Journal of Current Trends in Electrical Engineering
Volume 5, Issue 3, September-December, 2020

Three and Five-Phase Multi-phase Permanent Magnet Synchronous Machines (PMSMs) - A Comparative Study of Fault-Tolerant Capability Performance

***Deepanshu*[1], *Ramesh*[2], *Arvind Rai*[3]**
Student[1], Assistant Professor[2]
Department of Electrical Engineering
Shree Mahavir Education Society's Institute of Technology Polytechnic, Nashik
Corresponding Author's Email id: *Deepanshuk1452@gmail.com*

Abstract

Multi-phase permanent magnet synchronous machines (PMSMs) propose an improved alternative to conventional three-phase PMSMs in faulty conditions. Multi-phase PMSMs have the ability to minimize the number of disturbances in industrial applications. In this study, mathematical models under health and fault conditions of three and five-phase PMSMs are investigated. Moreover, the performance and fault-tolerant capabilities of a five-phase PMSM are studied and compared to a conventional three-phase PMSM. During single and double-phase open-circuit fault conditions of the five-phase PMSM, a solution is offered that maximizes output torque and reduces torque pulsations. Simulation results show superiority of the five-phase PMSM, in addition to sustaining more fault-tolerant capability than the conventional three-phase PMSM. Simulation results are carried out using Matlab/Simulink software.

Keywords: - *Fault-tolerant control, five-phase open-circuit fault, permanent magnet synchronous machine*

INTRODUCTION

Nowadays, several industrial applications are implemented based on conventional three-phase permanent magnet synchronous machines (PMSMs). The excessive cost and the availability of power electronics devices with high power and high switching frequency make multi-phase PMSMs suitable for different operations. Several applications of multi-phase machines are implemented such as electric ship propulsion, compressors, pumps, electric aircraft, hybrid electric vehicles, generation of renewable energies, and marine applications. Researchers are more attractive to replace conventional three-phase PMSMs with multi-phase PMSMs in order to reduce their limitations. The advantages of utilizing multiphase machines are investigated in [1]. High reliability, lower amplitude of torque pulsation with higher power density, inferior rotor harmonic current, reduction in phase current without increasing the phase voltage, and lower ripples of DC link current, are several advantages of multi-phase PMSMs [2−4]. To obtain variable voltage or frequency control for high power industrial applications, a multi-leg voltage source inverter (VSI) is utilized for multi-phase machine drives. If an open-phase fault occurs in conventional three-phase machines, high torque oscillations are obtained which have the worst influence on the machine shaft. Therefore, it is essentially required to fault-tolerant control (FTC) systems to keep operating under health and fault conditions with high performance. Generally, many FTC systems are applied to three-phase machines as deliberated in [10−22], however, they require extra hardware devices which increases the cost and complexity of the proposed system.

Recently, other FTC techniques are established to solve previous limitations [19, 20]. The dual three-phase PMSMs are the most motivating application of multi-phase PMSMs which have two groups of three-phase winding sated on the stator with specific electrical degrees shift. They can be considered as two identical three-phase PMSMs with two three-leg VSIs. During different fault types, the traditional solution is isolating the faulted phase which reduces the maximum torque, whereas using FTC systems, improves system reliability in several applications [5]. Numerous FTC systems are applied to overcome open-phase faults as considered in [5, 23]. The six-phase machines are investigated in many articles as an enhanced application of multi-phase machines [6, 7]. Furthermore, several FTC systems are proposed based on six-phase machines drives as discussed in [24, 25].

Five-phase machines have been extended for many applications because they can operate as four-phase machines if a single-open phase fault exists. In addition, they can also operate as three-phase machines if double open-phase faults occur. Many drawbacks have appeared under these faulty conditions such as torque oscillations because of disturbed rotating MMF in the air gap [8]. To avoid this problem, the neutral point of the load is connected to the midpoint of the DC link which minimizes the negative sequence MMF component and oscillations without any extra control strategy [9]. Many FTC systems are investigated based on five-phase PMSMs in [26–33]. The literature review of several FTC system is discussed in Table 1.

The main contribution of this paper can be summarized as:

- Mathematical model of three-phase PMSM under open-phase fault is proposed.
- Mathematical model of five-phase PMSM under open-phase and double-phase faults is investigated.
- Advantages and fault-tolerant capability of multi-phase machines are discussed.
- A comparative study-based fault tolerant capability for three and five PMSM is established.

Simulation results show the superiority of the five-phase PMSM which maintains much more fault-tolerant capability than the three-phase PMSM. The rest of the paper is arranged as; section 2 deliberates various advantages of multi-phase machines. In section 3, fault-tolerant capability performance is discussed. The mathematical model of three-phase PMSM under open-phase fault is proposed in section 4. The mathematical model of five-phase PMSM under open-phase and double- phase faults is investigated in section 5. Simulation results are given in section 6. The work conclusion is given in section 7.

