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Research on Symmetrical Six-phase PMSM Series-Connected Three-phase PMSM Based on SVPWM

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Abstract

A number of multi-phase motors can be series- connected and driven by a single inverter via the appropriate phase transformation rules, and all motors in series can be independently controlled. In this paper, the working principle of symmetrical Six-phase PMSM series connecting three-phase PMSM is proposed, a novel SVPWM method to achieve the decoupled control is presented. The implementing method of SVPWM is presented. In Matlab/simulink, the motor operating conditions, via id=0 vector control strategy, of variable load and speed are analyzed; the feasibility of the proposed SVPWM control strategy is verified.

Keywords: *symmetrical six-phase PMSM, three-phase PMSM, series system, SVPWM*

1. Introduction

With the development of power electronics technology, phase number of motors can be a variable independent from the constraint of being just single-phase or three-phase. Multiphase motors have the following advantages when compared with traditional motors: the application of multiphase motors is an effective solution to the problem of high power in circumstances of power supply voltage restriction. With the increase of phase number, torque ripple is reduced and ripple frequency increases, thus the low speed performance is greatly improved; and vibration and noise are also reduced, the reliability of the driving system is largely improved with the increase of phase number. However, research on multiphase series-connected multi-motor drive system is a novel concept only developed in recent years[1-2].

Among various PWM (Pulse Width Modulation) methods, SVPWM (space-vector pulse width modulation) is widely applied in AC speed regulation system [3] because of its advantages such as high voltage utilization, clear physical concept and easy digitalization. Research on SVPWM in multiphase motor series-connected drive system would be more complicated with implementation method largely differs from that of general speed regulation systems[4]. Therefore, this paper, taking symmetrical six-phase PMSM series connecting three-phase PMSM as an example, explains the control principal of SVPWM and presents the selection method and algorithm of basic voltage vectors to achieve independent operation of two motors. The feasibility of the proposed SVPWM control strategy is verified via simulation analysis during variable speed and variable load operation, with integration of the id =0 vector control strategy.

2. Series Connection Model of Symmetrical Six-phase PMSM and Three-Phase PMSM

Phase sequence transformation should be carried out and physical quantities in the system (including voltage, current and flux, etc) need to be decomposed to three planes which are

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mutually orthogonal, namely d-q, x-y and o1-o2. When the two motors are series-connected, physical quantities in plane o1-o2 don't control any motor while plane d-q and plane x-y control one motor each. Detailed stator connection sequence is shown in Fig. (**1**) [5-8].

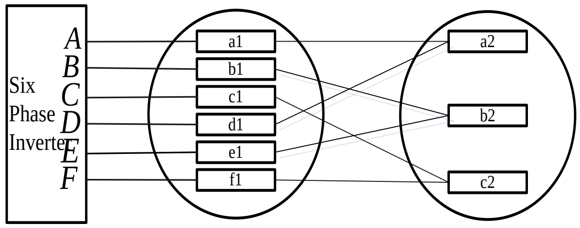


Figure 1. Stator Winding Connection Sequence

According to the general theory of multiphase circuit coordinate transformation, while analyzing series-connected symmetrical six-phase PMSM and three-phase PMSM, vector space transformation matrix needs to be applied.

$$T_6 = \sqrt{\frac{1}{3}} \begin{pmatrix} 1 & \cos\theta_1 & \cos 2\theta_1 & \cos 3\theta_1 & \cos 4\theta_1 & \cos 5\theta_1 \\ 0 & \sin\theta_1 & \sin 2\theta_1 & \sin 3\theta_1 & \sin 4\theta_1 & \sin 5\theta_1 \\ 1 & \cos 2\theta_1 & \cos 4\theta_1 & \cos 6\theta_1 & \cos 8\theta_1 & \cos 10\theta_1 \\ 0 & \sin 2\theta_1 & \sin 4\theta_1 & \sin 6\theta_1 & \sin 8\theta_1 & \sin 10\theta_1 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{pmatrix}$$

Series connection control system is shown in Fig. (**2**).

