



RESEARCH ARTICLE

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FAULT DETECTION OF STATOR WINDINGS FOR PMSM BASED ON FAST FOURIER AND DISCRETE WAVELET TRANSFORM

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ABSTRACT

Fault detection in permanent magnet synchronous motor (PMSM) is important and necessary to ensure reliability, performance and reduce downtime. In this study, a mathematical model is developed that describes the healthy and faulty states of the PMSM, including inter-turn short circuit (ITSC) faults. This dynamic mathematical model is simulated and its performance and behavior under different fault conditions are studied. Fast Fourier transform (FFT) technique is employed to analyze the frequency spectrum of motor speed and stator current signals, which allows us to detect harmonic distortions caused by short circuit faults in the windings. However, FFT technique is not sufficient for non-stationary conditions. To address this, the discrete wavelet transform (DWT) is utilized to analyze motor signals across various frequency ranges, which allows the detection of faults under non-stationary conditions and improves the accuracy of diagnosis under real operating conditions. The effectiveness of the studied techniques is demonstrated through simulation, with DWT showing superior performance in detection of PMSM faults.



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I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) are among the most widely used types of motors and have been commonly employed in various industrial applications, including electric vehicles, aircraft, wind generators, ship propulsion motors [1-3]. This motor has a compact size, lightweight design, and high load capacity, indicating that PMSM offers high torque density and excellent dynamic performance [4], [5]. Nonetheless, PMSM is susceptible to diverse forms of damage, including electrical faults in the stator windings, magnetic issues involving the permanent magnets and mechanical defects such as imbalance, bearing failures and eccentricity, which arise from various stresses during prolonged operation in severe environmental circumstances, and is influenced by the fluctuating power supply and load parameters [6].

The stator insulation thermal stress condition, leading to an inter-turn short circuit (ITSC), is a common electrical fault in permanent magnet synchronous motors. Short circuit faults between windings constitute 30% to 40% of failures in Permanent Magnet Synchronous Motors (PMSM) [7], [8]. This fault type arises from many pressures impacting the stator windings, including electrical, mechanical, thermal, and environmental loads [9]. The effects are amplified in electrical equipment that uses transformers [10]. The stator winding faults of PMSM cause significant current surges. These faults must be detected and identified quickly to avoid power losses [8]. Tolerating these damages in their initial stage and detecting and identifying them is a fundamental issue [11].

Various models have been established to examine and evaluate the effect of ITSC on synchronous machines in both normal and defective conditions [12], [13]. Equivalent circuit models are valuable for analyzing and examining the system behavior [14]. Three common fault diagnosis methods exist: based signal method, based model method and based knowledge method. The model-based approach necessitates a precise mathematical representation of the motor, whereas the knowledge-based approach demands comprehensive data and experience from specialists [15]. Consequently, the signal-based approach is extensively employed in PMSM

fault diagnostics due to its efficiency and that it does not require any specific models of motor. In signal processing, the fast Fourier transform (FFT) analyzes the signal as a linear combination of waves with varying frequencies, hence facilitating the extraction and determination of the overall frequency information included in the signal [5], [16]. Furthermore, owing to the absence of temporal information, the FFT applies just to the analysis of stationary conditions. Consequently, time-frequency technique, including wavelet transform (WT), short-time Fourier transform (STFT), have garnered considerable interest from several scholars at present, which can diagnose faults in non-stationary conditions [17-19]. Recently, the discrete wavelet transform (DWT) has been extensively employed in signal processing applications due to its ability to analyze signals in the frequency and time domains.

Numerous studies have investigated the application of DWT in diagnosing faults in electrical machines [20], [21]. This work presents models that enhance the comprehension of the behavior of various parameters of a PMSM within healthy conditions and in the presence of a winding short-circuit fault. The Concordia transform is employed in the equations of a three-phase equivalent model of the machine. Subsequently, using FFT, the frequency domain of both motor current and speed signals is analyzed under different fault conditions. Then, the discrete wavelet transform (DWT) decomposes the stator currents and extracts the wavelet coefficients from these signals. The simulation results in MATLAB indicate the efficacy of both techniques for fault detection.

II. MODEL OF THE PMSM IN THE PRESENCE OF A SHORT-CIRCUIT FAULT

Insulation breakdown between two windings within the same stator phase leads to short circuit faults between windings. To model this fault, we use an inter-winding fault model, as shown in figure 1. In this proposed model, the affected phase is divided into two sub-windings: the short-circuited winding (as2) and the healthy winding (as1). This approach enables us to model and investigate the properties of a motor under various failure scenarios, offering valuable insights for fault detection techniques. A high fault resistance helps to prevent damage to the entire winding. To diagnose and prevent faults, it is essential to evaluate the performance of the machine at different fault resistance values and to predict the faults between turns when the fault development is in the early stages, and the resistance of the fault is relatively high and not close to zero [14].

