Off-line Parameter Identification of Permanent Magnet Synchronous Motor

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Abstract—This paper first explains the necessity of off-line parameter identification of permanent magnet synchronous motors, and then introduces the identification methods and principles of the stator resistance, stator d/q axis inductance and back-EMF coefficient of permanent magnet synchronous motors. An identification method of stator d/q axis inductance injected with high frequency voltage is proposed. Finally, based on the MBD development model, the proposed identification method is modeled by Matlab/Simulink and the code is generated for experiments. The results verified the accuracy and feasibility of the proposed method well.

1. Introduction
AC servo motor has the characteristics of small size and light weight, and also has excellent performance such as wide speed range and fast dynamic response. In recent years, AC servo systems have gradually become the main development trend of modern servo drive systems. Among them, the permanent magnet synchronous motor (PMSM) has good low-speed performance, fast dynamic response, small moment of inertia, and high torque-to-current ratio, which can well meet the requirements of high-performance servo drives. Therefore, it has become the mainstream of AC servo systems\cite{1}.

The motors and servo drives of the motor servo control system are often provided by different manufacturers. If the user lacks an understanding of the motor parameter measurement theory or does not have equipment to measure the motor parameters, we hope that the servo drive can automatically complete the self-identification of the motor parameters for the needs of control. Moreover, in the motor servo control system, the current loop design, speed sensorless control, and field weakening control also depend on the accuracy of the motor parameters. Therefore, this article mainly studies how to accurately identify the parameters of induction motors and permanent magnet synchronous motors offline.

2. Influence of Motor Parameter Changes
Take the induction motor as an example for analysis. For induction motors, in the rotor field orientation, when the parameters are accurate, the rotor magnetic field orientation is accurate; when the parameters are deviated, there is an error between the magnetic field orientation position and the actual magnetic field position, which will cause system instability and degradation of dynamic performance\cite{2-3}.

In the sinusoidal steady state, there are the rotor voltage vector equation and the flux vector equation:

\begin{equation}
\begin{cases}
u_r = R_i + p\psi_r + j\omega\psi_r \\
\psi_r = L_n i + L_i r
\end{cases}
\end{equation}

(1)

If the motor is a squirrel-cage induction motor, \(u_r=0\). The phase relationship between the stator and
rotor current and the flux linkage space vector can be obtained as follows:

\[ R_i i_r + j \omega_L i_r + j \omega_f L_m i_s = 0 \]  

(2)

The vector diagram is shown in Figure 1.

![Vector diagram under accurate positioning](image1)

![Vector diagram under inaccurate positioning](image2)

The magnetic field phase vector diagram under the condition of accurate positioning is shown in Figure 1. The quantities marked with * in the figure are all set values or control target values, in this case \( i_{sd} = \hat{i}_{sd} \) and \( i_{sq} = \hat{i}_{sq} \). But if the set value of the rotor parameter deviates from the actual value, such as the winding temperature rise causes the actual value of the stator resistance to be greater than the set value. \( R_r > \hat{R}_r \), then \( L_r^* / R_r < L_r^* / \hat{R}_r \). And the actual impedance angle of the rotor deviates from the positioning angle of the rotor, \( \phi_s < \theta_s^* \). Therefore, there is a deviation between the actual rotor current \( i_r \) and the decoupled \( q \) axis, and the actual rotor flux \( \psi_r \) deviates from the decoupled \( d \) axis by a certain angle. As a result, the magnetic field orientation is not accurate. As shown in figure 2, the actual excitation and torque components of the rotor are \( i_{sd} \), \( i_{sq} \), \( \hat{i}_{sd} > i_{sq} \) and \( \hat{i}_{sq} < i_{sq} \). If the original d/q shaft system is used to maintain a constant torque output, it will inevitably cause the motor to overexcite and increase the loss.

3. Off-line Parameter Identification Method of PMSM

3.1 Identification Method of Stator Resistance

The phase resistance of the motor is measured by DC voltmeter. The DC voltage signal is injected through the inverter, and the winding resistance is calculated after measuring the current feedback. Since the inverter cannot be given a constant DC source, the inverter is actually used to input a high-frequency voltage signal and maintain a fixed duty cycle to obtain an equivalent DC voltage. Due to the effect of inductance, the current becomes stable after a period of time. At this time, the current value is measured and the resistance value is calculated by the following formula.

\[ R_s = \frac{2U_{dc} \cdot d}{3I} \]  

(3)

As shown in Figure 3, the specific setting of the switching state of the inverter's three-phase bridge arm is as follows: \( VT_1 \) and \( VT_2 \) are high frequency complementary PWM signals, \( VT_3 \) and \( VT_4 \) are always off, \( VT_6 \) and \( VT_7 \) are always on. In this case, the inverter is equivalent to a buck circuit. The schematic diagram is shown in Figure 4.
The existence of the dead zone of the inverter makes a large error between the given reference voltage and the actual output voltage. Since the dead time is usually fixed, the voltage drop caused by it can be regarded as constant and set to \( \Delta U \). Different duty ratios \( d_1, d_2 \) can be given, and the corresponding currents \( I_1, I_2 \) can be measured. Formula (4) is used for calculation to overcome the error influence caused by the dead zone of the inverter.