ADVANTAGES OF MULTI-PHASE PMSM

To design a convenient power converter for a machine drive, the power rating of power converters should cope the required evaluation of machine and determined load which can't be increased over a specific range due to industrial limitation of semiconductor devices. In order to solve this problem, multi-level converters are utilized to implement high rating power converters. However, it may offer control complexity with a high cost. In the last decades, researchers are more attractive with machine design developing to investigate and apply multi-phase machines as a replacement of multi-level converters utilization. The key idea of implementing multi-phase machines is dividing the power rating among multiple phases which develop an enhancement performance over conventional three-phase machines. Multi-phase machines do not only reduce torque pulsation but also, they propose other important advantages such as minimizing the stator current per phase without the voltage per phase increment, reducing the dc link current harmonics and high reliability. Furthermore, the torque per ampere or power density can be increased for the same machine volume and multi-phase system permits to inject harmonic currents or supplies a required power through a single converter. Enhancement of noise features and minimizing stator copper losses are other advantages of multi-phase machines [1].

Table 1: *A literature review of FTC systems.*

Ref.	**Details**
[10]	Mathematical model of three-phase PMSM under open-phase fault and the relating vector control strategy are proposed. To maintain continuous operation under open-phase faults, the midpoint of two separate capacitors is coupled with the neutral point of the three-phase PMSM.
[11–13]	A fault-tolerant leg can be used as a replacement of the two separate capacitors.
[14, 15]	One of the five-leg VSI is applied to control two different three-phase motors. Two-phase windings from two motors use one leg as a common while the other four-phase winding are coupled with the remaining four legs.
[16]	One four-leg VSI is used to feed two three-phase motors by connecting two-phase windings from two different motors with the midpoint neutral point of two separate capacitors.
[17, 18]	Several studies depend on using a four- leg inverter to detect and isolate the faulty phase.
[19, 20]	Many FTC systems are proposed to detect the open-phase fault and reduce the overall cost.
[21]	Proposes a comparative study of three typical FTC systems based on split-capacitor, extra-leg split- capacitor (ELSC), and extra-leg extra-switch under open-phase fault.
[22]	Two parallel connected three-phase induction motors are applied by using single three-leg VSI and a weighted control is specifically considered.
[23]	An FTC system is used based on the dual three-phase PMSM to reduce the system copper loss without any additional components. However, phase copper losses are neglected although they are very important in the design of overcurrent protection circuits which make the behavior of the dual three-phase PMSM drives is very serious.
[5]	Another FTC system based on the dual three-phase PMSM is proposed to maximize the torque capacity whereas the overcurrent protection is considered.

[24]	TSKFNN-AMF is proposed as an FTC system based on six-phase PMSM to detect and isolate the faulty phase. It achieves complete controllability and maintains the system stability under faulty condition.
[25]	This article proposes a simple and new fault indicator based on six-phase induction motor drives that notice and find the open-phase faults without extra hardware and is independent of the parameters of machine drive.
[26]	This article examines FTC operations of an open-end five-phase drive, in which the five-phase PMSM is fed by using dual-inverter supply. Moreover, the short-circuit fault of the inverter switch is taken into account and gotten a simple vital solution.
[27]	A five-phase surface mounted PMSM is modeled under varied rotor magnet trailing edges demagnetization, and stator unbalanced phases as a result of high resistance connections. A control scheme is applied to detect the demagnetization of the rotor magnet and the unsymmetrical resistance of stator windings and keep the uninterrupted behavior of the system.
[28]	The reduced-order Clarke and Park transformations are used to cancel the torque ripples under two-phase Faults. Moreover, the sliding mode controller is used to generate the reference q-axis current component.
[29-31]	Many articles investigate different FTC systems based on the marine current turbine.
[32, 33]	On hybrid electric vehicle applications, several FTC systems are studied to maintain stable performance overall machine drive conditions.

FAULT-TOLERANT CAPABILITY PERFORMANCE

The different faults of electrical applications are a serious and risky effect on human safety and system operation. Therefore, it is essential to use electrical drives for operating safely under healthy and faulty conditions. Several faults can occur within a machine or converter as summarized in Fig.

1. *Possible faults related to the machine and converter can be:*

Machine: Open circuit or short circuit faults in the winding, and short circuit at the terminals.

Converter: Open circuit or short circuit faults in the power device and the failure of the DC link capacitor.

The application of FTC strategies on multi-phase machines has been extended to maintain the same or comparable performance under fault as well as health mode. The use of PMSM drives in high performance and safety-critical applications has been studied in [1, 34]. There are many requirements for fault-tolerant strategies such as; electrical, magnetic, thermal and physical separation of phases [35].