Voltage-current relation of the first motor in rotating reference frame d-q:

$$\begin{cases} u_{d1} = R_1 i_{d1} + L_1 \dfrac{di_{d1}}{dt} - \omega_{r1} L_1 i_{q1} \\ u_{q1} = R_1 i_{q1} + L_1 \dfrac{di_{q1}}{dt} + \omega_{r1}\left(L_1 i_{d1} + \psi_{f1}\right) \end{cases} \quad (1)$$

Here, $L_1 = L_{s\sigma 1} + 3L_{sm1}$, $\psi_{f1} = \sqrt{3} N_{s1} \phi_{fm1}$, $L_{s\sigma 1}$ and L_{sm1} are the leakage inductance of the winding per phase and main magnetic flux inductance separately of the first motor stator. R_1 is the winding resistance per phase of the first motor, Φfm1is the main magnetic flux of the permanent magnet, Ns1is the stator winding turns, and ωr1is the rotational speed of the first motor.

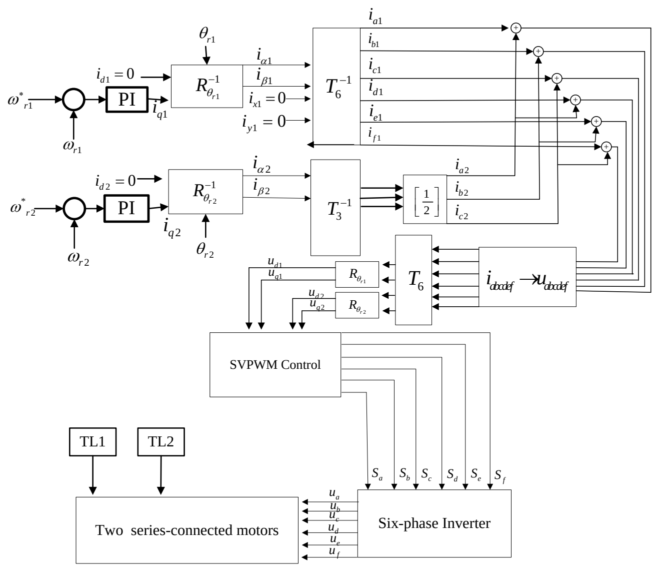


Figure 2. Stator Connection of Two Vector-controlled Series-connected Motors

The torque equation after rotational transformation:

$$\begin{aligned} T_{e1} &= \sqrt{3}P_1 \cdot \left(i_\alpha \sin\theta_{r1} - i_\beta \cos\theta_{r1}\right) \cdot N_{s1}\phi_{fm1} \\ &= p_1 \cdot ((i_{d1}\cos\theta_{r1} - i_{q1}\sin\theta_{r1}) \cdot \sin\theta_{r1} \\ &\quad -(i_{d1}\sin\theta_{r1} + i_{q1}\cos\theta_{r1}) \cdot \cos\theta_{r1}) \cdot \psi_{f1} \\ &= p_1 \cdot \psi_{f1} \cdot i_{q1} \end{aligned} \tag{2}$$

Here, p_1 denotes the number of pole-pairs of the first motor and θr1 is the angle between the rotor flux and stator phase A.

Voltage-current relation of the second motor in rotational coordinate system:

$$\begin{cases} u_{d2} = (R_1 + 2R_2)i_{d2} + L_2 \dfrac{d}{dt} i_{d2} - \omega_{r2} L_2 i_{q2} \\ u_{q2} = (R_1 + 2R_2)i_{q2} + L_2 \dfrac{d}{dt} i_{q2} + \omega_{r2}(L_2 i_{d2} + \psi_{f2}) \end{cases} \tag{3}$$

Here, $L_2 = L_{s\sigma1} + 2L_{s\sigma2} + 3L_{sm2}$, $\psi_{f2} = \sqrt{3}N_{s2}\phi_{fm2}$, $L_{s\sigma2}$ and L_{sm2} are the leakage inductance of the winding per phase and main magnetic flux inductance separately of the second motor stator. R_2 is the winding resistance per phase of the second motor, ϕ_{fm2} is the main magnetic flux of the permanent magnet, N_{s2} is the stator winding turns, and ω_{r2} the rotational speed of the second motor.

