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THE FLUX-WEAKENING CONTROL OF INTERIOR PERMANENT MAGNET SYNCHRONOUS TRACTION MOTORS FOR HIGH-SPEED TRAIN

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ABSTRACT

Interior Permanent Magnet Synchronous Motor (IPMSM) has the advantages of high efficiency, good performance of speed regulation and so on. So the IPMSM is suited to high-speed train traction system. This paper introduces the operation principle of IPMSM which used in high-speed train traction and the process of flux-weakening control under the limit of the current limit trajectory and the voltage limit trajectory. When the IPMSM's speed is higher than the rated speed, the q-axes current and d-axes current couple deeply, the traditional flux-weakening control strategy can't achieve ideal control effect. The paper introduces a flux-weakening control strategy which is easy to achieve and has good robustness—a single current regulator flux-weakening control strategy. The single current regulator flux-weakening control strategy broadens the motor speed range and makes the IPM used in high-speed train operate steady with high speed. The simulation of the traditional flux-weakening control strategy and the single current regulator flux-weakening control strategy in MATLAB/SIMULINK proves that the single current regulator flux-weakening control strategy can easy to achieve and has wide speed range, rapid response speed and good robustness.

KEYWORDS

High-speed train traction system, IPMSM, Flux-weakening, simulation.

INTRODUCTION

In recent years, due to the advantages of IPMSM such as low noise and maintenance quantity, small volume, simple structure, strong armature reaction, high mechanical strength, high power factor, high power density and efficiency, high torque to inertia ratio and high reliability (S. Chi. 2007), the IPMSM is suited to high-speed train traction system. The high-speed train traction system requires not only high output torque but also wide operating speed range. So the flux-weakening control research of IPMSM is of great significance (S. Morimoto, M. Sanada, and Y. Takeda. 1994). In traditional flux-weakening control strategy, there is a speed regulator and two current regulators, one for i_q and another i_d regulation. We calculate i_d through i_q and many motor parameters. As those motor parameters vary with motor running state, so the traditional flux-weakening control strategy has poor motor parameter robustness (P. Ching-Tsai and S. M. Sue. 2005; Z. X. Fu. 2003). When the IPMSM's speed higher than the rated speed, the q-axes current and d-axes current couple deeply, the two current regulators, one for i_q and another i_d regulation, become saturated and conflict with each other. As a result, the current, torque and speed of the IPMSM motor can't be controlled as desired and, worse yet, the whole system tends to become unstable. The single current regulator flux-weakening control strategy use one current regulator and directly give the q axes voltage (Longya Xu, ZHANG Yuan, MUSTAFA K G. 2008). The single current regulator flux-weakening control strategy recognizes that because of a strong mutual coupling between i_q and i_d at high speeds. The single current regulator flux-weakening control strategy can easy to achieve and has wide speed range, rapid response speed and good robustness.

ANALYSIS OF FLUX-WEAKENING CONTROL

Constant torque region

The air gap in the IPMSM is not homogeneous, so we use the dual axes theory to analysis the problem of IPMSM. We treat the base wave excitation magnetic axes as the d axle and pull ahead d axes 90° electrical down the rotor direction as q axes. Figure 1 is the vector diagram of the PMSM. The stator current vector is the resultant of the quadrature and direct axes currents and its magnitude is given by the peak value of the d and q currents.

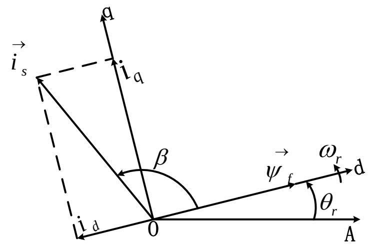


Figure 1 Vector diagram of the PMSM

$\vec{i}_s$ — Stator current vector;

$\vec{\psi}_f$ — Mutual air gap flux linkage;

β — Angle between the mutual Flux and stator current vector;

i_d — Stator d-axes current vector;

i_q — Stator q-axes current vector;

θ_r — Angle between d-axes and A-axes;

The air gap torque is obtained as

$$
\begin{aligned}
T_e &= \frac{3}{2} p_n [\psi_f i_s \sin\beta + \frac{1}{2}(L_d - L_q) i_s^2 \sin 2\beta] \\
&= \frac{3}{2} P_n [\psi_f i_q + (L_d - L_q) i_d i_q]
\end{aligned}
\tag{1}
$$

L_d — d-axes stator inductances;

L_q — q-axes stator inductances;

P_n — Number of poles;

The air gap torque and its individual components are shown in Figure 2 as a function of the torque angle. The sum of the synchronous and reluctance torque yields the air gap torque and its peak is at a torque angle greater than 90 °.

