Vector Control and SVPWM Strategy of Two-phase Hybrid Stepping Motor

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***Abstract*—Two-phase hybrid stepping motor vector control strategy is introduced in the paper, the system proposed maximum torque / current vector strategy after the two-phase hybrid stepping motor mathematics model is analyzed, which make full use of the current of stator winding. Space voltage vector pulse width modulation at the same time is put forward. At last, simulations and experiments of the double—closed loop control system of the motor are carried out and results of simulations and experiments are given.**

Keywords-*Two-phase hybrid stepping motor; SVPWM; Vector control; Simulition experiments*

I. INTRODUCTION

Hybrid stepping motor is the most popular stepping motor for industrial application, it was first designed as a low speed PM synchronous motor, and it based on the principal of permanent magnet and variable reluctance, so its overall performance is much better than other stepping motors[1]. The usual way to control stepping motor such as open-loop control, rise boost frequency control etc. As the machining accuracy is more and more strict, the traditional open-loop control is limiting the appliance of the two-phase hybrid stepping motor, so researches on the closed-loop is significant. At the basic of vector control of PM synchronous motor and AC motor, the article gives the vector control on hybrid stepping motor. According to analyses of mathematic model of the two-phase hybrid stepping motor, the paper adopts the way of maximum torque/current vector strategy to realize the vector control of two-phase hybrid stepping motor. This can make better use of stator winding current and to decrease the capacity of the inverter, and at the same time, to increase the utilization factor of power, so it is very practicability[2].

SVPWM is to control AC motor magnetic chain space vector track to approach roundness. Comparing with the traditional SPWM method, SVPWM can realize a higher DC voltage rate, and lower harmonic current and torque pulsation of the motor, what's more, it is very simple[3]. As all the advantages above, SVPWM is more and more popular in the application no matter open-loop speed governing system or the closed-loop system.

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II MATHEMATIC MODEL FOR TWO-PHASE HYBRID STEPPING MOTOR

Hybrid stepping motor is a highly nonlinear electromechanical device. There are lots of practical difficulties to describe it precisely and to determine its nonlinear parameter accurately. Therefore, simplifications and assumptions are necessary. Generally, some assumptions are made as below[4]:

1) The motor is linear and ignore the effect of saturation.
2) The magnetic flux linkage of permanent magnet in the phase winding changes according to the sine as the position of rotor changes without any effect of stator winding current.
3) Overlook the effects of eddy current and magnetic hysteresis, and assume the phase winding sinusoidal distribution along the circumference of the stator.
4) The mutual inductance between A and B is zero.

According to the assumptions above, the voltage equation s of two-phase hybrid stepping motor can be expressed as:

$$U_A = r_A i_A + (L_0 - L_2\cos 2\theta)\frac{di_A}{dt} - L_2\sin 2\theta\frac{di_B}{dt} + 2\mathrm{L}_2(i_A\sin 2\theta - i_B\cos 2\theta) - k_e w_r\sin\theta \quad (1)$$

$$U_B = r_B i_B + (L_0 + L_2\cos 2\theta)\frac{di_B}{dt} - L_2\sin 2\theta\frac{di_A}{dt} - 2\mathrm{L}_2(i_B\sin 2\theta + i_A\cos 2\theta) + k_e w_r\cos\theta \quad (2)$$

where U_A and U_B are the terminal voltages of two-phase winding, r_A and r_B are the internal resistances of two-phase winding, i_A and i_B are the currents of two-phase winding, L_0 is the constant component of coefficient of self induction, L_2 is the amplitude of self-inductance secondary harmonic component, θ is the position angle of rotor using the electrical degree to express, w_r is the mechanical rotating angle of rotor; k_e is back electromotive force coefficient.

The electromagnetic torque of two-phase hybrid stepping motor can be expressed as:

$$T_e = p\left[L_2\sin 2\theta\left(i_A^{\ 2} - i_B^{\ 2}\right) - 2i_A i_B L_2\cos 2\theta\right] + pI_m M_{sr}\left(-i_A\sin\theta + i_B\cos\theta\right) \quad (3)$$

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Where T_e is the electromagnetic torque, p is the number of pole pairs, and it equals to the rotor gear Z_r , I_m is a equivalent excitation current when the PM is equivalent to a exciting winding, M_{sr} is the maximum of mutual inductance between stators.

