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Computer Simulation of PMSM Motor with Five Phase Inverter Control using Signal Processing Techniques

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ABSTRACT

The signal processing techniques and computer simulation play an important role in the fault diagnosis and tolerance of all types of machines in the first step of design. Permanent magnet synchronous motor (PMSM) and five phase inverter with sine wave pulse width modulation (SPWM) strategy is developed. The PMSM speed is controlled by vector control. In this work, a fault tolerant control (FTC) system in the PMSM using wavelet switching is introduced. The feature extraction property of wavelet analysis used the error as obtained by the wavelet de-noised signal as input to the mechanism unit to decide the healthy system. The diagnosis algorithm, which depends on both wavelet and vector control to generate PWM as current based manage any parameter variation. An open-end phase PMSM has a larger range of speed regulation than normal PMSM. Simulation results confirm the validity and effectiveness of the switching strategy.

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1. INTRODUCTION

Nowadays, the energy and maintenance saving in the large-scale AC motor drive systems are very crucial requirement to modify machines to electric-powered for improve their performance. Multi-phase inverter drive is used for driving a large-scale motor as well as the other types of motors [1]. In the past few years, the conventional IMs has been replaced by PMSMs in spite their cost is relatively higher. PMSMs are popular in industry with advanced performance due to the high precision torque, lower maintenance cost such as in electric traction, steel mill ,military weapons, elevators, electric machines, servo systems, and hybrid vehicle [2].Multi-winding motors can be used with all types of control techniques either closed loop or open-loop control such as direct torque control (DTC), volt to frequency (V/f) control and vector control particularly with PMSM motors [3]. In the literature many research works on multiphase motors fault conditions such as in [4]. Signal processing techniques is used to detect the faults of PMSM control system [5]. In [6], current control is imposed to minimize the torque ripple in the five-phase segment motor when one phase get opened. Feedback current control, uses a sum of current of inverter phases to calculate the information to control the system faults with single or multi controllers. Fault tolerant studies presented different topologies to have sufficient operation of any given faulty system and increasing the reliability [7].Control schemes of open windings (OW) PMSM and inverters to optimize the motor's working range and efficiency is introduced in [8]. A fault tolerant control strategy for a single open phase fault (OPF) in a three-phase PMSM improved in [9]. A wavelet can be defined as a waveform of limited period that has zero average value [10]. The fault diagnosis task is to locate and identify the fault in the closed loop system model meanwhile FTC which is to obtain satisfactory operation and recover from the specific faults. Neural network combination with adaptive filter as one kind of the signal processing in the fault diagnosis sensorless control scheme is introduced in [11]. Digital signal processing with highly advanced chip to design a PMSM digital controller introduced in [12].

The sensors, electronic components of machine drives and the environment faults such as wires and connectors are the main types of system faults. Wavelet vector control PMSM motor drives analysis and feature extraction in FTC and signal processing combination with different degree of open circuit failure introduced in [13]. In high voltage high power energy control, the Multilevel inverter uses as an important alternative technology due to its less blocking voltage requirement of semiconductor power devices,THD and voltage insulation [14]. Power semiconductor is the most weakness devices in industrial applications [15]. PMSMs faults can be divided into two main parts, electrical faults and mechanical faults. Open and short stator winding short turn faults are common in electrical part and it is caused by the combination of various stresses acting on the stator, such as thermal, electrical, mechanical, and environmental stresses [16].

The of multiphase machines development specially five-phase, offers improved performance to realize sinusoidal input current and unity power factor [17].The main topologies of multilevel inverters are diode clamped or neutral point clamped multilevel inverter, DC link voltage stable adopt inverter one approach the multilevel inverter three-level neutral point clamped (3LNPC) capacitor clamped or flying capacitor multilevel inverter and cascaded H-bridge multilevel inverter [18]. Sensorless vector control strategy for the PMSM drive operating at low switching frequency with programmed PWM methods introduced in [19].

The multilevel inverter with discrete wavelet based fault diagnosis is explained in [20], [21]. PMSM motor multiple faults Identifying in with vector control method based on the wavelet and complex wavelet feature enhancements used in [22]. The singular value vectors is obtained using the output voltage waveforms of the faulty inverter through a decomposing of discrete orthogonal wavelet transform [23].

The safety, costs and condition monitoring equipment is the main considerations in any fault diagnosis [24]. The voltage current topology is used to diagnose the open circuit fault in the NPC three levels converter [25]. Wavelet packet transform (WPT) to diagnose a faulty inverter, sliding mode observer, expert systems, fuzzy logic and artificial intelligence proposed in [26]. Discrete wavelet transform (DWT) second harmonic component analysis used in the voltage source inverter circuit and stator fault diagnosis [27]. The multilevel converters offers a wide range of FTC options due to the inherent redundancies and modularity of such a topology [28].

