Fault-Tolerant Control for Five-Phase Permanent Magnet Synchronous Motor Servo System Based on Topological Reconstruction

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Abstract. Motors are required to possess the capacity to deal with sudden failure in the occasion where reliability are highly required, such as aerospace, more-electric aircraft, all-electric ship propelling and new energy automobile. In other words, motors should keep working for some time instead of shutting down immediately when failure happens, in order to ensure life safety or meet the requirement of high reliability and fault tolerance. The reliability, and the ability to keep working after failure (or fault tolerance) of permanent magnet synchronous motor (PMSM) have become necessary capacities of motor in several special application areas. In this paper, we build a mathematical model of five-phase permanent magnet synchronous motor (FPPMSM) and focus on the core techniques of fault-tolerant control for FPPMSM servo system based on the SVPWM algorithm, and then validate the result with simulation and experiment.

Keywords: FPPMSM · Motor servo system · Topological Reconstruction · Fault-tolerant control

1 Introduction

Due to the prevalent application of electro-mechanical servo system in aerospace, more-electric aircraft, all-electric ship propelling and new energy automobile, higher reliability and safety of motor system are more and more required. Therefore, fault-tolerant motor control system has been given more and more attention. Since fault-tolerant motor system was addressed, people have proposed several techniques to achieve the fault-tolerant control, which leads to the concept of the fault tolerance of motor. Fault tolerance means firstly that motor maintains identical or equivalent output as normal condition. Secondly it refers to the capacity of motor isolating faults and protecting the system itself in order to avoid fatal hazards in the occasion where high redundancy and reliability are needed. Motor winding is the key part of the electro-mechanical energy transformation. The performance property of motor depends mostly on the distribution of winding and the current in them. Further study of motor winding helps to comprehend the essence

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of electro-mechanical energy transformation, estimate the electromagnetic property of motor and provide theoretical support for optimizing motor design and improving control performance. Multi-phase fault-tolerant motor improves redundancy by increasing the number of motor phase, and change the control strategy of inverter to offset the effect of faulted phase. In comparison with traditional three-phase motor servo system, multi-phase motor servo system not only has an edge on the performance, but also possesses functions which the former one does not have. The primary cause is that the increase in phase number brings more freedom of control and design. The multi-phase motor servo system has many advantages [1–5]. The frequency of torque pulsation increases and its amplitude decreases with the increasing of phase number. That could reduce the noise and vibration of motor and improve the performance at low speed, which is suitable for direct drive occasion. Redundancy in phase ensures high fault tolerance for multi-phase motor. The utilization rate of bus voltage can be improved obviously. Harmonic current in DC bus decreases and thus smaller filter capacitor could be used to reduce the cost. Multi-phase motor control driver could provide more control resources which helps to improve control performance.

Multi-phase fault-tolerant motor has higher power density, higher reliability and smaller output torque pulsation in fault condition. However, increasing in phase number also brings the increase in driver device cost and complexity. Design of stator winding could also affect the design of servo driver. The influence of phase number is mostly reflected by the choice of driver topology and control of cost. The choice of phase number is actually a compromise of controller cost (more phase, more cost), probability of winding failure (more phase, more likely to fail) and motor fault tolerance (more phase, higher fault tolerance). Five-phase fault-tolerant motor becomes an ideal form of fault-tolerant motor due to its fault-tolerant performance and control feasibility. In this paper, a five-phase fault-tolerant PMSM servo system with one line attached with bridge arm and shared neutral point is adopted, which further improves reliability and fault-tolerance performance of FPPMSM servo system. This paper studies mathematical modeling, topological structure, multi-dimension vector control, fault-tolerant control and experiment validation of FPPMSM servo system.

2 Mathematical Model of the FPPMSM

FPPMSM servo system is mostly composed with one five-phase fault-tolerant PMSM, one fault-tolerant FPPMSM driver and one set of cable network. Fault-tolerant FPPMSM driver accepts control commands from the control system through CAN bus and controls the movement of FPPMSM, which ensures high efficiency and high reliability of the system. Five-phase fault-tolerant PMSM servo system frame is shown in Fig. 1. Figure 2 shows the stator structure of fault-tolerant FPPMSM.

