Chapter 53
Research on Flux Weakening Speed Control Strategy for PMSM

Lei Qian, Haizhen Liu, Rui He and Weiwen Deng

Abstract Electronic assisted brake systems require permanent magnet synchronous motor (PMSM) to work in a larger speed range, and to maintain a certain ability to resist load disturbance. In this paper, the mathematical model of PMSM and the flux weakening control theory are analyzed at first. Then a control strategy is proposed based on maximum torque per ampere (MTPA) control combined with flux weakening control principle, which also takes the current compensation decoupling into account. In the MATLAB/Simulink environment, a double closed-loop model of flux weakening speed control of PMSM is presented. Finally simulation experiments prove that the control strategy can improve both the speed range of PMSM and the ability to resist load disturbance.

Keywords Electronic assisted brake · PMSM · MTPA · Flux weakening control

53.1 Introduction

With the development of new energy vehicles, many manufactures are devoting themselves to electronic assisted brake systems, which not only provide more excellent braking performance than traditional braking system, but also recycle braking energy efficiently to improve the fuel economy of vehicles. In case of an emergency, it can also realize the function of the automatic emergency braking to ensure the safety of the vehicle. However, the automatic emergency braking requires that motor speed is as high as possible, while the system nonlinear friction needs that the motor has certain ability to resist load disturbance.

Many scholars bend themselves to flux weakening speed control of PMSM to improve the speed of the motor constant power operation scope and the ability to resist load disturbance of the machine. The literature [1] proposes a sliding mode current decoupling control strategy based on an internal model, which improves the

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system dynamic performance and has good robustness. The literature [2] uses the gradient descending method to make motor running along the weak magnetic curve by real-time adjustment of weak magnetic direction, but it is difficult to achieve because of the large amount of calculation. The literature [3] adopts the negative *d* axis current compensation method, which adjusts *d* axis degaussing current size according to deviation between the *d* axis, *q* axis voltage reference value and its maximum limit. The literature [4] builds a model based on voltage feedback weak magnetic algorithm of the control system, and the simulation results verify the feasibility and effectiveness of the weak magnetic control method based on voltage feedback.

In this paper, a new control strategy is put forward based on maximum torque per ampere (MTPA) control combined with flux weakening control principle, which also takes the current compensation decoupling into account. And in the MATLAB/Simulink environment, the simulation results improve the effectiveness of the strategy.

53.2 PMSM Model and Flux Weakening Control Principle

In the *d/q* coordinate system, the following assumptions is proposed for the simplified model for deduction.

1. Ignoring iron core saturation.
2. Regardless of the eddy current and hysteresis losses.
3. Rotor without damping windings and permanent magnet without damping effect.
4. The three-phase winding is completely symmetrical, and the stator current and rotor magnetic field distribution is symmetrical.

Based on the above assumptions, in the *d/q* coordinate system, the voltage equation of PMSM is:

$$\begin{cases} u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \psi_f \\ u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \end{cases} \tag{53.1}$$

Electromagnetic torque equation is:

$$T_e = 1.5 P_n \left[\psi_f i_q - (L_d - L_q) i_d i_q \right] \tag{53.2}$$

Motion equation is:

$$T_e = J \frac{d\omega_r}{dt} + B\omega_r + T_l \tag{53.3}$$

In Eqs. (53.1), (53.2), and (53.3), u_q, u_q is the q, d axis voltage of the motor. i_q, i_d is the q, d axis stator current. L_q, L_d is the q, d axis inductance. ω, ω_r is the rotor electrical angular velocity and mechanical angular velocity. R_s is the stator resistance. ψ_f is the rotor flux linkage. P_n is the magnetic poles logarithmic. T_e is the electromagnetic torque. J is the moment of inertia of the motor. B is the motor damping coefficient. T_l is the motor load torque.

For surface-mounted PMSM, Eq. (53.2) can be simplified as follows:

$$T_e = 1.5 P_n \psi_f i_q \tag{53.4}$$

By DC side voltage and output current largest capacity constraints of PMSM, motor stator voltage and current have a limit value, which will affect the range of maximum speed and output torque of the motor. The flux weakening control is to reduce the induction electromotive force by weakening the air-gap flux, and make it less than the input voltage in order to expand the scope of the motor speed.

