Fault Diagnosis of Inter Turn Short Circuit for Permanent Magnet Synchronous Machine Using Fast Fourier Transform (FFT)

Abdelmoumin Ouali [1], Hassina Megherbi [2], Djalal-Eddine Khodja [3], Yahia Laamari [4]

[1] *LI3CUB Laboratory, Department of Electrical Engineering, University of Biskra, Algeria*
E-mail: abdelmoumin.ouali@univ-biskra.dz,

[2] *LARHYSS Laboratory, Faculty of Technology, University of Biskra Algeria*

h.megherbi@univ-biskra.dz.

[3,4] *Research Laboratory on the Electrical Engineering, Faculty of Technology, University of M'Sila, Algeria*
E-mail: djalaleddine.khodja@univ-msila.dz.

[4] *Electrical Engineering Department, Faculty of Technology, University Batna 2, Algeria*
E-mail: y.laamari@univ-batna2.dz.

Abstract: This paper presents modeling and analysis of short-circuit faults between the stator windings of a permanent magnet synchronous machine (PMSM). The studied method is based totally on growing and developing a mathematical model that describes both the healthy and faulty states of the studied machine. Furthermore, this dynamic model was simulated and Examined to study the kinetic behaviour under different failure conditions. Also, frequency domain analysis based on the Fast Fourier transform (FFT) has been established. The proposed approach analyzes the frequency spectrum of the stator current to detect harmonic signatures that indicate the presence of short circuits between the windings, Total harmonic distortion (THD) may also be used as a good indicator to predict the presence of a short circuit fault. The simulation results confirm the effectiveness of this technique and show that it can accurately distinguish between healthy and defective motor states.

Keywords: Permanent Magnet Synchronous Machine (PMSM), Fault diagnosis, Inter-turns short circuit, Modeling, Fast Fourier transform (FFT).

1. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have gained popularity in a variety of industries due to their high-power density, outstanding dependability, and great dynamic performance (Laamari et al., 2021; Zheng et al., 2017). They are commonly used for applications that need great efficiency (Fitouri et al., 2016; Ebrahimi et al.,2020). However, PMSMs frequently operate in severe environments and are subjected to different pressures caused by the electrical power supply and charging circumstances. As a result, they are inherently prone to failure during extended continuous operation (Chen et al., 2019; MAANANI et al., 2023). These faulty are commonly classified as electrical, magnetic and mechanical defects.

Stator inter-turn short-circuits represent a common electrical fault in Permanent Magnet Synchronous Motors (PMSMs). According to reference (Zhang et al., 2019), these short-circuit faults constitute 30–40% of all PMSM faults. The primary causes of such faults are diverse stresses acting on the stator windings, including: Electrical, Mechanical and Thermal stress. It's important to note that these degradation factors are accelerated in electrical machines driven by inverters (Cintron et al., 2015). In permanent magnet synchronous motors (PMSMs), stator winding faults lead to high current circulating in the shorted turns. Detecting and rapidly locating these faults is crucial to minimizing damage. Effective failure diagnosis and continuous state monitoring of PMSMs are essential to maintaining their availability and ensuring long-term high-performance operation (Pacha et al., 2023). Stator winding faults significantly reduce motor efficiency, prompting researchers to experimentally validate various models (Vaseghi et al., 2011; Boileau et al., 2013). Numerous approaches have been developed to study the impact of inter-turn short circuits (ITSC) on synchronous machines under both healthy and faulty conditions (Pietrzak et al., 2022). Among these, equivalent circuit models have been particularly valuable for explaining machine dynamics and offer the advantage of faster computation times (Vaseghi et al., 2011).

This paper aims to develop models that contribute to the determination of the behavior of different parameters of a synchronous machine with short circuit between windings. Our study is dedicated to the modeling of the PMSM in a healthy state and in the presence of stator faults (short circuit faults between windings). A mathematical transformation (the Concordia transformation) is suggested and utilized in the equations of the three-phase equivalent model of the machine. Then, the fault conditions are analyzed using the FFT signal frequency domain analysis method, and the THD value can be used as an indicator of fault detection. The simulation results in MATLAB using the proposed PMSM model for fault detection ITSC Show the Efficiency of this technique.