The stator voltage equation of FPPMSM in five-phase static coordinate can be written as:

$$U_s = r_s I_s + \frac{d}{dt}\psi_s \tag{1}$$

where $\psi_s = L_s I_s + \psi_m$.

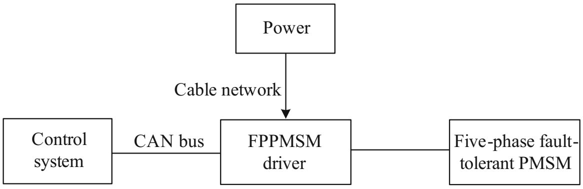


Fig. 1. Five-phase fault-tolerant PMSM servo system frame.

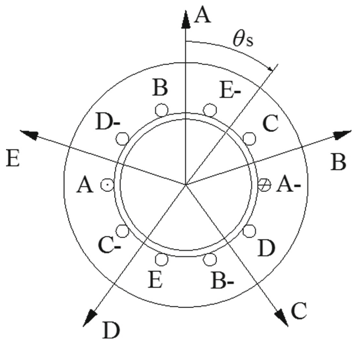


Fig. 2. Stator structure of fault-tolerant FPPMSM.

Taking amplitude-invariant principle, the decoupling transformation matrix for FPPMSM is:

$$T(\alpha) = \frac{2}{5}\begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \cos 4\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha \\ 1 & \cos 3\alpha & \cos 6\alpha & \cos 9\alpha & \cos 12\alpha \\ 0 & \sin 3\alpha & \sin 6\alpha & \sin 9\alpha & \sin 12\alpha \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (2)$$

By Eq. (2), the fundamental wave component in voltage and current are mapped to the fundamental space constituted by the first and second row. The third harmonic component is mapped to the harmonic space made up by the third and fourth row, while the last row refers to the zero-order component. The transformation matrix from five-phase static to five-phase synchronous coordinate for FPPMSM is:

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 & 0 \\ 0 & 0 & \cos 3\theta & \sin 3\theta & 0 \\ 0 & 0 & -\sin\theta & \cos 3\theta & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The transformation matrix from five-phase synchronous to decoupling synchronous rotating coordinate for FPPMSM is:

$$T(\theta) = R(\theta)T(\alpha)$$
$$= \frac{2}{5}\begin{bmatrix} \cos\theta & \cos(\theta-\alpha) & \cos(\theta-2\alpha) & \cos(\theta-3\alpha) & \cos(\theta-4\alpha) \\ -\sin\theta & -\sin(\theta-\alpha) & -\sin(\theta-2\alpha) & -\sin(\theta-3\alpha) & -\sin(\theta-4\alpha) \\ \cos 3\theta & \cos 3(\theta-\alpha) & \cos 3(\theta-2\alpha) & \cos 3(\theta-3\alpha) & \cos 3(\theta-4\alpha) \\ -\sin 3\theta & -\sin 3(\theta-\alpha) & -\sin 3(\theta-2\alpha) & -\sin 3(\theta-3\alpha) & -\sin 3(\theta-4\alpha) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{4}$$

Thus, the stator voltage equation of FPPMSM in decoupling synchronous rotating coordinate is:

$$U_{dqs} = \begin{bmatrix} U_{d1} \\ U_{q1} \\ U_{d3} \\ U_{q3} \\ U_0 \end{bmatrix} = r_s \begin{bmatrix} I_{d1} \\ I_{q1} \\ I_{d3} \\ I_{q3} \\ I_0 \end{bmatrix} + \begin{bmatrix} L_{d1} & 0 & 0 & 0 & 0 \\ 0 & L_{q1} & 0 & 0 & 0 \\ 0 & 0 & L_{d3} & 0 & 0 \\ 0 & 0 & 0 & L_{q3} & 0 \\ 0 & 0 & 0 & 0 & L_{ls} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_{d1} \\ I_{q1} \\ I_{d3} \\ I_{q3} \\ I_0 \end{bmatrix} + \omega \begin{bmatrix} 0 \\ \psi_{m1} \\ 0 \\ 3\psi_{m3} \\ 0 \end{bmatrix} \tag{5}$$