The torque equation for two-phase hybrid stepping motor is represented：

$$T_e = J\frac{dw_r}{dt} + Bw_r + T_L \qquad (4)$$

Where J is the total inertia, B is total friction coefficient, T_L is load torque.

The equations above form the mathematic model for two-phase hybrid stepping motor.

III THE DOMINATION PRINCIPLE OF TWO-PHASE HYBRID STEPPING MOTOR'S MAXIMUM TORQUE/CURRENT VECTOR

Fig. 1 shows the current vector diagram of two-phase hybrid stepping motor[5]. The key of vector control is the transformation of coordinates. Changing the stator's two phase windings current into direct axis and cross axis current, electromagnetic torque output can be controlled through controlling of the direct axis and cross axis current. In Fig.1, the stator winding is separately located on the static axis α and β , the direct axis d and the cross axis q form a counterclockwise synchronization rotate coordinate system. The centre line of the rotor tooth is axis d; comparing with d , the axis q leads ahead 90^0 electrical angles counterclockwise.

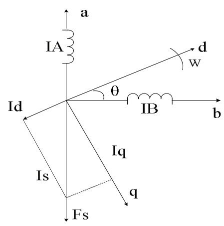

Fig.1 Current vector diagram of two-phase hybrid stepping motor

And put the stator current i_A and i_B on the axis **d** and **q**, i_d and i_q can be expressed as

$$\begin{cases} i_d = i_A\cos\theta + i_B\sin\theta \\ i_q = -i_A\sin\theta + i_B\cos\theta \end{cases} \qquad (5)$$

Substitute (5) into (3), the electromagnetic torque turns to be:

$$T_e = p\left(L_d - L_q\right)i_d i_q + pI_m M_{sr} i_q \qquad (6)$$

From (6), it can known that the electromagnetic torque consists of two parts. One of them is the reluctance torque caused by magneto-resistance effect; and the other one is the excitation torque caused by the interaction of the stator current and the permanent magnet' magnetic field.

The essence of the vector control is to control the phase and amplitude of stator current in the motor. The electromagnetic torque of the motor depends on the stator current vector i_s , and the numerical and phase of i_s depends on the direct axis current i_d and the cross axis current i_q . If the size and the direction of stator current vector can be controlled well, it can be realized to control the output torque with ease. Usually vector control adopts the way of rotor flux, which needs the i_d=0. Due to the air gap of the hybrid stepping motor is small, in that condition, the power output is dramatically affected by the magneto-resistance effect, and that's a waste of power, so the i_d should equals zero. From (6), it can see that in order to get maximal torque output and then improve the power efficiency, the reluctance torque should be made the best use when we control the two-phase hybrid stepping motor.

Adopting the maximum torque/current control, the i_d and i_q should meet the equation as follows:

$$\frac{\partial T_e}{\partial i_d} = 0 \qquad (7)$$

$$\frac{\partial T_e}{\partial i_q} = 0 \qquad (8)$$

From (6)-(8), the direct axis current can be follows:

$$i_d = \frac{-I_m M_{sr} + \sqrt{\left(I_m M_{sr}\right)^2 + 8\left(L_d - L_q\right)^2 i_s^2}}{4\left(L_d - L_q\right)} \qquad (9)$$

$$i_q = \sqrt{i_s^2 - i_d^2} \qquad (10)$$

By controlling the direct axis current and the cross axis current according to（9）and（10）, the maximum torque/current control can be realized.

IV H-BRIDGE DRIVE THE REALIZATION OF TWO-PHASE SVPWM

A. *The working principle of two-phase SVPWM*

The most important parts in the control system is the inverter output of the motor's two-phase SVPWM. The stepper motor's drive circuit is shown in Fig.2[6].

