Fault Tolerant Control Method to Improve the Torque and Speed Response in PMSM Drive with Winding Faults

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Abstract—Fault tolerant operation of motor drives is inevitable in many safety critical applications as failures could lead to complete shutdown or degrade the performance of the whole system. Therefore, it has become important to have fault tolerant capability to support continuous operation. This paper focuses on the control of a star connected fault tolerant permanent magnet synchronous motor (PMSM) drive which suffers from open winding fault that may result from broken or disconnected stator phase winding. The considered fault tolerant drive has the reconfiguration capability to support open winding faults which connect the neutral point of the motor to the mid point of the dc link. This allows exciting the remaining two windings and supports the fault tolerant operation. One of the main problems of this topology is the high torque and speed ripple generated during the fault mode operation. In this paper, a comprehensive literature review is presented to identify different fault tolerant converters and published control techniques. Then faulty mode operation with standard techniques is re-evaluated and based on the findings a control method is proposed to improve the performance of PMSM drive under open phase fault. Furthermore, a method to detect and diagnose open phase faults and a control method to improve the faulty mode performance are also presented. Proposed control technique is verified in simulation results.

I. INTRODUCTION

Permanent magnet synchronous machines (PMSM) are widely used in industrial applications including aircrafts, hybrid electric vehicles and industrial servo drives. PMSM’s have inherent advantages of high power density, large torque to inertia ratio and compact construction [1]. Despite its vast acceptance in many industrial applications, system reliability remains one of the key concerns. A single point failure in the drive system could lead to situations like complete shutdown, undesirable performance reduction like high torque and speed ripples or in ability to startup etc. The performance degrade may not be acceptable especially in safety critical applications where the drive system is expected to support continuous operation.

There could be many faults in a PMSM drive mainly due to electrical and mechanical problems. The electrical faults can be subdivided into inverter faults and winding faults. These faults have tendency to come into light much faster than mechanical faults. Mechanical faults and demagnetization faults would take relatively longer time to appear.

The common approaches for fault accommodation given in literature are having redundant architecture (machine or inverter), employing a fault tolerant drive [1-6] or using fault tolerant machine (multi phase windings). The redundant architectures are expensive, heavy and bulky which are some of the key limitations in certain applications like aerospace. On the other hand fault tolerant machines are also equally expensive due to custom made designs and complex driver requirements. However the fault tolerant converters are less expensive and complex. Hence, employment of fault tolerant drives is highly desirable [1].

Extensive research has already been done on fault tolerant converters, topologies, modulation strategies and fault detection identification techniques [1-4]. Many of them have focused on inverter faults and required fault tolerant strategies for both redundant and non redundant topologies [1]. For switch faults, the common topological reconfiguration option is to reconfigure the inverter by connecting the faulty phase to the dc mid point or redundant leg and modulate the healthy switches to generate balanced output currents [7].

Similarly, for open winding faults, redundant and non redundant fault tolerant topological options have been proposed in the literature. Majority of them are four leg based fault tolerant inverters [1, 7]. Also there are few papers proposing matrix and multilevel converters to support open winding faults. In non redundant topologies neutral point is connected to the dc mid point. However this topological variation requires modifications to the modulation and control method to maintain acceptable working conditions where speed and torque ripple hinders the performance of the drive. General solution to improve system performance under faulty mode is the use of modified modulation or control methods. Modulator modifications produce acceptable results under winding faults in the open loop operation [7]. In another research, controller is modified by adding a torque ripple compensation component (which is derived using the motor parameters and zero sequence current) to a standard controller [5]. In reference [4] a control method is proposed based on hysteresis controller, where the speed controller output is transformed into the abc reference frame and then controlled using hysteresis controllers [4]. Also reference [8] proposes a different transformation method to improve the fault mode
performance. However, their simulations results are not promising.

This paper, therefore, proposes new open winding fault detection and identification method and an alternative control technique to improve the performance in the faulty mode. The paper has seven sections. The second section presents a mathematical model for star connected PMSM in the abc reference frame. The third section presents a review on fault tolerant PMSM drives and operating principle. This section also includes an analysis and verification of unacceptable performance through simulations. In the fourth section a fault detection and identification (FDI) method is presented for open winding faults. A detailed description on the proposed control method is presented in section five, followed by simulation verifications presented in section six. Finally, conclusions are presented in the seventh section.