The electromagnetic torque of FPPMSM could be obtained by taking partial derivative of magnetic co-energy by rotor position angle. When the flux linkage of permanent magnet contains third harmonic component, it could produce extra torque together with the third harmonic component of armature current.

$$\begin{aligned} T_\varepsilon &= pI_s^T \frac{\partial \psi_m}{\partial \theta} \\ &= p(T^{-1}(\theta)I_{dps})^T \frac{\partial (T^{-1}(\theta)\psi_{dqm})}{\partial \theta} \\ &= pI_{dqs}^T (T^{-1}(\theta))^T \frac{\partial (T^{-1}(\theta)\psi_{dqm})}{\partial \theta} \\ &= pI_{dqs}^T \begin{bmatrix} 0 & -\frac{5}{2} & 0 & 0 & 0 \\ \frac{5}{2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{15}{2} & 0 \\ 0 & 0 & \frac{15}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \psi_{m1} \\ 0 \\ \psi_{m3} \\ 0 \\ 0 \end{bmatrix} \\ &= \frac{5}{2}p(I_{q1}\psi_{m1} + 3I_{q3}\psi_{m3}) = C_{T1}I_{q1} + C_{T3}I_{q3} \end{aligned} \tag{6}$$

where p is the pole pair number.

The motion equation is:

$$J\frac{d\omega_m}{dt} = T_\varepsilon - T_L - B\omega_m \tag{7}$$

where J is the moment of inertia, ω_m is mechanical angular velocity, T_L is load resistance torque and B is damping coefficient.

3 FPPMSM Multi-dimension Vector Control and Fault-Tolerant Control

This paper studies core techniques of fault-tolerant control for FPPMSM servo system based on the SVPWM algorithm by building a mathematical model of Five-phase fault-tolerant PMSM, and validate the result with simulation and experiment.

There are various types of multi-phase driver's topological structure. This paper picked a reconstructable five-phase topological structure expanded from traditional three-phase bridge structure, with one phase line that could be attached to a bridge arm on the neutral point. Since this kind of structure is simple and easy to control, we can use fully-proved studies of driver directly. When failure happens on a certain phase, we can use the attached bridge arm without difficulties, which helps to improve driver's fault tolerance. Five-phase topological structure with attached arm on the neutral point is shown in Fig. 3.

When phase number increases, number of voltage space vector increases exponentially. There are $2^5 = 32$ voltage vectors in two electrical level five-phase full-bridge control driver. Arranging these 32 vectors according to their phase sequence, the vector diagram of fundamental wave space and third harmonic space could be obtained [6].

We could know from Fig. 4 that the projection of voltage space vector can be divided into ten sectors on the plane. 30 of 32 vectors are non-zero vectors, which can be sorted into large, middle and small vectors according to their norm. The projection of each switch state on the fundamental wave space is different from the harmonic space. When using different basic vectors, the composite space vector will be different, and the system state variables of motor under SVPWM will also be different.

