Research and Design of DTC System Based on Six-phase Asymmetrical BLDCM

Chunyuan Bian, Guannan Zhao, Xiaoxia Li and Yongkui Man

Abstract—In this paper, the torque ripple problem of six-phase asymmetrical brushless DC motor (BLDCM) is studied. First, the basic structure of BLDCM is introduced, and the operation principle of six-phase asymmetrical BLDCM that is studied in the thesis is expounded. Then, the principle of direct torque control (DTC) system of BLDCM is also discussed, and the improved system is proposed, including using the torque hysteresis loop and opening current hysteresis loop, and choosing the improved voltage vector to make the PWM-ON-PWM modulation. Finally, the DTC system simulation model is built, and the system is also tested by the experiment. According to the results of experiment and simulation, the DTC system designed in this thesis can control the six-phase asymmetrical BLDCM stably and reliably, and the problem of high frequency and torque ripple is solved well.

Index Terms—Six-phase asymmetrical BLDCM, DTC, hysteresis loop, torque ripple, voltage space vector.

I. INTRODUCTION

BLDCM has many advantages, such as small volume, simple structure, running high efficiency, wide speed range, high power density, high output torque and so on. The mechanical properties of brushless DC motor (BLDCM) are similar to the traditional brushed motors. The traditional dc motor uses the brushes and commutator to change the phase, which lead to the high cost. The BLDCM replaces the mechanical phase with electronic commutation, so it also has the advantage of low maintenance cost. After several decades of development, brushless dc motor and its control technology have become increasingly mature, including position sensorless control technology [1-2], neural network control, and active disturbance rejection control [3-4] and many other control methods for suppressing communication torque ripple. So its applications are more and more extensive. However, due to the complexity of the above control methods algorithms, it is not easy to achieve. The problem of torque pulsation has constantly been applied to the application of brushless dc motors in high-precision applications [5].

In response to this problem, direct torque control system was first proposed in [6]. And have gradually developed into the direct torque control (DTC) with no flux linkage loop [7-8].

However, there would be many shortcomings if the existing DTC should be applied to the six-phase asymmetrical BLDCM that is studied in this paper.

In order to make DTC system can be better applied to six-phase asymmetrical BLDCM, the basic structure of BLDCM is introduced, including the body of motor, position sensor and inverter. The operation principle of the motor is discussed in detail, and the mathematical model is established, and the equivalent circuit of the motor is obtained. Then the operating characteristics of the motor in three phases and six phases are analyzed. For the existing direct torque control system, the voltage vector table is improved, the mode of three-three conduction in commutation phase is proposed. In addition, the previous voltage zero vector is modified, and a method of motor commutation discrimination is designed so that the commutating torque ripple of the motor at high speed can also be suppressed.

II. THE SIX-PHASE ASYMMETRICAL BRUSHLESS DC MOTOR MATHEMATICAL MODEL

Six-phase asymmetric BLDCM has two independent three-phase windings, and there are 30° electrical angle difference between them. Each winding is Y-type connection. Figure 1 shows the six-phase BLDCM's equivalent circuit. Every winding of the motor works independently. There is one of them changes phases every 30°, and the other one works normally.

Compared with three-phase motor, the accuracy of motor position detection changes to 30° from 60°.

To facilitate the establishment of the mathematical model of the six-phase asymmetric BLDCM, assuming that the magnetic

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The authors are with the Department of Information Science & Engineering, Northeastern University, Shenyang 110189, China. (e-mails:bianchy@sina.com, zongzhi69@163.com, 825566401@qq.com)
circuit is always in an unsaturated state. The voltage equation of the stator winding of six phase asymmetric BLDCM is:

\[ \begin{align*}
    u_U &= R_i i_U + (L - M_1) \frac{di_U}{dt} + M_2 \frac{di_s}{dt} - M_2 \frac{di_s}{dt} + e_U \\
    u_V &= R_i i_V + (L - M_1) \frac{di_V}{dt} + M_2 \frac{di_r}{dt} - M_2 \frac{di_r}{dt} + e_V \\
    u_W &= R_i i_W + (L - M_1) \frac{di_W}{dt} + M_2 \frac{di_w}{dt} - M_2 \frac{di_w}{dt} + e_W \\
    u_S &= R_i i_S + (L' - M_1') \frac{di_S}{dt} + M_2' \frac{di_s}{dt} - M_2' \frac{di_s}{dt} + e_S \\
    u_T &= R_i i_T + (L' - M_1') \frac{di_T}{dt} + M_2' \frac{di_r}{dt} - M_2' \frac{di_r}{dt} + e_T
\end{align*} \]

