Permanent Magnet Synchronous Motors Direct Torque Control Considering the Effect of Salient Pole

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Abstract: Salient effect without considering the impact study for the direct torque control of permanent magnet synchronous motors existing problem, it established a permanent magnet synchronous motor mathematical model involving motor saliency, describing the working principle of direct torque control system, building control system simulation model, and use of motor torque, power angle simulation waveform analysis reveals the influence of the mechanism of saliency by reluctance torque of permanent magnet synchronous motor direct torque control.

Keywords: Salient effect; permanent magnet synchronous motor; direct torque control; reluctance torque; motor power angle.

1. Introduction

Permanent magnet synchronous motor has high efficiency, high power density, small torque ripple, starting torque and dynamic response fast, wide speed range and advantages has become research hot point in the field of power transmission, and has been widely used in electric traction and electric vehicle electric drive field [1-2]. Due to the simple control method and torque response fast, easy to realize the digital good dynamic performance advantages, permanent magnet synchronous motor direct torque control caused many scholars to conduct the research, and achieved certain outcomes [3].

Torque and stator flux linkage double hysteresis loop structure is adopted in the direct torque control, and the speed of the motor torque is realized by selecting the appropriate voltage vector control stator flux linkage amplitude and rotation speed by the look-up table method. A new direct torque control method for permanent magnet synchronous motor based on back stepping control is proposed in this paper [3]; A direct torque control method of permanent magnet synchronous motor based on duty cycle modulation is proposed in the paper [4]; A direct torque control strategy based on motor torque angle is proposed in this paper [5]; A novel [6] adaptive quadrature feedback compensation stator flux observer for permanent magnet synchronous motor direct torque control is proposed; In order to improve the dynamic and static performance and to improve the robustness of the speed control, a fractional order intelligent integral control strategy is proposed in this paper [7]; A speed estimation method based on the rotor flux of the direct torque control algorithm is proposed in this paper[8]. Through the analysis of the literature it shows that the permanent magnet synchronous motor direct torque control is based on the existing multi salient pole permanent magnet synchronous motor as the research object, ignoring the influence of the saliency of direct torque control. However, even the implicit pole type permanent magnet synchronous motor is difficult to completely eliminate the salient pole effect due to the limitation of the motor assembly process.

In view of the above problems. Firstly, this paper studies the permanent magnet synchronous motor salient pole effect of physical causes, analysis of the salient pole effect of permanent magnetic synchronous motor torque and angle and flux effect, permanent magnet synchronous motor reluctance torque and angle of mathematical expression is derived and MATLAB were built to mimic really is obtained by considering the effect of salient pole permanent magnet synchronous motor direct torque control parameters of response curves, and reveals the effect of salient pole effect on motor control.

2. Salient Pole Effect of Permanent Magnet Synchronous Motor

Permanent magnet synchronous motor salient pole effect has two causes: one is due to the asymmetric structure of the motor and another is due to the rotor or stator iron magnetic saturation. Among them,
asymmetry of motor structure, especially the rotor magnetic circuit asymmetry and is a major cause of all the permanent magnet synchronous motor salient pole effect.

Fig. 1 is the rotor structure of permanent magnet synchronous motor. Permanent magnet synchronous motor according to permanent installation position of the magnet on the rotor can be divided into three different types, including surface mounted, plug type and embedded type, the interpolation type permanent magnet synchronous motor rotor due to the presence of larger permeability rotor ferromagnetic material between adjacent permanent magnetic materials, leading to the rotor magnetic circuit asymmetry salient pole rate is higher; Similarly, in the permanent magnet synchronous motor of permanent magnetic material located inside the rotor due to the ferromagnetic material of the rotor, the magnetic circuit asymmetry, salient pole rate higher; The rotor of surface mounted permanent magnet synchronous motor is in the electromagnetic performance of the rotor structure, the salient pole effect is not obvious. The rotor of surface mounted permanent magnet synchronous motor is in the electromagnetic performance of the rotor structure, the salient pole effect is not obvious.

The vector diagram of permanent magnet synchronous motor is shown in Figure 2. D-q for rotor synchronous rotating coordinate system; \( u_s \), \( i_s \) are stator voltage vector and current vector; \( \psi_s \) is the stator flux vector; \( \psi_r \) is the rotor flux vector; The included angle between the stator flux and rotor flux is \( \delta \), that is, the power angle. According to the theory of motor analysis, while ignoring the permanent magnet synchronous motor direct axis inductance \( L_d \) and the change of axis \( L_q \) inductances, and consider the effect of salient pole magnetic circuit, permanent magnet synchronous motor in d-q rotating coordinate expression of electromagnetic torque of the stator flux linkage equation and d-q rotating coordinate system are as follows:

\[
\begin{align*}
\psi_{sd} &= i_{sd}L_d + \psi_f \\
\psi_{sq} &= i_{sq}L_q \\
T &= \frac{3}{2} P(\psi_{sd}i_{sq} - \psi_{sq}i_{sd})
\end{align*}
\]  

(1)

(2)

In the formula, \( L_d \), \( L_q \) is the cross, direct axis inductance, \( P \) is the pole logarithm.