2. MODEL OF THE MSAP IN THE PRESENCE OF A SHORT-CIRCUIT FAULT

An inter-turn short circuit occurs when the insulation between two turns within the same stator phase fails. To model this fault condition, we employ a permanent inter-turn fault model as illustrated in figure 1, for a given fault severity factor (μ). In this model, the affected winding is split into two segments: the short-circuited portion (as2) and the healthy portion (as1).

Comprehension the machine's behavior under various fault resistance conditions is essential. When the fault resistance is high, it helps avoid complete winding damage. Therefore, analyzing the machine's performance across different fault resistance values is essential for comprehensive fault diagnosis and protection Methods.

This approach enables us to simulate and study the motor's characteristics under different fault conditions, providing valuable insights for fault detection and mitigation techniques.

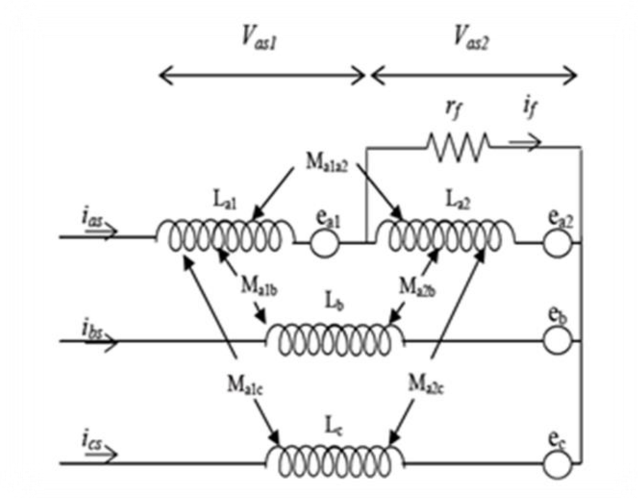

Figure 1. PMSM stator with ITSC in phase (as)

Inter-turn short circuit (ITSC) faults are represented by a variable resistance, which reflects the severity of the insulation collapse. As this resistance approaches zero, the fault advances towards a complete short circuit between turns. In many insulating materials, this transition from high to near-zero resistance happens rapidly. The current that flows through the fault resistance (Rf) is known as (if).also, parameter (μ) is defined as the ratio of shorted turns (Nf) to the total turns in a phase (Ns) [10].These two factors, the fault resistance (Rf) and the short circuit percentage (μ) together characterize the severity of the inter-turn short circuit fault.

The resistances of healthy and faulty parts of stator winding are articulated by the equations:

$$N_f = N_{as2} = \mu(N_{as1} + N_{as02}) = \mu N_s \quad (1)$$

$$\begin{cases} R_{a1} = (1-\mu)R_a \\ R_{a2} = \mu R_a \end{cases} \quad (2)$$

2.1 Model of a faulty PMSM in frame (a, b, c)

In order to Build the mathematical model of the Permanent Magnet Synchronous Motor (PMSM) drive, we have made the following simplifying assumptions: The magnetic circuit is presumed to have no saturation effects, and the impact of temperature on parameters is Ignored (Laamari et al., 2021). The equations of the PMSM voltages with ITSC in the phase (as) can be written in (abc) frame as follows:

$$\begin{aligned} V_{as} = {} & (R_{a1} + R_{a2})i_{as} \\ & + (L_{a1} + L_{a2} + 2M_{a1a2})\frac{d}{dt}i_{as}(M_{a1b} \\ & + M_{a2b})\frac{d}{dt}i_{bs} \\ & + (M_{a1c} + M_{a2c})\frac{d}{dt}i_{cs} + (e_{a1} + e_{a2}) \\ & - R_{a2}i_f - (L_{a2} + M_{a1a2})\frac{d}{dt}i_f \end{aligned} \quad (3)$$

$$\begin{aligned} V_{bs} = {} & R_s i_{bs} + L\frac{d}{dt}i_{bs} + e_{bs} + (M_{a1b} + M_{a2b})\frac{d}{dt}i_{as} \\ & + M\frac{d}{dt}i_{cs} - M_{a2b}\frac{d}{dt}i_f \end{aligned} \quad (4)$$

$$\begin{aligned} V_{cs} = {} & R_s i_{cs} + L\frac{d}{dt}i_{cs} + e_{cs} + (M_{a1c} + M_{a2c})\frac{d}{dt}i_{as} \\ & + M\frac{d}{dt}i_{bs} - M_{a2c}\frac{d}{dt}i_f \end{aligned} \quad (5)$$