The ITSC is represented by a variable resistance, which indicates the severity of the insulation failure. As the fault resistance diminishes and approaches zero, the fault develops into a complete short circuit between the windings. This transition from high resistance to nearly zero often occurs rapidly in many insulating materials [9]. The current passing through the fault resistance (R_f) is indicated as (i_f), and the parameter (μ) is denoted as the ratio of shorted turns (N_f) to the total turns in a phase (N_s). To enable accurate modeling of short circuits between windings, the equations consider the distribution of short circuits and the associated fault resistance. The resistances of the healthy and faulty sections of the stator winding are articulated through the following equations:

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

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

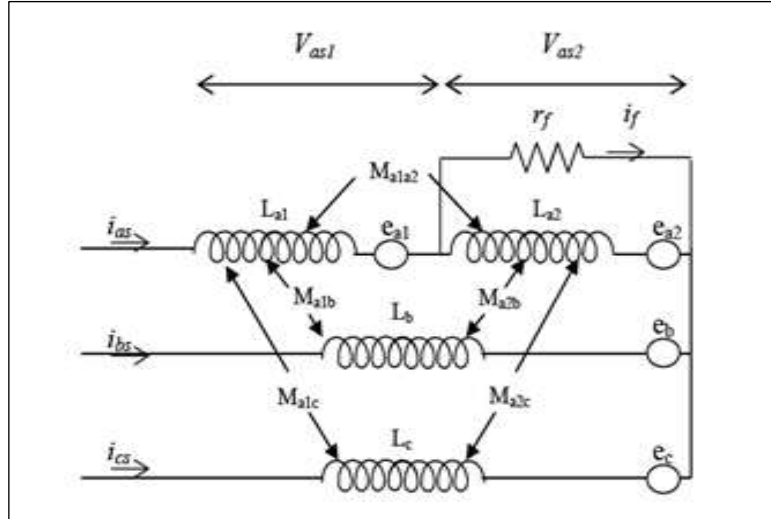


Figure 1: Stator winding with ITSC.

Source: [22].

II.1 MODEL OF A FAULTY PMSM IN FRAME (a, b, c)

To model a PMSM, we made the following simplifying assumptions: the magnetic circuit is considered to have no saturation effects, and temperature effects on parameters are disregarded [10]. The PMSM voltage equations with ITSC in the phase (as) can be expressed in the (abc) frame as follows:

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

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

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

The following relations are commonly accepted:

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

Typically, the three phases of stator are arranged in a star, resulting in the sum of currents equaling zero: $i_{as} + i_{bs} + i_{cs} = 0$. Under these conditions, the homopolar component of the current is zero and only the cyclic inductance of the machine ($L_s = L - M$) limits the phase currents. The PMSM performance in the presence of a short circuit, which can be written as a matrix:

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

The electromagnetic torque generated by a motor during short-circuit fault in the stator can be calculated using the power conservation principle:

$$C_e = \frac{(e_{as} i_{as} + e_{bs} i_{bs} + e_{cs} i_{cs} - e_f i_f)}{\Omega} \quad (8)$$

II.2 MODEL OF A FAULTY PMSM IN FRAME (α, β)

The concordia transformation is implemented, defined as follows:

$$[T]^t = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & 0 \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} & 0 \\ 0 & 0 & 0 & \sqrt{\frac{3}{2}} \end{bmatrix} \quad (9)$$

The PMSM equations with ITSC fault in the reference frame (α, β) are formulated as follows:

$$\begin{bmatrix} V_{\alpha} \\ V_{\beta} \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 & -R'_{a2} \\ 0 & R_s & 0 \\ -R'_{a2} & 0 & R'_f \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \\ i_f \end{bmatrix} + \begin{bmatrix} L_s & 0 & M_{f\alpha} \\ 0 & L_s & M_{f\beta} \\ M_{f\alpha} & M_{f\beta} & L_{a2} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \\ i_f \end{bmatrix} + \begin{bmatrix} e_{\alpha} \\ e_{\beta} \\ -e_f \end{bmatrix} \quad (10)$$

Where,

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

$$M_{f\alpha} = -\sqrt{\frac{2}{3}} [L_{a2} + M_{a1a2} - (M_{a2b} + M_{a2c})/2] \quad (11)$$

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

III. FFT ANALYSIS OF STATOR FAULT IN PMSM

Fast Fourier transform (FFT) analysis is an important tool for identifying and detecting stator winding faults in PMSMs. When the observed spectrum is compared to a correctly operating motor, any anomalous changes in the amplitude of certain frequency components may indicate an ITSC fault in the stator winding [22], [8]. ITSC faults directly affect individual multiples of the fundamental frequency. These anomalies in the spectrum act as indicators for detecting faults.

IV. DISCRETE WAVELET TRANSFORM (DWT)

Wavelet analysis is a technique based on the time and frequency domains that performs signal decomposition into a collection of oscillatory components as wavelets [23], [24]. The fundamental concept of decomposition involves low-pass and high-pass filtering by down-sampling and up-sampling, respectively. Wavelet decomposition is a hierarchically structured process. The level of decomposition

can be selected according to a specified cutoff frequency [25], [26]. As seen in Figure 2, the forward DWT coefficients are computed by successively filtering the discrete time domain signal $x(n)$ with low-pass $g(n)$ and high-pass $h(n)$ with variations in sampling rates [10].

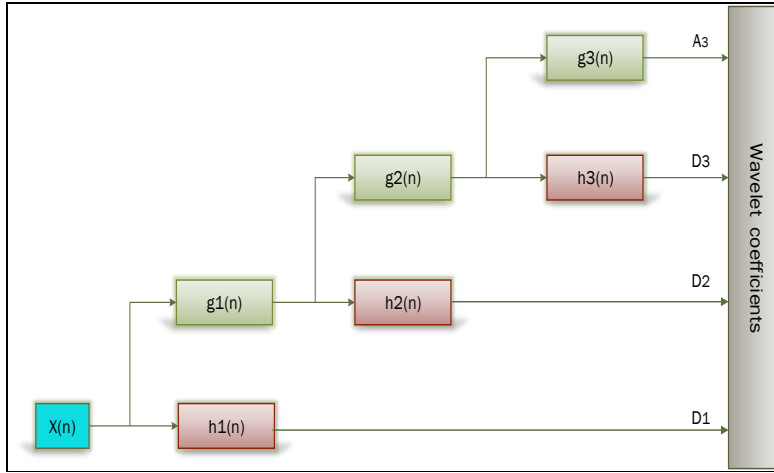


Figure 2: DWT three level decomposition tree.
Source: Authors, (2025).