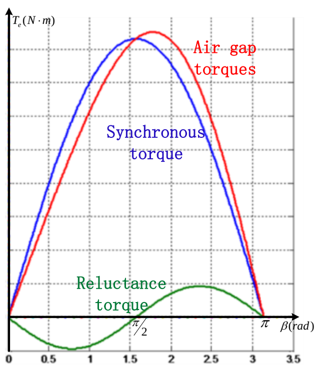


Figure 2 Reluctance, synchronous and air gap torques versus torque angle

It may be seen from Figure 2 that the maximum torque per unit current occurs in the torque angle region between 90 ° and 180 °. From the Figure 1, we can see that the current i_d is negative when the torque angle range between 90 ° and 180 °.

A control strategy to maximal electromagnetic torque for a unit stator current (MTPA) is valuable from the optimum machine (T. M. Jahns, G. B. Kliman and T. W. Neumann. 1986). When the electromagnetic torque is given, we make the stator current vector modulus minimum. The stator current vector modulus:

$$i_s = \sqrt{i_d^2 + i_q^2} \tag{2}$$

It is a problem of conditional extreme, we introduce the auxiliary function

$$H = \sqrt{i_d^2 + i_q^2} + \lambda \left\{ T_e - \frac{3}{2} P_n [\psi_f + (L_d - L_q) i_d] i_q \right\} \tag{3}$$

λ — Lagrange multiplier;

We solve the partial derivative of formula (3) and make them equal to zero

$$\begin{cases} \dfrac{\partial H}{\partial i_d} = \dfrac{i_d}{\sqrt{i_d^2 + i_q^2}} - \dfrac{3}{2} \lambda P_n (L_d - L_q) i_q = 0 \\ \dfrac{\partial H}{\partial i_q} = \dfrac{i_q}{\sqrt{i_d^2 + i_q^2}} - \dfrac{3}{2} \lambda P_n [\psi_f + (L_d - L_q) i_d] = 0 \\ \dfrac{\partial H}{\partial \lambda} = T_e - \dfrac{3}{2} P_n [\psi_f + (L_d - L_q) i_d] i_q = 0 \end{cases} \tag{4}$$

The result is

$$i_d = \frac{\psi_f}{2(L_q - L_d)} - \sqrt{\frac{\psi_f^2}{4(L_d - L_q)^2} + i_q^2} \tag{5}$$

The constant torque curve, current limit curve and trajectory of MTPA in d-q axes plane are shown in Figure 3.

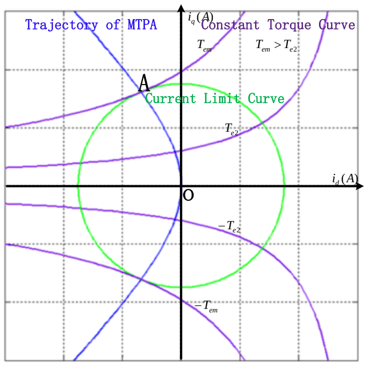


Figure 3 constant torque curve, current limit curve and trajectory of MTPA in d-q axes plane

Constant power region

The maximal input current of IPMSM is limited by the maximal output current of inverter.
The formula of current limit curve is

$$i_d^2 + i_q^2 \le i_{s\max}^2 \tag{6}$$

Formula (6) expresses the current limit and inner circle area. The stator current vector track symmetric distribute in the second and third quadrant. The torque in second quadrant is positive (motoring) and in the third quadrant is negative (generating).