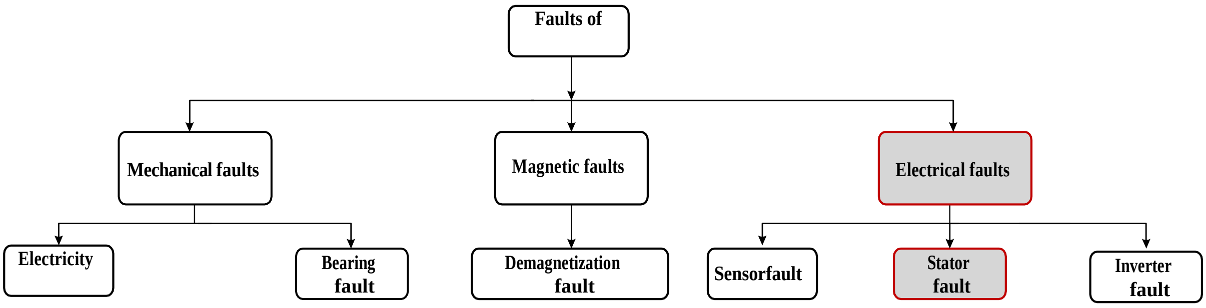


Figure 1: Classifications of possible faults in PMSMs

A MATHEMATICAL MODEL OF THREE-PHASE PMSMS

Healthy Operation Mode

The three-phase PMSM model has been investigated in [17, 36]. Stator voltages in the d-q synchronous reference frame are formulated as:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = r_s \boldsymbol{I} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \dot{\lambda}_d - \omega_e \psi_q \\ \dot{\lambda}_q + \omega_e \psi_d \end{bmatrix} \qquad (1)$$

here, $\dot{\lambda}_d = L_d \frac{di_d}{dt}, \dot{\lambda}_q = L_q \frac{di_q}{dt}, \omega_e$ gives the electric angular of rotor speed. id and iq are the d–q stator current components. Here, r_s denotes the similar winding resistance,***I*** is 5 by 5

identity matrix.

Here, stator flux linkage d-q components can be formulated as:

$$\psi_q = L_q i_q \qquad (2)$$

$$\psi_d = L_d i_d + \psi_{pm} \qquad (3)$$

By substituting Eqs. (2,3) in Eq. (1),

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} r_s + \frac{d}{dt} L_d & -\omega_e L_q \\ \omega_e L_d & r_s + \frac{d}{dt} L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \dot{\psi}_d \\ \omega_e \psi_{pm} \end{bmatrix} \qquad (4)$$

Where, ψ_{pm} is the amplitude of the permanent magnet flux linkage.

The developed electromagnetic torque of PMSM is given by,

$$T_e = \frac{3}{2} p (\psi_d i_q - \psi_q i_d) \qquad (5)$$

Where, p is a number of pair pole.

The shaft dynamic system and the mechanical torque are stated as:

$$T_m = T_e + f\,\omega_m + J \frac{d\omega_m}{dt} \qquad (6)$$

Where, *f* is the vicious damping coefficient and *J* is the total moment of inertia.

From the aforementioned equations, the equivalent circuit of three-phase PMSM in the synchronous frame is shown in Fig. 2.

One Phase Fault-Tolerant Operation Mode

The representation of the d-q axis current components, which are expressed in the synchronous reference frame, is not influenced by the faulty condition because they are controlled the required torque and flux via outer speed control. Therefore, the three-phase PMSM drive performance is investigated using $\alpha - \beta$ axis current components which give a good indication at healthy or faulty conditions. A zero-sequence component current is formulated as:

$$i_0 = \frac{1}{3}(i_a + i_b + i_c) \qquad (7)$$

In one-phase fault, it is obvious that must be increased to obtain the same performance. To represent stator currents $\alpha - \beta$ plan, the following equation is used.

$$i_{dq} = i_{\alpha\beta}e^{-i\theta} \qquad (8)$$

Where, θ is rotor electrical angle. Now, the zero-current component $i_0 = -i_a$ and $i_a = 0$ at fault condition. By substituting at the following equation to find the new reference currents which the machine drive must operate to compensate the single phasing condition.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -1/2 & \sqrt{3}/2 & 1 \\ -1/2 & -\sqrt{3}/2 & 1 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \qquad (9)$$

The new current references are formulated as:

$$\begin{aligned} i_b^* &= -\frac{3}{2}i_\alpha^* + \frac{\sqrt{3}}{2}i_\beta^* = \sqrt{3}\, i_q^* \sin\left(\theta + \frac{\pi}{6}\right) - \sqrt{3}\, i_d^* \cos\left(\theta + \frac{\pi}{6}\right) \\ i_c^* &= -\frac{3}{2}i_\alpha^* - \frac{\sqrt{3}}{2}i_\beta^* = \sqrt{3}\, i_q^* \sin\left(\theta - \frac{\pi}{6}\right) + \sqrt{3}\, i_d^* \cos\left(\theta - \frac{\pi}{6}\right) \end{aligned} \qquad (10)$$

A MATHEMATICAL MODEL OF FIVE-PHASE PMSMS

Healthy Operation Mode

The five-phase PMSM mathematical model at the normal operation can be formulated. Using an extended Park's transformation, stator voltage and torque equations can be derived as follows [37−41]:

Stator voltages are expressed as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = r_s \boldsymbol{I} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ I_e \end{bmatrix} + \begin{bmatrix} \dot{\lambda}_a \\ \dot{\lambda}_b \\ \dot{\lambda}_c \\ \dot{\lambda}_d \\ \dot{\lambda}_e \end{bmatrix} \qquad (11)$$

