Research on Control Methods of Six-phase Permanent Magnet Synchronous Motor

Jianguang Zhu¹ and Xu Chu¹

¹School of Information Science and Engineering, Shenyang University of Technology, Liaoning Province, China

Abstract. Compared with three-phase motors, multi-phase motor speed control systems have many advantages, which make them have good prospects in many fields, such as the control system of electric vehicle power equipment. In these control systems, it is necessary for the motor to have a wider speed range. This paper takes six-phase permanent magnet synchronous motors as the research object, and analyzes several control methods of vector control theory for permanent magnet synchronous motor control based on the derivation of its mathematical model, including \( i_d = 0 \) control, maximum torque per ampere (MTPA) control, and flux weakening control. Finally, MATLAB / Simulink is used for simulation research, and the advantages and disadvantages of different control methods are compared. In this paper, a strategy of MTPA control below the base speed and flux weakening control above the base speed is proposed, which not only reduces the copper consumption of the motor, but also expands the speed-up range of the permanent magnet synchronous motor.

Keywords: Six-phase permanent magnet synchronous motor; Electric vehicle power equipment; Weak magnetic control; Motor speed control system; Simulation.

1. Introduction

Permanent magnet synchronous machine (PMSM) has been widely used in speed control drive systems because of its high power density, high reliability, high efficiency and weak magnetic speed expansion [1]. In the field driven by six-phase permanent magnet synchronous motors, the speed regulation system should not only have good torque control performance, but also have a wide range of speed regulation. With the increase of the speed of PMSM, the reactive electromotive force (EMF) of motor stator windings will inevitably increase. When the back EMF reaches the rated voltage of the motor or the DC side voltage of the inverter, the input current of the motor will not be able to track the given output current of the controller, and the current regulator will be in a saturated state. At this point, it is necessary to use weakening magnetic control to reduce the reactive EMF of PMSM, in order to increase the torque output ability of PMSM at high speed [2-3].

At present, scholars at home and abroad have done a lot of research on motor control methods. [4] presents a universal maximum torque per ampere torque control algorithm for any type of permanent magnet synchronous motors, however, it is necessary to make tables, which is more complicated to implement. In [5], the curve fitting method is used to obtain the relational expression between the quadrature-direct axis current and the electromagnetic torque maximum torque per ampere control method, which is easy to realize, beneficial to engineering practice, but reducing the precision. In [6], on the basis of the voltage feedback method of weak magnetic control, the static small signal analysis, dynamic analysis and gain scheduling are added to ensure the stability of the system, but the real-time performance was poor.
In [7] a six-step voltage method is designed to realize the weak magnetic speed increasing. The power factor angle is adjusted by six voltage space motion vectors of the three-phase inverter bridge, thus controlling the electromagnetic torque of the motor output and improving the utilization ratio of the DC bus voltage. But there are many parameters needed in actual calculation, so the control system is complicated. In [8-9] a new winding switching strategy is proposed to realize the weak magnetic control, but when the winding is fully loaded, the winding switching will produce serious transient response. In [10], Chen Kunhua puts forward a control method of linearizing the weak magnetic field area by sections. Though the accuracy of the control effect after linearization will be lost, the workload of the controller will be greatly saved.

This paper proposes a strategy of MTPA control below the base speed and weak magnetic control above the base speed. The mathematical model of the multi-phase motor is established by the derivation of the formula. According to the operation state of the motor, the reference value of the AC-DC shaft current is obtained through calculation. At the same time, the AC-DC shaft voltage is obtained according to the numerical calculation of system feedback, which makes the control have good stability. Finally, the feasibility and effectiveness of the scheme are verified by simulation.

2. Mathematical Model of Six-phase Permanent Magnet Synchronous Motor

2.1. Six-phase motor vector decoupling transformation

After the coordinate transformation, the mathematical model of the six-phase PMSM meets the following equations [11].

