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A Study on Open Switch Fault Detection in Inverters of PMSM Drive

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Abstract

Due to the factors such as high efficiency, power density and excellent torque speed characteristics, PMSM is being widely used in Electric Vehicles and other industrial applications. Hence, a lot of research works are going on to improves its control strategies. PMSM being costlier than induction motor, this paper focuses on quicker and real time fault detection of the inverters used with PMSM so that it prevents further damage to the motor as well to the users. Several methods such as signal based and data-based methods are already in discussion for the fault detections. Inverters being the main component of the system, faster fault identification methods in real time systems are necessary. Also identifying the exact switch with open circuit fault will aid in replacement of one single switch instead of replacement of complete system and can reduce e-waste as well. In this paper we use current variation between various phases and the rotor angle, with the healthy state value to identify the fault in less than 1/8th cycle of the current.

Keywords: *PMSM, Inverters, Open switch, fault detection*

1. Introduction

Electric vehicles (EVs) are much cleaner than traditional internal combustion engine (ICE) cars in many ways. With the growing realization that solving climate change is one of the most pressing issues of our time, EV is an accepted solution. Automotive electronics have replaced many mechanical components. Electronics now account for over 40 percent of a new vehicle's total cost, having grown from just 18 percent in 2000, according to Deloitte. Hence, continuous monitoring of the components and different subsystem are of prime importance. Electric vehicles (EVs) commonly use various motor types, including brushless DC motors, permanent magnet synchronous motors, induction motors, switched reluctance motors, series wound DC motors, and dual motor systems, each offering distinct advantages in efficiency and performance. The choice of motor depends on factors such as cost, application requirements, and desired vehicle characteristics. Permanent Magnet Synchronous Motors (PMSM) are electric motors that utilize permanent magnets embedded in the rotor, allowing for synchronous operation with the stator's magnetic field. Compared to brushless DC motors, PMSMs offer higher efficiency and better torque characteristics, but they can be more expensive due to the cost of permanent magnets. Unlike induction motors, PMSMs provide greater power density and responsiveness but may require complex control systems. Their high efficiency makes them suitable for automotive applications, but reliance on rare-earth materials can pose supply chain risks. Overall, PMSMs deliver excellent performance and efficiency, but their cost and dependence on specific materials are important considerations. Many electric and hybrid vehicles, including the Tesla Model S, Nissan Leaf, BMW i3, Audi e-tron, Hyundai Kona Electric, and Chevrolet Bolt EV, utilize Permanent Magnet Synchronous Motors (PMSM) for their efficient and high-performance drivetrains. A Permanent Magnet Synchronous Motor (PMSM) drive system in automobiles consists of key components, including the PMSM itself, an inverter that converts DC power from the battery to AC power, and a controller that manages motor operation and efficiency. Additionally, the system includes a battery pack for energy storage, cooling systems to regulate temperatures, and various sensors for feedback on motor performance. Together, these components enable efficient and responsive electric propulsion in vehicles. Different types of controllers for electric vehicles include Pulse Width Modulation (PWM), Field-Oriented Control (FOC), Direct Torque Control (DTC), Vector Control, and Sensorless Control, each with varying levels of efficiency, complexity, and cost. While PWM is simpler and cost-effective, FOC and DTC offer higher performance and efficiency but come with increased complexity and expense, making the choice dependent on specific application requirements. OEMs typically prefer Field-Oriented Control (FOC) for Permanent Magnet Synchronous Motors (PMSM) due to its high efficiency, excellent dynamic response, and smooth torque delivery. FOC allows for precise control of both torque and speed, making it ideal for applications that require quick acceleration and responsiveness, such as electric vehicles. Additionally, its ability to optimize motor performance across various operating conditions makes it a popular choice in the automotive industry. FOC works by decoupling the torque and flux control of the motor, allowing for independent control of each, which leads to improved efficiency and performance. FOC achieves this by transforming the three-phase motor currents into a two-axis coordinate system (d-q coordinates), enabling precise control over motor dynamics. Research on Field-Oriented Control (FOC) is focusing on improving algorithm efficiency, enhancing sensorless control methods, and integrating advanced strategies like predictive control and machine learning. Future possibilities include the adaptation of AI for real-time control, advancements in sensorless techniques, and expanded applications in electric vehicles and renewable energy systems, driving the evolution of efficient motor control technologies. The key components of Field-Oriented Control (FOC) include a motor model for representing dynamics, a current controller to regulate motor currents in the d-q coordinate system, and an inverter that converts DC voltage to AC for motor drive. Feedback from position and speed sensors is crucial for accurate control, while a Digital Signal Processor (DSP) or microcontroller executes the control algorithms and coordinates operations. Together, these elements facilitate precise and efficient control of AC motors, particularly in high-performance applications like electric vehicles. Vehicles can experience a variety of faults, including electrical issues (like sensor failures), mechanical problems (such as engine or transmission failures), fuel system malfunctions, brake system faults, and cooling system issues. Regular maintenance and diagnostic checks are essential for identifying and addressing these faults to ensure vehicle performance and safety. In a Permanent Magnet Synchronous Motor (PMSM) drive system, common faults include open circuit faults, which reduce torque and can lead to overheating; short circuit faults, which may cause catastrophic failures due to excessive current draw; and stator winding faults, resulting in inefficiency and potential motor damage. Rotor faults can lead to torque fluctuations and increased vibrations, while sensor faults impair feedback control, causing instability. Inverter faults disrupt power delivery to the motor, and overtemperature faults reduce component lifespan, potentially leading to thermal shutdown. Effective fault detection and management are crucial for maintaining performance and safety in PMSM drives. According to reported diagnosis methods of OC fault switch in PMSM inverters, there are mainly-two categories: off-line and on-line. The knowledge-based method with a large historical data belongs to one of the typical off-line methods, which can be independent of the system model and load condition. Unfortunately, the off-line diagnosis method is obviously not suitable for the continuous working motor [1]. Consider other method like Kalman Filter. It can only be applied to linear system. But in reality, most systems are nonlinear systems. The PMSM control system is also a nonlinear system. Extended Kalman filter (EKF), is introduced in [2] in which primary concept behind EKF is to normalize the nonlinear areas of the network before applying the Kalman filter to the linear system network. In [3],a method using FPGA is explained which detects the fault in a very short interval. The method detects the fault in less than µs by using simultaneously a 'time criterion' and a 'voltage criterion' In order to attain this short detection time a field programmable gate array (FPGA) is used. Another classification is based on current and voltage measurement. Although additional conditioning circuits like voltage dividers and filters are needed for the voltage measurement-based method, it has the advantage for identifying the source of faults. In this method a residual difference between a reference and actual quantity of AC voltage like as pole, phase, line and neutral voltage measurement is used.[4]. Open-circuit faults lead to change in average/rms current offset in both the faulty and healthy phase. The interaction between the dc component and the field generates a pulsating torque at the stator current frequency, which may substantially reduce the maximum average torque available to the drive. Unequal stress is also generated in the upper and lower transistors due to the dc current. Secondary faults happens in the inverter, motor, or load due to this. Even though Open-circuit faults generally do not cause system shutdown, but degrade its performance of the system [5]. In this paper, we introduce a current based on a sliding window for fault detection in PMSM drive. Here we try to achieve a speedy identification of fault in the system using stator phase current monitoring over a period of time based on the rotor angle. [1-5]