IV.1 DWT OF STATOR CURRENT ANALYSIS

The stator phase currents are analyzed using the DWT to decompose the signal and extract features indicative of ITSC faults. Daubechies 44 (db44) wavelet is selected as the mother wavelet. The number of decomposition levels is determined by [27]:

$$Ns = int \left(\frac{\log \left(\frac{f}{f_s} \right)}{\log(2)} \right) + 1 \text{ or } 2 \quad (12)$$

This analysis utilized a sampling frequency of $f=10000$ samples/sec, $f_s = 50\text{Hz}$, and commonly employed db44 as the mother wavelet. The frequency bands of wavelet decomposition of the stator current are detailed in Table 1.

Table 1: Frequency bands of wavelet decomposition.

Decomposition details	Frequency bands (Hz)
Detail at level 1 (d1)	[2500-5000]
Detail at level 2 (d2)	[1250-2500]
Detail at level 3 (d3)	[625-1250]
Detail at level 4 (d4)	[312.5-625]
Detail at level 5 (d5)	[156.25-312.5]
Detail at level 6 (d6)	[78.12-156.25]
Detail at level 7 (d7)	[39.06-78.12]
Detail at level 8 (d8)	[19.53-39.06]
Detail at level 9 (d9)	[9.76-19.53]

Source: Authors, (2025).

V. RESULTS AND DISCUSSIONS

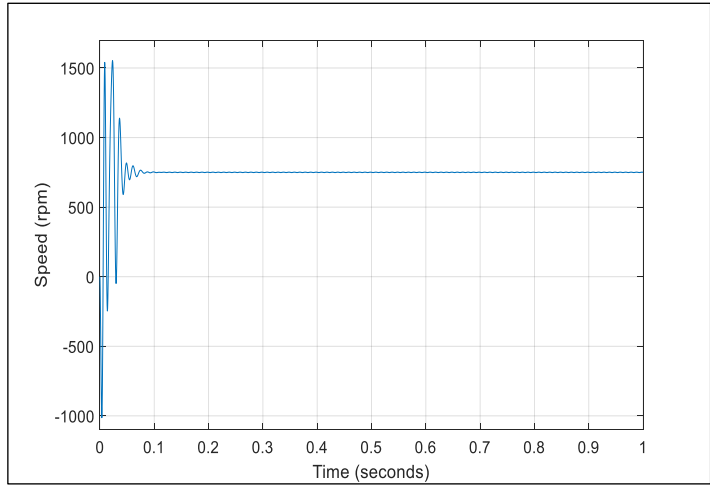
To verify the proposed model and confirm his validity, simulation was used in MATLAB SIMULINK. To study and understand PMSM behavior in the event of faults occurring between the stator coil turns, healthy and faulty operating conditions of the PMSM are simulated. The nominal parameters of simulation for PMSM are included in the table 2.

Table 2: Parameters of the PMSM.

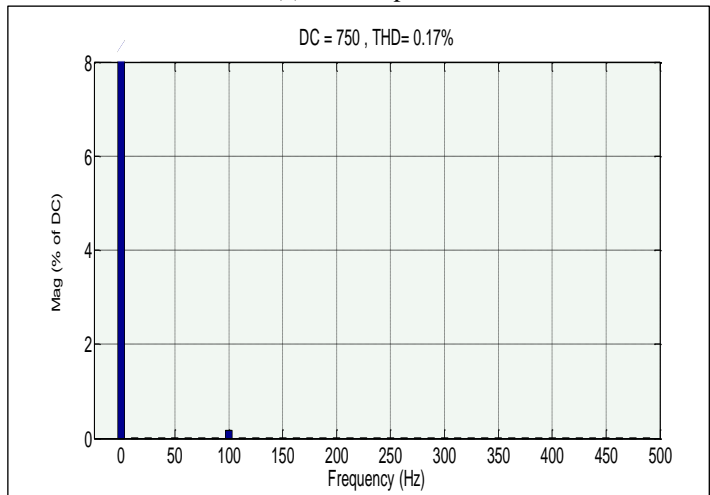
Parameters	Value
Stator Inductance L_s (mH)	2.82
Stator resistance R_s (Ω)	0.44
Number of pole pairs p	4
Moment of inertia J (kg.m ²)	0.0006
Friction coefficient f (N.m.s)	0.007
Magnetic flux Φ (wb)	0.108
Rated current I_n (A)	19
Nominal torque T_n (N.m)	10

Source: Authors, (2025).

Considering that the fault occurs on phase (as) windings and the rest of the phases are intact. The dynamic model with faults is simulated under various values resistance of fault. The simulation is conducted with three fault resistance values $R_f = 0.5 \text{ } (\Omega)$, $1 \text{ } (\Omega)$ and $5 \text{ } (\Omega)$, a fault ratio of $\mu = 0.5$, and a load torque of 10 (Nm) at $(t = 0\text{s})$, with the fault introduced at $(t = 1\text{s})$. In the health status of the PMSM. The figure 3 (a) shown the motor speed where there are distortions only at take-off and then it stabilizes. The figure 3 (b) shown the frequency spectrum for motor speed, the amplitude of the second and fourth harmonics is close to zero. As for the motor faulty condition as shown in Figures 4, 5 and 6, speed distortions appear at the moment of failure. As the fault isolation resistance decreases, the amplitudes of the second harmonic (100 hz) and fourth harmonic (200 hz) components in the motor speed signal increase. This behavior is attributed to higher circulating fault currents, which intensify harmonic distortions within the system.