(1)

The self-inductance in the phases of U, V, W is expressed as \( L \), the mutual inductance is \( M_1 \); The self-inductance between R, S, T is \( L' \); The mutual inductance between two sets of windings is \( M_1' \); The stator winding resistance of each phase is \( R_i \); The stator winding phase current of each phase is \( i_U, i_V, i_W, i_S, i_T \). The opposite phase electromotive force of each phase stator winding is \( e \).

Electromagnetic torque equation is:

\[ T_e = \frac{E_a I_s}{\Omega} = \frac{e_U i_U + e_V i_V + e_W i_W + e_R i_R + e_S i_S + e_T i_T}{\Omega} \]

(2)

Mechanical equation of motion is:

\[ T_e - T = J \frac{d\Omega}{dt} + B\Omega \]

(3)

In the equations, \( T_e \) is electromagnetic torque, \( T \) is the load torque, \( J \) is the moment of inertia, \( \Omega \) is the mechanical angular velocity of the motor, \( B \) is the viscous friction coefficient.

The stator flux equation is:

\[ \begin{align*}
    \psi_{SU} &= \int (u_U - R_i i_U) \, dt \\
    \psi_{SV} &= \int (u_V - R_i i_V) \, dt \\
    \psi_{SW} &= \int (u_W - R_i i_W) \, dt \\
    \psi_{SR} &= \int (u_R - R_i i_R) \, dt \\
    \psi_{SS} &= \int (u_S - R_i i_S) \, dt \\
    \psi_{ST} &= \int (u_T - R_i i_T) \, dt
\end{align*} \]

(4)

The permanent magnet brushless motor due to its own structure causes the current to be unable to meet the strict rectangular wave that we expect in the actual application. Therefore, there will be current overlapping phenomena when the phase is changed, which will lead to Commutation torque ripple. Six-phase brushless motors have a significant advantage over three-phase motors in high-capacity motor systems. Six-phase brushless motors use two sets of windings that are independent of each other and have an electrical angle difference of 30° between them, which can better suppress commutation torque compared to three-phase motors. The related equations are as follows.

Three-phase winding commutation torque:

\[ T = \frac{E_a I_s}{\Omega} = \frac{e_U i_U + e_V i_V + e_W i_W + e_R i_R + e_S i_S + e_T i_T}{\Omega} \]

(5)

The torque before commutation is:

\[ T_0 = 2k_i i_0 \]

(6)

The torque ripple is difference between the two torques:

\[ \Delta T = T_e - T_0 = \frac{k_i}{3(L - M)} (2U_d - 8k_i \Omega - 6R_i) \]

(7)

In order to facilitate the calculation, assuming the two sets of windings are completely symmetric. When the six-phase motor is in the commutation process, one of the windings is in the commutation state, and the other one is working normally. The commutation winding is the same as the three-phase winding analyzed above, so the commutation torque ripple is:

\[ \Delta T' = \frac{k_i}{3(L - M)} (2U_d - 8k_i \Omega - 6R_i) \]

(8)

Assuming the six-phase motor is completely symmetrical, the six-phase motor current is half that of the three-phase motor with the same inductance and twice resistance of the three-phase motor, so:

\[ M' = M, R' = 2R_i, i' = \frac{1}{2} i \]

(9)

At the moment of commutation:

\[ U = L \frac{di'}{dt'} = L \frac{\Delta i'}{\Delta t'}, \Delta t' = \frac{L \Delta i_0}{2U} = \frac{\Delta t}{2} \]

(10)

And:

\[ \Delta T' = \frac{k_i}{6(L - M)} (2U_d - 8k_i \Omega - 6R_i) \]

(11)

In summary, under ideal conditions, it is proved that the torque ripple of a six-phase brushless motor is half that of a three-phase brushless motor.