2. Method

Here we consider a PMSM with following specificationas shown in Table 1. (Refer Figure 1)

Table 1 Specification of PMSM

Rated power	400 W
Rated current	10A
Rated torque	1.27 Nm
Pair of poles	10
Rated speed	3000 r/min
Phase resistance	0.28 Ω
Phase inductance	0.52 mH

2.1.Figures

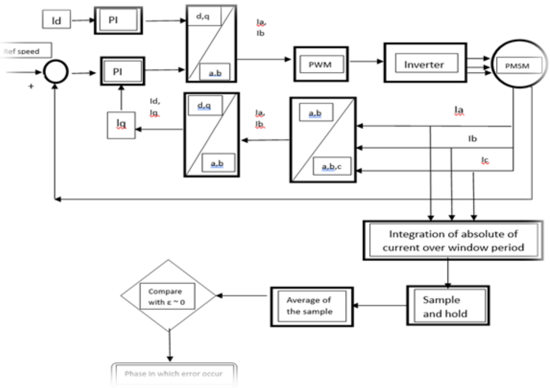

Figure 1 General Configuration of FOC PMSM Drive with Proposed Fault Detection

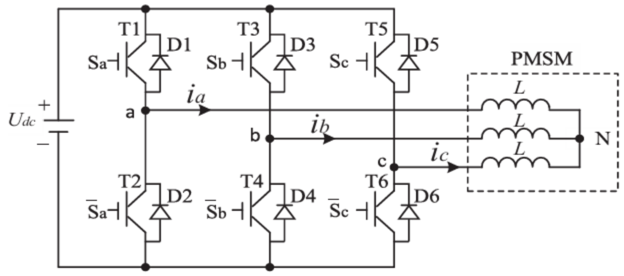

Figure 2 Inverter System (SVPWM) For PMSM[7]