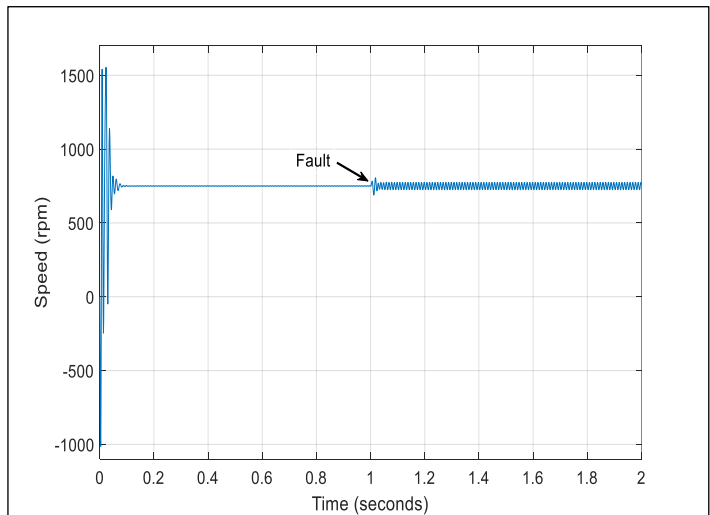


(a) Motor speed

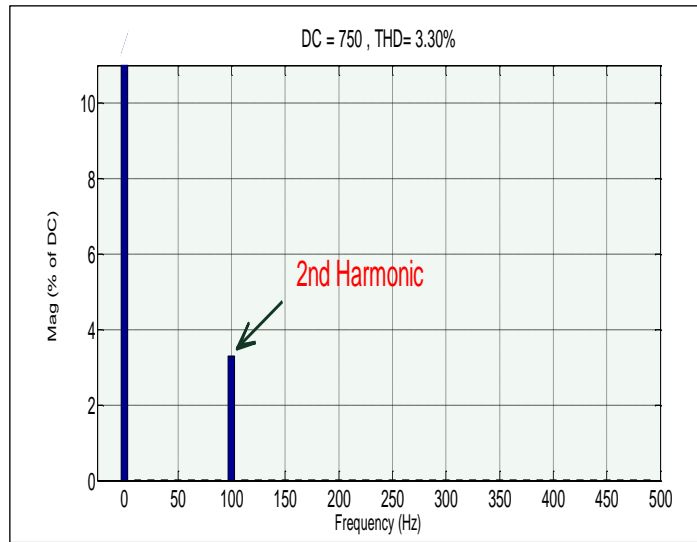


(b) Frequency analysis

Figure 3: Motor speed spectral analysis for healthy PMSM
Source: Authors, (2025).

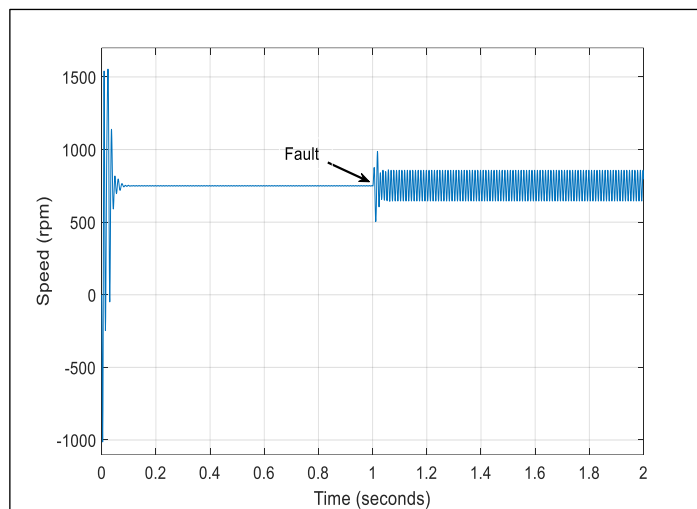


(a) Motor speed

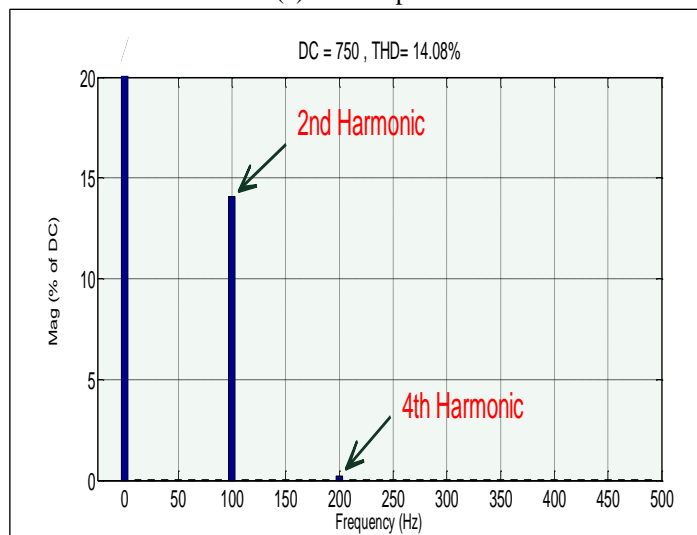


(b) Frequency analysis

Figure 4: Motor speed spectral analysis for faulty PMSM with $R_f=5 \text{ } (\Omega)$.
Source: Authors, (2025).

