, and the maximum value increases with increasing flux linkage. Fig. 2 shows the torque characteristics under constant stator flux linkage. Limitation of either torque or torque angle is necessary for stable control because a SynRM cannot produce more than its maximum torque. Therefore, MTPF control is important.

In this case, the relationship of (19) is imposed on the $d$- and $q$-axis currents. Substituting (19) into (10) yields $L_T$ under MTPF conditions, as shown in (20).

$$L_{dM} = \frac{L_q I_q}{L_d - L_q} \quad \text{(19)}$$

$$L_{T\text{-MTPF}} = \frac{2 L_d I_q}{L_d - L_q} \quad \text{(20)}$$

Substituting $L_T = L_{T\text{-MTPF}}$ into (11) yields the maximum torque $T_{m-dm}$ for the case in which $\delta$ is 45 degrees, as follows:

$$T_{m-dm} = \frac{P_n}{\sqrt{2}} L_{T\text{-MTPF}} \quad \text{(21)}$$

### 2.5 Control Laws for Voltage and Current Limitations

The proposed scheme adopts the FW control for maintaining the armature voltage $V_a$ at its limiting value. Using $V_a = \sqrt{V_{dM}^2 + V_{fT}^2}$ and solving (2) for the variable $\Psi_s \tau$ yields the stator flux linkage $\Psi_{s-FW}$ for voltage limitation, as follows:

$$\Psi_{s-FW} = \frac{1}{\omega} \left(-R_{aT} + \sqrt{V_{adm}^2 - (R_{aT} I_{adm})^2}\right) \quad \text{(22)}$$

where $V_{adm}$ is the limiting value of the armature voltage.

The torque is restricted to satisfy the current limiting. The relationship between the torque and the current is generally nonlinear, and so deriving this relationship is complicated. In the M–T frame, however, the limiting torque $T_{lim}$ can be calculated by using (3), as follows:

$$T_{lim} = P_n \Psi_s I_{lim} \quad \text{(23)}$$

where $i_{lim}$ is the T-axis limiting current and is given by:

$$i_{Tlim} = \sqrt{I_{adm}^2 - I_{adm}^2} \quad \text{(24)}$$

where $I_{adm}$ is the limiting armature current.

### 3. SynRM Drive System based on DTC

#### 3.1 Flux and Torque Estimation

Generally, in the DTC system, the stator flux linkage and the torque are estimated and controlled in the $\alpha$–$\beta$ frame. The stator flux linkage in the $\alpha$–$\beta$ frame is estimated by the following equations $^{(12)}$:

$$\hat{\Psi}_\alpha = \int (v_\alpha - R_{aT} i_\alpha) dt \quad \text{(25)}$$

$$\hat{\Psi}_\beta = \int (v_\beta - R_{aT} i_\beta) dt \quad \text{(26)}$$

where $v_\alpha$ and $v_\beta$ are the $\alpha$- and $\beta$-axis components of the armature voltage, $i_\alpha$ and $i_\beta$ are the $\alpha$- and $\beta$-axis components of the armature current; $\hat{\Psi}_\alpha$ and $\hat{\Psi}_\beta$ are the estimated stator flux linkage, respectively; $\hat{\theta}$ is the amplitude and position of the estimated stator flux linkage, respectively. Note that, in this paper, the $\hat{}$ symbol denotes an estimated value.

The estimated torque $\hat{\tau}_e$ can be calculated by:

$$\hat{\tau}_e = P_n (\hat{\Psi}_\alpha i_\beta - \hat{\Psi}_\beta i_\alpha) \quad \text{(28)}$$

#### 3.2 Proposed Control Scheme of Torque and Flux

In a DTC-based motor drive system, it is necessary for wide speed range operation to appropriately determine the reference values of the torque and stator flux linkage. A novel control scheme suitable for DTC is proposed in this paper.

Fig. 3 shows a direct torque controlled SynRM drive system. In the calculator of reference torque and reference flux, the change of the control method is achieved by the limiter of the torque and flux. Each control is independent of the other controls, and thus it expects that the maximum efficiency control can be applied instead of the MTPF control in the future.

Table 1 summarizes the control modes of the proposed system. The MTPA control based on (14) is applied in low speed region. The flux-weakening control based on (22) is applied when the armature voltage reaches its limiting value. In higher speed region, the torque is restricted by the MTPF control based on (21). In the MTPF control region, the flux-weakening is also used for the stator flux-linkage control because of voltage limitation.