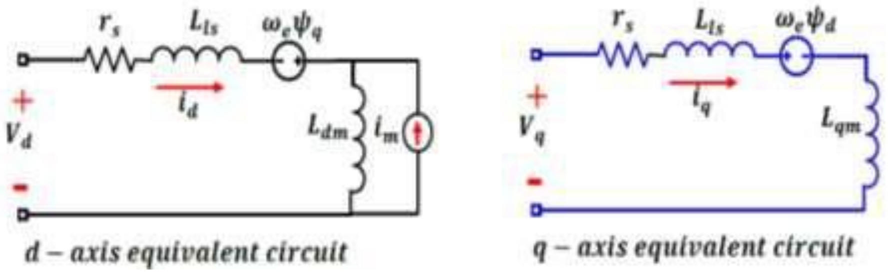


Figure 2: Three-phase PMSM equivalent circuit

Here, r_s denotes the similar winding resistance, $\boldsymbol{I}$ is 5 by 5 identity matrix and $\dot{\lambda}_s = \frac{d\lambda_s}{dt}$. While the air gap flux linkage is defined by:

$$\lambda_s = L_{ss}I_s + \lambda_m \tag{12}$$

Where λ_m specifies the matrix of permanent magnet flux linkage in addition, L_{ss} symbolizes a matrix inductance of each stator phase self and mutual inductances.

$$L_{ss} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{ad} & L_{ae} \\ L_{ba} & L_{bb} & L_{bc} & L_{bd} & L_{be} \\ L_{ca} & L_{cb} & L_{cc} & L_{cd} & L_{ce} \\ L_{da} & L_{db} & L_{dc} & L_{dd} & L_{de} \\ L_{ea} & L_{eb} & L_{ec} & L_{ed} & L_{ee} \end{bmatrix} \tag{13}$$

In order to obtain different dynamic performance in the d-q synchronous reference frame, it is required to apply the following transformation matrix,

$$T(\theta) = \frac{2}{5}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{5}\right) & \cos\left(\theta - \frac{4\pi}{5}\right) & \cos\left(\theta + \frac{4\pi}{5}\right) & \cos\left(\theta + \frac{2\pi}{5}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) \\ \cos\theta & \cos\left(\theta + \frac{4\pi}{5}\right) & \cos\left(\theta - \frac{2\pi}{5}\right) & \cos\left(\theta + \frac{2\pi}{5}\right) & \cos\left(\theta - \frac{4\pi}{5}\right) \\ \sin\theta & \sin\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{14}$$

By using the following pseudo-orthogonal property, the inverse transforming matrix can be found as,

$$T^{-1}(\theta) = \frac{5}{2}T^t(\theta) \tag{15}$$

Where, $T^t(\theta)$ is transpose matrix of $T(\theta)$.

By applying previous transformation matrixes, stator voltages in the d-q synchronous reference frame are formulated as:

$$\begin{bmatrix} V_{d1} \\ V_{q1} \\ V_{d3} \\ V_{q3} \end{bmatrix} = r_s \boldsymbol{I} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d3} \\ i_{q3} \end{bmatrix} + \begin{bmatrix} \dot{\lambda}_{d1} - \omega_e \psi_{q1} \\ \dot{\lambda}_{q1} + \omega_e \psi_{d1} \\ \dot{\lambda}_{d3} - 3\omega_e \psi_{q3} \\ \dot{\lambda}_{q3} + 3\omega_e \psi_{d3} \end{bmatrix} \tag{16}$$

Where, $\dot{\lambda}_{d1} = L_{d1} \frac{di_{d1}}{dt}$, $\dot{\lambda}_{q1} = L_{q1} \frac{di_{q1}}{dt}$, $\dot{\lambda}_{d3} = L_{d3} \frac{di_{d3}}{dt}$ and $\dot{\lambda}_{q3} = L_{q3} \frac{di_{q3}}{dt}$. ω_e gives the electric angular of rotor speed. i_{d1}, i_{q1}, i_{d3} and i_{q3} are the d–q stator current components.
Here, stator flux linkage d-q components can be formulated as:

$$\psi_{q1} = L_{q1}\, i_{q1} \tag{17}$$
$$\psi_{d1} = L_{d1}\, i_{d1} + \psi_1 \tag{18}$$
$$\psi_{q3} = L_{q3}\, i_{q3} \tag{19}$$
$$\psi_{d3} = L_{d3}\, i_{d3} + \psi_3 \tag{20}$$

Where ψ_1 and ψ_3 are the amplitude of fundamental and third harmonic components of the permanent magnet flux linkage, respectively. L_{d1}, L_{q1}, L_{d3} and L_{q3} are the d–q stator inductance components.

$$\begin{aligned} L_{q1} &= L_{d1} = L_{ls} + \frac{5}{2} L_{ms1}\,; \\ L_{q3} &= L_{d3} = L_{ls} + \frac{5}{2} L_{ms3} \end{aligned} \tag{21}$$

Where, L_{ls} and L_{ms} are the leakage and mutual inductances, respectively. From above-mentioned equations, the equivalent circuit of five-phase PMSM in the synchronous frame is shown in Fig. 3.