The torque equation after rotational transformation:

$$\begin{aligned} &T_{e2} = \sqrt{3}P_2 \cdot \left(i_x \sin\theta_{r2} - i_y \cos\theta_{r2}\right) N_{s2}\phi_{fm2} \\ &= p_2 \cdot ((i_{d2}\cos\theta_{r2} - i_{q2}\sin\theta_{r2}) \cdot \sin\theta_{r2} - (i_{d2}\sin\theta_{r2} + i_{q2}\cos\theta_{r2}) \cdot \cos\theta_{r2}) \cdot \psi_{f2} \\ &= p_2 \cdot \psi_{f2} \cdot i_{q2} \end{aligned}$$

(4)

Here, p_2 is the number of pole-pairs of the second motor and θ_{r2} is the angle between the rotor flux and stator phase A[3].

3. Control Principle of SVPWM

3.1 Vector Distribution

Circuit of symmetrical six-phase inverter and loads is shown as Fig. (**3**).

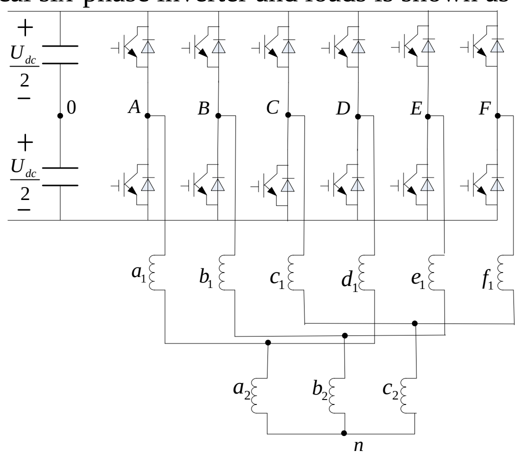


Figure 3. Circuit of Symmetrical Six-phase Inverter and Loads

Supposing switch function is $\boldsymbol{S}=[S_A \quad S_B \quad S_C \quad S_D \quad S_E \quad S_F]$ .When the upper $k(k=A,B,C,D,E,F)$ of VSI is conducted, then $S_k=1$, the polar output voltage of VSI is $U_{dc}/2$, otherwise, the lower switch is conducted, then $S_k=0$, the polar output voltage of VSI is

$$u_{k0}=S_k\cdot U_{dc}-\frac{U_{dc}}{2} \tag{5}$$

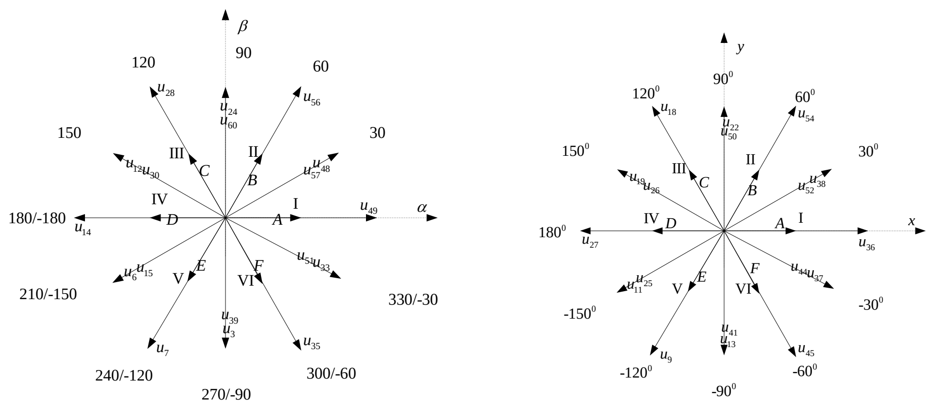
The working platform of SVPWM method is a two-phase stationary reference frame. Voltage space vector of inverter on plane α-β and plane x-y is defined as:

$$\begin{aligned}\boldsymbol{U}_{\alpha\beta k}&=\frac{2}{6}U_{dc}\left[e^{j0^\circ} \quad e^{j60^\circ} \quad e^{j120^\circ} \quad e^{j180^\circ} \quad e^{j240^\circ} \quad e^{j300^\circ}\right]\cdot\boldsymbol{S}_k^T\\ \boldsymbol{U}_{xyk}&=\frac{2}{6}U_{dc}\left[e^{j0^\circ} \quad e^{j120^\circ} \quad e^{j240^\circ} \quad e^{j0^\circ} \quad e^{j120^\circ} \quad e^{j240^\circ}\right]\cdot\boldsymbol{S}_k^T\end{aligned} \tag{6}$$

Here, $V_{\alpha\beta k}$ denotes voltage space vector on plane α-β , and V_{xyk} denotes voltage space vector on plane x-y. $\boldsymbol{S}=[S_A \quad S_B \quad S_C \quad S_D \quad S_E \quad S_F]$. When z is “1”, the upper switch of the VSI is conducted while “0” means the lower switch is conducted. The binary instantaneous value S_k representing switch status can be expressed equivalently using decimal number l :

$$l=S_A\times 2^0+S_B\times 2^1+S_C\times 2^2+S_D\times 2^3+S_E\times 2^4+S_F\times 2^5 \tag{7}$$

For a six-phase full-bridge inverter, there are altogether $2^6=64$ space voltage vectors. Distribution of the 64 vectors including 62 nonzero voltage vectors on plane α-β and plane x-y is shown in Fig. (**5**). Calculated value of vector 0(000000) and 63(0000000) is 0, which makes the origin of coordinates in Fig. (**4**).



$A=(u_{17},u_{32},u_{41},u_{50},u_{53},u_{59}),B=(u_{16},u_{25},u_{40},u_{52},u_{58}.u_{61}),C=(u_{8},u_{20},u_{26},u_{29},u_{44},u_{62}),$
$D=(u_{4},u_{10},u_{13},u_{22},u_{31},u_{46}),E=(u_{2},u_{5},u_{11},u_{23},u_{38},u_{47}),F=(u_{1},u_{19},u_{34},u_{37},u_{43},u_{55}),$
$O=(u_{0},u_{9},u_{18},u_{21},u_{27},u_{36},u_{42},u_{45},u_{54},u_{63})$

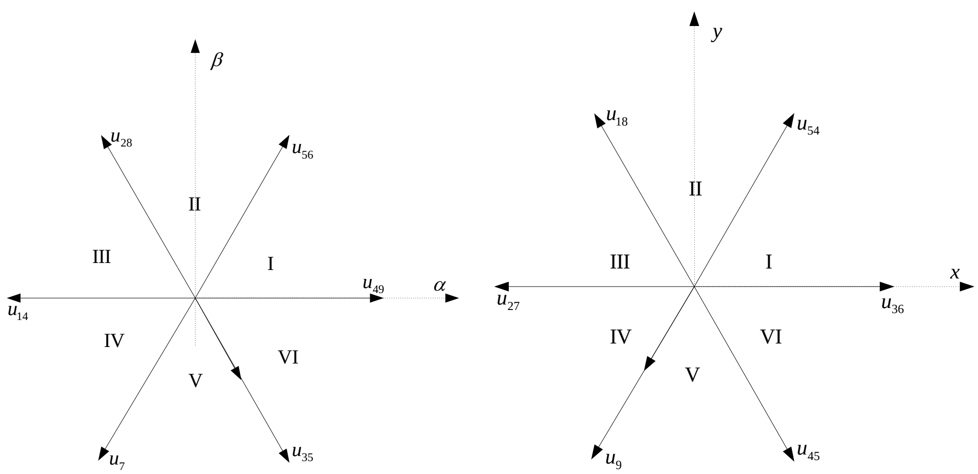
$A=(u_{4},u_{32},u_{39},u_{46},u_{53},u_{60}),B=(u_{6},u_{20},u_{34},u_{48},u_{55},u_{62}),C=(u_{2},u_{16},u_{23},u_{30},u_{51},u_{58}),$
$D=(u_{3},u_{10},u_{17},u_{24},u_{31},u_{59}),E=(u_{1},u_{8},u_{15},u_{29},u_{43},u_{57}),F=(u_{5},u_{12},u_{33},u_{40},u_{47},u_{61}),$
$O=(u_{0},u_{7},u_{14},u_{21},u_{28},u_{35},u_{42},u_{49},u_{56},u_{63})$

