PHM Design of Permanent Magnet Synchronous Motor Stability Control System

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***Abstract*—The Permanent Magnet Synchronous Motor stability control system (PMSMSCS) is one of the core parts of armored vehicle. Now the manual mode and experience method are adopted in the maintenance and support of PMSMSCS. It is far away from the actual combat requirement. In this paper, the characteristics of PMSMSCS were studied and the principles and methods of the system fault diagnosis were analyzed. The prognostic and health management (PHM) system of PMSMSCS was designed. It includes the design of PMSM simulator, state monitoring module and fault diagnosis and prediction module. The simulation results show that this system could monitor and diagnose the working state of PMSMSCS in real time. It provides effective guidance for the design of actual system.**

Keywords-Permanent Magnet Synchronous Motor stability control system; PMSM simulator; state monitoring; fault diagnosis; fault prediction

I. INTRODUCTION

With the increasing integration and intelligentization of armored vehicle components, more and more attention is attracted to system fault diagnosis, maintenance & support and reliability. Nowadays equipment users are scattered all over the world under the background of globalization, which brings great challenges for operation and guarantee of equipment [1]. Permanent Magnet Synchronous Motor (PMSM) stability control system is one of the core components of armored vehicle. Its performance determines the function realization of the system.

But for a long time, the maintenance and support of PMSMSCS are based on manual method and experience method. These methods are no longer sufficient. With the development of computer technology, people begin to study the method of fault diagnosis based on health management. It brings about a new revolution in the field of fault diagnosis. As a brand- new solution for health management, prognostics and health management technology is the result of comprehensive use of modern information technology and artificial intelligence technology [2-4]. It is capable of improving the efficiency of fault monitoring and diagnosis and reducing maintenance costs. So the PHM technology becomes the focus of research in the field of security, reliability and maintainability. W. Qu studied the health management technology of the electromechanical control system of airborne equipment [5]. The physics-of-failure approach for fan PHM in electronics applications was discussed by Rhem in Ref. [6]. Li studied the application of prognostics and health management system in requirements and validation [7]. Lei studied PHM technology which based predictive maintenance optimization for offshore wind farms [8]. Xu did the research on PHM technology application of ship maintenance program optimization. Wu did the research on PHM-oriented integrated fusion prognostics for aircraft engines which based on sensor data [9]. In another paper, Wang established the simulation modeling for prognostics and health management (PHM) in airline industry [10]. However, the research on PHM technology of motor stability control system is not deep enough.

Based on the principle of PHM system and characteristics of PMSMSCS, a health management system capable of fault prediction and diagnosis is designed in this paper. The health management system creates a PMSM simulator according to the mathematical model of PMSM. With reference to the simulated output signal form simulator, it can not only monitor the working state of the closed-loop control system in real time, but also diagnose and locate faults if any occurs in the closed-loop control system. It solves such problem that the control system fails to locate the fault. The control loop is opened due to component failure. Consequently, it can realize the real time monitoring of working states and on-line location of faults for PMSMSCS.

II. FAULT DETECTION PRINCIPLE OF PMSMSCS

PMSMSCS is a feedback closed-loop, normally composed of servo controller, motor driver, motor and transmission mechanism, position and speed feedback elements, as shown in Fig. 1.

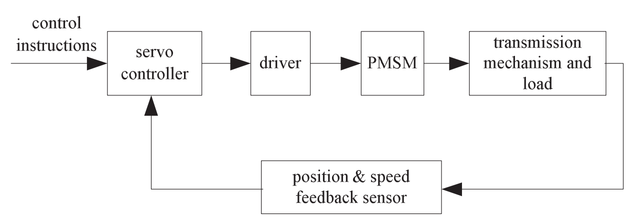

Figure1. Block diagram of PMSMSCS

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The servo controller usually adopts microprocessor system as hardware basis, collects load location and speed value by AD or other means, and then obtains the error of the control system by comparison with the received control instruction. The control algorithm is realized by microprocessor software, which is run once by the servo controller in each control cycle. Take the control error as input variable to figure out the motor control variable and then drive the motor to rotate by PWM motor driver, finally drive load to the specified position with aid of transmission mechanism.

Generally, servo controller and motor driver are assembled into an electronic subassembly (as control component) while motor, transmission mechanism, position & speed feedback components and load assembled together to form an electrically-operated mechanism subassembly (as control system actuator). The whole system is a closed-loop circuit, which will be open if failure occurs on any component and subsequently the servo control system fails to work properly. Since the control loop has a greater open-loop gain, the wrong signal will saturate the amplifier and the motor will drive the transmission mechanism to run at high speed up to the limit position of the mechanism. Therefore, once the servo control system gets into the open-loop working state, fault location will be more difficult.