When the current maximum value is $I_{\max}$, the current limit equation is:

$$i_d^2 + i_q^2 \le I_{\max}^2 \tag{53.5}$$

When the voltage maximum value is $U_{\max}$, the voltage limit equation is:

$$(L_d i_d + \psi_f)^2 + (L_q i_q)^2 \le \left(\frac{U_{\max}}{\omega}\right)^2 \tag{53.6}$$

On the basis of Eqs. (53.5) and (53.6), current limit circle and voltage limit ellipse are drawn under the d/q axis coordinates as shown in Fig. 53.1.

Figure 53.1 shows that when the motor is running, stator current vector must be in the intersection of the current limit circle and voltage limit ellipse (the shadow

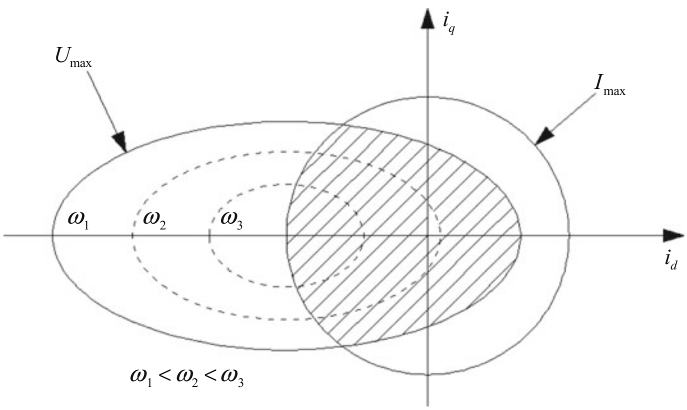

Fig. 53.1 The current limit *circle* and voltage limit *ellipse*

part of the figure). At the same time, with the increase of rotor electrical angular velocity, the voltage limit ellipse and the motor working range will decrease. Decreasing i_q or negatively increasing i_d can make the working point to keep within the shadow of the machine.

53.3 Strategy of Flux Weakening Speed Control

Taking surface-mounted PMSM as an example, a control strategy is put forward based on the current compensation decoupling and the combination of the maximum torque current ratio control and weak magnetic control. The constant torque area adopts the maximum torque current ratio control, while the constant power area carries out the flux-weakening control strategy.

When motor mechanical angular velocity is less than the base velocity, it is in the constant torque area, and the maximum torque current ratio control strategy works. In order to make the electromagnetic torque as bigger as possible under the condition of certain stator current, there will be:

$$\begin{cases} i_d = 0 \\ i_q = i_s \end{cases} \tag{53.7}$$

Equation (53.7) is the basis of maximum torque current ratio control strategy (i_s is stator current vector).

When the motor mechanical angular velocity is greater than the base velocity, it is in the constant power area, and the weak magnetic control works. Due to the constant power, there are:

$$i_q = \frac{\omega_{rt}}{\omega_r} i_s \tag{53.8}$$

$$i_d = -i_s \sqrt{1 - \left(\frac{\omega_{rt}}{\omega_r}\right)^2} \tag{53.9}$$

The flux weakening speed control strategy can be executed according to Eqs. (53.8) and (53.9).

By the voltage Eq. (53.1), it can be seen that d axis and q axis exist coupling voltage, which will increase with the rise of rotor electrical angular velocity. It will seriously affect the current loop regulation performance during the high speed range. In this paper, the current feedback is adopted to compensate current loop, which weakens the effect of rotating electromotive force and the disturbance.

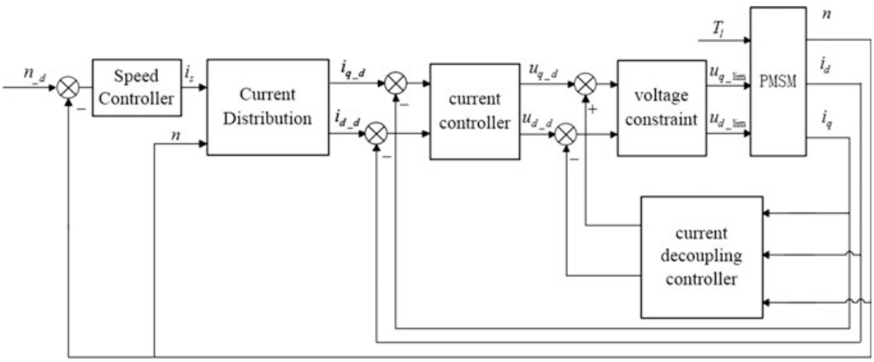

Fig. 53.2 Frame of the strategy of flux weakening speed control

$$\begin{cases} \bar{u}_q = u_q + \omega L_d i_d + \omega\psi \\ \bar{u}_d = u_d - \omega L_q i_q \end{cases} \tag{53.10}$$

Equation (53.10) can be used to current compensation decoupling.