II. MODELLING OF PMSM

The PMSM model available in simpowersystem is designed for a delta connected machine, where each winding cannot individually be accessed and controlled independently. Also, that model is developed assuming the symmetric nature of windings which inherently simplifies the modeling with equal mutual inductances. Therefore, it is not suitable for this study. As a solution to this issue authors have developed a simulation model for star connected PMSM in the abc reference frame. In the first half of this section the general model of PMSM and its simplifications are discussed. The proposed model developed for simulating the PMSM with open winding condition is presented in the latter part of this section.

By applying Kirchhoff’s voltage law state equations for each winding of the PMSM can be derived as in (1)-(3).

\[
\begin{align*}
V_a &= R_{ia} + L \frac{di_a}{dt} + M \frac{di_b}{dt} + M \frac{di_c}{dt} + e_a \\
V_b &= R_{ib} + L \frac{di_b}{dt} + M \frac{di_a}{dt} + M \frac{di_c}{dt} + e_b \\
V_c &= R_{ic} + L \frac{di_c}{dt} + M \frac{di_a}{dt} + M \frac{di_b}{dt} + e_c
\end{align*}
\]

Where \( I \) is the self inductance and \( M \) is the mutual inductance, \( V_a, I_a, e_a, \ldots, e_c \) are applied voltage, phase current and generated back emf respectively.

Generally, for a balanced system three phase currents sum-up to zero hence terms due to mutual inductance in equations (1)-(3) can be removed by modifying the mode as give in equations (4)-(6) where \((L-M) = L_0\) is known as synchronous inductance.

\[
\begin{align*}
V_a &= R_{ia} + (L-M) \frac{di_a}{dt} + e_a \\
V_b &= R_{ib} + (L-M) \frac{di_b}{dt} + e_b \\
V_c &= R_{ic} + (L-M) \frac{di_c}{dt} + e_c
\end{align*}
\]

This symmetrical model is simple and requires only the knowledge of particular phase current to determine the inductive voltage drop. However, in the case of a single phase open circuit fault current in that phase become zero loosing the symmetric nature. This has an effect on voltage equations derived in (1)-(3) where the loss of one current put an end to the cancellation of mutual inductance. Therefore, the model can not be simplified as given in equations (4)-(6). However, if the machine is star connected and when the motor operates in single phase mode then the same current flows through both the windings. Under that condition voltage equations given in (1)-(3) can still be simplified to equations (4)-(6). If the PMSM is operated in the two phase mode with neutral connection the effect of mutual inductance will not be canceled out. In such situation motor behavior cannot completely be modeled with the simple representation. Hence for this paper full state space modeling of the machine is considered.

Since simulations were carried out on the Matlab \(\text{simulink}\) \(\text{simpowersystem}\) environment complete model of the PMSM consists of two parts. The mechanical model of the PMSM is developed in the Matlab/Simulink while the electrical model is developed using simpowersystem components. In the electrical model each phase of PMSM is represented with a resistor, an inductor with coupling mutual inductance to other phases and a variable voltage source. The variable voltage source represents the back emf of the machine. Back emf of each phase can be calculated using equations (7)-(9).

\[
\begin{align*}
e_a &= K \phi_0 \omega_a \sin(\omega_f t) \\
e_b &= K \phi_0 \omega_b \sin(\omega_f t - 2\pi/3) \\
e_c &= K \phi_0 \omega_c \sin(\omega_f t + 2\pi/3)
\end{align*}
\]

Where \( \phi \) is the flux linkage of PMSM and \( K \) is the back emf constant.

Knowing the phase currents and back emf electromagnetic torque can be calculated using equation (10)

\[
T_e = i_a e_a + i_b e_b + i_c e_c
\]

(10)

Mechanical dynamics of the PMSM are linked in (11).

\[
J \frac{d \omega_m}{dt} = T_e - T_L + B \omega_m
\]

(11)

Where \( J \) is the inertia of the machine, \( B \) is the friction coefficient, \( T_e \) is the electric torque, \( T_L \) load torque, \( \omega_m \) mechanical speed. \( \omega_m = \omega p \) where \( p \) is number of pole pares. From the equations (10) and (11) mechanical speed can be calculated. The mechanical speed is then used to calculate the
electrical speed and then electrical angle is obtained by taking derivative of the electrical speed, hence the back-emfs are obtained using equations (7)-(9). Fig. 1 shows the electrical subsystem of the PMSM where the winding inductances are represented by the mutual inductance model in SimPowersys and the back emf is represented by the variable voltage source of which the magnitude is calculated in mechanical subsystem implemented using equations (7)-(11) in simulink which link the simulink model with the SimPowersys. The developed model supports excitation of any two phases by connecting neutral point into the dc mid point.