The expression of the current in the d-q coordinate system can be obtained by the above formula (1):

\[
\begin{align*}
i_{sd} &= \frac{\psi_{sd} - \psi_f}{L_d} \\
i_{sq} &= \frac{\psi_{sq}}{L_q}
\end{align*}
\]  

(3)

And the formula (2) is derived to obtain the expression of the following:

\[
T = \frac{3}{2} P(\psi_{sd}i_{sq} - \psi_{sq}i_{sd})
= \frac{3}{2} P((L_{sd} + \psi_f)i_{sq} - (L_{sq}i_{sq})i_{sd})
= \frac{3}{2} P(\psi_{f, sq} + (L_d - L_q)i_{sd})
\]  

(4)

The expression (1) and (3) the expression given by (4), the torque of the motor torque expressions can be salient effect:

\[
T = \frac{3}{2} P \left|\psi_f\right| \sin \delta + \frac{3}{4} P \left|\frac{1}{L_d} - \frac{1}{L_q}\right| \sin 2\delta
\]  

(5)

In expression (5), the definition of \( T_m = \frac{3}{2} P \left|\psi_f\right| \sin \delta \) is the main electromagnetic torque. \( T_m \) is the magnetic field of the stator and rotor of permanent magnet magnetic field through the air gap caused by the interaction of electromagnetic torque, is due to the reluctance torque motor caused by unbalanced magnetic
field DQ axis, the reluctance torque caused by motor salient effect.

![Fig.2 definition of d-q coordinate system in permanent magnet synchronous motor](image)

3. Direct Torque Control of Permanent Magnet Synchronous Motor

Permanent magnet synchronous motor stator flux is produced by the stator winding self-inductance of armature reaction flux and rotor permanent magnet in the stator winding excitation of rotor induction flux through the vector synthesis, including induction rotor flux is by permanent magnet synchronous motor parameters decision; sub armature reaction flux produced by the stator current.

Direct torque control of permanent magnet synchronous motor is according to the amplitude of stator flux and electromagnetic torque bias, based on the stator flux linkage vector where the position chosen directly suitable voltage space vector, to achieve the control of motor torque and stator flux linkage.

The stator flux linkage formula for permanent magnet synchronous motor:

$$\psi_f = L_d i_d^s + \psi_s e^{j\theta}$$  \hspace{1cm} (6)

Under the condition that the stator resistance is neglected, the stator flux vector increment is:

$$\Delta \psi_f = \psi_f(t_0) - \psi_f(t) \approx u_i \Delta t$$  \hspace{1cm} (7)

If the stator flux amplitude is approximately constant, the torque increment expression can be got:

$$\Delta T = \frac{3p}{2L_i L_q} L_i \left[ |\psi_q| L_d \cos \delta - |\psi_f| L_q \cos 2\delta \right] \Delta \delta$$  \hspace{1cm} (8)

The instantaneous value of work angle can be expressed as:

$$\delta = \arctan(\psi_q / \psi_d)$$  \hspace{1cm} (9)

The expression is only related to $\psi_d$ and $\psi_q$, which can not only represent the power angle of the implicit pole motor, but also the power angle of the salient pole motor. The stator flux angle can be expressed as:

$$\delta + \theta = \arctan(\psi_q / \psi_d)$$  \hspace{1cm} (10)

Permanent magnet synchronous motor direct torque control block diagram shown in Fig.3. Direct torque control contains two closed-loop control of flux self-control and torque self-control. Flux self-control part includes the three-phase voltage and current detection, three-phase static to two-phase stationary coordinate transformation, flux estimator, flux hysteresis comparators and the switching table. The torque control part includes the torque estimator, torque hysteresis comparators and the switching table.