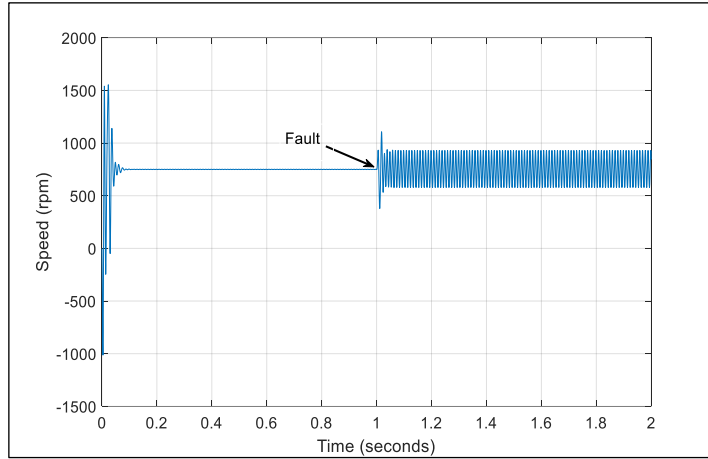


(a) Motor speed

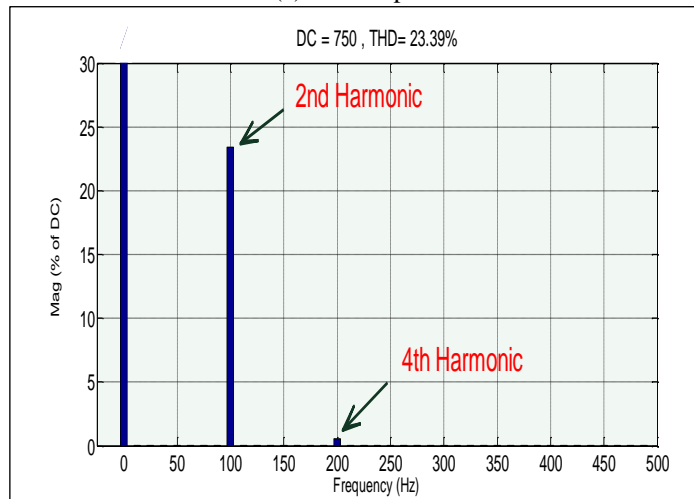


(b) Frequency analysis

Figure 5: Motor speed spectral analysis for faulty PMSM with $R_f=1 \text{ } (\Omega)$.
Source: Authors, (2025).



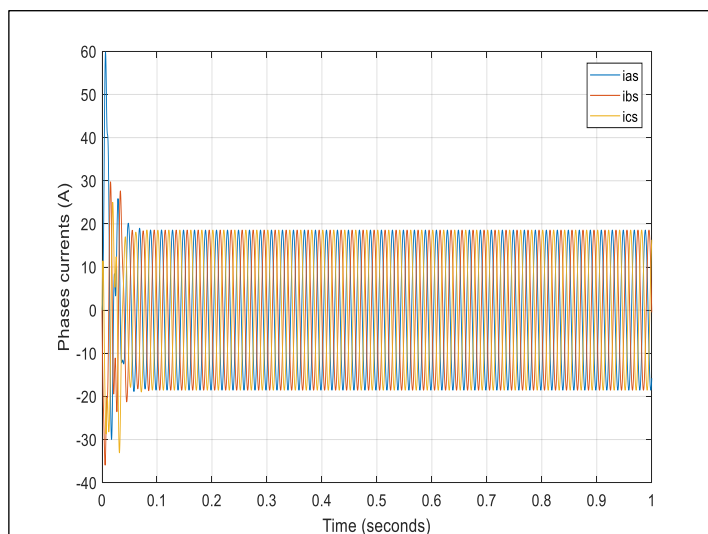
(a) Motor speed



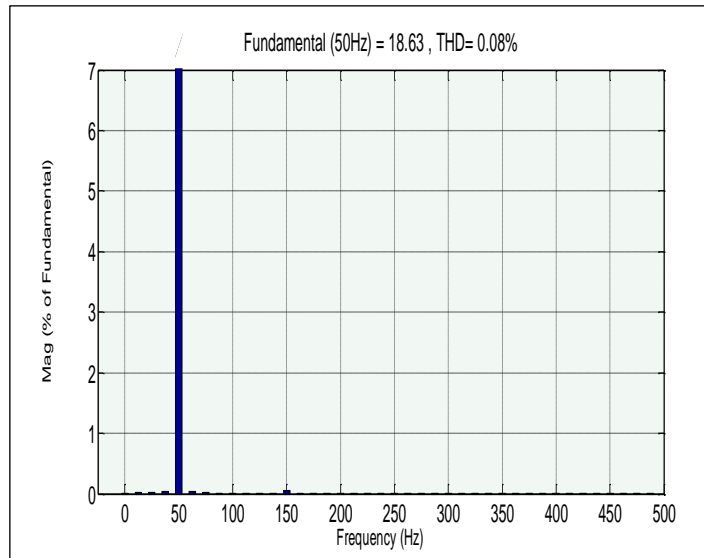
(b) Frequency analysis

Figure 6: Motor speed spectral analysis for faulty PMSM with $R_f=0.5 \text{ } (\Omega)$.
Source: Authors, (2025).