T_{em} is the maximum torque of IPMSM corresponding to the point A in Figure 3. Point A is the point of tangency of the constant torque curve and the current limit curve and it is in the line of trajectory of MTPA.

The voltage equations of IPMSM in the synchronous reference frame at steady state can be expressed as follows:

$$\begin{cases} u_d = R_s i_d - \omega_r L_q i_q \\ u_q = R_s i_q + \omega_r (L_d i_d + \psi_f) \end{cases} \tag{7}$$

u_d, u_q —d-axes and q-axes components of stator terminal voltage;

R_s —resistance of armature winding;

ω_r —rotor (electrical) angular velocity;

We use the VVVF control below the rated speed. For a given load torque, we regulate d-axes and q-axes current according to the principle maximum torque per current and make the current vector in the trajectory of MTPA. The motor speed increase and input voltage rise. When the input voltage to the limit voltage of inverter, we should weaken the flux to increase the speed. From the Figure 1, we can see that the d-axes current become more negative and the q-axes current decrease.

The maximal input voltage of IPMSM is limited by the maximal output voltage of inverter. When the motor speed is higher than the rated speed, we can neglect the stator resistant. From the formula (7), we can get the formula (8) as blew

$$(L_q i_q)^2 + (L_d i_d + \psi_f)^2 \le (\frac{u_{s\max}}{\omega_r})^2 \tag{8}$$

Formula (8) expresses the current limit and inner circle area. With the rise of the motor speed, voltage limit curve narrow. The constant torque curve, current limit curve, voltage limit curve, trajectory of MTPA and trajectory of maximal torque per voltage (MTPV) in d-q axes plane are shown in Figure 4 (S. Morimoto, Y. Takeda, T. Hirasa and K. Taniguchi. 1990).

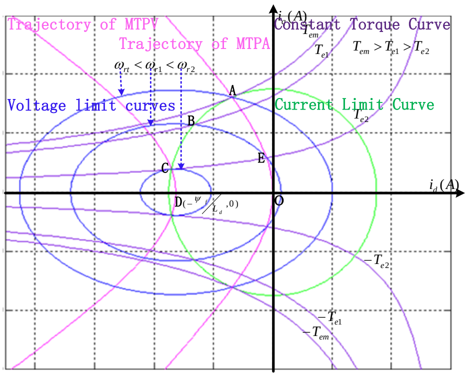


Figure 4 constant torque curve, current limit curve, voltage limit curve, trajectory of MTPA and trajectory of maximal torque per voltage in d-q axes plane neglecting stator resistance

When the motor speed is ω_{rt}, the output torque of IPMSM is T_{em} and the input voltage of IPMSM achieve to the limit voltage which point A is in. The speed ω_{rt} is the turning speed. When the speed is ω_{r1}, point B is in the voltage limit curve and point A is outside of the voltage limit curve. The points which are outside of the voltage limit curve can't be tracked. When the speed is ω_{r1}, the maximal output torque of IPMSM is T_{e1} which point B is in. Point B is intersection of the voltage curve and current limit curve. When the speed is ω_{r2}, the maximal output torque of IPMSM is T_{e2} which point C is in. Point C is intersection of the voltage curve and current limit curve. Point C is the point of tangency of constant torque curve and voltage limit curve. If the motor speed continues to rise, the point of tangency of constant torque curve and voltage limit curve is in the trajectory of maximal torque per voltage which is in the internal of the current limit curve.

To get the trajectory of maximal torque per voltage, base on the formula (1) and (8), we introduce the auxiliary function

$$H = \sqrt{(L_d i_d + \psi_f)^2 + (L_q i_q)^2} + \lambda \left\{ T_e - \frac{3}{2} P_n [\psi_f + (L_d - L_q) i_d] i_q \right\} \tag{9}$$