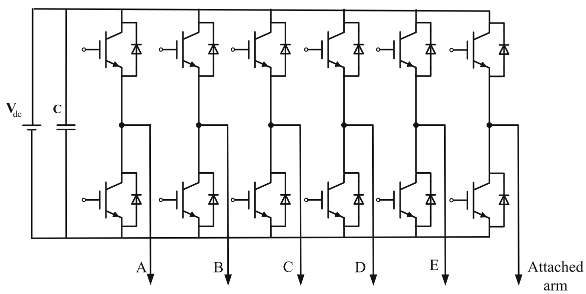
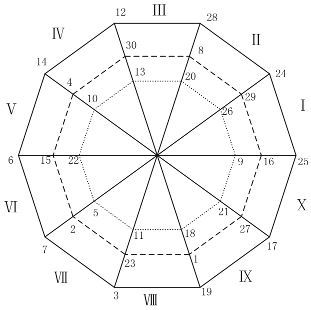
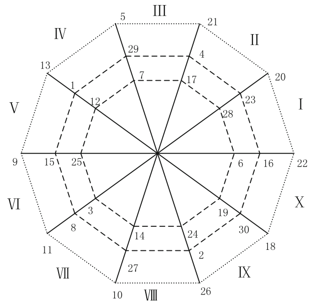


Fig. 3. Five-phase topological structure with attached arm on the neutral point.



(a) $\alpha_1 - \beta_1$ fundamental wave space

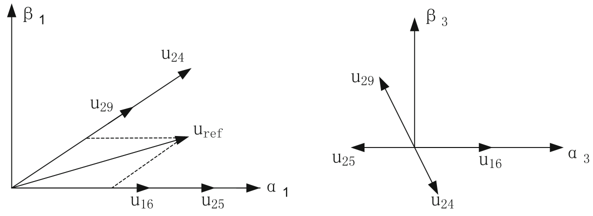


(b) $\alpha_3 - \beta_3$ third harmonic space

Fig. 4. Five-phase five-bridge-arm voltage space vector diagram.

Taking into account control performance and utilization rate of DC voltage, this paper uses multi-dimension SVPWM based on composition of two large and two middle vectors in the sector where rotor locates. The schematic diagram in $\alpha_1 - \beta_1$ space are shown in Fig. 5. The output voltage vector composed by the corresponding four vectors in $\alpha_1 - \beta_1$ space meets the reference vector and the volt second values of these four vectors in $\alpha_3 - \beta_3$ space are close to 0. Thus, the ripple current and switching loss could be reduced. We can refer to sector judging algorithm, introduce five voltage components and *sign(x)* function, and define the sector judging value. Then we could get the true sector judging value and dwell time of each voltage vector.

Fault diagnosis and fault-tolerant control techniques for high efficiency, high reliability and fault-tolerant motor require the study of high-accuracy, high frequency response technique and fault-tolerant technique based on topological reconstruction structure. Then we could validate the designed performance with prototype and experiments, and find the principle of fault diagnosis and fault-tolerant control design with high efficiency and high reliability. The topological reconstruction schematic diagram of attached bridge arm on neutral point is shown in Fig. 6.



(a) $\alpha_1 - \beta_1$ frame (b) $\alpha_3 - \beta_3$ frame

Fig. 5. Voltage vector composition of 1st sector in two-phase static coordinate.

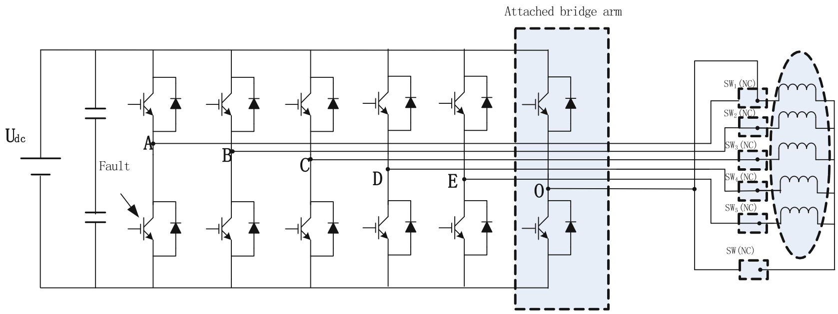


Fig. 6. Schematic diagram of attached bridge arm on neutral point (fault on A phase).