Complex space vectors are used to analyze three-phase voltages, currents and fluxes of AC-motors. Consider i_a, i_b, i_c as instantaneous currents in the stator phases, then the stator current vector is defined as follow: (Refer Figure 2)

$$\vec{i}_s = i_a + i_b e^{j2\pi/3} + i_c e^{j4\pi/3}$$

where, (a, b, c) are the axes of three phase system. This three dimensional space current vectors are transformed to two dimensional time invariant system using Clark's and Park's transformation. (a, b, c) → (α, β) (the Clarke transformation), which gives outputs of two coordinate time variant system. (a, β) → (d, q) (the Park transformation), which gives outputs of two coordinate time invariant system. Three phase current is mathematically transformed into time varying two-phase voltages or currents, along the axes α and β by the following transformation matrix: (Refer Figure 3)

$$i_{\alpha\beta o} = 2/3 * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

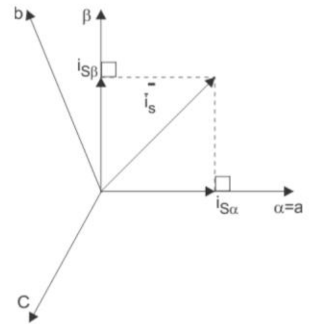

Figure 3 Transformation Matrix

Parke’s transformation converts the two dimensional vector voltages or currents, along the axes α and β to d, q axes that is time invariant using the following matrix:

$$\begin{bmatrix} d \\ q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos(\theta) & cos(\theta-120°) & cos(\theta+120°) \\ sin(\theta) & sin(\theta-120°) & sin(\theta+120°) \end{bmatrix}\begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

where dq are the voltage, current, flux values in the DC domain. abc are the values in the AC domain. Theta is the rotor position angle. Usually, theta is defined as 0 when rotor magnet flux field is aligned with stator flux field. From the transformation, although the motor system is in the AC domain, we can now control the dq variables in the DC domain, and then convert it back to three-phase system. In addition, by controlling the flux in the dq axis, the combined flux (magnet field) is also easily controlled. This is why it is called Field Oriented Control (FOC). In dq domain, a permanent magnet AC motor can be modelled as following[7]:

$$u_d = i_d R_s + L_d \frac{di_d}{dt} - \omega_e L_q i_q$$

$$u_q = i_q R_s + L_q \frac{di_q}{dt} + \omega_e(\psi_{pm} + L_d i_d)$$

$$T_e = \frac{3}{2}P(\psi_{pm} i_q + (L_d - L_q) i_d i_q)$$

Effect of single switch OC on phase current[7]:

$$\begin{cases} i_a(t) = \frac{1}{2}I_m \sin(\omega_e t) + \Delta i_a - I_{dc} \\ i_b(t) = \frac{1}{2}I_m \sin\left(\omega_e t - \frac{2\pi}{3}\right) + \frac{1}{4}I_m \sin(\omega_e t) - \frac{1}{2}\Delta i_a + \frac{1}{2}I_{dc} \\ i_c(t) = \frac{1}{2}I_m \sin\left(\omega_e t + \frac{2\pi}{3}\right) + \frac{1}{4}I_m \sin(\omega_e t) - \frac{1}{2}\Delta i_a + \frac{1}{2}I_{dc} \end{cases}$$

where.

$$I_{dc} = 0.3183 I_m$$

$$\Delta i_a = \sum_{n=1}^{\infty} \frac{2I_m}{\pi(4n^2 - 1)} \cos(2n\omega_e t)$$

Load of the motor has an effect on the phase current and the speed of the motor is related to the frequency of the phase current. If the phase current is sampled over a period of time to get slope value k, we can notice is will be either greater than zero or will be less than zero. If k is zero, it can be either dead zone of inverter system or an OC fault. In order to avoid false alarm, we consider a sliding window period[7].