(a) Space voltage vector distribution on plane α-β (b) Space voltage vector distribution on plane x-y

Figure 4. Space Voltage Vector of Six-phase Inverter

3.2 Selection and Calculation of basic Voltage Vector

According to the average vector concept in a sampling period, reference voltage vectors on plane α-β and plane x-y can be achieved through adjusting the application time of the basic voltage vector and two zero vectors. To guarantee decoupled control of two motors, i.e. independent control of motor 1 from motor 2, it is necessary that within one sampling period, when the control system is working on plane α-β, the sum of projections of basic voltage vectors onto plane x-y must be zero during that period, and vise versa, when the control system is working on plane x-y, the sum of projections of basic voltage vectors onto plane α-β be zero during the period. Basic voltage vectors on plane α-β and plane x-y are as shown in Fig. (5).



(a) Basic voltage vector on plane α-β (b) Basic voltage vector on plane x-y

Figure 5. Basic Voltage Space Vectors on Plane α-β and Plane x-y

As is seen in Fig 4 and Fig 5, projection of selected basic voltage vector of plane α-β onto plane x-y is zero, and vise versa. This selection method not only guarantees decoupled control of the system but also reduces calculation effort of working time.

When control system works on plane α-β, working time on each basic voltage vector is

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} u_{\alpha 1} & u_{\alpha 2} \\ u_{\beta 1} & u_{\beta 2} \end{bmatrix}^{-1} \cdot \begin{bmatrix} u_{\alpha}^{*} \\ u_{\beta}^{*} \end{bmatrix} \cdot T_S \qquad (8)$$
$$T_S = T_1 + T_2 + T_0$$

Here, $T_k\,(k=1,2)$ denotes the working time on basic voltage vector number k. T_0 is the working time of zero vector. $u_{\alpha k}$, $u_{\beta k}$ are projections of basic voltage vector number k on axis α and axis β separately.

In the same way, when the control system works on plane x-y, working time on each basic voltage vector is

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} u_{x1} & u_{x2} \\ u_{y1} & u_{y2} \end{bmatrix}^{-1} \cdot \begin{bmatrix} u_{x}^{*} \\ u_{y}^{*} \end{bmatrix} \cdot T_S \qquad (9)$$
$$T_S = T_1 + T_2 + T_0$$

Here, $T_k\,(k=1,2)$ denotes working time on basic voltage vector number k and T_0 denotes working time of zero vector. u_{xk}, u_{yk} are projections of basic voltage vector number k on axis x and axis y separately.

In addition, when $T_1 + T_2 > T_s$, working time of basic voltage vector should also be modulated (there is no zero vector in function during this period). The modulation method is

$$T_1^{'} = \frac{T_1}{T_1 + T_2}; \quad T_2^{'} = \frac{T_2}{T_1 + T_2} 。 \qquad (10)$$

Take sector II on plane α-β as an example. The voltage vector sequence and responsive switch status are as shown in Fig. (**6**). When T_k^{+} is at high level ($S_k = 1$), the upper leg switch of phase k is on and lower leg switch is off.