Voltage equation:

\[
\begin{align*}
    u_d &= R \cdot i_d + p \cdot \psi_d - \omega_s \psi_q \\
    u_q &= R \cdot i_q + p \cdot \psi_q + \omega_s \psi_d
\end{align*}
\]  

(1)

Where: \( u_d \) and \( u_q \) are the Stator d- and q-axis voltages; \( i_d \) and \( i_q \) are the Stator d- and q-axis currents; \( \psi_d \) and \( \psi_q \) are the d- and q-axis flux linkage; \( \omega_s \) is the Electrical angular frequency of the motor; \( R \) is the Stator winding resistance.

Flux equation:

\[
\begin{align*}
    \psi_d &= L_d \cdot i_d + \sqrt{3} \psi_f \\
    \psi_q &= L_q \cdot i_q
\end{align*}
\]  

(2)

Where: \( L_d \) and \( L_q \) are the d- and q-axis inductances, respectively; \( \psi_f \) is the permanent magnet flux linkage.

Electromagnetic torque equation:

\[
T_{em} = n_p \left( \sqrt{3} \psi_f \cdot i_q + (L_d - L_q) i_d i_q \right)
\]  

(3)

Where: \( n_p \) is the number of pole pairs of the six-phase; \( T_{em} \) is the electromagnetic torque.

Equation of motion:

\[
T_{em} - T_L - B \cdot \omega = J \frac{d\omega}{dt}
\]  

(4)

Where: \( T_L \) is the Load torque; \( B \) is the Damping coefficient; \( J \) is the Moment of inertia; \( \omega \) is the Mechanical angular velocity

2.2. Principle of flux weakening control for permanent magnet synchronous motor

In vector control of PMSM, because the stator current and the terminal voltage are limited by the inverter output capacity, if the maximum output current is \( I_{smax} \) and the maximum supply voltage is \( U_{smax} \), then there are the following restrictions [12-13].

\[
i_d^2 + i_q^2 \leq I_{smax}^2
\]  

(5)
\[
\left(\psi_f L_d i_d\right)^2 + \left(L_q i_q\right)^2 \leq \left(\frac{U_{\text{smax}}}{\omega_e}\right)^2
\] (6)

Equation (5) indicates the value range of the current limit trajectory in the two-phase rotation coordinate system. It is within the circle with the origin as the center and \(I_{\text{smax}}\) as the radius. This circle is called the current limit circle. Equation (6) represents the value range of the voltage limit trajectory in the two-phase rotation coordinate system. It is an ellipse with \(\left(\frac{\psi_f}{L_d}, 0\right)\) as the center, which is called a voltage limit ellipse. These two limit circles are shown in Figure 1:

![Figure 1. Voltage limit ellipse and current limit circle.](image)

### 3. Six-phase PMSM Control Method

#### 3.1. \(I_d = 0\) control

\(I_d = 0\) control method is simple. In terms of the motor port, it is equivalent to a separately excited DC motor. There are only quadrature axis current, and there are only permanent magnet flux linkage in electromagnetic torque [14], and its value is:

\[
T_e = n_p \left(\sqrt{3}\psi_f i_q\right)
\] (7)

#### 3.2. MTPA control

When a PMSM runs stably under a constant torque state, any point on its constant torque curve corresponds to a pair of straight-axis current and quadrature-axis current. It can generate electromagnetic torque of the same size. Among them, there is a stator current vector that produces the same magnitude of electromagnetic torque with the smallest amplitude. It is beneficial to reduce the copper loss in the operation of the motor, improve the efficiency of the inverter, and reduce the energy loss of the entire motor system [15-17].

The problem is equivalent to (3) and (5) satisfying the conditional extreme value problem. According to the Lagrange extreme value theorem, the auxiliary function is introduced.

\[
G = \sqrt{i_d^2 + i_q^2 + \lambda \left[T_e - n_p \left(\sqrt{3}\psi_f i_q + (L_d - L_q) i_d i_q\right)\right]}
\] (8)

Find the partial derivative of (8) and make it equal to zero, get the relational equation of the quadrature-direct axis current as:

\[
i_q^* = i_d^* - \sqrt{3} i_d^*
\] (9)

Where: \(i_d^*\) and \(i_q^*\) are the Stator d- and q-axis per unit currents.