Now, the electromagnetic torque of five-phase PMSM can be investigated using a well-defined magnetic co-energy method as follows:

$$T_e = \frac{\partial W_{co}}{\partial \theta_r} \tag{22}$$

Here, θ_r is the mechanical rotor angle and W_{co} is the magnetic co-energy which is formulated as,

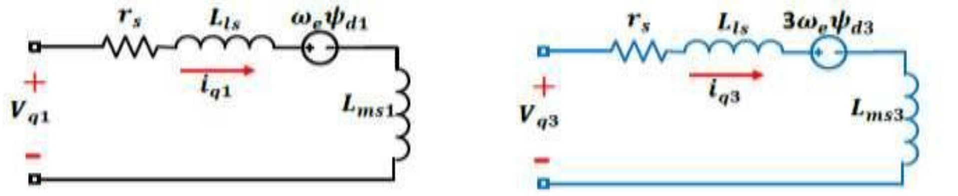
$$W_{co} = \frac{1}{2}\, I_s^t L_{ss} I_s + I_s^t \lambda_m \tag{23}$$

Therefore, T_e is expressed by following with no saliency on the rotor yield consideration,

$$T_e = p\left(T^{-1}(\theta)\, i_{d1q1d3q30s}\right)^t \frac{\partial \lambda_m}{\partial \theta_r} \tag{24}$$

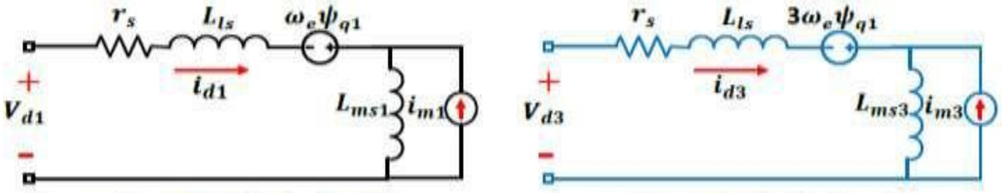
Finally,

$$T_e = \frac{5}{2} p\left(\psi_{d1} i_{q1} - \psi_{q1} i_{d1} + 3\psi_{d3} i_{q3} - 3\psi_{q3} i_{d3}\right) \tag{25}$$



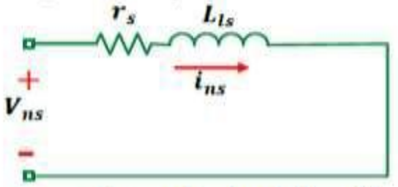
q_1 – axis equivalent circuit

q_3 – axis equivalent circuit



d_1 – axis equivalent circuit

d_3 – axis equivalent circuit



n – axis equivalent circuit

Figure 3: Five-phase PMSM equivalent circuit

Fault-Tolerant Operation Mode

The three-phase PMSM is still operating with one phase loss by using a divided dc bus and neutral connection. However, multi-phase machines provide conceivably fault tolerant because of their extra degrees of freedom. The five-phase PMSM is not only safely operating under losing one or two phases using closed-loop control but also the FTC control scheme eliminates the neutral line usage during maintaining the same torque-producing MMF [32, 33, 42−44]. In this study, sinusoidal phase currents are assumed and considering sinusoidal distributions for stator windings. the stator phases MMFs are formulated as follows:

$$\begin{aligned}
MMF_a(\varphi,\theta) &= \frac{N_s}{2} I_m \cos(\varphi)\cos(\theta) \\
MMF_b(\varphi,\theta) &= \frac{N_s}{2} I_m \cos\left(\varphi - \frac{2\pi}{5}\right)\cos\left(\theta - \frac{2\pi}{5}\right) \\
MMF_c(\varphi,\theta) &= \frac{N_s}{2} I_m \cos\left(\varphi - \frac{4\pi}{5}\right)\cos\left(\theta - \frac{4\pi}{5}\right) \\
MMF_d(\varphi,\theta) &= \frac{N_s}{2} I_m \cos\left(\varphi + \frac{4\pi}{5}\right)\cos\left(\theta + \frac{4\pi}{5}\right) \\
MMF_e(\varphi,\theta) &= \frac{N_s}{2} I_m \cos\left(\varphi + \frac{2\pi}{5}\right)\cos\left(\theta + \frac{2\pi}{5}\right)
\end{aligned} \qquad (26)$$

N_s denotes a total number of each phase turns, φ is the spatial angle, and $\theta = \omega t$. I_m gives the phase current.

The total stator MMF is expressed as,

$$MMF_t(\varphi,\theta) = MMF_a(\varphi,\theta) + MMF_b(\varphi,\theta) + MMF_c(\varphi,\theta) + MMF_d(\varphi,\theta) + MMF_e(\varphi,\theta) \tag{27}$$

Which equals,

$$MMF_t(\varphi,\theta) = \frac{5}{4}(N_s I_m \cos(\theta-\varphi)) = \frac{5}{8}\left(N_s I_m (e^{\iota\theta}e^{-\iota\varphi} + e^{-\iota\theta}e^{\iota\varphi})\right) \tag{28}$$