III. COMPOSITION OF DIRECT TORQUE CONTROL SYSTEM

The principle of DTC without flux observer for permanent magnet BLDCM [42] is described below. When the torque hysteresis comparison output is 1, it indicates that the torque needs to be increased. At this time, the corresponding vector can be selected to increase the torque according to the vector selection switch table. When the output of the torque hysteresis loop is 0, the torque needs to be reduced and the zero vector effect is selected. The influence of the adjustment process on the magnetic chain is shown in FIG.2. As can be seen from the
figure, when the torque needs to be increased, the output is 1. At the same time, the inverter outputs the non-zero voltage vector, and the torque and the voltage magnetic chain increases accordingly. When the torque reaches limit, the output is 0. In this case, the inverter inputs zero voltage vector to the motor, the stator flux is at a standstill, the flux angle is reduced, the output of the electromagnetic torque of the motor is reduced, and the amplitude of the flux linkage is unchanged. Therefore, the torque can be well controlled within the tolerance range to achieve the purpose of suppressing torque ripple.

![Effect of direct torque control system without flux link on flux linkage.](image1)

![Direct torque control system without flux link for six-phase BLDCM.](image2)

**FIG. 3** is a block diagram of the control system, where the hysteresis of the electromagnetic torque is set and the commutation current comparison ring is used for the suppression of high-speed commutation torque ripple. When speed is high, commutation ripple suppression module works. Then the action can achieve the goal of high speed ripple rejection. The specific working principle is that the difference between the given speed and feedback speed is given by the PI regulator output as a given electromagnetic torque. The difference between the given electromagnetic torque and feedback is divided into two outputs, one is the hysteresis control input of the electromagnetic torque, and the other is the input of the current loop after the proportional device. So that it can be determined whether the motor is in the process of high-speed commutation.

As is known, the electromagnetic torque is proportional to the non-commutating phase current in an acceptable range. When the motor speed is higher than 1700r/min and the motor is commutated, the three-phase current is selected to be phase-current through the selector. Then the current is compared with the value of the electromagnetic torque reduced by proportion. If the current is relatively small, it is considered that the commutation is not completed, and the commutation pulsation is continuously suppressed. The vector selected to suppress the commutation torque ripple is the voltage vector of the three-three conduction mode. If the commutation current reaches the comparison value, it is considered that the commutation is over, and the space voltage vector is selected to be the two-two conduction mode. In this way, not only can the high-speed pulsation be suppressed, but also the complicated calculation of the overlap commutation method adopted by the predecessors for the high-speed commutation pulsation can be omitted. The direct use of the hardware can be realized, and the speed is fast and the precision is high. The voltage vectors of three-three conduction mode are $V_1(101001)$, $V_2(011001)$, $V_3(010110)$, $V_4(010110)$, $V_5(100110)$, and $V_6(100101)$.

The DTC system introduced in this paper adopts pwm-on-pwm modulation strategy. When the torque needs to be reduced, the zero vector at the corresponding position is used. Six zero vectors are $V_{01}(100000)$, $V_{02}(010000)$, $V_{03}(001000)$, $V_{04}(000100)$, $V_{05}(000010)$, and $V_{06}(000001)$. In order to be able to select the corresponding zero vector, the 360° angle is divided into 12 parts by the six-phase Hall position sensor. The selection of the zero vector is achieved with a high accuracy.