Substitute into torque scale value formula

\[
T_e^* = i_q^* \left(\sqrt{3} + i_d^*\right)
\] (10)

Where: \(T_e^*\) is the per unit electromagnetic torque.

The relationship between torque and direct axis current can be obtained

\[
i_d^* - 3\sqrt{3} i_d^* + 9 i_d^* - 3\sqrt{3} i_d - T e^2 = 0
\] (11)
3.3. Flux weakening control

The idea of weak field control of permanent magnet synchronous motor is derived from the magnetic control of separately excited DC motor. In order to achieve higher speed and constant power operation when the terminal voltage of the separately excited DC motor reaches the limit voltage, the excitation current of the motor should be reduced to balance the voltage. The magnetomotive force of a magnetic synchronous motor cannot be adjusted because it is generated by a permanent magnet. Only by adjusting the stator current, that is, increasing the demagnetizing current component of the stator shaft to maintain the voltage balance during high-speed operation, to achieve the purpose of weak field expansion.

At a certain voltage, the electrical angular speed of the motor is inversely proportional to the synthetic flux, so the control of the minimum flux torque ratio can effectively widen the speed range of the motor while keeping the torque output capability of the motor constant. The trajectory of the minimum magnetic flux torque ratio is actually the tangent point trajectory of the torque curve and the maximum magnetic flux trajectory.

From the flux equation and torque equation:

\[(i_d + \sqrt{3}\psi_f)^2 + (L_q i_q)^2 = \psi_s^2\]  \((12)\)

Where: \(\psi_s\) is the Synthetic flux linkage.

Under a certain torque, the flux linkage and the torque equation can be solved simultaneously to obtain the relationship between the combined flux linkage and the direct axis current:

\[\frac{T_e}{n_0(\sqrt{3}\psi_f + (L_d - L_q)i_d)} + (L_d i_d + \sqrt{3}\psi_f)^2 = \psi_s^2\]  \((13)\)

It can be obtained by calculation:

\[i_d = \frac{T_e^2 L_q^2 (L_d - L_q)}{n_0^2 L_d^3 (\sqrt{3}\psi_f + (L_d - L_q)i_d)^3} \cdot \sqrt{3}\psi_f \]  \((14)\)

**SIMULATION RESEARCH**

In order to verify the theoretical analysis of this article, \(i_d = 0\), MTPA and field weakening control system are established in MATLAB / Simulink, and the corresponding comparative analysis is performed.

3.4. \(i_d = 0\) and MTPA simulation comparison

Figure 2 shows the simulation waveform diagram of the speed, electromagnetic torque and stator current amplitude of the PMSM at the same speed and the same load torque under the control of \(i_d = 0\) and MTPA. The simulation results show that the motor speed of PMSM can track the given speed well under the control of \(i_d = 0\) and MTPA. With the motor speed reaching the given value, the electromagnetic torque of the motor is balanced with its load torque. Compared with the simulation results obtained by the \(i_d = 0\) control algorithm, the overshoot of the electromagnetic torque is greatly reduced, and the oscillation period of the motor to the given rotational speed decreases relatively, which makes the system can achieve stability more quickly. After the speed is stable, the stator current amplitude under \(i_d = 0\) control is 7, while that under MTPA control is 5. With the same speed and load torque, the stator current amplitude of MTPA is smaller. As a result, MTPA control can reduce the copper consumption during motor operation and improve the efficiency of the inverter.
3.5. Flux weakening control simulation

The simulation model of field weakening control is established by the formula as shown in Figure 3. The base speed of the Six-phase PMSM is 350. Above the base speed, the weak magnetic control is used to raise the speed. It can be seen from Figure 4 that the speed of the motor can finally reach 700, and it is in a stable operation state, realizing the speed up.