As well, the following relations are normally accepted:

$$\begin{aligned} R_s &= R_a = R_{a1} + R_{a2} \\ L &= L_{a1} + L_{a2} + 2M_{a1a2} \\ M &= M_{a1b} + M_{a2b} = M_{a1c} + M_{a2c} \\ e_a &= e_{a1} + e_{a2} = e_{a1} + e_f \end{aligned} \quad (6)$$

Typically, the stator's three phases are arranged in a star, resulting in the sum of currents equaling zero: *ias + ibs + ics = 0*. Under these conditions, the homopolar component of the current is zero and only the cyclic inductance of the machine (*Ls = L- M*) limits the phase currents. The PMSM performance in the presence of a short circuit, which can be written as a matrix:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & -R_{a2} \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ -R_{a2} & 0 & 0 & R_{a2}+r_f \end{bmatrix} + \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_f \end{bmatrix} + \begin{bmatrix} L_s & 0 & 0 & -L_{a2}-M_{a1a2} \\ 0 & L_s & 0 & -M_{a2b} \\ 0 & 0 & L_s & -M_{a2c} \\ -L_{a2}-M_{a1a2} & -M_{a2b} & -M_{a2c} & L_a \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_f \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \\ -e_{a2} \end{bmatrix} \quad (7)$$

2.2 Model of a faulty PMSM in frame (α, β)

The extended Concordia transformation is applied, defined as follows (Laamari et al., 2021):

$$[T]^t = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & 0 \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} & 0 \\ 0 & 0 & 0 & \sqrt{\frac{3}{2}} \end{bmatrix} \quad (8)$$

the machine equations with inter-turn fault in (α, β) reference frame are written as follows:

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 & -R'_{a2} \\ 0 & R_s & 0 \\ -R'_{a2} & 0 & R'_f \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_f \end{bmatrix} + \begin{bmatrix} L_s & 0 & M_{f\alpha} \\ 0 & L_s & M_{f\beta} \\ M_{f\alpha} & M_{f\beta} & L_{a2} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_f \end{bmatrix} + \begin{bmatrix} e_\alpha \\ e_\beta \\ -e_f \end{bmatrix} \quad (9)$$

Where,

$$R'_{a2} = \sqrt{\frac{2}{3}} R_{a2} \; ; \; R'_f = R_{a2} + r_f \; ; \; e_f = e_{a2}$$

$$M_{f\alpha} = -\sqrt{\frac{2}{3}} [L_{a2} + M_{a1a2} - (M_{a2b} + M_{a2c})/2] \quad (9)$$

$$M_{f\beta} = -\frac{1}{\sqrt{2}} (M_{a2b} + M_{a2c})$$

3. FFT ANALYSIS OF STATOR FAULT IN PMSM

The literature denotes that Fast Fourier Transform (FFT) analysis is an important method for detecting stator winding faults in permanent magnet synchronous motors (PMSMs). This technique involves examining the frequency spectrum of the motor's current or voltage signals. When comparing the observed spectrum to that of a properly functioning motor, any unexpected changes in the amplitude or phase of specific frequency components can indicate the presence of an inter-turn short circuit (ITSC) fault in the stator winding (Romdhane et al., 2023). These deviations from the normal spectrum serve as diagnostic markers for identifying such faults.

4. SIMULATION AND RESULTS

Simulations in the MATLAB/Simulink environment were used to Confirm and validate the proposed model. To investigate the motor's behavior for a failure between stator winding revolutions, both healthy and faulty situations were simulated. The nominal parameters for the simulated PMSM are displayed in the appendix.

In the healthy state as shown in Figure 2, The three-phase stator currents are balanced and sinusoidal with an amplitude of 18.55 amperes. For the faulty condition, The simulation results are shown in Figures 3, 4 ,and 5 respectively for three error resistance values Rf = 0.5 (Ω), 1 Ω, and 5 (Ω), under error ratio μ =50%, with a load torque of 10 N.m at (t = 0s), The fault will be introduced at (t = 0.5s).