Based on current compensation decoupling, a new control strategy is proposed which is shown in Fig. 53.2. With double closed loop control scheme, outer ring is speed loop that makes actual speed consistent with the target speed, while inner ring is current loop that plays a role on the distribution of current. Then through current decoupling controller the rotating electromotive force and the disturbance are eliminated. Finally *d* axis and *q* axis voltage are input to PMSM model by the voltage constraints module.

53.4 Simulation Experiment and Results

Based on the control flame in Fig. 53.2, the whole weak magnetic speed control is divided into the following several modules: speed controller module, current distribution module, current controller module, voltage constraints module, current decoupling controller module, PMSM module, etc. And each module is modeled in the MATLAB/Simulink environment. Below two groups of simulation experiments are done to validate that the flux weakening speed control strategy is effective.

The parameters of PMSM in the simulation experiment are shown in Fig. 53.3.

1. Simulation Experiment One
   The motor starts with 1 Nm load from zero speed. The target speed is 3500 rpm. And the simulation time is set to 0.2 s. Conduct simulation experiments without flux weakening speed control strategy and with flux weakening speed control strategy in turn. The result is shown in Fig. 53.4.

Fig. 53.3 The parameters of PMSM in the simulation experiment

Motor Parameter	**value**
Stator Resistance (Ω)	0.0085
q/d Axis Inductance (mH)	0.00017
Magnetic Poles logarithmic	4
Rotor Flux Linkage (Wb)	0.00875
Rated Torque(Nm)	4.2
Rated Speed (rpm)	1000
Rated Current (A)	80
DC Bus Voltage (V)	12
Moment of Inertia (kg·m^2)	1×10^{-4}

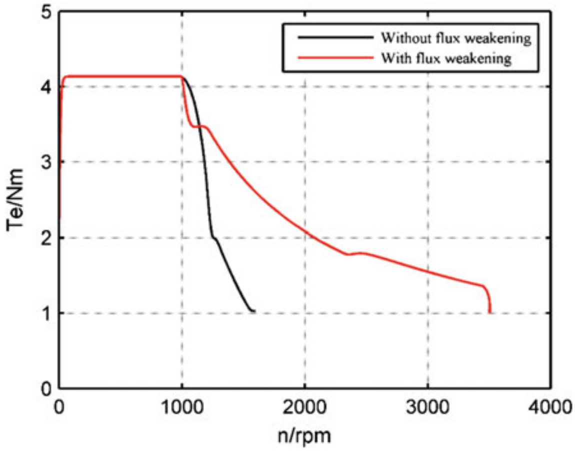

Fig. 53.4 Torque and speed characteristic curve of PMSM

In Fig. 53.4, the black curve is the torque and speed characteristic curve without flux weakening speed control strategy, while the red curve is with flux weakening speed control strategy. Comparing the two curves, it can be found that the working speed range is extended after adding flux weakening speed control strategy.

2. Simulation Experiment Two

   The motor speed starts with no-load from zero speed. A given motor target speed is 2000 rpm. A 1 NM load is applied on the motor suddenly at 0.1 s. And the simulation time is set to 0.2 s. Conduct simulation experiments with flux weakening speed control strategy. The result is shown in Figs. 53.5, 53.6 and 53.7.