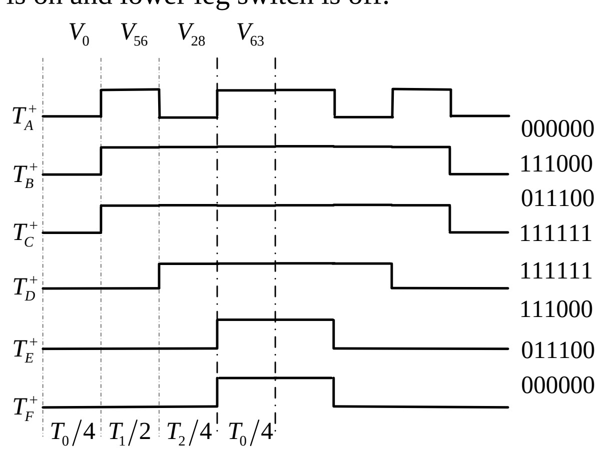


Figure 6. SVPWM Controlled Vector Sequence and Switch State

3.3. Selection of Working Plane

Selection of reference voltage vector should be capable of improving the utilization of DC bus voltage. Here selection of switch vector is determined by reference vector and its magnitude of plane *d-q* in one period, i.e., if the reference vector value of plane *d-q* is larger than that of plane *x-y*, then switch vector is determined by the two largest and two second largest vectors of plane *d-q*. And vice versa, if reference vector value of plane *x-y* is larger than reference vector of plane *d-q*, then switch vector is determined by the two largest and two second largest vectors of plane x-y. Selection process of reference voltage vector is shown in Fig. (**7**) .

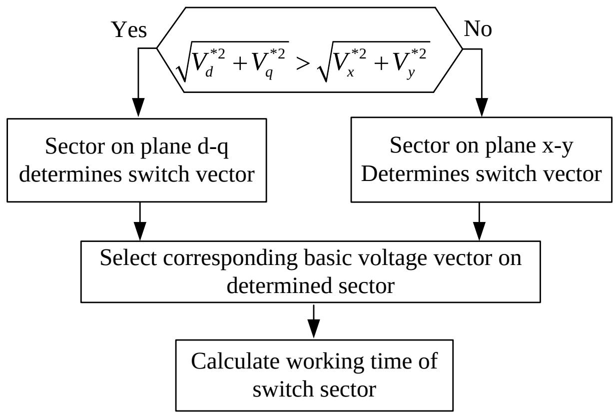


Figure 7. Selection Process of Reference Voltage Vector

4. Simulation Analysis of Series-connected Drive System

Series-connected system model is built in Matlab/Simulink. The system includes motor series-connected module, speed regulation module, coordinate transformation module and inverter module, etc. Simulation configuration of the system is as follows: Basic motor parameters are set up as follows:

$$R_1 = R_2 = 2.875\ \Omega,\ \ p_1 = p_2 = 6,\ \ \psi_{f_1} = 0.175\ \text{Wb},\ \ \psi_{f_2} = 0.2\ \text{Wb},$$

$$L_1 = 0.008\ \text{H},\ \ L_2 = 0.013\ \text{H}, T_{l1} = 5\ \text{N}\cdot\text{m},\ T_{l2} = 3\ \text{N}\cdot\text{m}$$

when *t*=0 s, speed of motor 1 is 300 rpm(30 Hz) and remains the same during the process; when *t*=0 s, speed of motor 2 is 200 rpm(20 Hz) and accelerates to 400 rpm(40 Hz) when *t*=0.6 s. Speed, set current, output current and torque is shown in Fig. (**8**)- (**10**).

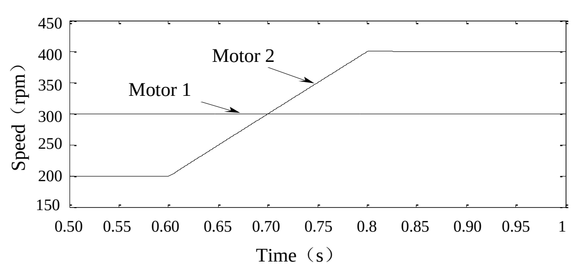


Figure 8. Time-speed Curve

It can get conclusion that as the speed of three-phase PMSM accelerates from 200rpm to 400rpm when t=0.6s, there is relative change in the torque of three-phase PMSM with the motor supply current frequency changes from 20HZ to 40HZ. However, the speed, torque and supply current frequency of motor 1 remain the same. Phase-a current of the inverter presents irregular periodic variation.