It can be seen that when the fault resistance (Rf) reduces, the fault current (if) raises, the phase currents become unbalanced and the phase current (a) is larger in amplitude than the phase currents (b) and (c).

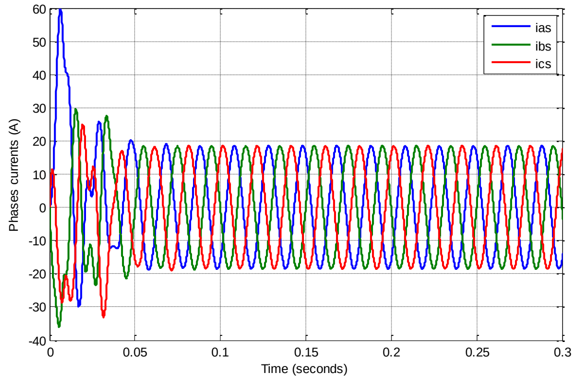

Figure 2. Simulation of healthy PMSM

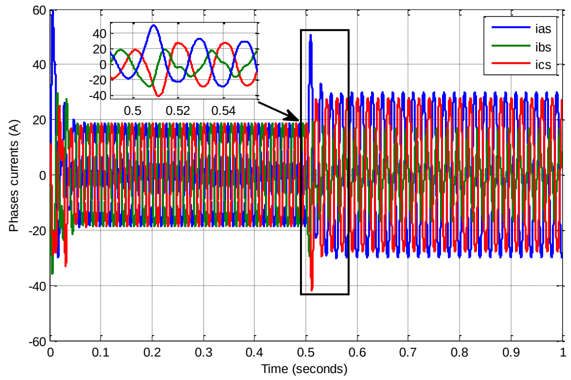

Figure 3. PMSM faults stator currents with Rf=0.1 (Ω)

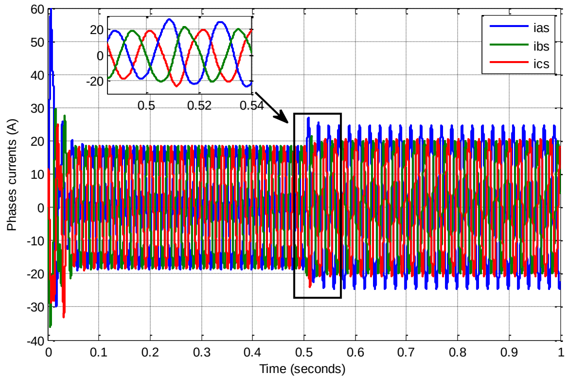

Figure 4. PMSM faults stator currents with Rf=1 (Ω)

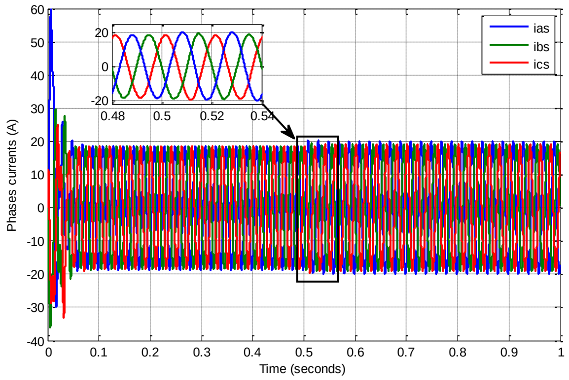

Figure 5. PMSM faults stator currents with Rf=5 (Ω)

The figure 6 shows the healthy condition of the motor, where the amplitude of the third and fifth harmonics is close to zero. As for the fault condition of the motor, as shown in the figure 7, 8, and 9, the more the number of shorted turns expands, the amplitude of the third and fifth harmonic current signal in the faulty phase boosts.

Analysis of the stator current in the faulty state of the phase winding reveals three peaks. The first peak Compatible with fundamental frequency of 50 Hz, the other peaks at 150 Hz (third harmonic) and 250 Hz (fifth harmonic). This spectral signature is indicative of a short-circuits defect.