Also, the total MMF can be also rewritten as:

$$MMF_t = \frac{1}{4}\Big\{N_s\Big[\left(I_a + e^{-\iota\frac{2\pi}{5}}I_b + e^{-\iota\frac{4\pi}{5}}I_c + e^{\iota\frac{4\pi}{5}}I_d + e^{\iota\frac{2\pi}{5}}I_e\right)e^{\iota\varphi} + \left(I_a + e^{\iota\frac{2\pi}{5}}I_b + e^{\iota\frac{4\pi}{5}}I_c + e^{-\iota\frac{4\pi}{5}}I_d + e^{-\iota\frac{2\pi}{5}}I_e\right)e^{-\iota\varphi}\Big]\Big\} \tag{29}$$

$$\frac{5}{2}I_m e^{\iota\theta} = I_a + aI_b + a^2 I_c + a^3 I_d + a^4 I_e \tag{30}$$

By using the Eqs. (28,29), the following equation is obtained,
Where, $a = e^{\iota\frac{2\pi}{5}}$,

One-Phase Fault:

To verify the FTC of five-phase PMSM, one phase is opened because of machine or phase winding fault. For maintaining the forward rotating field, ***I***$_a$ is set to zero in Eq. (30). By assuming,

$I'_b = -I'_d$; $I'_c = -I'_e$

Now, the current of unfaulted phases are,

$$I'_b = -I'_d = \frac{5I_m}{4\left(\sin\frac{2\pi}{5}\right)^2}\cos\left(\theta - \frac{\pi}{5}\right)$$
$$I'_c = -I'_e = \frac{5I_m}{4\left(\sin\frac{2\pi}{5}\right)^2}\cos\left(\theta - \frac{4\pi}{5}\right) \tag{31}$$

It is obvious that in the case of open phase fault, the remaining phases are still operating to maintain the same MMF when the new compensating currents are applied. The fundamental current amplitude should be increased up to 1.382 from its initial healthy mode value as follows,

$$\begin{aligned} i^*_{bs} &= 1.382\left(I^*_{qs}\cos\left(\theta-\frac{\pi}{5}\right) + I^*_{ds}\sin\left(\theta-\frac{\pi}{5}\right)\right)\\ i^*_{cs} &= 1.382\left(I^*_{qs}\cos\left(\theta-\frac{4\pi}{5}\right) + I^*_{ds}\sin\left(\theta-\frac{4\pi}{5}\right)\right)\\ i^*_{ds} &= 1.382\left(I^*_{qs}\cos\left(\theta+\frac{4\pi}{5}\right) + I^*_{ds}\sin\left(\theta+\frac{4\pi}{5}\right)\right)\\ i^*_{es} &= 1.382\left(I^*_{qs}\cos\left(\theta+\frac{\pi}{5}\right) + I^*_{ds}\sin\left(\theta+\frac{\pi}{5}\right)\right) \end{aligned} \tag{32}$$

For FTC control, the FTC algorithm estimates and detected the open circuit fault with current sensors and takes the action to overcome the fault condition. The previous remaining current commands are considered for ***I***$^*_{qs}$ and ***I***$^*_{ds}$ torque-flux currents.

Two-Phase Fault:

Like one-phase fault, if both a and b phases are lost. The remaining three-phase currents are formulated as,

$$I_c^* = \frac{5I_m \cos\left(\frac{\pi}{5}\right)}{2\left(\sin\frac{2\pi}{5}\right)^2} \cos\left(\theta - \frac{2\pi}{5}\right) \tag{33}$$

$$I_d^* = \frac{5I_m \cos\left(\frac{\pi}{5}\right)^2}{\left(\sin\frac{2\pi}{5}\right)^2} \cos\left(\theta + \frac{4\pi}{5}\right)$$

$$I_e^* = \frac{5I_m \cos\left(\frac{\pi}{5}\right)}{2\left(\sin\frac{2\pi}{5}\right)^2} \cos(\theta)$$

Now, the remaining reference current will be,

$$i_{cs}^* = 2.2361\left(I_{qs}^* \cos\left(\theta - \frac{2\pi}{5}\right) + I_{ds}^* \sin\left(\theta - \frac{2\pi}{5}\right)\right)$$

$$i_{ds}^* = 3.618\left(I_{qs}^* \cos\left(\theta + \frac{4\pi}{5}\right) + I_{ds}^* \sin\left(\theta + \frac{4\pi}{5}\right)\right) \tag{34}$$

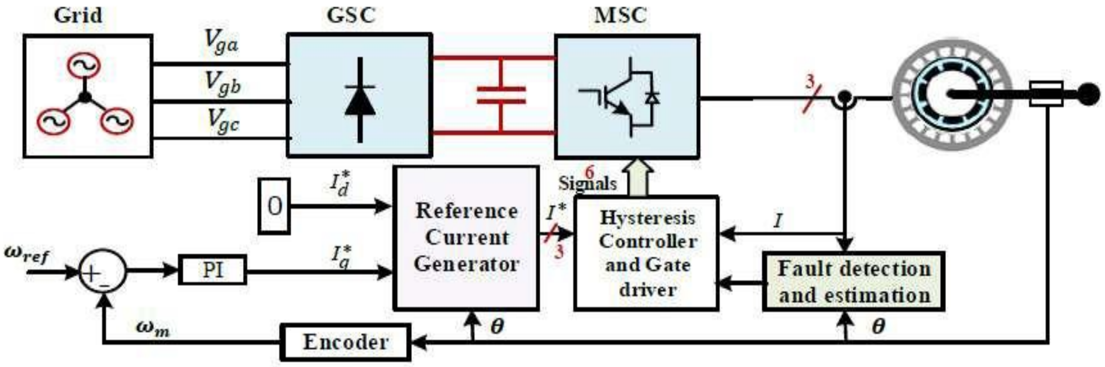
$$i_{es}^* = 2.2361\left(I_{qs}^* \cos(\theta) + I_{ds}^* \sin(\theta)\right)$$