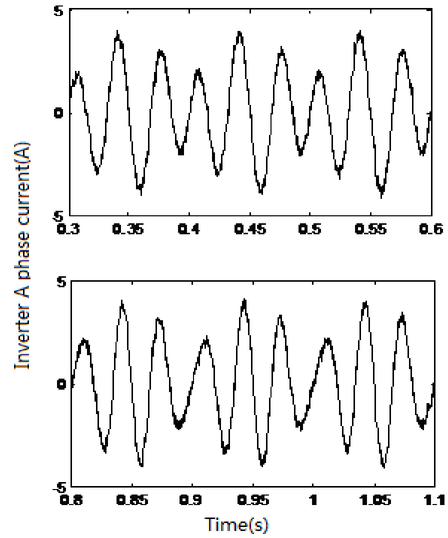


Fig. (9). Current curve

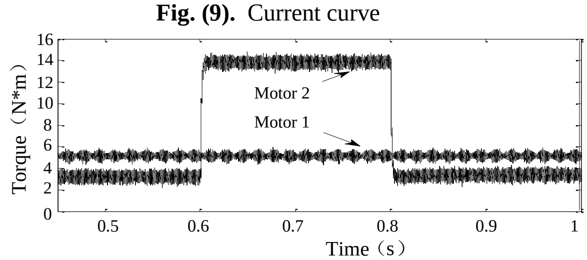


Figure 10. Time-torque Curve

If the condition above is changed as follows: when t=0.6s, motor 2 rotates inversely at 100rpm（10Hz）, the simulation results are:

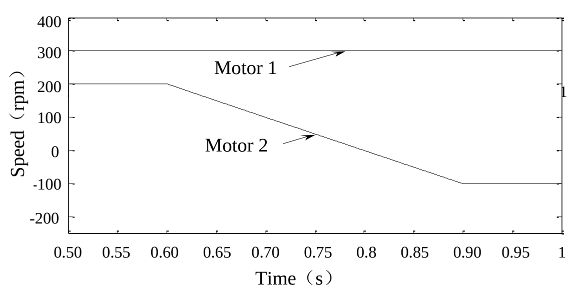


Figure 11. Time–speed Curve

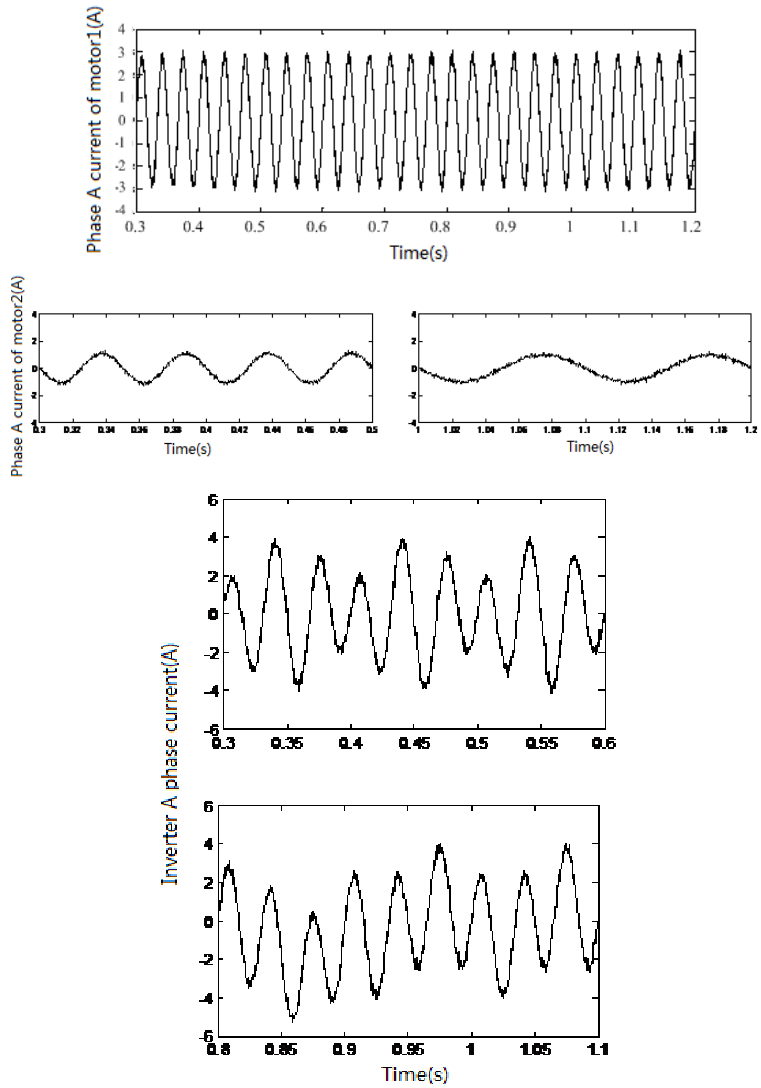


Figure 12. Current Curve

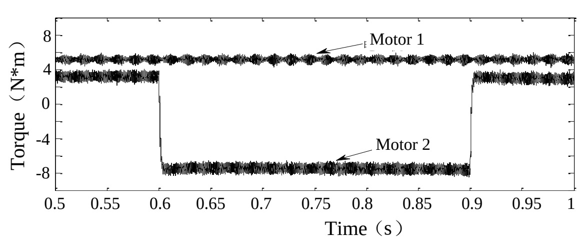


Figure 13. Torque Curve

It is get conclusion that six-phase PMSM torque and current do not change with the inverse rotation of the three-phase PMSM when t=0.6s.Thus it is known that there is decoupling of the two motors taken place. Phase-a current of the inverter also presents irregular periodic variation.

The speed change of motor 2 leads to corresponding change of physical quantities of motor 2 such as power supply frequency and torque, but it has no effect on motor 1. In the same way, it can be verified that change in motor 1 has no effect on motor 2. Thus it is safe to conclude that independent control of the speed of the two machines is realized and control of the two motors is decoupled.

5. Conclusion

This paper introduces the principle of symmetrical six-phase PMSM series-connected three-phase PMSM and the method of controlling strategy via SVPWM. A simulation module of the series module is created in Simulink, and the result shows that decoupling control of two motors in a SVPWM controlled series system driven by the same inverter can be realized, i.e., two motors can operate independently. In-depth research can be done on multiphase motor series system on this basis.

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References

[1] E. Levi, "Operating principles of a novel multiphase multimotor vector-controlled drive", IEEE Trans. On Energy Convertion, **(2004)**, vol. 19, no. 3, pp. 508-517
[2] Levi, M. Jones, S. N. Vukosavic and H. Toliyat, "A novel concept of a multiphase, multi-motor vector controlled drive system supplied from a single inverter", IEEE Trans. Power Electronics, vol.19, no. 2, **(2004)**, pp. 320–335.
[3] Y. Zhao and T. A. Lipo, "Space vector PWM control of dual three-phase induction machine using vector", IEEE Trans. on Industry applications, vol. 31, no. 5, **(1995)**, pp. 1100-1109.
[4] A. Iqbal and E. Levi, "Space vector PWM for a five-phase VSI supplying two five-phase series-connected Machines", Proc. Int. Conf. EPE-PESC, **(2006)**; Portoroz, Slovenia.
[5] M. B. R. Correa, C. R. Da Silva and H. Razik, " Independent voltage control for series connected six-phase and three-phase induction machines", IEEE Transactions on Industry Application, vol.45, no. 4, **(2009)**, pp. 1287-1293
[6] M. Jones, S. N. Vukosavic and E. Levi, "Independent vector control of a six-phase series-connected two-motor drive", Second international conference on power electronics, machines and drives, **(2004)**; Edinburgh, United kingdom.
[7] E. Levi, S. N. Vukosavic and M. Jones, "Vector control schemes for series-connected six-phase two-motor drive systems", IEE proceedings-Electric Power Applications, **(2005)**.
[8] E. Levi, M. Jones and S. N. Vukosavic, "A series-connected two-motor six-phase drive with induction and permanent magnet machines", IEEE Transactions on Energy Conversion, vol. 21, no. 1, **(2006)**, pp. 121-129.

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