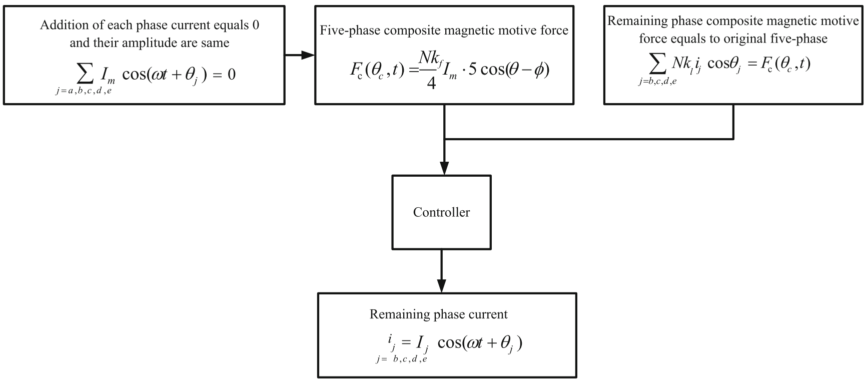


Fig. 7. Offset strategy of open-circuit fault (fault on A phase).

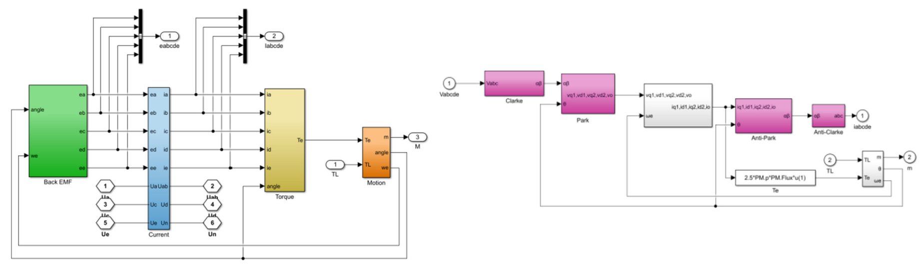
Analysing on the fault properties of FPPMSM, such as open circuit on one phase, two adjacent phases and two nonadjacent phases, we can get the state variables of fault-tolerant motor control, and then the operation mechanism of FPPMSM at open circuit.

For shared-neutral-point winding motor servo system, both open-circuit and short-circuit fault are treated as open circuit in order to reduce the complexity of fault-tolerant offset algorithm. When fault happens, run the debugging program first and find whether the fault happens at the driver or winding. If it happens at one phase of the driver, we can replace this phase with attached bridge arm and reconstruct the topological structure. If it happens at the winding, we can shut down this bridge arm to isolate the fault, and then run the vector control program after fault to realize 3-level fault-tolerant control.

Fault on one phase or two phases at the driver could lead to asymmetry of motor's power supply, which may cause large pulsation in output torque. After getting the fault-tolerant current with analytical method, we can control the phase current in closed loop with hysteresis controller. The keys to fault-tolerant control are recognition of fault position and offset against asymmetry of composite magnetic-motive force in motor gap, which finally lead to fault isolation and torque pulsation restraint. A decoupling fault tolerant control method [7] based on the principle of the constant stator magnetic motive force and minimum copper loss is proposed to calculate the fault-tolerant current. The decoupling vector control method may bring the asymmetric model, and the additional compensation is used to adjust it. On condition of the circle magnetic motive force, the left phase currents are optimized to control the sinusoidal fundamental wave air-gap magnetic field, to improve the steady state performance of the PMSM. With the adoption of fault-tolerant current control based on the unchanged magnetic motive force, although the left phase currents amplitude and phase position are transformed, the tracking performances of the motor torque and speed are safeguarded. Figure 7 shows the offset strategy of open-circuit fault.