THREE-PHASE AND FIVE-PHASE PMSMS WITH THE POSTFAULT OPERATING STRATEGY

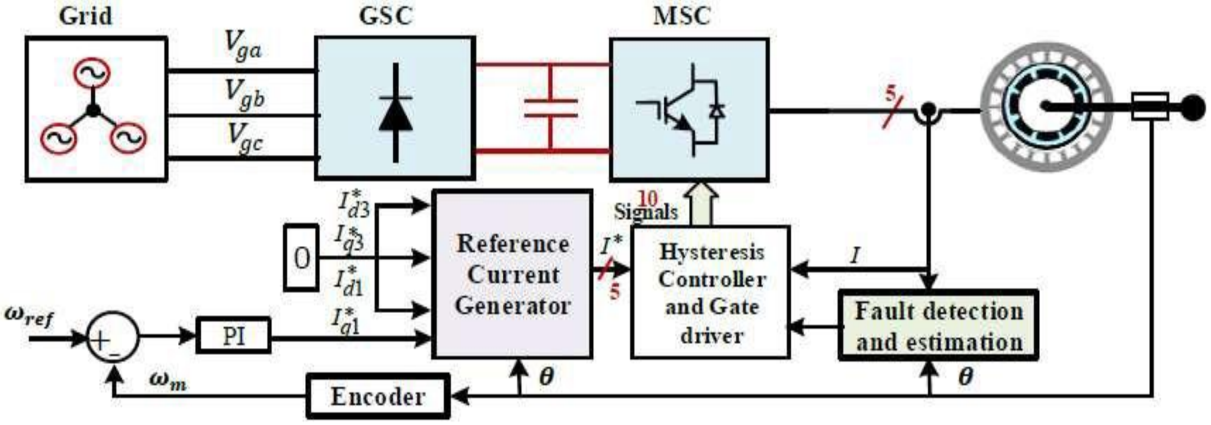
To validate the FTC system of three-phase and five-phase PMSMs with post fault strategy, a five-phase motor and a three-phase PMSMs both rated 4.4 kW are fed by grid side converter (GSC) that rectifier AC voltage to DC voltage on the terminal of DC-link capacitor. The machine side converter (MSC) controls the applied voltage and current to the PMSM block's stator windings. The load torque which applied to each machine's shaft is fixed to 7 N.m. Two control loops are utilized. The outer loop is a speed control loop that regulates the rotor speed for generating reference q-axis current component. The inner loop is the current control loop which regulates the motor's stator currents as shown in Fig. 4. Simulation process can be summarized as:

- Each machine starts under normal operation (all healthy phases).
- At t = 0.06 second, phase "A" of both machines is disconnected.
- At t = 0.09 second, each controller's current references are varied to compensate for the phase loss.
- At t = 0.12 second, phase "B" is also disconnected from the five-phase PMSM.
- At t = 0.15 second, the controller's current references of the five-phase PMSM are varied to compensate for the two phases loss.

In Fig. 5 (a), rotor speed of three-phase PMSM contains a lot of ripples compared to the five-phase PMSM which maintains a good speed regulation as shown in Fig. 6 (a). The variation of current references during the two successive faults, the five-phase PMSM currents are increased to maintain the electromagnetic torque at the same value and to avoid large ripple as shown in Fig. 5 (b, c). So, good speed regulation is sustained. However, the electromagnetic torque of the three-phase PMSM has a lot of ripples which propagates to the speed regulation as shown in Fig. 6 (b, c). Simulation results show the superiority of the five-phase PMSM which maintains much more FTC than the three-phase PMSM.