$$M = \alpha T f_s$$

where α is the search coefficient of sliding window, T is the period of three phase currents, and fs is the sampling frequency. The value of α is related to the dead time. Generally, the dead time of the inverter is<3 µs, and current period is often>1 ms [14]. Considering rapidity and reliability of the fault detection, the value of α should be based on the dead time of different motors, ensuring that one period of sliding window αT is greater than the dead time and not too large to influence the performance of the observation. Therefore, α is set to 1/2r (4 ≤r ≤6) according to above considerations, which is suitable for operating speed of most PMSMs [15]. The slope k of the current in sliding window can be calculated as in [7]:

$$k = \sum_{n=1}^{M} \frac{(tn-\bar{t})(In-\bar{I})}{(tn-\bar{t})2}, \ (j=1\ldots N)$$

$$\bar{t} = 1/M \sum_{n=1}^{M} tn$$

$$\bar{I} = 1/M \sum_{n=1}^{M} In$$

From analysis of current it is observed the slope k of the current in sliding window will not be exactly zero due to other components. Hence, the threshold ε is selected through repeated tests and the slope k is compared with ε. Through testing a value of -0.001 is found. The absolute of phase currents are analysed through a defined number samples over the time period. In this method, we consider the average of each phase current over a period of time (assume 2*pi). The current variation of each phase current is observed against the total average of the three-phase current to detect the faulty leg of inverter. The state changes of this output is tabulated as below:

Table 2 State Changes in Each Phase Current

State Change	Fault location	Probable switches
0 0 0	No fault	-
0 1 0	Fault in switches either of two phases (2 or more)	T3 or T4 and T5 or T6
0 1 1	Fault in single phase (1 or 2 switch in same leg)	T1/T2 or T3/T4 or T5/T6

3. Results and Discussion

3.1.Results

The proposed method was simulated in MATLAB/Simulink and was tested in hardware set with ELVM6040V48EH-M17-HD motor and with Texas C2000 Microcontrollers for inverter control logic. (Refer Figure 4)

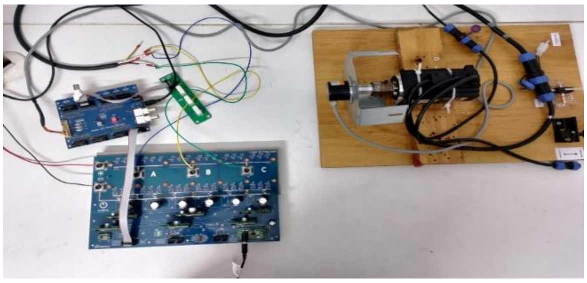

Figure 4 Experimental Platform for OC Fault Detection

Below figure 5 shows the change in phase currents when no fault is present:

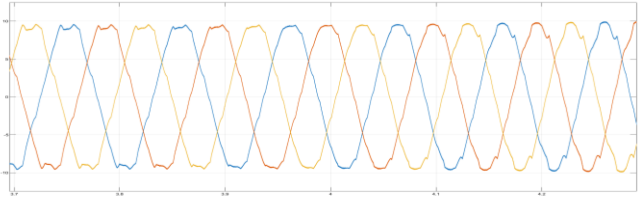

FIGURE 5 Stator Current in a Healthy FOC PMSM Drive

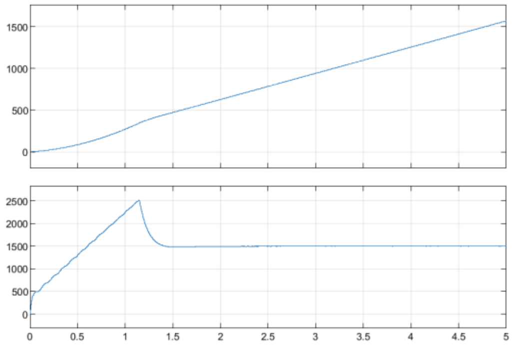

Figure 6 Rotor Speed Variation in a Healthy PMSM Drive

When Fault is injected in any one leg (phase C) of the inverter circuit and it can be observed that the current in that phase tends to 0. Below figure shows the change in phase current with fault: (Refer Figure 6,7)

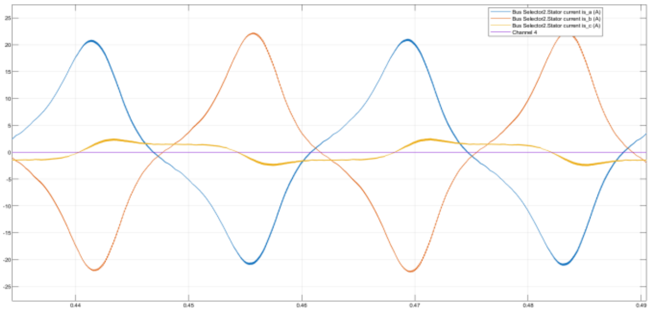

Figure 7 Fault Injected In Phase C

As mentioned in Table 2, fault in one single switch in phase C (T5/T6) is located as in below figure 8.