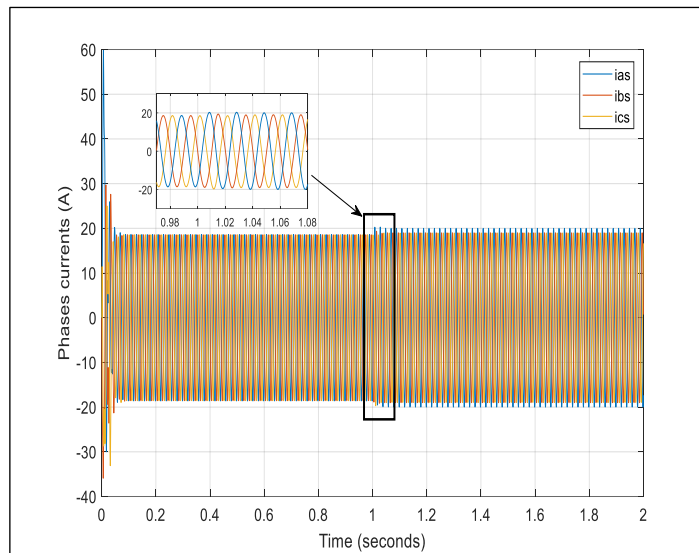
In the next part, a healthy condition as shown in Figure 7, the stator currents are sinusoidal, balanced and equal in amplitude. Figure 7(b) shows the spectrum current phase (as), the third harmonic amplitude is close to zero. The results of simulation for the defective state are displayed in Figures 8, 9, and 10 for fault resistance values of $R_f = 0.5 \text{ } (\Omega)$, $1 \text{ } (\Omega)$ and $5 \text{ } (\Omega)$ respectively. Decreasing fault resistance (R_f) increases fault current (i_f), causing an imbalance in the phases currents, with phase current (a) having a greater amplitude than phase currents (b) and (c). As depicted in the figures, a short circuit leads to the emergence of harmonic frequencies. Specifically, as number of short circuits grows and the fault insulation resistance decreases, the amplitudes of the third and fifth harmonic current signals rise. An analysis of the stator current frequency in the defective phase (as) reveals three distinct peaks, appearing at the fundamental frequency as well as the third (150 hz) and fifth harmonics (250 hz). Detecting these harmonics can indicate a short circuit in the windings.



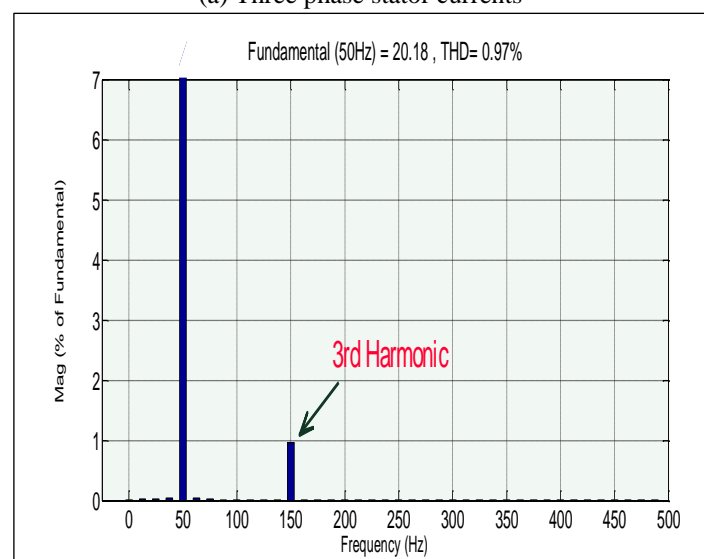
(a) Three phase stator currents



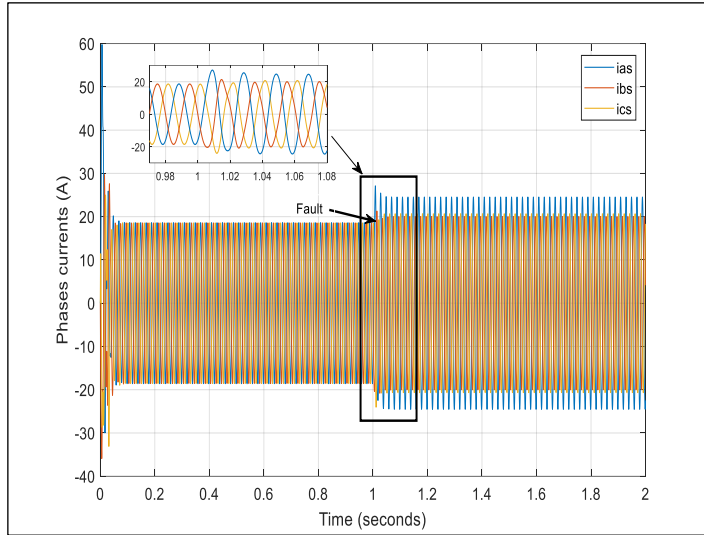
(b) FFT analysis of current phase (as)
 Figure 7: Simulation in healthy PMSM
 Source: Authors, (2025).



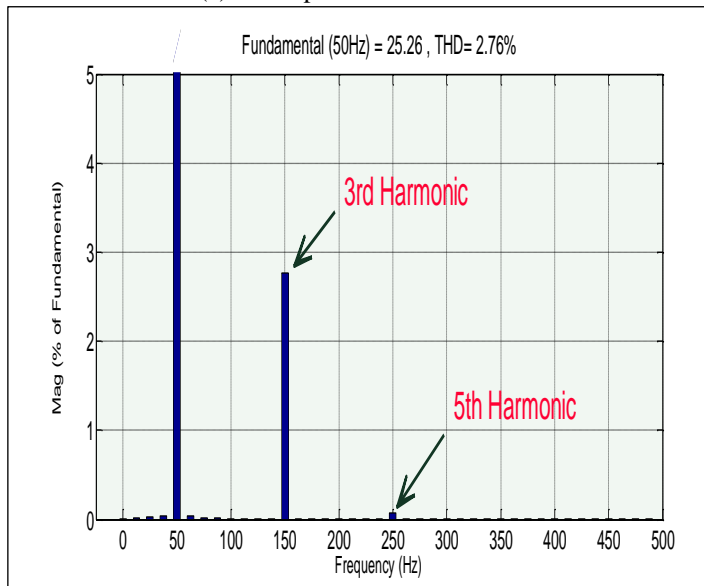
(a) Three phase stator currents



(b) FFT analysis of current phase (as)
 Figure 8: Simulation in faulty PMSM with $R_f=5 \text{ } (\Omega)$.
 Source: Authors, (2025).