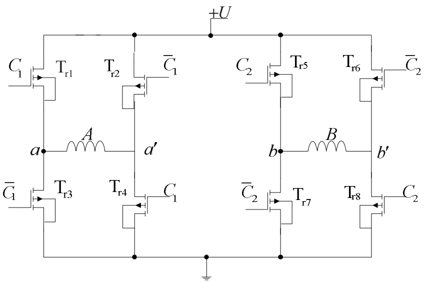

Fig.2 Power driving circuit of 2-phased hybrid synchronous motor

For convenience, in this paper the dead impact of the drive signal in the same bridge arm is ignored, and the diagonal drive signals are shown in the same symbol. It just reverse that the phases of A phase winding drive signal C_1 and $\overline{C_1}$, and the definite method of B phase winding drive signal C_2 and $\overline{C_2}$ is the same as A phase. So the space position of given voltage space vector is decided through the drive signal C_1 of A phase power tube T_{r1} and the drive signal C_2 of B phase power tube T_{r5} .Through the drive signal's logical combination the working state of the motor two-phased SVPWM inverter can be controlled, then decide the stepper motor winding's power mode at last.

In Fig.2, the working states of driving signals C_1 and C_2 can be expressed; "1" means the drive signal opened, "0" means closed on the contrary. Follow the state of C_1、C_2, the two-phased SVPWM inverter come into being altogether four non-zero basic voltage space vectors U_1、U_2、U_3、U_4, which can divide the voltage space vectors into four sectors. Fig.3 shows them. Their modulus is $\sqrt{2}U$ and phase differ 90^0 electric angle each other. The operating principle of 2-phased SVPWM is to make use of the logical combination of the two adjacent basic voltage space vectors to close in the given voltage space vector randomly. In a working sector, the more resultant vector the better the actual flux waveform to close in the sine.

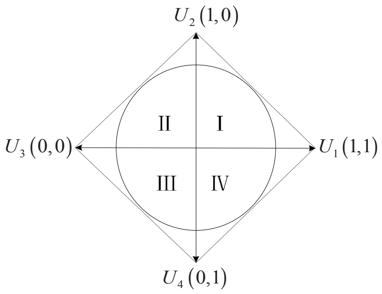

Fig.3 Four basic space-voltage vectors

B. Determine the parameters of two-phase SVPWM

Define the given space voltage vector –based sector is the main sector, and its corresponding sector is the secondary sector, the other two sectors are non-working sectors. Because the four sectors' methods to determine the parameters is similar, therefore, sector I is set an example to explain the principle of the parameters of SVPWM.

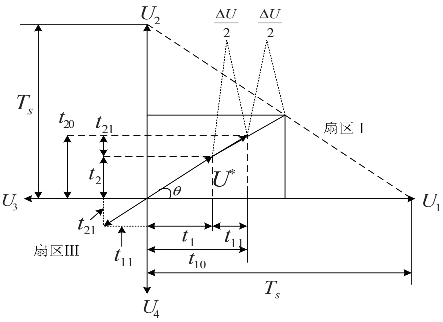

Fig.4 Operating principle of 2-phased SVPWM

If the given voltage space vector is in sector I shown in Fig.4, sector I is the main sector, sector III is the secondary sector, sector II and IV is non-working sectors.

The principle of two-phase SVPWM is shown in Fig.4, where U^* is the given space voltage vector, U_1 and U_2 are the two basic voltage space vectors of U^* in sector I. t_1 and t_2 are the action time of U^* equivalent in the basic voltage space vector U_1 and U_2. Because t_1 and t_2 are not equal to the carrier cycle generally and two-phase SVPWM does not have zero vector which is different from the three-phase SVPWM. In order to meet the frequency constraints, time difference can be distributed to the main sector I and the secondary sector III evenly. ΔU which is corresponding to the time difference can be divided into two parts evenly in which each part effect on the two coordinate reference axes are t_{11} and t_{21}. The same time acts on the sector III. New voltage vector $U^* + (\Delta U/2)$ generates in sector I. In sector I the given increment voltage vector $(\Delta U/2)$ is the additional reference voltage vector which is to meet the frequency constraint. The opposite voltage reference vector $(-\Delta U/2)$ generated in the secondary III to offset the flux by the additional reference voltage vector $(\Delta U/2)$ in sector I which can achieve the two-phase SVPWM control function that adopts H structure.

