A Combined Control Strategy Over Full Speed Range of Synchronous Reluctance Motor Considering Iron Loss

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Abstract. For the perspective of efficiency optimization and field-weakening speed expansion, the research on the optimal control scheme of SynRM is of great significance. This paper proposes a novel control strategy combined maximum torque per ampere (MTPA) control with maximum efficiency (ME) control, for fast and efficient performance of SynRM considering iron loss. As the speed exceeds the rated speed, maximum torque per voltage (MTPV) control is proposed to realize deep field-weakening. The proposed approach is determined by operating conditions of the motor which avoids the deterioration of dynamic performance due to the switching. In particular, while the working speed is increasing, the control must be able to drive SynRM under the combined MTPA and ME control at first, and then on the MTPV trajectory. In this paper, the current feedback decoupling current control in the SynRM model including the iron loss is developed to compensate the cross-coupling effect for high dynamic control performance. The proposed control strategy has been successfully implemented and verified via MATLAB/Simulink software of a vector control system in changing status.

1. Introduction

With so many merits, SynRM has been proved to be an attractive alternative to induction motor (IM), switched reluctance motor (SRM) and permanent magnet synchronous motor (PMSM) in variable speed drive applications. SynRM motor is advantaged on IM by the lower copper loss, on brushless motor by inexpensive and simple rotor structure, and on SRM by a much smaller torque ripple and low noise. The field-weakening control can be easily achieved without considering the irreversible demagnetization and the vanish of permanent magnets at high temperature, in contrast to PMSM[1].

Since SynRM is a complicated system with a nonlinear and strong coupling, high precision current loop control is an essential part of the system. Current feedback decoupling compensates in the voltage model at the input of the controller to achieve complete decoupling of d-q axis voltage. Without regard to the changes of parameters, current feedback decoupling in the SynRM model including the iron loss is proposed to realize the complete decoupling control of the current loop.

For high performance SynRM drive systems, maximum torque per ampere (MTPA) is widely used due to implementation simplicity and minimum copper loss[2]. Nevertheless, when iron loss outweighs copper loss and have to be taken into account as well, maximum efficiency (ME) control is more appropriate to minimize the total loss in any state[3]. When the speed exceeds the rated value, maximum torque per voltage (MTPV) control is designed to realize deep field-weakening, which the traditional field-weakening control with negative d-axis current compensation is incapable of[4].

In this paper, current feedback decoupling is derived for SynRM model considering the iron losses to realize the complete decoupling control. More importantly, a novel control strategy combined...
MTPA, ME and MTPV determined by operating conditions of the motor is introduced and implemented in a vector control system and verified with the aid of experimental results.

2. Mathematical model of synchronous reluctance motor

The d- and q-axis equivalent circuits for the SynRM, including iron loss[3], are shown in figure 1.

Based on the aforementioned equivalent circuits, the mathematical model of the SynRM is given by the following equations:

\[
\begin{align*}
u_d &= R_s i_{sd} + L_d \frac{d i_{sd}}{dt} - \omega L_{q,iq} i_{iq}(1 + \frac{R_s}{R_c}) \\
u_q &= R_s i_{sq} + L_q \frac{d i_{sq}}{dt} + \omega L_{d,iq} i_{iq}(1 + \frac{R_s}{R_c})\end{align*}
\]

(1) (2)

\[
\begin{align*}i_{sd} &= i_{sd} + L_d \frac{d i_{sd}}{dt} - \frac{\omega L_{q,iq} i_{iq}}{R_c} \\
i_{sq} &= i_{sq} + L_q \frac{d i_{sq}}{dt} + \frac{\omega L_{d,iq} i_{iq}}{R_c}\end{align*}
\]

(3) (4)

On the basis of the d- and q-axis equivalent circuits, the total power loss, \(P_{loss}\), of the SynRM can be calculated by the sum of the copper loss, \(P_{cu}\) and the iron loss, \(P_{fe}\), as (5).

\[
P_{loss} = P_{cu} + P_{fe} = \frac{3}{2} R_s (i_{sd}^2 + i_{sq}^2) + \frac{3}{2} R_c (i_{sd}^2 + i_{sq}^2)\]

(5)