**Figure 3.** Flux weakening control simulation model.

**Figure 4.** Weak field speed waveform.
4. Conclusion
This paper discusses $i_d = 0$ control, maximum torque per ampere control and minimum flux per torque control, and establishes the corresponding mathematical model. Compared with $i_d = 0$ control, the maximum torque per ampere control can make the motor output torque meet a certain requirement and the minimum stator current, which is improve inverter voltage utilization and reduce the copper consumption of the motor. When the bus voltage is fixed, the electrical angular velocity of the motor is inversely proportional to the synthetic flux, and the control of the minimum flux per torque can effectively widen the range of the motor's speed control on the premise of keeping the output power of the motor's torque constant.

Acknowledgment
This work was supported by the Education Department of Liaoning Province, China (project number LGD2016010)

References
[1] Liu Wei, Research on Weakening Control Strategy of Permanent Magnet Synchronous Motor, Beijing Jiaotong University, 2014.
[2] Cao Xianqing, Research on Permanent Magnet Synchronous Motor Drive System for Hybrid Electric Vehicles, Shenyang University of Technology, 2008.
[3] XU W, ISMAIL M M, LIU Y, Parameter Optimization of Adaptive Flux-Weakening Strategy for Permanent-Magnet Synchronous Motor Drives Based on Particle Swarm Algorithm, IEEE Transactions on Power Electronics, 2019, vol. 34, pp. 12128-12140.
[4] Lei, H, Universal MTPA control for permanent magnet synchronous motor drives, 2017 2nd International Conference on Robotics and Automation Engineering (ICRAE).
[5] Tian Yitao, Wang Ying, Vector control of permanent magnet synchronous motor based on maximum torque-current ratio, Application of Motor and Control, 2013, vol. 40, pp. 25-28.
[6] Bolognani S, Calligaro S, Petrella R, Optimal voltage feed-back flux-weakening control of IPMSM. IEEE Industrial Electronics Society, 2011.
[7] Gi-Young Choi, Mu-Shin Kwak, Tae-Suk Kwon, Seung-Ki Sul, Novel Flux-Weakening Control of an IPMSM for Quasi Six-Step Operation, IEEE Transactions on Industry Applications, 2007.
[8] Hemmati S, Lipo T A, Field weakening of a surface mounted permanent magnet motor by winding switching, Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM) International Symposium, 2012.
[9] P. Sandulescu, F. Meinguet, X. Kestelyn, E. Semal, and A. Bruyère, “Control strategies for open-end winding drives operating in the fluxweakening region,” IEEE Trans. Power Electron., vol. 29, pp. 4829-4842, 2014.
[10] Chen Kunhua, Sun Yukun, Ji Jinglian, Xiang Qianwen, Research on piecewise linear ratio of field weakening control of embedded permanent magnet synchronous motor, Transactions of China Electrotechnical Society, 2015, pp. 17-22.
[11] Qiao M Z, Zhao X F, Research of the mathematical model and sudden symmetrical short circuit of the multi-phase permanent magnet motor, IEEE Proceeding on Power System Technology, 2002, pp. 769-773.
[12] Liang Bo, Research on the driving system of double Y shift 30 degree permanent magnet synchronous motor, Hunan University, 2009.
[13] Tang Renyuan, Theory and Design of Modern Permanent Magnet Motors, Beijing: Mechanical Industry Press, 2002, pp. 258-63.
[14] Morimoto S, Sanada M, Takeda Y, Wide-speed operation of interior permanent magnet synchronous motors with high-performance current regulator, IEEE Transactions on Industry Applications, 1994, vol. 30, pp. 920-926.
[15] M A Rahman. High Efficiency Permanent Magnet Synchronous Motors, LAS Annual Meeting, 1979, pp. 561-564.
[16] Sun Xuxia, Yue Jingkai, Research on MTPA Weakening Control Method of Permanent Magnet Synchronous Motor, Electric Drive, 2012.

[17] Y. S. Jeong, S. K. Sul, S. Hiti, and K. M. Rahman, “Online minimumcopper-loss control of an interior permanent-magnet synchronous machine for automotive applications,” IEEE Trans, vol. 42, pp. 1222–1229, October 2006.