When the frequency constraints meet, there is

$$T_s = (t_1 + t_{11}) + (t_2 + t_{21}) + (t_{11} + t_{21}) = t_{10} + t_{20} + t_{11} + t_{21} \tag{11}$$

Where $t_{10} = t_1 + t_{11}$, $t_{20} = t_2 + t_{21}$.

As is shown in Fig.4, when the angle of the given voltage vector and the basic voltage space vector U_1 is θ, new voltage vectors generated in sector I and III are (12) and (13) .

$$U^* + \frac{\Delta U}{2} = \frac{\sqrt{2}U}{2(\sin\theta + \cos\theta)} + \frac{U^*}{2} \tag{12}$$

$$-\frac{\Delta U}{2} = -\frac{\sqrt{2}U}{2(\sin\theta + \cos\theta)} + \frac{U^*}{2} \tag{13}$$

So there is (14) and (15) in sector I and III

$$\int_0^{t_{10}+t_{20}} \left[U^* + \frac{\Delta U}{2} \right] dt = \int_0^{t_{10}} U_1 dt + \int_{t_{10}}^{t_{10}+t_{20}} U_2 dt \tag{14}$$

$$\int_{t_{10}+t_{20}}^{T_s} \left[-\frac{\Delta U}{2} \right] dt = \int_{t_{10}+t_{20}}^{t_{10}+t_{20}+t_{11}} U_3 dt + \int_{t_{10}+t_{20}+t_{11}}^{T_s} U_4 dt \tag{15}$$

(14) and (15) can be expressed by (16) and (17) when the carrier frequency is high

$$(t_{10} + t_{20}) \left[U^* + \frac{\Delta U}{2} \right] = t_{10} U_1 + t_{20} U_2 \tag{16}$$

$$(t_{11} + t_{21}) \left[-\frac{\Delta U}{2} \right] = t_{11} U_3 + t_{21} U_4 \tag{17}$$

So (18) and (19) can be got

$$T_s \left[U^* + \frac{\Delta U}{2} \right] \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} = t_{10} \sqrt{2}U \begin{bmatrix} 1 \\ 0 \end{bmatrix} + t_{20} \sqrt{2}U \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{18}$$

$$T_s \left[\frac{\Delta U}{2} \right] \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} = t_{11} \sqrt{2}U \begin{bmatrix} 1 \\ 0 \end{bmatrix} + t_{21} \sqrt{2}U \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{19}$$

When the given voltage vector is U^* the action time of every basic voltage vector are

$$t_{10} = \frac{T_s}{2\sqrt{2}U} \left[\frac{\sqrt{2}U}{\sin\theta + \cos\theta} + U^* \right] \cos\theta \tag{20}$$

$$t_{20} = \frac{T_s}{2\sqrt{2}U} \left[\frac{\sqrt{2}U}{\sin\theta + \cos\theta} + U^* \right] \sin\theta \tag{21}$$

$$t_{11} = \frac{T_s}{2\sqrt{2}U} \left[\frac{\sqrt{2}U}{\sin\theta + \cos\theta} - U^* \right] \cos\theta \tag{22}$$

$$t_{21}=\frac{T_s}{2\sqrt{2}U}\left[\frac{\sqrt{2}U}{\sin\theta+\cos\theta}-U^*\right]\sin\theta \qquad (23)$$

The times of four basic space vectors in a carrier cycle can be obtained according to (20)-(23).