3. Proposed control strategy

3.1. Current feedback decoupling control considering iron loss

It can be seen from equation (1) and (2) that the d-axis voltage is not only controlled by the d-axis current, but also affected by the change of the q-axis current. The coupling component accretes with speed increasing, which will cause the inaccuracy of current control and the deterioration of dynamic performance. The current feedback decoupling control can realize the decoupling control of the current controller by introducing a compensation term equal to the coupling term at the output of the d- and q-axis current controllers as follows:

\[
\begin{align*}u_d^* &= G_{i_{sd}}(s)(i_{sd}^* - i_{sd}) - \omega L_{q,iq} i_{iq}(1 + \frac{R_s}{R_c}) \\
u_q^* &= G_{i_{sq}}(s)(i_{sq}^* - i_{sq}) + \omega L_{d,iq} i_{iq}(1 + \frac{R_s}{R_c})\end{align*}
\]

(6) (7)
After the current decoupling, the mathematical model of the SynRM is transformed from a nonlinear system into a linear one which does not include the coupling term of speed and current. The actual control variable is no longer \( s_d \) and \( s_q \) but \( o_d \) and \( o_q \), which omits the process of variable conversion. At the same time, the proposed method also avoids the oscillation and instability problem caused by the conversion process with differential terms and speed related terms.

3.2. Combined control of MTPA and ME in constant torque region

According to [5], the speed has little effect on \( c_R \), so it can be approximately considered that \( c_R \) is a constant value in the process of speed variations. In order to distinguish the iron loss under different working conditions, define the control variable \( \beta = T_L / T_{rate} \) \((0 < \beta < 1)\), where \( T_L \) is the load torque and \( T_{rate} \) is the rated torque[6]. Thus, the electrical power loss \( (P_{loss}) \) can be rewritten as:

\[
P_{loss} = P_{cu} + \beta P_{fe} = \frac{3}{2} R_s (i_d^2 + i_q^2) + \frac{3}{2} \beta R_c (i_d^2 + i_q^2)
\]

\[
= \frac{3}{2} \left[ R_s + (R_s + \beta R_c) \frac{\omega_c^2 L_d^2}{R_c^2} \right] i_d^2 + \frac{3}{2} \left[ R_c + (R_c + \beta R_s) \frac{\omega_c^2 L_q^2}{R_c^2} \right] i_q^2 + \frac{3}{2} \left[ \frac{2 R_s}{R_c} \omega_c (L_d - L_q) \right] i_d i_q
\]

Define the ratio of torque producing d-axis current to torque producing q-axis current as \( \xi = i_q / i_d \), by solving \( \partial P_{loss} / \partial \xi = 0 \), the optimal ratio of currents can be found as (9), refered to [3]:

\[
\xi = \frac{i_q}{i_d} = \frac{R_s R_c^2 + (R_s + \beta R_c) \omega_c^2 L_d^2}{R_c R_s^2 + (R_c + \beta R_s) \omega_c^2 L_q^2}
\]

3.3. MTPV control in field-weakening region

MTPV control is to maximize the utilization of DC bus voltage under a given electromagnetic torque in the voltage limit circle restricted by the output capacity of the inverter, which is equivalent to the following extremum problem considering iron loss as below:

\[
\begin{align*}
\{ (1 + \frac{R_s}{R_c})^2 \left( \omega_c L_d i_{dq} \right)^2 + \left( \omega_c L_q i_{eq} \right)^2 \} & \leq u_{smax}^2 \\
T_c & = \frac{3}{2} n_p (L_d - L_q) i_d i_q
\end{align*}
\]

The auxiliary function is established by Lagrange multiplier method:

\[
F = \frac{3}{2} n_p (L_d - L_q) i_d i_q + \lambda \left\{ (1 + \frac{R_s}{R_c})^2 \left( \omega_c L_d i_{dq} \right)^2 + \left( \omega_c L_q i_{eq} \right)^2 \right\}
\]

By solving \( \partial F / \partial i_d = 0 \), \( \partial F / \partial i_q = 0 \) and \( \partial F / \partial \lambda = 0 \) simultaneously, we can get the current distribution of MTPV as \( \xi = i_q / i_d = L_d / L_q \).