In Fig. 53.5, the time that motor starts to achieve speed 2000 rpm is about 10 ms. And in the high speed with no load, it is running smoothly and less volatile. When a 1 NM load is applied on the motor suddenly at 0.1 s, motor speed

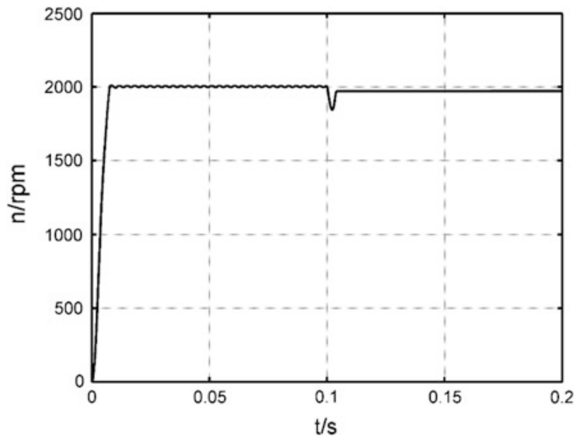

Fig. 53.5 Speed curve of PMSM with flux weakening speed control strategy

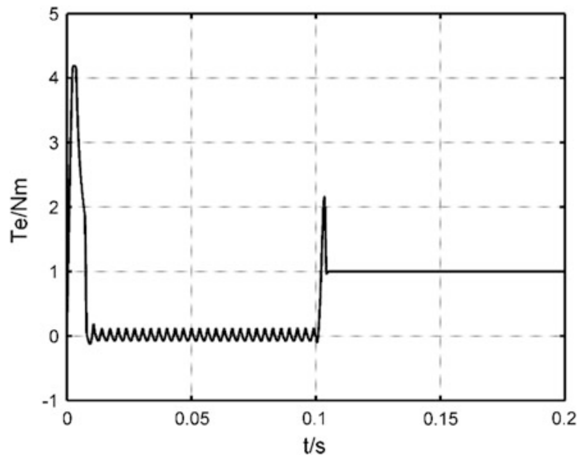

Fig. 53.6 Torque curve of PMSM with flux weakening speed control strategy

decreases slightly. But within 5 ms it is back to about 2000 rpm and motor keeps steady state. It proves that the motor has a good ability to resist the torque disturbance in high speed range.

As shown in Fig. 53.6, electromagnetic torque increases to a maximum first for making motor to approach the target speed faster, and then keep stable around 0. When a 1 NM load is applied at 0.1 s, the motor rapidly promotes electromagnetic torque to 1 NM or so.

In Fig. 53.7, three phase stator current can be separated clearly in the three different stages: motor start, weak magnetic with no load, weak magnetic with load. And the waveform of each stage is good.

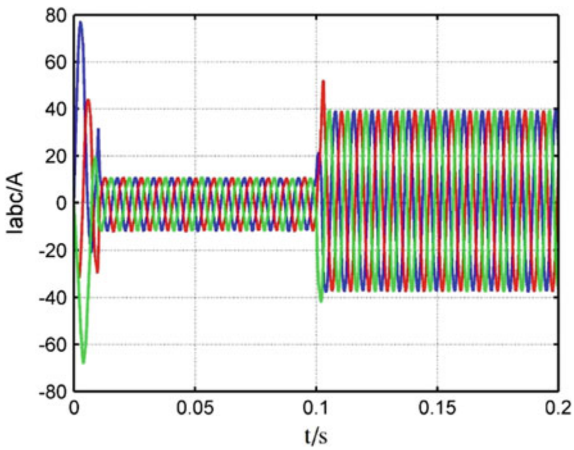

Fig. 53.7 Three phase stator current curve of PMSM with flux weakening speed control strategy

53.5 Conclusions

In this paper, a control strategy is proposed based on maximum torque per ampere control combined with flux weakening control principle, which also takes the current compensation decoupling into account. Then in the MATLAB/Simulink environment, a PMSM model with flux weakening speed control strategy is established. Simulation experiments show that the control strategy is simple, reliable and good robustness, which can improve the speed range of permanent magnet synchronous motor and the ability to resist load disturbance.

References

1. Zhou H, Zhou X, Zhao F, Zhang J (2012) Decoupled current control of permanent magnet synchronous motors drives with sliding mode control strategy based on internal model. Proc CSEE 15:91–99+10
2. Sheng Y, Yu S, Gui W, Hong Z (2010) Field weakening operation control strategies of permanent magnet synchronous motor for railway vehicles. Proc CSEE 09:74–79
3. Wang A, Jia X, Dong S (2012) Flux-weakening control for interior permanent magnet synchronous motor considering voltage saturation. J North China Electric Power Univ 05:17–21
4. Ma C (2014) Research on field-weakening control methods of permanent magnet synchronous motor. Chang’an University