We solve the partial derivative of formula (9) and make them equal to zero

$$\begin{cases} \dfrac{\partial H}{\partial i_d} = \dfrac{(L_d i_d + \psi_f) L_d}{\sqrt{(L_d i_d + \psi_f)^2 + (L_q i_q)^2}} - \dfrac{3}{2}\lambda P_n (L_d - L_q) i_q = 0 \\ \dfrac{\partial H}{\partial i_q} = \dfrac{L_q^2 i_q}{\sqrt{(L_d i_d + \psi_f)^2 + (L_q i_q)^2}} - \dfrac{3}{2}\lambda P_n [\psi_f + (L_d - L_q) i_d] = 0 \\ \dfrac{\partial H}{\partial \lambda} = T_e - \dfrac{3}{2} P_n [\psi_f + (L_d - L_q) i_d] i_q = 0 \end{cases} \tag{10}$$

The result is

$$i_d = -\frac{\psi_f}{2L_d} - \frac{\psi_f}{2(L_d - L_q)} + \frac{\sqrt{L_d^2 L_q^2 \psi_f^2 + 4L_d^2 L_q^2 i_q^2 (L_d - L_q)^2}}{2L_d^2 (L_d - L_q)} \tag{11}$$

The formula (11) is the analytical expressions of the trajectory of maximal torque per voltage. The curve of A-B-C-D represents the maximal output torque of IPMSM. The flux-weakening area is surrounded by the curve of O-A-B-C-D-O. When the output torque of IPMSM is T_{e2} and the motor speed is ω_{r1}, the steady working point E is the intersection of the constant torque curve of T_{e2} and the trajectory of MTPA. The point E is also in the voltage limit curve. If the motor speed continues to rise, the steady working point is the intersection of the constant torque of T_{e2} and the voltage limit curve. The formula of the steady working point is as below

$$i_d = -\frac{\psi_f}{L_d} + \frac{1}{L_d}\sqrt{\left(\frac{u_{s\max}}{\omega_r}\right)^2 - (L_q i_q)^2} \tag{12}$$

THE FLUX-WEAKENING CONTROL STRATEGY

The traditional flux-weakening control strategy

In traditional flux-weakening control strategy, there is a speed regulator and two current regulators, one for i_q and another i_d regulation. We calculate i_d through i_q. When the input voltage is lower than the limit voltage, we can use the formula (5) to get the current i_d. When the input voltage is higher than the limit voltage, we can use the formula (12) to get the current i_d. The control diagram is shown in Figure 5.

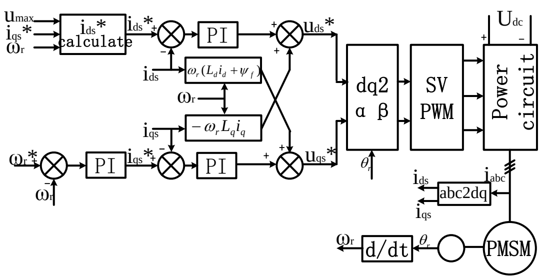


Figure 5 control diagram of the traditional flux-weakening control strategy

The traditional flux-weakening control strategy has poor motor parameter robustness. When the IPMSM's speed higher than the rated speed, the q-axes current and d-axes current couple deeply, the two current regulators, one for i_q and another i_d regulation, become saturated and conflict with each other. As a result, the current, torque and speed of the IPMSM motor can't be controlled as desired and, worse yet, the whole system tends to become unstable.

The single current regulator flux-weakening control strategy

The single current regulator flux-weakening control strategy use one current regulator and directly give the q axes voltage. The single current regulator flux-weakening control strategy recognizes that because of a strong mutual coupling between i_q and i_d at high speeds. The control diagram is shown in Figure 6 (S. Chi. 2007; Longya Xu; Shengming Li. 2001; S. Chi and L. Xu. 2006).

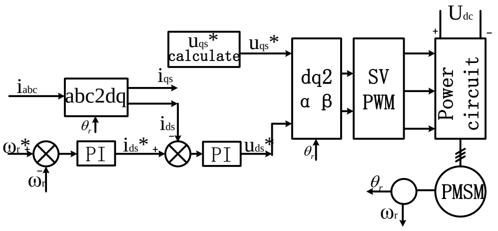


Figure 6 control diagram of the single current regulator flux-weakening control strategy

The single current regulator flux-weakening control strategy can easy to achieve and has wide speed range, rapid response speed and good robustness.