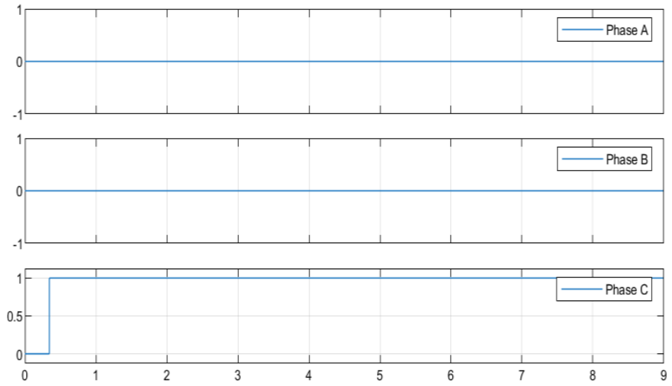

Figure 8 Fault Location Identification When Single Switch Fault Occurs

Fault was injected through simulation in phase B and C simultaneously using a step input and the results are as in below figure 9, 10, 11 which indicates fault in switches of second and third leg of the inverter. [6-10]

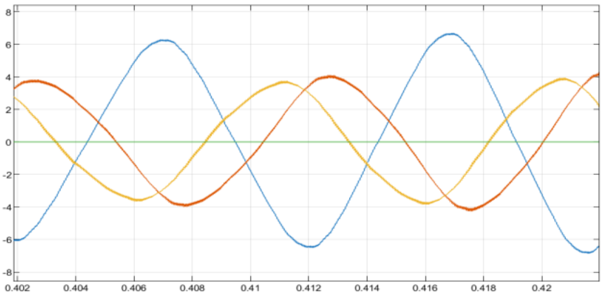

Figure 9 Stator Current in a Healthy FOC PMSM Drive

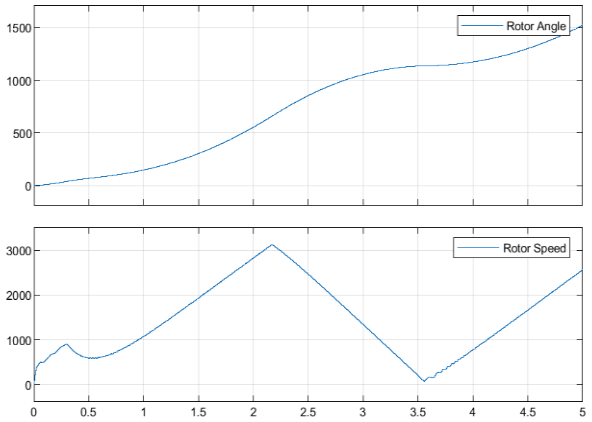

Figure 10 Rotor Speed Variation Due To Fault in Inverter Phase Currents

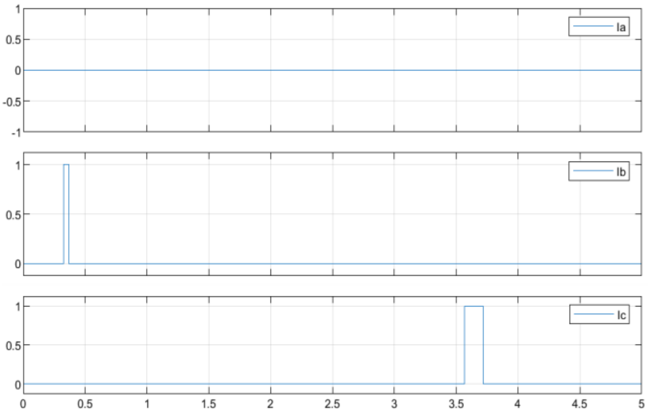

Figure 11 Fault Location Identification When Double Switch Fault Occurs

3.2.Discussion

With the proposed method the fault is identified in one single current cycle. Compared to other methods the responsiveness of this method is higher which is required for better performance of the system and for safety feature. [11-16]

Conclusion

Even if there are various methods available for fault detection, considering the factors as robustness, detection time and cost, the proposed methods provide an optimized solution for these factors. It contributes to safety of the PMSM and EVs. An attempt is made to faster identification of fault at the initial stage to avoid further damage of other components due to accumulation of voltage. In the future work, an adaptive sliding mode observer can be analysed to make the system more robust and accurate in predicting the error.

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