A. Fault Detection

Varieties of check and test methods are used to judge of the system running status and abnormal situations, checking if the system is faulty. When a fault occurs, type, location and cause of the fault shall be diagnosed by means of principle, experience and keyword search etc., and eventually a proper maintenance policy is given. At the same time, the historical fault message is provided for record and summary of those high-frequent faults, which might be prevented from being reoccurred.

1) MPU system fault detection

The MPU system of servo control system adopts TI series 28335 hardware platform, which is configured of RAM, FLASH, A/D, D/A and digital I/O interfaces and connected via bus. MPU system detection includes detection of RAM, FLASH, A/D, D/A and digital I/O interfaces.

Write specific data into RAM or FLASH at the specified address, and then read it out. Compare the read data with the written data to determine if RAM or FLASH is faulty.

Introduce an output of precision voltage reference which has the known voltage amplitude into the A/D sampling input end to do sampling by use of A/D. Convert the AD sampling value to the voltage value and compare the voltage value with the amplitude of the voltage reference to determine if A/D works normally. Then introduce the output of D/A into the verified A/D sampling input end and collect the output of D/A by A/D. Consequently, compare the data sent by D/A with the data obtained by A/D to determine if D/ A works normally.

The detection of the digital I/O interface will follow the same detection method as A/D and D/A detection. Firstly, determine if the digital input interface is correct or not by read-in of the specific discrete quantity, then write the data into the digital output interface and read back into processor through the same digital input interface, finally compare data to determine if the digital I/O interface works properly.

2) Driver fault detection

Driver normally adopts PWM power amplifier of IPM, mostly made into high power amplifier circuit by use of integrated circuit. PWM power amplifiers are typically designed with elements such as resistors, capacitors and comparators for protection against overcurrent, overheat or overvoltage. When power amplifier works normally, no overcurrent, overheat or overvoltage occurs. In case of overcurrent, overheat or overvoltage, IPM protection circuit will generate a protection signal, which will pass though the enable pin of power amplifier to stop power amplifier from working. This protection signal is the fault detection signal of the power amplifier. Regularly collect IPM protection signal to determine if the power amplifier works normally or not.

3) Feedback component fault detection

Servo control system usually employs sine-cosine revolver or photoelectric encoder as angular position feedback element. Sine-cosine resolver and selsyn are widely used in airborne equipment for their high reliability, stability and adaptability to humidity, temperature, vibration and impact. Most solvers of sine-cosine resolvers utilize application-specific integrated circuit (ASIC), according to its working principle. Once the resolution error exceeds the set threshold value, this signal will be given. If the excitation signal or angle measuring signal is lost, the fault signal will also be output, which is the detection signal of the feedback component.

B. Fault prediction

1) Mathematical modeling of PMSM

The d and q axis are equivalent to the three-phase coordinate system of three-phase windings of PMSM and the rotation speed of the rotor coordinate is obtained. Set CCW direction as the positive rotation direction. Through modeling and coordinate conversion, the AC three-phase winding is equivalent to the DC motor model. When the d-axis current is always controlled to be 0, the coordinate components of stator voltage at d axis & q axis and instantaneous torque equations are respectively obtained as shown in Equation 1 and Equation 2

$$\begin{aligned} u_d &= -\omega_r L_a i_q \\ u_q &= R_s i_q + L_a p i_q + \omega_r \phi_f \end{aligned} , \tag{1}$$

$$T_{em} = K_t i_q = T_l + B\Omega_r + Jp\Omega_r , \tag{2}$$

where, R_s is the stator resistance, L_a is the armature inductance, both d and q axis inductance are L_a , J is the inertia moment of motor, ϕ_f is the flux generated by a permanent magnet (as constant), ω_r is the rotor electrical angular velocity, B is the viscous friction coefficient, p is the differential operator, T_l is the load torque, K_t is torque coefficient, u_d , u_q , i_d , i_q are the voltage and current at axis d and axis q respectively, Ω_r is the mechanical angular velocity.

Judging from only the quadrature-axis voltage equation, it shows that PMSM is equivalent to a separately excited DC motor; there is only quadrature-axis current component in stator armature winding; the excitation EMF in the equivalent quadrature-axis winding is in direct proportion to the rotor electrical angular velocity. Therefore, the control block diagram based on id=0 is shown in Fig. 2.