THE SIMULATION RESULTS AND DISCUSSIONS

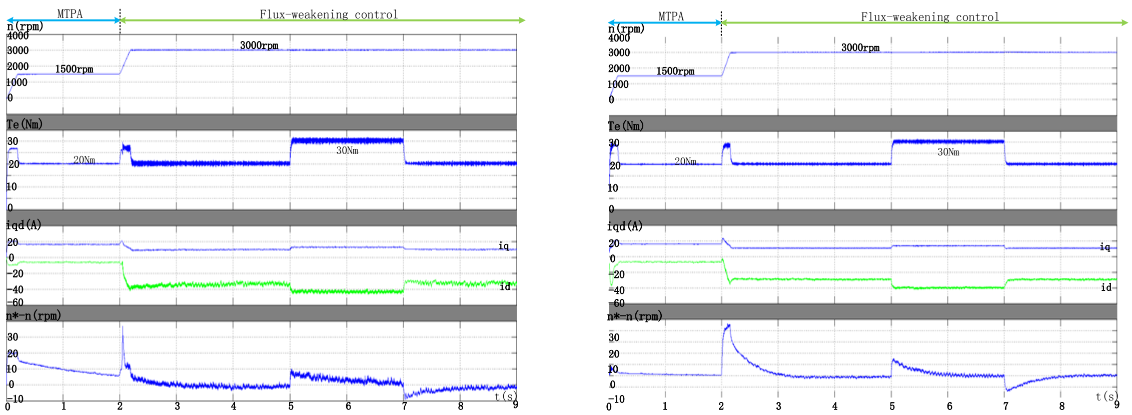
In order to verify the above analysis, we use MATLAB/SIMULINK to simulate both the traditional flux-weakening control strategy and the single current regulator flux-weakening control strategy. Some important parameters and rating of IPMSM are listed in Table Ⅰ.

Table Ⅰ Parameters and ratings of IPMSM

Rated output power	20kW
Rated DC bus voltage	300V
Rated phase current	56A
Number of poles	4

The DC bus voltage is fixed at 300V. The motor speed rises from 0 revolutions per minute to 1500 revolutions per minute in 0 SEC and from 1500 revolutions per minute to 3000 revolutions per minute in 3 SEC. At 0 to 5 seconds, the load torque is 20 Nm. At 5 to 7 seconds, the load torque is 30 Nm. At 7 to 9 seconds, the load torque is 20 Nm. The output speed, electromagnetic torque, q-axes and d-axes current and D-value of the given speed and the current speed of the simulation are shown in Figure 7.

When the load torque varies from 20Nm to 30 Nm, or from 30 to 20 Nm, the motor with traditional flux-weakening control strategy takes two seconds to recover steady and the motor with single current regulator flux-weakening control strategy only need one second.

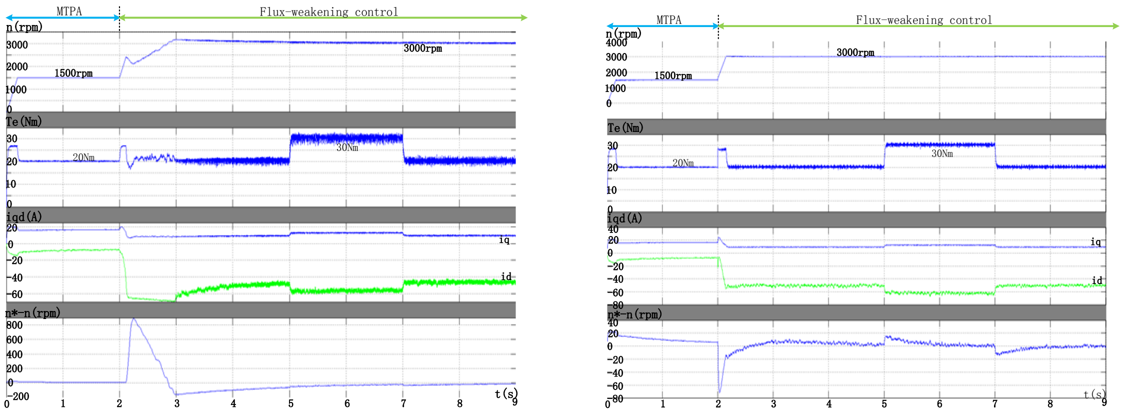


(a) The traditional flux-weakening control (b) The single current regulator flux-weakening control