A DTC method using the PI controller for torque control $^{(35)}$ is applied in this study. The SynRM drive system based on
Control Scheme of SynRM in M–T Frame (Yukinori Inoue et al.)

Fig. 3. Proposed SynRM drive system based on DTC

Table 1. Control Modes and Motor Conditions

<table>
<thead>
<tr>
<th>Motor conditions</th>
<th>Voltage</th>
<th>Current</th>
<th>Torque angle</th>
<th>Torque limiting</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Torque Per Ampere</td>
<td>$V_a &lt; V_{cm}$</td>
<td>$I_a \leq I_{cm}$</td>
<td>$\delta &lt; 45$ deg.</td>
<td>Eq. (23)</td>
<td>Eq. (14)</td>
</tr>
<tr>
<td>Flux Weakening</td>
<td>$V_a = V_{cm}$</td>
<td>$I_a &lt; I_{cm}$</td>
<td>$\delta = 45$ deg.</td>
<td>continues.</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4. Block diagram of reference flux vector calculation DTC

Table 2. Parameters of Tested SynRM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pole pairs $P_s$</td>
<td>2</td>
</tr>
<tr>
<td>$d$-axis inductance $L_d$</td>
<td>0.4347 $-0.063L_d$ (H)</td>
</tr>
<tr>
<td>$q$-axis inductance $L_q$</td>
<td>0.055 H</td>
</tr>
<tr>
<td>Armature resistance $R_a$</td>
<td>11.45 $\Omega$</td>
</tr>
<tr>
<td>Base speed</td>
<td>615 min$^{-1}$</td>
</tr>
<tr>
<td>Rated torque</td>
<td>1.3 Nm</td>
</tr>
<tr>
<td>Rated phase current</td>
<td>1.27 A (rms)</td>
</tr>
</tbody>
</table>

4. Experimental Results

4.1 Experimental Configuration The effectiveness of the proposed controls is evaluated by using the experimental results. The parameters of the SynRM drive system are listed in Table 2. The measured value of the $d$-axis inductance is shown in Fig. 5. The inductance varies because of magnetic saturation. All of the controls are processed through a digital signal processor (Texas Instruments TMS320C6713). The period of speed control is 5 ms, and the sampling period of other controls is 100 $\mu$s. An insulated gate bipolar transistor module is used for the inverter, and the DC link voltage of the inverter is 135 V. The rotor speed is detected by an incremental encoder attached to the tested motor.

Flux estimation is based on a first-order low-pass filter in order to avoid divergence of the estimated flux from DC offset caused by the current transducer and initial error of the

this method of DTC is shown in Fig. 4. The reference voltages ($v^*_a$ and $v^*_b$) are generated by the difference between the reference flux and the estimated flux in the reference voltage vector calculator. Note that the proposed control scheme in this paper can be applied to any methods of DTC (e.g., References (6) and (14)).
estimated value.

4.2 Influence of Parameter Variation on MTPA Control

The proposed MTPA control law of (14) requires appropriate value of \( L_{T-\text{MTPA}} \), which depends on motor parameters. The influence of the parameter variation is discussed.

Fig. 6 shows the characteristics of the phase current and electrical input power with respect to the \( L_{T-\text{MTPA}} \) variation. The value of \( L_{T-\text{MTPA}} \) used in the controller is changed step by step. Figs. 6(a) and (b) are the experimental results under no-load condition at speeds of 600 min\(^{-1}\) and 1200 min\(^{-1}\), respectively. Figs. 6(c) and (d) are the results under 100% load condition at speeds of 300 min\(^{-1}\) and 600 min\(^{-1}\), respectively. In addition, Figs. 6(e) and (f) are the overload characteristics under 125% load condition. As can be seen, there is an appropriate value of \( L_{T-\text{MTPA}} \) to minimize the copper loss at each condition. The value of \( L_{T-\text{MTPA}} \) calculated by (18) is close to the optimal value. Therefore, \( L_{T-\text{MTPA}} \) can be calculated from \( k_d, L_d, \) and \( I_a \) when the magnetic saturation is not negligible.

It was confirmed that the proposed control law based on (14) is effective for MTPA control.