<table>
<thead>
<tr>
<th>Hall position signal (Binary code)</th>
<th>OT</th>
</tr>
</thead>
<tbody>
<tr>
<td>100101</td>
<td>$V_1(100001)$, $V_6(100000)$</td>
</tr>
<tr>
<td>100100</td>
<td>$V_1(100000)$, $V_6(000001)$</td>
</tr>
<tr>
<td>110100</td>
<td>$V_2(010001)$, $V_6(000001)$</td>
</tr>
<tr>
<td>110110</td>
<td>$V_2(001001)$, $V_6(001000)$</td>
</tr>
<tr>
<td>010110</td>
<td>$V_3(011000)$, $V_6(010000)$</td>
</tr>
<tr>
<td>010101</td>
<td>$V_3(010001)$, $V_6(010000)$</td>
</tr>
<tr>
<td>001101</td>
<td>$V_4(001010)$, $V_6(000010)$</td>
</tr>
<tr>
<td>001111</td>
<td>$V_4(000110)$, $V_6(000010)$</td>
</tr>
<tr>
<td>101001</td>
<td>$V_5(100001)$, $V_6(000001)$</td>
</tr>
<tr>
<td>101011</td>
<td>$V_5(100100)$, $V_6(000001)$</td>
</tr>
</tbody>
</table>

The six-phase BLDCM studied in this paper runs in different modes at different speeds. When the motor is running at medium and low speed, it works in the six-phase state. UVW and RTS two windings work together to achieve the rated power. As the back EMF coefficient of RST winding is too large, when the motor runs in high-speed operation, the back EMF of RST winding will be greater than the bus voltage. When the motor is working in high speed mode, the RST winding needs to be cut off. The motor enters the three-phase working state, the output power of the RST winding is 0, and the output power of UVW rises to the rated power.
TABLE II
THE SELECTION OF RST PHASES SPACE VOLTAGE VECTOR IN UNECHANGING CURRENT

<table>
<thead>
<tr>
<th>Hall position signal (Binary code)</th>
<th>OT 1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>100101</td>
<td>V_0 (100001)</td>
<td>V_0 (100000)</td>
</tr>
<tr>
<td>100100</td>
<td>V_0 (100001)</td>
<td>V_0 (000001)</td>
</tr>
<tr>
<td>110100</td>
<td>V_0 (001001)</td>
<td>V_0 (000001)</td>
</tr>
<tr>
<td>110110</td>
<td>V_0 (001001)</td>
<td>V_0 (001000)</td>
</tr>
<tr>
<td>010110</td>
<td>V_0 (011001)</td>
<td>V_0 (001000)</td>
</tr>
<tr>
<td>010111</td>
<td>V_0 (011010)</td>
<td>V_0 (001000)</td>
</tr>
<tr>
<td>001011</td>
<td>V_0 (100110)</td>
<td>V_0 (001000)</td>
</tr>
<tr>
<td>010011</td>
<td>V_0 (100110)</td>
<td>V_0 (000010)</td>
</tr>
<tr>
<td>101011</td>
<td>V_0 (100110)</td>
<td>V_0 (000010)</td>
</tr>
<tr>
<td>101101</td>
<td>V_0 (100110)</td>
<td>V_0 (000000)</td>
</tr>
</tbody>
</table>

Table I and II show the switch vector tables of the motor that runs in the stable state. In order to suppress torque pulsation when the motor is running at high speed, a vector selection mode that is shown in the Table III is added. Only the vector used when the electromagnetic torque needs to be increased is shown in Table III. When the electromagnetic torque needs to be reduced, it means that the current is large enough. The electromagnetic torque can be reduced according to the vector selection of stable operation that is shown in Table I.

IV. SIMULATION AND EXPERIMENTAL RESULTS

In this paper, PLECS software is used to build a simulation model, and the results obtained are as follows.

Fig. 4. The current waveforms of two windings.

The parameters of the six-phase asymmetric brushless DC motor studied in this paper are as follows.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power P_N</td>
<td>22kW</td>
<td>Rated phase current I_s1</td>
<td>56.5A</td>
</tr>
<tr>
<td>Rated voltage U_N</td>
<td>440V DC</td>
<td>Rated phase current I_s2</td>
<td>36.7A</td>
</tr>
<tr>
<td>Rated speed n_h</td>
<td>1500r/min</td>
<td>Peak current I_p1</td>
<td>139A</td>
</tr>
<tr>
<td>Maximum speed n_p</td>
<td>3000r/min</td>
<td>Peak current I_p2</td>
<td>90A</td>
</tr>
<tr>
<td>Rated torque T_N</td>
<td>2×70N·m</td>
<td>Stator resistance R_s1</td>
<td>0.137Ω</td>
</tr>
<tr>
<td>Overload torque T_p</td>
<td>2×175N·m</td>
<td>Stator resistance R_s2</td>
<td>0.31Ω</td>
</tr>
<tr>
<td>Back-EMF coefficient k_e1</td>
<td>1.26V/rad×s</td>
<td>Stator wire inductance L_s1</td>
<td>0.76mH</td>
</tr>
<tr>
<td>Back-EMF coefficient k_e2</td>
<td>1.94V/rad×s</td>
<td>Stator wire inductance L_s2</td>
<td>1.81mH</td>
</tr>
</tbody>
</table>