Figure 7 Dynamic response of flux-weakening control strategy

Based on the above condition, we only change the d-axes and q-axes stator inductances. The output speed, electromagnetic torque, q-axes and d-axes current and D-value of the given speed and the current speed of the simulation are shown in Figure 8.

The traditional flux-weakening control strategy contains stator inductances of motor while the single current regulator flux-weakening control strategy does not. When the motor speed rises from 1500 revolutions per minute to 3000 revolutions per minute in 2 SEC, the motor with traditional flux-weakening control strategy takes six seconds to recover steady and the motor with single current regulator flux-weakening control strategy only need two second. The D-value of the given speed and the current speed of the motor with traditional flux-weakening control strategy is bigger than the D-value of the motor with single current regulator flux-weakening control strategy. When the load torque varies from 20Nm to 30 Nm or from 30 to 20 Nm, the motor with single current regulator flux-weakening control strategy only need one second. The single current regulator flux-weakening control strategy has rapid response speed and good robustness.

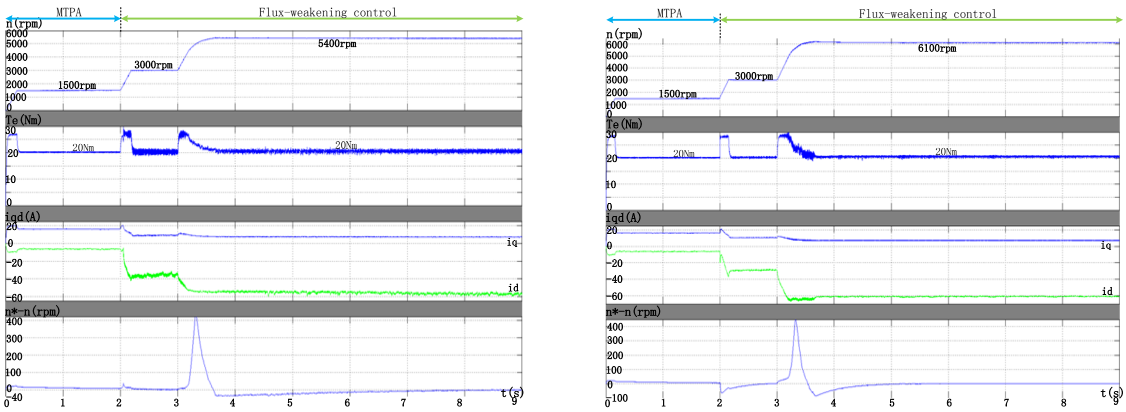


(a) The traditional flux-weakening control (b) The single current regulator flux-weakening control

Figure 8 Parameters robustness of flux-weakening control strategy

The DC bus voltage is fixed at 300V. The load torque is fixed at 20 Nm. The output speed, electromagnetic torque, q-axes and d-axes current and D-value of the given speed and the current speed of the simulation are shown in Figure 9.

The top speed of motor with traditional flux-weakening control strategy is 5400 revolutions per minute and the top speed of motor with single current regulator flux-weakening control strategy is 6100 revolutions per minute. The single current regulator flux-weakening control strategy has wide speed range.



(a) The traditional flux-weakening control (b) The single current regulator flux-weakening control

Figure 9 Top speed of flux-weakening control strategy

CONCLUSIONS

We introduced the principle of weakening-flux control and we can see that the single current regulator flux-weakening control strategy can easy to achieve and is less affected by motor parameters. From the simulation results of traditional flux-weakening control strategy and single current regulator flux-weakening control strategy, we can see that the single current regulator flux-weakening control strategy has rapid response speed good robustness and wide speed range.

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