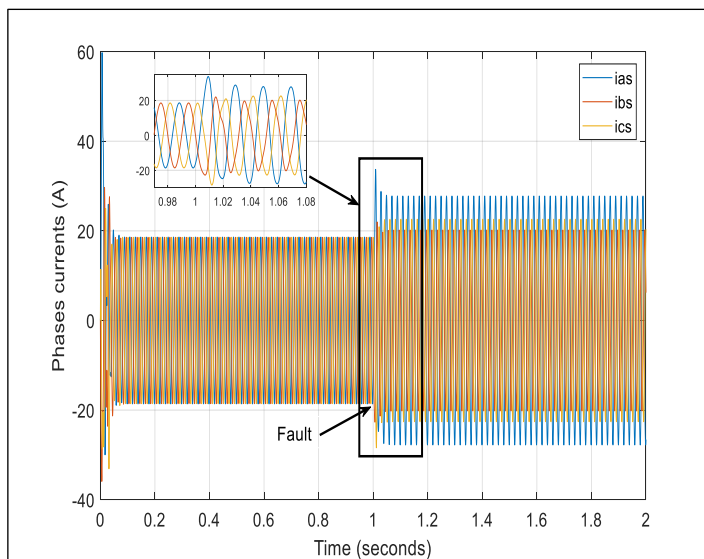


(a) Three phase stator currents

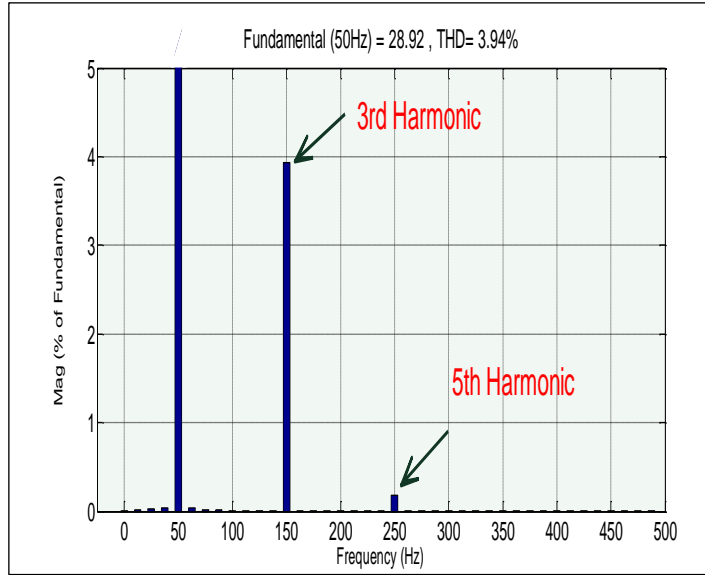


(b) FFT analysis of current phase (as)

Figure 9: Simulation in faulty PMSM with $R_f=1 (\Omega)$.
Source: Authors, (2025).



(a) Three phase stator currents



(b) FFT analysis of current phase (as)

Figure 10: Simulation in faulty PMSM with $R_f=0.5 (\Omega)$
Source: Authors, (2025).

The wavelet analysis technique is employed to examine the stator current under healthy and faulty conditions of the PMSM, as shown in figures 11 (healthy condition), 12, 13, and 14 (faulty conditions). The Daubechies (44) mother wave is used to compute the wavelet coefficients, showing suitable and effective diagnosis results. High-frequency detail levels do not furnish relevant information regarding the original signal, so it indicates that low-frequency components provide us advantage for detecting faults and distortions. From the simulation results, amplitudes increase in wave details at levels 5, 6 and 7 at the moment of fault occurrence because they include both the fundamental frequency range and frequencies caused by ITSC faults. This is most evident in the wave details at level 7 (39.06-78.12), which corresponds to the fundamental frequency of the motor. On the other hand, it appears in the wave details at level 6 (78.12-156.25), which corresponds to the third frequency harmonic, as well as in the wave details at level 5 (156.25-312.5), which matches the fifth frequency harmonic. The signal showed larger amplitudes when the fault occurred at these levels compared to the other frequency ranges. Therefore, the wave details of these levels can be useful for detecting this type of fault.

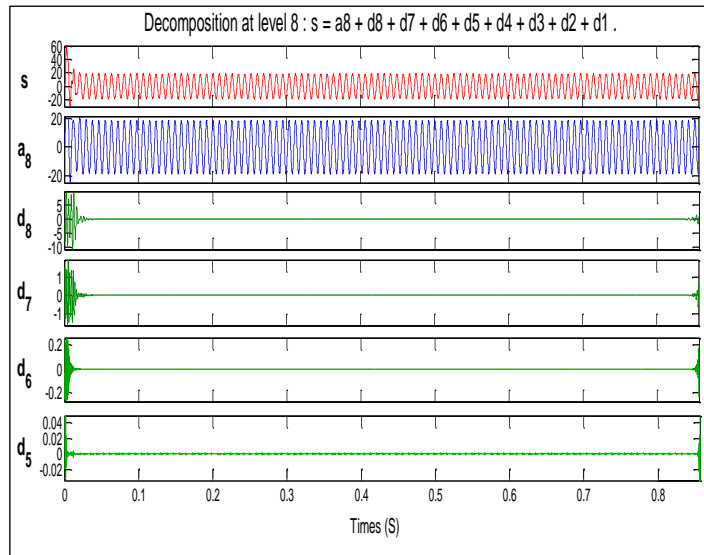


Figure 11: DWT analysis in healthy PMSM.
Source: Authors, (2025).