Fig. 5. Motor speed waveform.

Comparing Fig. 3 and Fig. 4, When the motor speed reaches 1700r/min, the RST winding is turned off and the current becomes 0. At the same time, the current of the UVW winding becomes twice as the original. Therefore, the electromagnetic torque of the motor can be kept unchanged.

Fig. 6. The current of UVW winding waveform when the motor is running at low speed.
Fig. 7. The current of UVW winding waveform when the motor is running at medium speed.

Fig. 8. The current of UVW winding waveform when the motor is running at high speed.

Fig. 6, Fig. 7, and Fig. 8 are the motor current simulation results at different speeds. It can be seen from the simulation results that the torque control system plays a role of restraining the torque ripple no matter whether the motor operates in six-phase mode or in three-phase mode at high-speed operation.

In this paper, the experimental equipment used as shown in the figures below.

Fig. 12, and Fig. 13 are the experimental current waveforms of the UVW winding when the motor is running at low and high speed. Waveform is obtained through the Hall element conversion.

Through the oscilloscope showing the waveform of the current, it can be seen that the torque ripple is suppressed by the direct torque control system, whether the motor is running at low speed or high speed.
V. CONCLUSION
In this paper, the advantages of six-phase motor in comparison with three-phase motor in torque ripple was analyzed based on the mathematical model of six-phase brushless DC motor. Then the direct torque control system applied to asymmetric six-phase BLDCM was introduced in detail. The direct torque control system was applied to six phase motors, and compared with the traditional direct torque control system, the voltage vector table was improved to better suppress the torque ripple of the motor at high speed. According to the simulation results and experiments, the torque ripple of the six-phase BLDCM in different working modes was inhibited by the DTC system studied in this paper. However, the research on brushless dc motor is still developing, and it is hoped that more advanced control algorithm can be realized in the speed ring and the direct torque control system can be applied to the position sensorless brushless dc motor.

REFERENCES

Guannan Zhao was born in Henan, China, in 1994. He received the B.S degree in automation engineering from the Northeastern University at Qinhuangdao, Hebei, China, 2016. He is currently working toward a M.S degree in Electrical engineering from Northeastern University, Shenyang, China. His research interests include the analysis and control of Permanent magnet brushless DC motor.

Chunyuan Bian was born in Henan, China, in 1973. He received the B.S degree and M.S degree in automation major, and Ph.D degree in control engineering from the Northeastern University, Shenyang, China. His research interests include Motor control technology and motion control, power converter technology and its application, intelligent control of complex systems.

Xiaoxia Li was born in Hubei, China, in 1995. She received the B.S degree in electrical engineering and automation from the Harbin University of Science and Technology, Haebin, China, 2017. She is currently working toward a M.S degree in Electrical engineering from Northeastern University, Shenyang, China. Her research interests include the analysis and control of Permanent magnet brushless DC motor.

Yongkui Man was born in Liaoning, China, in 1957. He received the B.S, M.S, and Ph.D degree from the Northeastern University, Shenyang, China. From 1987 to 1991, he was a visiting scholar at Sheffield University in the UK to study two hybrid stepping motors and their drive systems. From 1997 to 2000, he worked as a Senior Research Fellow at Leicester University in the UK on wind power research, the hardware engineer at EliteGroup Computer Systime Ltd in the UK, and postdoctoral research electric locomotive at East London University. He was previously the Dean of the Northeastern University of Electrical Engineering. His research interests include electric drives, power electronics, renewable energy utilization.