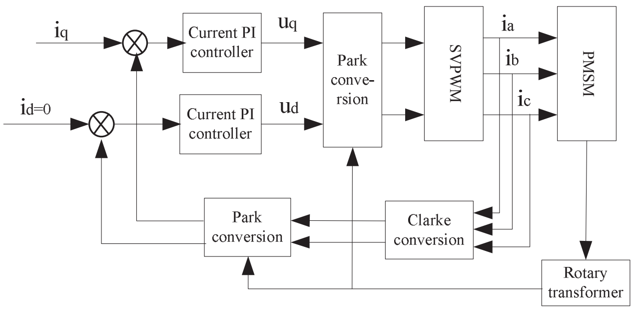

Figure2. Control block diagram of PMSM based on id=0

According to PMSM model as specified in Eq. (1), it can be equivalent to the first-order series circuit as shown in Fig. 3, which contains a resistor, an inductor and a counter potential voltage source. Set counter potential voltage as a constant for the counter potential voltage changes slowly, the small signal transfer function from motor voltage to motor current can be defined as

$$\frac{I(s)}{V(s)}=\frac{\frac{1}{R}}{(1+\frac{L}{R}s)} \quad . \tag{3}$$

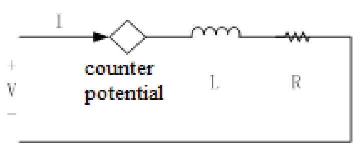

Figure3. Circuit diagram of equivalent PMSM model

The current loop controller adopts serial PI controller as shown in Fig. 4, and its transfer function in S domain is

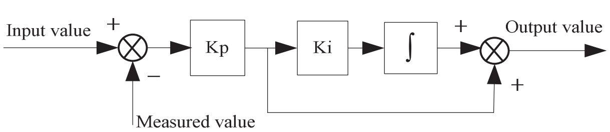

Figure4. Serial PI controller

$$PI(\mathrm{s})=\frac{K_\mathrm{p}*K_\mathrm{i}}{\mathrm{s}}+K_\mathrm{p}=\frac{K_\mathrm{p}*K_\mathrm{i}(1+\frac{s}{K_\mathrm{i}})}{s} \quad . \tag{4}$$

Assume that Kp contains bus voltage and PWM gain ratio, the simplified closed-loop transfer function containing PI controller can be obtained as

$$G(s)=\frac{(1+\frac{s}{K_\mathrm{i}})}{(\frac{L}{K_p*K_i})s^2+(\frac{R}{K_p*K_i}+\frac{1}{K_i})s+1} \quad . \tag{5}$$

Thus, the controls parameters of the current loop controller are designed according to the band width method, as shown in Eq. (4). The current loop closed-loop transfer function can be corrected as shown in Eq. (5). So

$$K_i=\frac{R}{L} \quad . \tag{6}$$

$$G(s)=\frac{(1+\frac{s}{K_\mathrm{i}})}{(1+\frac{R}{K_p*K_i}s)(1+\frac{s}{K_\mathrm{i}})}=\frac{1}{\frac{L}{K_p}s+1}=\frac{k_1}{(t_1s+1)} \quad . \tag{7}$$

Simplified according to the torque equation, the first-order inertia element may be approximated based on the form of the load inertia

$$G_{speed}(s)=\frac{k_2}{(t_2s+1)} \quad . \tag{8}$$

Finally, the velocity is converted into position through the integral link

$$G_\theta(s)=\frac{k_3}{s} \quad . \tag{9}$$

Where, k1/k2/k3/t1/t2/t3 in above equation are the parameters of each link.

Therefore, the model is obtained as shown in Fig. 5.

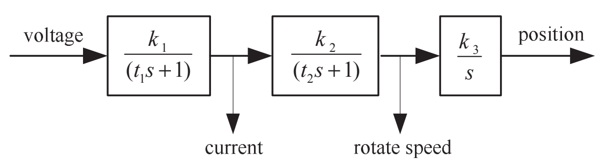

Figure5. PMSM control mode

2) Fault prediction method

In normal working condition, servo controller takes real actuator as control object to constitute a closed-loop control system and execute control instructions. While controlling the real actuator load, the servo controller sends control quantity to PMSM simulator that works in parallel with the real actuator.

Although PMSM simulator and servo controller do not constitute a closed loop system, the simulator can still reflect the internal running status of the real actuator based on its mathematical model. Taking the output value of simulator as standard value, the servo controller can determine the degree of deviation of real actuator from the mathematical model as built by comparison of real actuator output with simulator output, and realize the monitoring of the servo control system's working state. According to the degree of deviation of the servo control system from the expected working state, fault prediction is carried out.