4.3 Influence of Parameter Variation on MTPF Control

Fig. 7 shows the torque angle and rotor speed when the rotor speed is accelerated from 200 to 2300 min\(^{-1}\). In Fig. 7(a), the \( L_{T-\text{MTPF}} \) used for MTPF control is calculated by (20) from the nominal values of the \( d \)- and \( q \)-axis inductances. In this case, \( L_{T-\text{MTPF}} \) is 0.13 H. From the result of Fig. 7(a), the torque angle never exceeds 45 degrees. As the result, operation at high speeds and stable torque control are achieved.
Next, the change of control performance is verified when the $LT-MTPF$ variation is applied. In Fig. 7(b), $LT-MTPF$ is 95% of the nominal value, and the torque angle exceeds 45 degrees. This situation is undesirable, although acceleration of the rotor continues. In Fig. 7(c), $LT-MTPF$ is 110% of the nominal value. It can be seen that the torque angle never exceeds 45 degrees, but is maintained at 30 degrees, and this angle is smaller than that in Fig. 7(a).

The torque angle should be 45 degrees in theory, but stable operation at a torque angle of 45 degrees is difficult for DTC system. Hence, such a margin is required for stable torque control. Note that the torque variation is small for torque angles close to 45 degrees, as shown in Fig. 2. In this case, the torque variation is negligible.

### 4.4 Influence of Parameter Variation on Flux Weakening

Fig. 8 shows the influence of resistance variation on the performance of FW control. In Fig. 8, the resistance used for the control, such as the flux estimation and the reference calculation of (22), is changed. The limiting voltage $V_{lim}$ is 82 V.

From the result of Fig. 8, the values of the armature voltage, current and the input power are constant. Thus, the proposed method is insensitive to resistance variation. This is because the variation of the reference flux calculated by (22) is countered by the variation of the stator flux linkage estimated by (25).

Note that the tested motor drive system becomes unstable when the resistance used in the controller is 1.13 times larger than 11.45 ohms. On other hand, when the actual value of the armature resistance is larger than the value used in the controller, the motor drive system works good and the resistance variation does not affect the control characteristics of the flux weakening. Therefore, resistance increase due to increase in temperature of the armature winding does not affect the control characteristics of the flux weakening.

### 4.5 Transient Characteristics of Torque Limiting

Fig. 9 shows the effectiveness of the proposed torque limiting method under the transient state. The reference torque $T^*_e$ is equal to the limiting torque $T_{lim}$ while under torque limitation. In Fig. 9(b), the armature current is maintained below its limiting value for both steady and transient states. In the proposed torque limiting method, the voltage error due to the inverter and the resistance variation do not affect the performance of the torque limiting because the error of the limiting torque is countered by the estimation error. Therefore, the torque limiting based on (23) achieves precise current limitation for both steady and transient states.

Fig. 10 shows comparison of the torque limiting characteristics between the proposed method and a conventional method. Fig. 10(a) is the result of the proposed method. The armature current is maintained at its limiting value by only one control law of (23) over wide speed ranges.

Fig. 10(b) is the result of the conventional method, which is given by

$$T_{lim-conv} = \begin{cases} 1.38 \text{Nm} & \text{for } N_m \leq 620 \text{ min}^{-1} \\ k_4 \omega^4 + k_3 \omega^3 + k_2 \omega^2 + k_1 \omega + k_0 & \text{for } N_m > 620 \text{ min}^{-1} \end{cases} \quad (29)$$

where $k_4$, $k_3$, $k_2$, $k_1$ and $k_0$ are coefficients of the approximated polynomial and they are calculated from mathematical
model in the $d$-$q$ frame. In the tested SynRM, $k_4$ is $-1.36 \times 10^{-10}$, $k_3$ is $1.48 \times 10^{-7}$, $k_2$ is $-4.83 \times 10^{-5}$, $k_1$ is $9.86 \times 10^{-4}$, and $k_0$ is 1.81.

In this case, the armature current is also maintained at its limiting value, but the fluctuation is larger than that of the proposed method. In addition, the calculation of the coefficients is complicated.

5. Conclusions

This paper proposed a novel control scheme for wide-speed-range operation of a DTC-based SynRM drive system. The proposed control law was derived from mathematical equations in the M–T frame, which is synchronized with the stator flux-linkage vector. From the experimental results, it was confirmed that the proposed scheme satisfies the limitations of the armature voltage, armature current and torque angle. The inductance variation due to magnetic saturation affects the performance of the MTPA control, but the optimal value of $L_T-MTPA$ can be obtained from the armature current and the approximated curve of the inductance. In addition, the proposed torque limiting method is found to be insensitive to the parameter variation and the estimation error. The proposed flux-weakening method is insensitive to the resistance variation when the actual value of the armature resistance is larger than the value used in the controller.

As the next topic, the magnetic saturation models for both the $d$- and $q$-axis inductances are required for performance improvement of the MTPA and the MTPF controls.

References


Control Scheme of SynRM in M–T Frame (Yukinori Inoue et al.)

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