4. Direct torque control simulation considering salient pole effect

In the MATLAB6.5/SIMULINK environment, based on the principle of direct torque control, a simulation model of permanent magnet synchronous motor with salient pole effect is set up, and the simulation model is shown in Fig.4. Simulation model of the main modules include: coordinate transformation module, torque hysteresis and flux hysteresis ring module, flux partitioning of the choice and implementation modules, switching table module, the stator flux calculation module, a permanent magnet synchronous motor module and the motor electromagnetic torque and reluctance torque calculation module etc. Among them, the inverter switching table is shown in Table 1.
Fig. 3 The block diagram of direct torque control of permanent magnet synchronous motor

Fig. 4 Simulation model of permanent magnet synchronous motor with salient pole effect

Table 1 Inverter switch table

<table>
<thead>
<tr>
<th>φ</th>
<th>τ</th>
<th>(\theta_0)</th>
<th>(\theta_1)</th>
<th>(\theta_2)</th>
<th>(\theta_3)</th>
<th>(\theta_4)</th>
<th>(\theta_5)</th>
<th>(\theta_6)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>(u_2)</td>
<td>(u_2)</td>
<td>(u_4)</td>
<td>(u_3)</td>
<td>(u_3)</td>
<td>(u_2)</td>
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<td>0</td>
<td>(u_3)</td>
<td>(u_2)</td>
<td>(u_2)</td>
<td>(u_2)</td>
<td>(u_4)</td>
<td>(u_3)</td>
<td></td>
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<tr>
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<td>0</td>
<td>(u_2)</td>
<td>(u_4)</td>
<td>(u_3)</td>
<td>(u_3)</td>
<td>(u_2)</td>
<td>(u_2)</td>
<td>(u_4)</td>
</tr>
</tbody>
</table>
### Table 2 Parameters of permanent magnet synchronous motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage /V</td>
<td>110</td>
<td>Magnetic chain given value /Wb</td>
<td>0.207</td>
</tr>
<tr>
<td>Rated current /A</td>
<td>5</td>
<td>Quadrature axis inductance /mH</td>
<td>16.93</td>
</tr>
<tr>
<td>Rated frequency /HZ</td>
<td>50</td>
<td>Direct axis inductance /mH</td>
<td>13.11</td>
</tr>
<tr>
<td>Rated rotor speed /r/min</td>
<td>1500</td>
<td>Stator resistance /Ω</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Considering effect of salient pole permanent magnet synchronous motor simulation parameters such as Table 2 shows, in the actual simulation, PI speed regulation device proportion coefficient and integral coefficient was 1 and 100, torque limiting 5N. M, width of torque hysteresis 0.01N.m and flux hysteresis loop width 0.001Wb.

### 5. Simulation results and analysis

Fig.5-10 is a permanent magnet synchronous motor at a load of 2N.m speed from zero speed to a given speed 1000r/min response waveform. From the simulation results visible, direct torque control, permanent magnet synchronous motor can smoothly from zero speed to rise to 1000r/min; starting time lasted about 0.02s. In the start stage, total motor torque to accelerate to 5N. M of maximum torque, although gradually decline, to 1000r/min and stable operation in the 2N.m; electromagnetic torque in 6N. M of maximum torque acceleration and 1000r/min to stable operation in 2.5N.m; reluctance torque maximum torque -1.5N.m weaken of electromagnetic torque, 1000r/min to stable operation in -0.5N.m. Based on the starting stage total torque of motor, the electromagnetic torque and the reluctance torque of the comparative analysis, it can be found that the permanent magnet synchronous motor salient pole effect caused by the reluctance torque offset the electromagnetic torque, reduce the motor torque, delaying the process of motor starting. From Fig.9 it can be seen direct torque control in permanent magnet synchronous motor stator flux linkage locus can still control a standard circular, the stable amplitude to a given value 0.2074Wb, the illustrate salient pole effect is considered not to the permanent magnet synchronous motor stator flux control effect. Fig.10 for motor starting process of power angle curve, as shown in the figure, the motor power angle in the motor starting phase change is larger, the change trends and total torque of motor, electromagnetic torque and reluctance torque variation trend consistent, motor starting moment, angle to nearly 40 DEG peak, motor speed after a smooth power angle stability in the vicinity of 15 degrees.
6. Conclusions

In this paper, in order to take into account the salient pole effect of the permanent magnet synchronous motor as research object to study the effect of salient pole effect mechanism of direct torque control of permanent magnet synchronous motor, through the theoretical analysis and the simulation research obtained conclusions are as follows: permanent magnet synchronous motor is running, the salient pole effect will produce contrary to the direction of the electromagnetic torque of the reluctance torque, and its size and electromagnetic torque amplitude variation trend. The reluctance torque offset a portion of the electromagnetic torque, weakening the permanent magnet synchronous motor's torque output capacity, how to control due to the effect of salient pole motor reluctance torque will be the next step needed for key research problems.

7. Acknowledgment

This work was financially supported by National Natural Science Foundation of China (61503161).

8. References