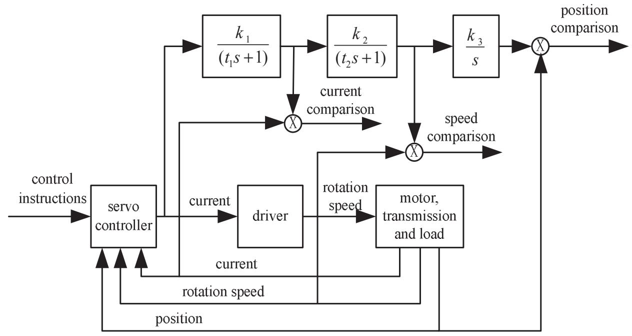

Figure6. PMSM simulator

C. Fault Diagnosis

When the control system is judged to be faulty, servo controller and real actuator constitute a closed-loop control system which cannot work normally any more. The servo controller is switched to take the electrically operated mechanism simulator as the control object to realize the closed-loop work of the simulation system. When the simulation system works, the control quantity is sent to the motor driver simultaneously to drive the real actuator to work under the condition of fault diagnosis and isolation. In order to prevent the real actuator from moving to the limit position, the instructions input to servo controller is designed as the sine instructions of the specified amplitude and period. When the electrically operated mechanism simulator works at a certain point under the control of servo controller, the electric current, speed and displacement parameters of real actuator will be collected at same time. By comparison of these parameters in turn with the output parameters of the electrically operated mechanism simulator, the faults can be isolated into power amplifier module, motor & tachometer module and the angular displacement measuring module, and then further fault isolation can be made according to fault detection results of the internal electronic circuits of power amplifier tachometer module and the angular displacement measuring module. For example, if the working current of power amplifier module and motor is normal but speed measurement data is wrong, it may be inferred that there is something wrong with the transmission mechanism only depending on fault detection of the resolver module which proves tachometer is under normal operation condition.

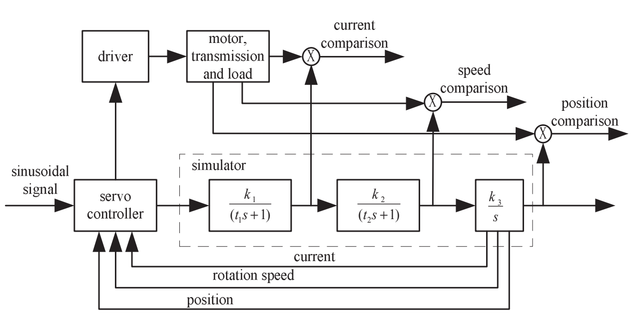

Figure7. Fault diagnosis principle of PMSM simulator

III. DESIGN OF SYSTEM FUNCTION MODULE

The health management system of PMSMSCS is mainly composed of status monitoring module and fault diagnosis & prediction module.

A. Design of status monitoring module

The function of status monitoring module is to monitor the working status of PMSMSCS. The status monitoring module includes fault detection circuit for PMSMSCS hardware circuit, PMSMSCS simulator and the corresponding AD acquisition circuit. Status monitoring module is to monitor the working status of MPU, PWM power amplifier and angle measurement system by use of fault detection circuit. The AD acquisition circuit is to collect the data from PMSM simulator and motor of real actuator such as current, rotation speed and displacement, filtrate environmental noise by filter and send them to fault prediction module as the system working state data for prediction, or send them to fault diagnosis & isolation module for diagnosis.

B. Design of fault prediction module

The fault prediction module is generally a software module which is running in the servo controller for receiving system operation data from status monitoring module and predicting system faults. Main methods of fault prediction include: (1) Data-based prediction method, which is only related to historical data and regardless of application of servo control system [11], is divided into time series prediction and causal prediction; (2) Model-based prediction method, which uses dynamic response modeling of servo control system object, identifies parameters for current system response output, compares them to the parameter statistical characteristics in normal state, and then confirm and predict fault mode; (3) Combined prediction method based on data & model, which is to predict historical data at first and then predict in combination with servo control system model. In this paper, the model-based prediction method is adopted for design and simplified as per actual situation.

Due to some differences existed between mathematical model and physical implementation of actuators and failure in modeling & difficulties in accurate modeling of some actuators, the output of the electrically operated mechanism simulator is not identical to that of the real actuator. According to the characteristics of electro-mechanical servo control system, the criteria are adopted as follows:

a. $I_m < I_s(\min) or I_m > I_s(\max)$ and time of duration is more than 100ms.

b. $\omega_m < \omega_s(\min) or \omega_m > \omega_s(\max)$ and time of duration is more than 100ms.

c. $\theta_m < \theta_s(\min) or \theta_m > \theta_s(\max)$ and time of duration is more than 100ms.