3.4. Smooth switching strategy between constant torque and field-weakening regions

The voltage amplitude \( \sqrt{u_d^2 + u_q^2} \) is calculated from the voltage reference \( u_d, u_q \), and compared to a limit value \( u_{smax} \). The error \( u_{smax} - \sqrt{u_d^2 + u_q^2} \) is then processed by an integral controller that generates
the parameter $K_1$ which is limited between ±1. Then $K_1$ is used for the calculation of the coefficient $K_2$: When $K_1$ is positive, $K_2 = K_1$; when $K_1$ is negative, $K_2 = 0$. The actual current angle controlled by $K_2$ is $\alpha = K_2 \alpha_{MTPA} + (1 - K_2) \alpha_{MTPV}$. Until the voltage amplitude $\sqrt{u_d^2 + u_q^2}$ is lower than $u_{s,max}$, the drive is forced to operate along the trajectory of combined control of MTPA and ME control. Afterwards, with $K_1$ ranging from 1 down to 0, the SynRM is commanded to work in a point of the field-weakening region determined by MTPV[4].

4. Simulation results

The specification and parameters of the SynRM used throughout this paper are summarized in table 1.

Table 1. Simulation parameters of SynRM.

| SynRM specifications | Rate voltage (V) | 220 |
|----------------------|-----------------|-----|
| Rate torque (Nm)     | 9.55            |
| Rate current (A)     | 11              |
| Rate speed (rpm)     | 1500            |
| SynRM parameters     |                 |
| Stator resistance (Ω) | 1.03            |
| Iron loss resistance (Ω) | 480          |
| Quadrature-axis inductance (mH) | 9       |
| Inertia coefficient (kg.m2) | 0.000265       |
| Friction coefficient (Nm/sec/rad) | 0.000036     |
| Number of pole pairs | 2               |

The simulation based on 1.5kW SynRM were carried out in MATLAB/Simulink on the basis of figure 2 in order to verify the feasibility and superiority of the proposed combined control method.

Figure 3 shows simulation results of the electromagnetic torque for desired torque reference in case of the proposed combined control approach. When the load torque is suddenly increased to the rated torque at 2s and 4.5s, the comparison shows that the MTPA control has less torque ripple and better dynamic response than ME control. It can be seen from figure 3 (c) that the dynamic performance is significantly improved after combining ME control with MTPA control.
As can be seen from figure 4, the operating efficiency reaches 75% at rated speed and torque using ME control and the combined control of MTPA and ME as in figure 4 (b) (c), which is higher than the efficiency using MTPA control as 72.5%.

Figure 5 presents simulation results of the d-q axis torque producing currents according to the given speed and desired torque reference. From simulation results, $i_{ad}$ keep equal to $i_{aq}$ in MTPA control. On the contrary, according to the ME control strategy, these two current are not equal. When the motor is running at no-load, $i_{ad}$ and $i_{aq}$ are equal in accordance with MTPA control. The current allocation method transforms from MTPA control toward the ME control when the command torque is increasing, therefore, the d-q axis current are no longer equal. When the speed command exceeds the rated speed, $i_{aq}$ increases with the decrease of $i_{ad}$ in line with MTPV control as in figure 5 (c).

Figure 6 shows the simulation results of the d-q axis torque producing currents for a sudden change of reference command torque at different rotational speeds. When the speed reaches 2200rpm, it cannot continue to accelerate with the given speed by

![Figure 3. Comparison of dynamic torque responses](image1.png)

![Figure 4. Comparison of efficiency](image2.png)

![Figure 5. Comparison of d- and q-axis stator currents distribution](image3.png)
traditional negative d-axis current compensation control. However, the proposed control strategy can achieve at least twice the rated speed which has higher field-weakening speed range as in figure 6.

![Figure 6](image)

**Figure 6.** Comparison of effect of field weakening: (a) Proposed combined control; (b) Traditional negative d-axis current compensation control

5. Conclusion

In this paper, an improved current feedback decoupling control strategy is proposed with iron loss considered, which realizes the complete decoupling. In order to achieve efficiency optimization and flux weakening speed expansion, a control strategy combining MTPA and ME is proposed under the base speed, and the flux weakening control strategy based on MTPV is adopted above the base speed. The idea of combined control proposed in this paper is intended to use different control ideas under different working conditions according to the optimal operation performance objectives of the motor, so as to maximize the advantages of the three control ideas to achieve the operation performance optimization. The combined control method is verified and researched via steady state and dynamic simulations of the SynRM’s vector control system. In order to make the proposed control strategy closer to the practical application, it is of great significance to consider the variation of motor parameters based on the proposed method in the future research.

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