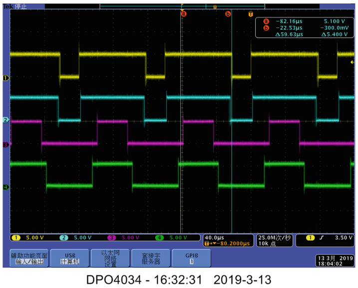
4 Simulation and Experiment

Though the research on five-phase multi-dimension space vector control and fault-tolerant control, this paper provides a product solution of reconstructable five-phase control servo system based on topological structure and develops a fault-tolerant FPPMSM system prototype by itself design. The validation of system performance index and design thought is achieved by simulation research and experiments. Figures 8, 9, 10 and

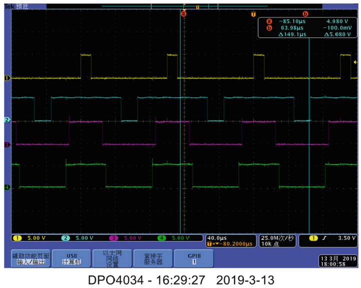


（1）Simulation diagram of FPPMSM based on a-b-c-d-e （2）Simulation diagram of FPPMSM based on d-q

Fig. 8. Simulation diagram of FPPMSM

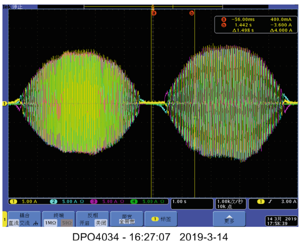


(a) A/B/C/D phase PWM

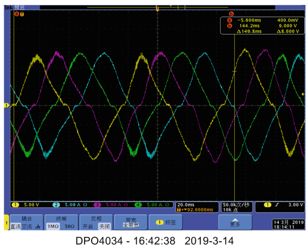


(b) E/A/B/C phase PWM

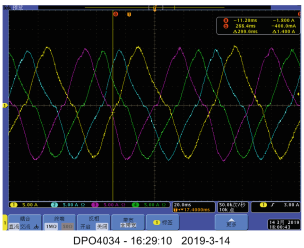
Fig. 9. Five-phase PWM waves generated by multi-dimension algorithm.



(a) Five-phase current



(c) E/A/B/C current



(b) A/B/C/D current

Fig. 10. Five-phase current waveform under sinusoid command.

11 show respectively the simulation diagram of fault-tolerant FPPMSM, the five-phase PWM waves generated by multi-dimension algorithm, five-phase current waveform under sinusoid command, load test experiment, and curves of current.

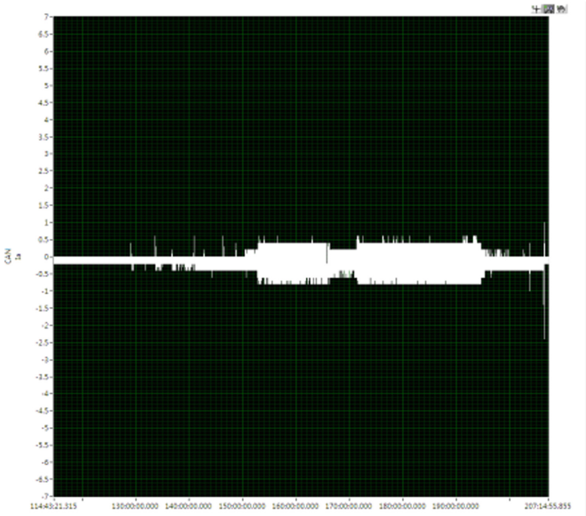


Fig. 11. Curves of current

5 Conclusion

This paper studies the key technology of fault-tolerant control for FPPMSM servo system by building a mathematical model of fault-tolerant FPPMSM, develops a fault-tolerant FPPMSM system prototype based on topological reconstruction and verifies the result with simulation and load test experiments. With the application of new type power electronic devices, new fault detection methods and fault-tolerant strategies as well as the improvement of permanent magnet material and silicon steel sheet, it is expected that the higher power density, fault tolerance and reliability of the new motor servo system, will lead to its expanded application in various special occasions and hostile environments.

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Authors' Contributions. A mathematical model of five-phase permanent magnet synchronous motor (FPPMSM) based on topological reconstruction is built, the key technology of the improved fault-tolerant control for FPPMSM servo system is focused on, and then verified by the results of simulation and load test experiment.

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