Where, I_m , ω_m and θ_m respectively stands for the current, rotation speed and position of PMSM simulator, I_s , ω_s and θ_s are the thresholds value of the current, rotation speed and position respectively.

C. *Design of fault diagnosis module*

The fault diagnosis and isolation module is generally a software module which is running in the servo controller for receiving system operation data from status monitoring module and diagnosing system faults. This research project uses the model-based diagnosis method and the diagnosis process is as follows.

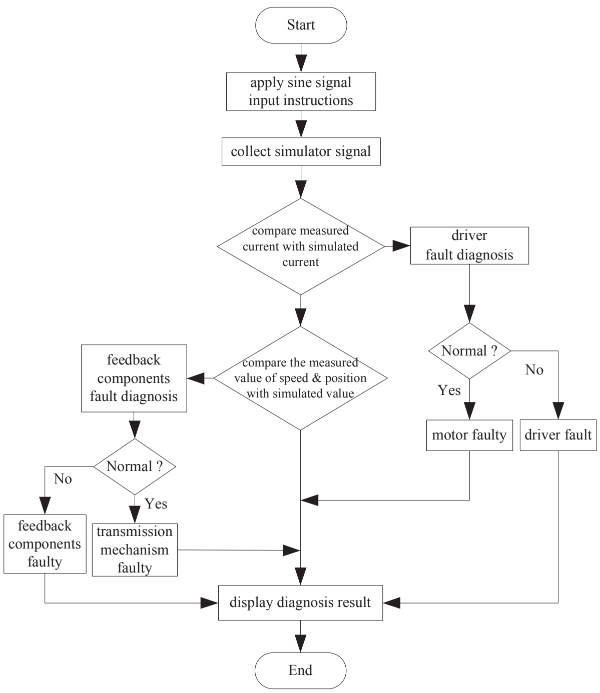

Figure8. Fault diagnosis flow chart of PMSMSCS

IV. SIMULATION AND VERIFICATION

Based on the existing armored vehicle's PMSMSCS model, the model of PMSM simulator is built by MATLAB. Input controls parameter k and give proper step length according to parameter characteristics, the simulator model is simulated. When the input is sinusoidal signal control instruction, the current output from actual control system and simulator system is shown in Fig. 9. The position output from actual control system and simulator system is shown in Fig. 10.

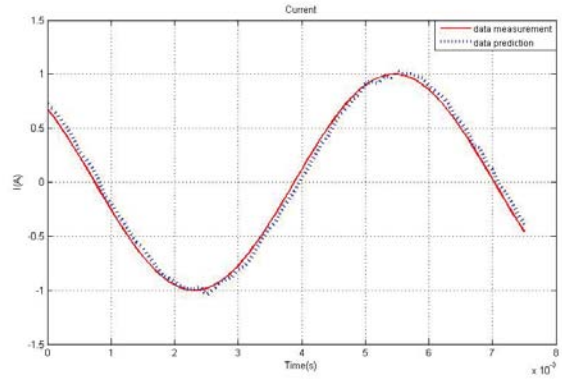

Figure9. Data analysis and failure prediction curve (Current)

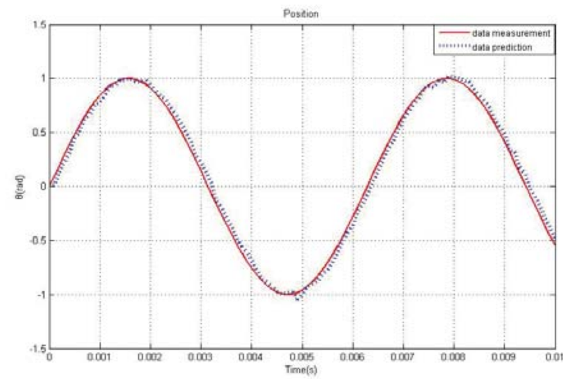

Figure10. Data analysis and failure prediction curve (Position)

The above-stated simulation verification shows that the designed PMSM simulator can follow the output of actuator in real time for fault diagnosis and location.

V. CONCLUSION

With PMSMSCS simulator working in parallel with the real actuator, the servo controller sends control quantity to PMSMSCS simulator while controlling the real actuator load. PMSMSCS simulator outputs digital signal of the current, rotation speed and position which simulates the real actuators. In normal working condition, servo controller takes real actuator as control object, compares to output of electrically operated mechanism simulator to monitor the system's working state. Once control system is found to be abnormal, servo controller is switched to take the electrically operated mechanism simulator as the control object, compares to output of real actuators to realize fault diagnosis and location. This health management system of PMSMSCS is well designed either in principle or in practice, having essential reference value for design of actual system.

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