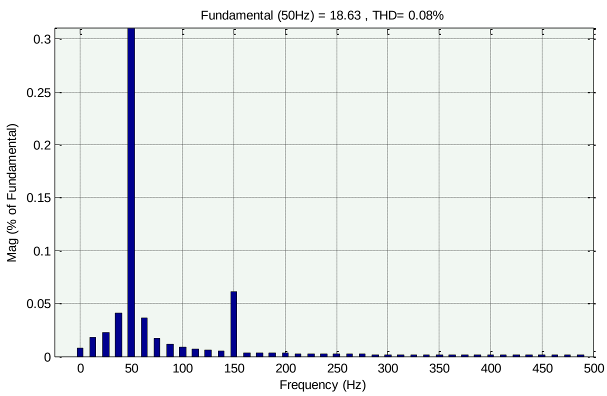

Figure 6. FFT analysis of current phase (as) in healthy state

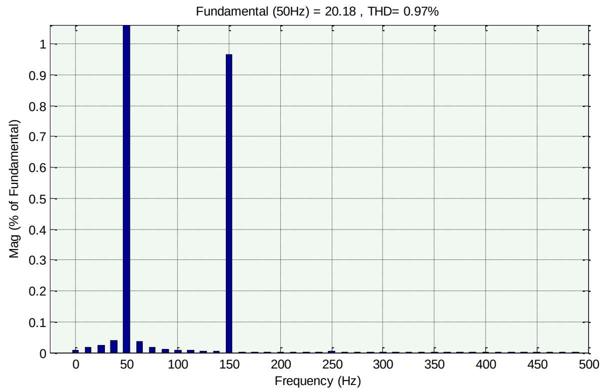

Figure 7. FFT analysis of current phase (as) in faulty state with Rf=5 (Ω)

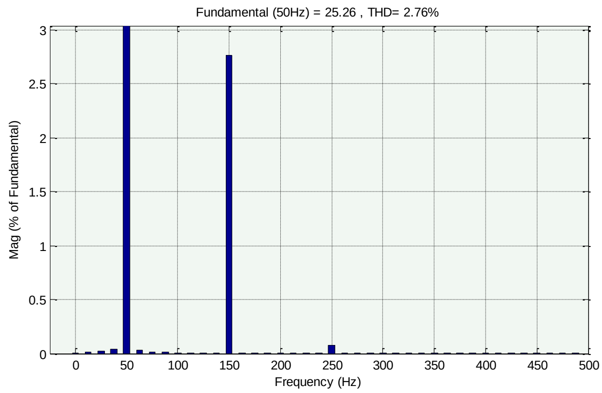

Figure 8. FFT analysis of current phase (as) in faulty state with Rf=1 (Ω)

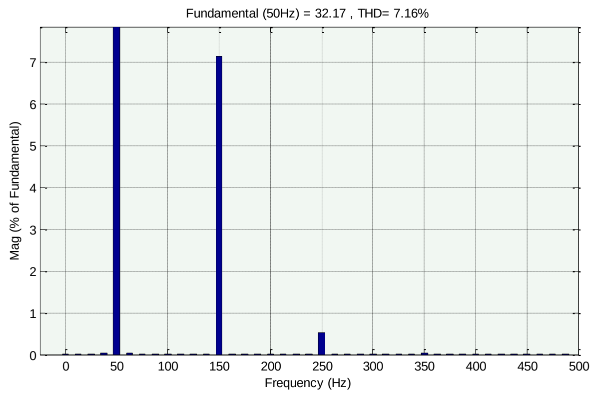

Figure 9. FFT analysis of current phase (as) in faulty state with Rf=0.1 (Ω)

5. CONCLUSION

This study presents a model for stationary phase short-circuit (ITSC) faults of permanent magnet synchronous motors (PMSMs). Accurate modeling of PMSMs using (ITSC) is essential to diagnose, monitor and understand the fault behavior and to propose effective detection methods. To lessen the risk of damage to the motor windings, Fast Fourier Transform (FFT) technology is used to detect stator current faults under various fault conditions. The fault detection results have shown very satisfactory results, which effectively identify the signature of turning defects in PMSMs.

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Appendix

Parameters of the PMSM:

Parameters	Value	Parameters	Value
Rs (Ω)	0.44	f (N.m.s/rad)	0.007
Ls (mH)	2.82	Φ (web)	0.108
P	4	Ns	40
J (kg.m^2)	0.0006	In (A)	19