III. FAULT TOLERANT PMSM DRIVE AND ITS OPERATING PRINCIPLE

As discussed earlier, there are two common failures in PMSM windings, open circuiting or short circuiting of turns of the winding. If the level of turn to turn short circuit is severe it may be detrimental to excite the faulty winding as it could cause further damage. In such conditions motor may stop working or work in single phase operation. This leads to the loss of rotating magnetic field and as a result increases torque and speed ripples. If the drive is designed to have fault tolerance, to keep the system operational, reconfiguration of the inverter drive is required. The two common topologies which have been proposed in literature for PMSM with accessible neutral point are three phase four leg inverter [1, 6] as shown in Fig 2(a), or three phase inverter with access to dc mid point shown in Fig. 2(b).

In the four leg inverter shown in Fig. 1(a), the neutral point is connected to the fourth leg. During the fault mode operation neutral point voltage is controlled to keep the rotating magnetic field. In the three phase inverter with a dc mid point, neutral point can be connected to the dc mid point as shown in Fig. 2(b). Excitation of the remaining two windings is controlled by modulating the four switches of the inverter. In comparison to the four leg topology accessing the dc mid point has advantages in terms of reduced number of switches. However, capacitors should be rated high enough to cater the neutral currents and also keep the unbalance of dc-link capacitor voltages under control. Furthermore, switches should have increased current rating by the factor of \( \sqrt{3} \) to support the fault mode current increase to maintain the same torque performance. Otherwise, fault mode power rating would be reduced by the same factor [1].

One thing to note here is that depending on the faulty phase three different topologies would be used in the faulty mode of operation. For this research topology shown in Fig. 3 is considered, where it shows the PMSM drive with a winding fault where the phase A is open circuited and the neutral point is connected to the dc mid point after the fault has been detected and diagnosed. In a faulty condition it is important to select the correct modulation methods based on the faulty phase. The standard control method adopted by many researchers is to shift the reference vectors by 30 degree away from there original position. Vector diagram for the phase A fault is shown in Fig. 4. In addition to the shift in phase angles phase current magnitudes need to be increased by \( \sqrt{3} \) to support the same level of mechanical torque. This method found to be working well in the open loop operation and \( V/F \) control techniques. However, under the closed loop vector control scenario (as shown in Fig. 5) performance degradations were observed.
Fig. 6 shows the speed and torque response of the system shown in Fig. 5, with standard PI controller in synchronous reference frame. It is possible to observe a large speed and torque ripple after the open circuit fault occurs. Fig. 7 shows measured currents and controller error at the $d-q$ current controller. From the current response, it can be seen that one phase current drops to zero during winding open circuit. From the $d-q$ controller error it can clearly be observed that the controller fails to track references after the fault is initiated at 150ms. That indicates the inability to track the reference. With careful analysis it can be found that the unbalanced state is caused by the second harmonic components in $d-q$ currents components is resulted from the lack of one phase measurement. This poor reference tracking is due to the PI controller, which is effective only for operating at dc quantities. Instability persists even if corrective actions are taken in modulation as suggested in the literature and shown in Fig. 4 [7]. Therefore it is apparent that in the closed loop scenario modification of the modulation method alone would not work and corrective actions are required for the controller.

IV. OPEN PHASE FAULT DETECTION

As identified in previous sections fault detection and identification are important to apply the correct reconfiguration and modulation. Once the fault is detected corresponding TRIAC would connect the neutral point into the dc mid point and depending on the faulty phase correct phase shift is added to the reference voltages. There are many fault detection and diagnostic methods proposed in the literature. Mainly they can be categorized as signal based, reference band based or model based techniques [2]. However many of them are proposed for detecting switch faults [2]. Only few methods published for the detection of open winding faults. Reference [9] uses an extended kalman filter (EKF) based stator resistance estimation technique, some of them also used residual generation based techniques [2, 10]. In this paper, a new residual generation based simple technique is employed to detect fault conditions.