V THE COMPOSITION OF THE TWO-PHASE HYBRID STEPPING MOTOR VECTOR CONTROL SYSTEM AND ANALYSIS OF SIMULATION RESULTS

The principle of stepping motor torque vector control is shown in Fig.5. A limited output of PI control algorithm can be used on the current loop and speed loop. The given value of current loop comes from the speed controller output and the given value i_d^* and i_q^* of direct axis and cross-axis current can be given by (9) and (10) when the given current value i_s is determined. Two-phase SVPWM control signal can be got by the combination of the amplitude of the voltage space vector which comes from the transformation of current controller output by rotating/stationary coordinate transformation and the stationary coordinate/space vector coordinate transformation. The two-phase winding terminal voltage U_A and U_B can be got after the power amplifier. The feedback signal i_d and i_q comes from the transformation of two-phase winding feedback current signal i_A and i_B, which will constitute a current loop. The actual speed is got by the coefficient transformation of the angular calculated by the position sensor[7] .

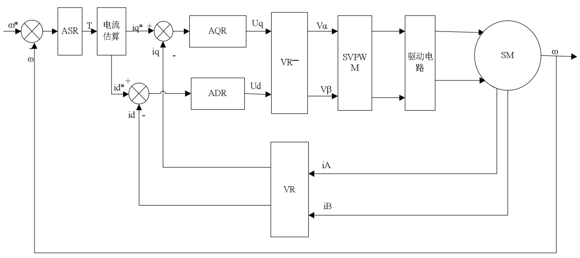

Fig.5 Principle of stepping motor torque vector control

The vector control simulation system build in Matlab/Simulink is shown in Fig.6[8]

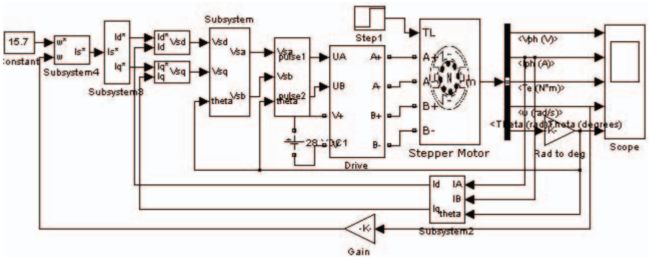

Fig.6 Simulation of hybrid stepping motor vector control system

Where winding resistance Rs=0.7Ohm, winding inductance L=1.4mH, rated torque Te=0.002N.m, carrier frequency is 500HZ, drive voltage is 28V. The simulation result based on above parameters is shown from Fig.7 and Fig.8

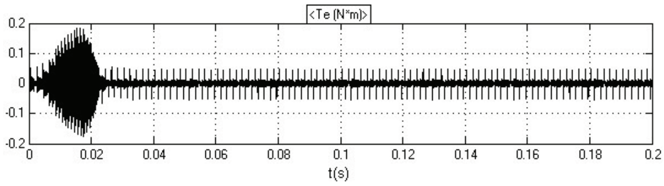

Fig.7 Output torque response curve

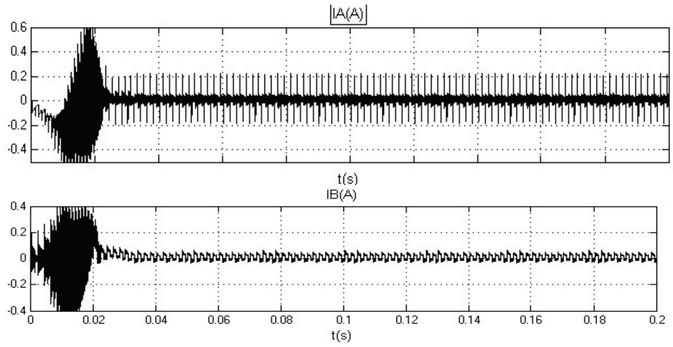

Fig.8 Two-phase winding output current IA,IB response curve

The given speed is 150r/min, the added load is 0.0015N.m. As shown in above figures, the track effect of the closed-loop control of two-phase stepping motor is good that means an input pulse produces a torque pulse accordingly. As for the parameter disturbance of motor, there will be some vibration in the initial stage. But the motor can return to a stable state quickly. The system has better dynamic and stead-state characteristics and the output result consistent with the law of the operation of stepping motor.

VI CONCLUSION

The maximum torque/current control strategy is proposed through the analysis of the mathematical model of the two-phase hybrid stepping motor. The simulation and experimental results show that the system has better dynamic and steady-state characteristics, and proved the method is correct and valid.

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