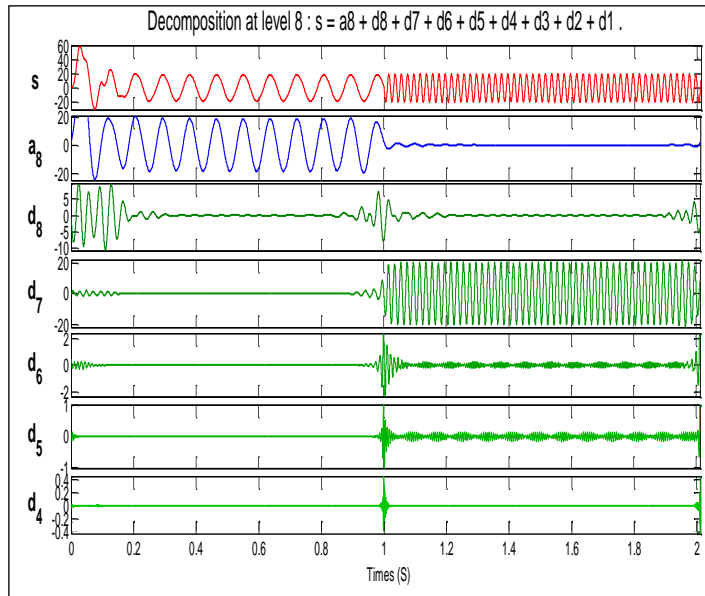


Figure 12: DWT analysis in faulty PMSM with $R_f=5$ (Ω).
Source: Authors, (2025).

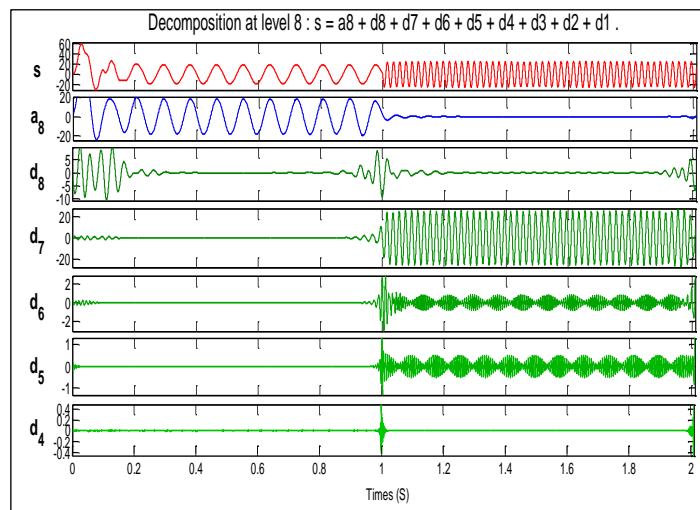


Figure 13: DWT analysis in faulty PMSM with $R_f=1$ (Ω).
Source: Authors, (2025).

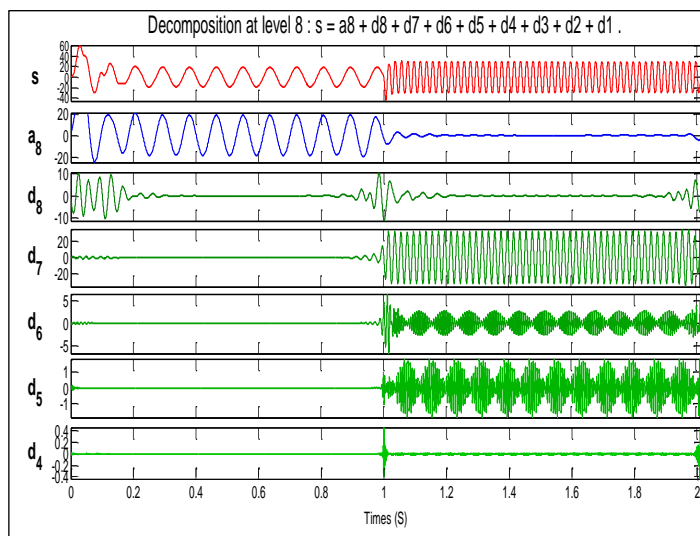


Figure 14: DWT analysis in faulty PMSM with $R_f=0.5$ (Ω).
Source: Authors, (2025).

V. CONCLUSIONS

Accurate modeling of PMSM in fault conditions is essential for fault diagnosis and understanding of their behavior. In this study, mathematical models of PMSM in healthy and faulty conditions under ITSC faults in stator winding were established. To mitigate and reduce the risk of stator winding damage and to detect faults, FFT technique was applied to analyze the frequency spectrum of stator current and motor speed in the healthy state and under different fault severity conditions, enabling the detection of harmonic distortions caused by faults. This technique has proven effective in signal processing for stationary faults conditions. The THD value can serve as a fault detection indicator. However, FFT is unable to predict and determine the timing of fault occurrence. To overcome this issue, discrete wavelet transform was applied to analyze the motor signals into different frequency ranges. This technique provided us with an effective solution for signal processing under non-stationary faults conditions, where time-frequency analysis provides a more effective diagnostic approach than frequency analysis. This work provides a powerful solution for real-time fault monitoring in PMSM, which leads to improve predictive maintenance and reduce operational downtime.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

Methodology: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

Investigation: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

Discussion of results: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

Writing – Original Draft: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

Writing – Review and Editing: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

Resources: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

Supervision: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

Approval of the final text: Abdelmoumin Ouali, Djalal Eddine Khodja, Hassina Megherbi and Ibrahim Chouidira.

VII. REFERENCES

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