Fig. 8 shows the speed and torque response of PMSM with PI control.
equal rms values. Therefore, the subtraction will produce only a small residue. However during the faulty mode only the faulty phase current become zero while the healthy phase have increased magnitudes. Hence, output of two subtract blocks show large residue. However, only one phase current shows positive residue hence this can be used to detect and identify the fault. The generated residue can be normalized to help the setting of realistic and fixed threshold value for detecting the fault. Also, this would prevent the false fault detection in load step changes in the motor drive and also open switch faulty conditions. During open switch fault generated residue is small and which will not trigger the pre set threshold. Performance of the developed fault detection method is shown in Fig. 9 where the fault is emulated at 152ms. The fault detection algorithm is able to identify the faulty condition within 5ms which is reasonable.

**V. PROPOSED ADAPTIVE P+ RESONANCE CONTROLLER**

Performance degradation, observed in the section III is due to the inability of the controller to track non dc components. The proposed control method is focused on addressing this problem whereby enhancing the tracking capability of the controller. In literature one can find wide variety of publications which uses P+ resonance controllers, many of them are employed in grid connected converters. The resonance controller is derived based on the internal model principle and a second order filter which is tuned to have a peak at the desired frequency. Generally P plus resonance controllers are used in abc or alpha-beta reference frame which found to work perfectly to track the fundamental voltage or current components without the requirement of transforming into synchronous reference frame. A similar control concept could be used in the case of PMSM drives to track second and higher order harmonics [11]. Hence, the originally designed PI controller is supplemented with resonance controllers to track the 2nd and 4th harmonics and if needed, further filters can be supplemented to improve the reference tracking capability. The mathematical representation of resonance controller for 2nd order harmonic is given in equation (12).

\[
G_c = \frac{KR \cdot S}{S^2 + 2W_C \cdot S + 4W_e^2} \tag{12}
\]

Where \(W_C\) is the cut-off frequency and \(W_e\) is the fundamental electrical frequency in rad/sec and \(K_R\) is the controller gain.

Unlike grid converters PMSM drives are required to operate over a wide speed range, hence the inverter may demand to operate in a wide fundamental frequency range. Therefore, if the resonance controller designed to operate at one particular frequency it may not work effectively when the fundamental frequency is changed. It is, therefore, necessary to change the resonance frequency online based on the changes in operating frequency.

The newly designed PI plus resonance controller is shown in Fig. 10 and its resonance frequency is adjusted based on the operating speed (which is a function of the fundamental frequency \(W_e = \text{pwm}\)). The speed measurement is passed through a low pass filter which is used to update the resonance frequency. The low pass filter is employed to delay

![Fig. 9. Open winding fault detection and diagnose simulation results.](image_url)

![Fig. 10. Modified controller with supplementing adaptive resonance controllers (a) system diagram, (b) resonance controller implementation in simulink.](image_url)
the response time of the adaptive loop to prevent it from interacting with the speed loop. Fig. 10(a) shows the diagram of the proposed controller where only the 2nd and 4th adaptive harmonic filters are supplemented to the PI controller. Fig. 10(b) shows the correct structure used to implement the second harmonic adaptive filter in Matlab/Simulink of which the transfer function is given in equation (12).

VI. SIMULATION RESULTS

In order to verify the developed control method a simulation model has been developed in Matlab/Simulink/Simpowersystems. Obtained simulation results are depicted in Fig. 11 and Fig. 12. From Fig. 11(b) it can be observed that despite the loss of a winding the controller is able to track the reference well after small disturbances. However, note that there is a slight increase in speed and torque ripple in the transient condition. This is due to the delay in convergence of the resonance controller. In fact, resonance controller is a notch filter of which bandwidth determine the first order term of the numerator in equation (12) which is required to have a reasonable value to allow for the variation in speed. Hence, reducing the bandwidth to meet speed variations is also not viable due to the adaptive nature of the filter. In comparison to torque and speed response observed in Fig. 6, Fig. 12 shows much improved speed and torque responses with reduced ripple which confirms the efficacy of the designed controller.

![Fig. 11. Load current and response at current controller with PI plus resonance control.](image1)

![Fig. 12. Speed and torque response of PMSM with PI plus resonance control.](image2)

VII. CONCLUSIONS

In this paper, a control method is proposed to support the fault tolerant operation of PMSM under winding fault conditions. This includes a new open winding fault detection method and a fault tolerant control method. The aim of the proposed control methods is to reduce torque and speed ripples. Proposed controller improves the reference tracking of the standard PI controller by supplementing it with suitable resonance terms. The resonance controllers are tuned online based on the speed of the PMSM. The efficacy of the proposed methods is validated using simulation results obtained from PMSM controller developed in Matlab/simulink/simpowersystems.

REFERENCES