\[
R_s = \frac{2}{3} \left( \frac{U_{dc}d_1 - \Delta U}{I_1} - \frac{U_{dc}d_2 - \Delta U}{I_2} \right)
\]

### 3.2. Identification Method of Stator Inductance

At present, the most commonly used inductance identification methods are the step response method and the high frequency injection method. The basic principle of the step response method is to give a suitable step excitation signal to the motor, derive the response equation from the state equation of the permanent magnet synchronous motor, and calculate the inductance value by processing the response data. This method requires precise observation of the response data. It is more difficult to implement and not accurate enough. Therefore, this paper uses high-frequency injection method to identify the inductance parameters offline\([4-6]\).

In equation (5), \( P \) is the differential operator, \( u_d, u_q, i_d, i_q, L_d, L_q \), are respectively the voltage, current and inductance in the \( dq \) axis. Through 2r/3s coordinate transformation, the voltage equation in the \( dq \) axis coordinate system can be converted to the \( \alpha\beta \) axis, And the voltage relationship on the \( \alpha\beta \) axis of the \( dq \) axis inductance can be obtained by equation (6):

\[
\begin{align*}
    u_\alpha &= L_d P \left( i_\alpha \cos(\theta) + i_\beta \sin(\theta) \right) \cos(\theta) - L_q P \left( i_\beta \cos(\theta) - i_\alpha \sin(\theta) \right) \sin(\theta) \\
    u_\beta &= L_d P \left( i_\alpha \cos(\theta) + i_\beta \sin(\theta) \right) \sin(\theta) + L_q P \left( i_\beta \cos(\theta) - i_\alpha \sin(\theta) \right) \cos(\theta)
\end{align*}
\]

The electrical angle \( \theta \) is a precise angle, so there will be no inaccurate positioning as shown in Figure 2. By integrating both sides of equation (6) and inverting the coefficient matrix once. As shown in equation (7), the expression form of the current can be obtained.

\[
\begin{bmatrix}
i_\alpha \\
i_\beta
\end{bmatrix} = \frac{U_j}{\omega L_2 L_3} \begin{bmatrix}
L_1 \cos \left( \frac{\omega t - \pi}{2} \right) - L_2 \cos \left( \frac{2\theta - \omega t + \pi}{2} \right) \\
L_1 \sin \left( \frac{\omega t - \pi}{2} \right) - L_2 \sin \left( \frac{2\theta - \omega t + \pi}{2} \right)
\end{bmatrix}
\]

In equation (7), \( L_1 \) is \( \left( L_d + L_q \right) / 2 \), \( L_2 \) is \( \left( L_d - L_q \right) / 2 \), \( \omega \) is the electrical angular velocity of Injection voltage. Take the \( \alpha \) axis as the real axis and the \( \beta \) axis as the imaginary axis to put \( i_\alpha \) and \( i_\beta \) into the complex plane and rewrite them in the form of a rotation vector as equation (8):
In this case, the current vector can be regarded as the result of the synthesis of two vectors rotating in the complex plane. When the phases of the two rotation vectors are the same, the amplitude of the current vector on the $\alpha\beta$ axis is the largest at this time, and the maximum current vector amplitude can be obtained as:

$$I_{\alpha\beta} = \frac{U_i L_1}{\omega(L_1^2 - L_2^2)} e^{\left(\omega t - \frac{\pi}{2}\right)} - \frac{U_i L_2}{\omega(L_1^2 - L_2^2)} e^{\left(2\omega t - \omega t + \frac{\pi}{2}\right)}$$

(8)

When the two rotation vectors have opposite phases, the current vector amplitude is the smallest in the complex plane at this time, and the minimum current vector amplitude can be obtained as:

$$i_{\alpha\beta} = \frac{U_i (L_1 - L_2)}{\omega(L_1^2 - L_2^2)} = \frac{U_i}{\omega L_d}$$

(9)

$$i_{\alpha\beta} = \frac{U_i (L_2 + L_2)}{\omega(L_1^2 - L_2^2)} = \frac{U_i}{\omega L_q}$$

(10)

It can be seen from the above analysis that the identification of the $dq$ axis inductance by the high-frequency injection method can finally be completed by observing the amplitude of the motor current on the complex plane after the high-frequency voltage is injected. In order to facilitate the actual experimental operation, the voltage amplitude can be determined by specifying $U_d$ or $U_q$, and then by specifying $\theta_r$ to ensure that the injected voltage is a high-frequency sinusoidal quantity. Therefore, the control block diagram of the inductance parameter offline identification algorithm can be given:

![Block diagram of inductance offline identification](image)

Figure 5. Block diagram of inductance offline identification

Similar to the identification of the stator resistance, the identification of the $dq$ axis inductance also needs to consider the influence of the dead time voltage drop, so the difference between the two measurements can also be used to eliminate the influence of the dead time voltage drop on the identification. Finally, the calculation formula of is as follows:

$$L_d = \frac{(U_{i1} - \Delta U) - (U_{i2} - \Delta U)}{i_{\alpha\beta1}^{max} - i_{\alpha\beta2}^{max}}, L_q = \frac{(U_{i1} - \Delta U) - (U_{i2} - \Delta U)}{i_{\alpha\beta1}^{min} - i_{\alpha\beta2}^{min}}$$

(11)

3.3. Identification Method of Back EMF Coefficient

The excitation magnetic field of a permanent magnet synchronous motor is generated by the magnetic field of a permanent magnet. The permanent magnet magnetic field $\psi_f$ will induce electromotive force $e_f = d\psi_f / dt$ in the stator winding as the rotor rotates. Intuitively, the faster the motor speed, the faster the magnetic flux changes, and the higher the back-EMF voltage of the motor. As shown in equation (12):

$$K_e = \frac{e_f}{n \cdot 1000^4}$$

(12)
Where, $e_0$ is the back EMF and $n$ is the motor speed. The back-EMF coefficient of the motor can be understood as the voltage value of the back-EMF generated per thousand revolutions of the motor. Use another motor to drive the motor to be tested to rotate, and the back-EMF coefficient can be obtained according to the electric potential induced by the winding and the speed[7-8].

4. Off-line Identification Experiment of PMSM

The design of this automatic offline parameter identification is based on the MBD (Model Based Design) development model. This design method uses the technology of automatically generating software code, which can move from the modeling verification stage to the experimental stage more conveniently and quickly.

As shown in Figure 6, according to the method of off-line parameter identification of permanent magnet synchronous motors introduced earlier, the corresponding simulation model is built using Matlab/Simulink software to complete the verification.

![Figure 6. Offline parameter identification simulation model](image)

The frequency of the high-frequency voltage injected during the inductance identification is 500 Hz. Two motors with different parameters are used for experimental testing. Various parameters have been tested for many times under different conditions and averaged. The specific experimental results are as follows:

| Table 1. The offline parameter identification experiment results of motor 1 |
|-------------------|-----|-----|-----|-----|
| Motor 1           | $R_s$ ($\Omega$) | $L_d$ (mH) | $L_q$ (mH) | $K_e$ (V/krpm) |
| Actual value      | 1.69 | 2.42 | 2.44 | 36.52 |
| Identified average value | 1.77 | 2.48 | 2.68 | 35.31 |
| Absolute mean error | 4.7% | 2.5% | 9.8% | 3.3% |

| Table 2. The offline parameter identification experiment results of motor 2 |
|-------------------|-----|-----|-----|-----|
| Motor 2           | $R_s$ ($\Omega$) | $L_d$ (mH) | $L_q$ (mH) | $K_e$ (V/krpm) |
| Actual value      | 1.07 | 1.78 | 2.00 | 27.21 |
| Identified average value | 1.11 | 1.73 | 1.92 | 25.78 |
| Absolute mean error | 3.7% | 2.8% | 4.0% | 5.3% |

As shown in Table 1 and Table 2, each parameter of the two motors with different parameters can reach the identification accuracy with an absolute error of less than 10%, and it can even be reduced to less than 5% for MOTOR 2, which can fully meet the requirements of most motor control algorithms. Among them, the identification error of the $L_q$ of the Motor 1 is relatively larger. It may be because the identification process of this high-frequency injection method considers that $L_d$ and $L_q$ are not equal, so that the amplitude of the current vector can be detected, then $L_d$ and $L_q$ is obtained from the maximum
and minimum value. As surface mount motors, the $L_d$ and $L_q$ values of MOTOR 1 are almost the same, so the system error causes the identified $L_q$ value to be larger. If a servo system that can detect the current more accurately is used, the $L_q$ identification error in this case can be reduced. If it is known that it is a surface mount motor, the identified $L_d$ value can be used as the $L_q$ value[9-10].

5. Conclusion
This paper first introduces the influence of inaccurate motor parameter setting on the servo control system. Then the off-line identification method and principle of PMSM parameters are stated. Finally, based on the development model of MBD, a corresponding Matlab/Simulink simulation model of PMSM off-line parameter identification is established, and software code is generated and added to the existing servo system, then experiments are carried out on two motors with different parameters. The results confirm the correctness of the above-mentioned offline parameter identification method well. At the end, the possible causes and solutions of the large error when using the proposed high-frequency injection method to identify the $L_q$ parameters of the surface-mount PMSM is analyzed.

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