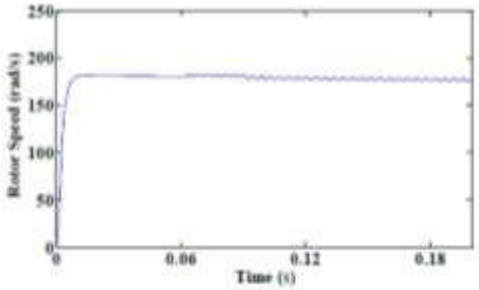


(a) Three-phase PMSM

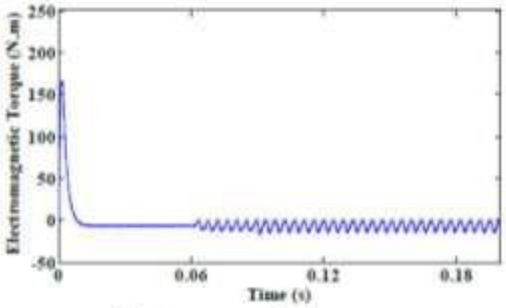


(b) Five-phase PMSM

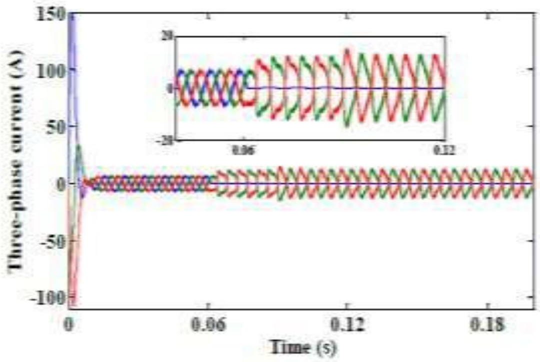
Figure 4: Three-phase and Five-phase PMSMs with postfault operating strategy



(a) Rotor Speed

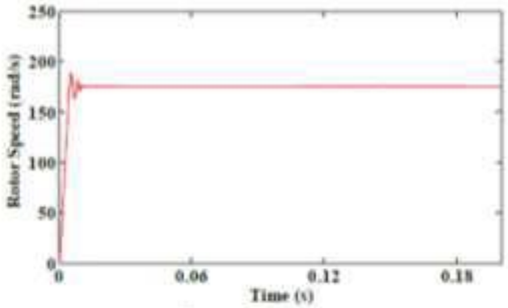


(b) Electromagnetic Torque

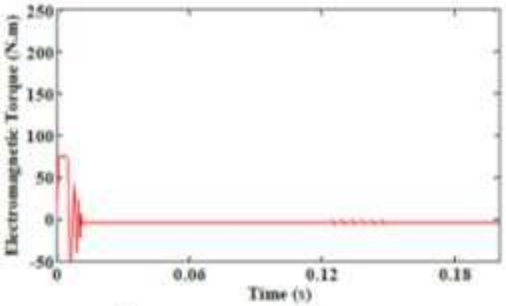


(c) Three-phase current

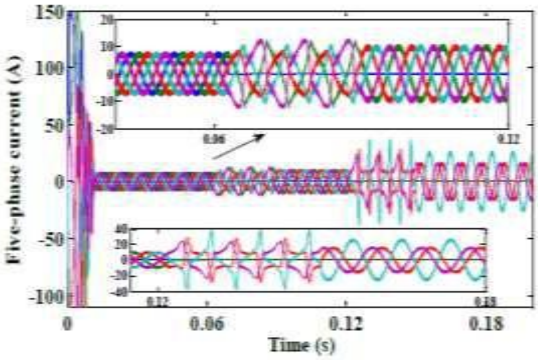
Figure 5: Three-phase PMSM under healthy and faulted phases.



(a) Rotor Speed



(b) Electromagnetic Torque



(c) Five-phase current

Figure 6: Five-phase PMSM under healthy and faulted phases.

CONCLUSION

Multi-phase PMSMs are implemented in many industrial applications to overcome the limitations of conventional three-phase PMSMs. In faulty conditions, multi-phase PMSMs give a better performance to sustain the average output torque with low torque pulsations. Mathematical models under health and faulty conditions of three and five-phase PMSMs are investigated. Furthermore, the performance and the fault-tolerant capability of a five-phase PMSM are studied and compared to a conventional three-phase PMSM. Simulation results show the superiority of the five-phase PMSM which detects and isolates the faulty phase. In addition to sustaining much more fault-tolerant capability than the conventional three-phase PMSM.

REFERENCES

I. L Parsa (2005), "On advantages of multi-phase machines", 31st Annual Conference of IEEE Industrial Electronics Society, IECON, pp. 6.

II. E Levi, F Barrero, MJ Duran (2016), "Multiphase machines and drives- Revisited", IEEE transactions on industrial electronics, Volume 63, pp. 429−432.

III. F Barrero, MJ Duran (2016), "Recent advances in the design, modeling, and control of multiphase machines—Part

IV. I," IEEE transactions on industrial electronics, Volume 63, pp. 449−458.

V. MJ Duran, F Barrero (2016), "Recent advances in the design, modeling, and control of multiphase machines—Part II", IEEE transactions on industrial electronics, Volume 63, pp. 459−468.

VI. W Wang, J Zhang, M Cheng, S Li (2017), "Fault-tolerant control of dual three-phase permanent-magnet synchronous machine drives under open-phase faults", IEEE Transactions on power electronics, Volume 32, pp. 2052−2063.

VII. S Green, D Atkinson, A Jack, B Mecrow, A King (2003), "Sensorless operation of a fault tolerant PM drive", IEE Proceedings-Electric Power Applications, Volume 150, pp. 117−125.

VIII. B Stumberger, G Stumberger, A Hamler, M Trlep, M Jesenik, V Gorican (2003), "Increasing of output power capability in a six-phase flux-weakened permanent magnet synchronous motor with a third harmonic current injection," IEEE Transactions on Magnetics, Volume 39, pp. 3343−3345.

IX. S Rangari, H Suryawanshi, M Renge (2018), "New fault-tolerant control strategy of five-phase induction motor with four-phase and three-phase modes of operation", Electronics, Volume 7, pp. 159.