The main contribution of this paper is, increase the reliability of the PMSM closed loop control system, introduce new FTWT combined with vector control strategy through smooth switching technique.

The structure of this paper follows: PMSM motor mathematical model in Section 2, vector control techniques is given in Section 3, in Section 4, the characteristic of the SPWM converter is obtained, the proposed signal processing techniques is given in Section 5, comparative study in Section 6. Finally, Section 7 gives a conclusions about this study.

2. PMSM MOTOR MATHEMATICAL MODEL

Interest in Multi-phase motor drives get a highly interest during last decade. PMSM are becoming attractive in many industrial applications due to their smooth output response, reliability, higher efficiency, lower torque pulsations at higher frequencies and power density. The main components of the electrical drives can be shown as in the Figure 1.

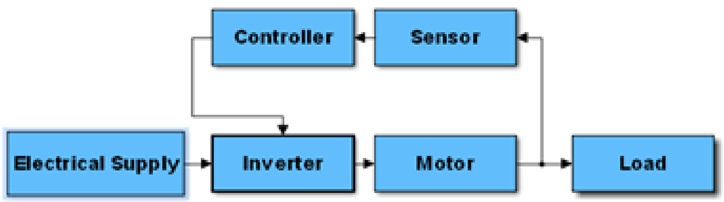

Figure 1. Main components of electrical drives

In the implementation of the five-phase PMSM machine, the stator windings are connected in wye to an internal neutral point. The five-phase machine has a sinusoidal back EMF waveform and round rotor. Mathematical model of PMSM describe in this paper is based on following assumptions [29].

a. No core saturation and
b. The winding leakage inductance can be ignored
c. Pure sine wave in air gap and the higher harmonic can be negligible.

The stator voltage equation can be written as;

$$v_s = i_s R_s + \frac{d\lambda_s}{dt} \tag{1}$$

The air gap flux linkages

$$\lambda_s = \lambda_{ss} + \lambda_m \tag{2}$$

$$\lambda_{ss} = L_{ss} i_s \tag{3}$$

Lss, λm, Rs, is, λs is the stator inductance matrix, the flux linkage matrix ,stator resistance matrix, current matrix, flux linkages matrix respectively. The stator currents are:

$$\left[i_s\right] = \left[i_{as} \quad i_{bs} \quad i_{cs} \quad i_{ds} \quad i_{es}\right]^T \tag{4}$$

The self and mutual inductances are assumed to have same value for all the phases as in (5).

$$\left[i_s\right] = \left[i_{as} \quad i_{bs} \quad i_{cs} \quad i_{ds} \quad i_{es}\right]^T \quad (4)$$

The self and mutual inductances are assumed to have same value for all the phases as in (5).

$$\begin{aligned} L_{aa} = L_{bb} = L_{cc} = L_{dd} = L_{ee} \\ L_{ab} = L_{bc} = L_{cd} = L_{de} \end{aligned} \tag{5}$$

The phase variables of the PMSM motor are transformed into a reference frame. This just simplify the PMSM model. The transformation matrix for this system is given by the following matrix [14].

$$A = \sqrt{2/5} * \begin{bmatrix} \cos\theta_s & \cos(\theta_s - \alpha) & \cos(\theta_s - 2\alpha) & \cos(\theta_s + 2\alpha) & \cos(\theta_s + \alpha) \\ -\sin\theta_s & -\sin(\theta_s - \alpha) & -\sin(\theta_s - 2\alpha) & -\sin(\theta_s + 2\alpha) & -\sin(\theta_s + \alpha) \\ 1 & \cos 2\alpha & \cos 4\alpha & \cos 4\alpha & \cos 2\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha & -\sin 4\alpha & -\sin 2\alpha \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{6}$$

By applying this transformation to the stator voltages and flux presented in (1) and (2) and taking the values of (θs= 0&α=2π/5) in this transformation, the following equations are obtained:

$$v_{ds} = R_s i_{ds} - \omega\lambda_{qs} + p\lambda_{ds} \tag{7}$$

$$v_{qs} = R_s i_{qs} - \omega\lambda_{ds} + p\lambda_{qs} \tag{8}$$

$$\lambda_{ds} = \left(L_{ls} + L_m\right) i_{ds} + \lambda_m \tag{9}$$

$$\lambda_{ds} = \left(L_{ls} + L_m\right) i_{qs} \tag{10}$$

Substituting the values from Equations (7)-(10), the following matrix is obtained:

$$A = \sqrt{2/5}\sqrt{a^2 + b^2} \begin{bmatrix} R_s + L_q P & \omega L_d & 0 & 0 & 0 \\ -\omega L_q & R_s + L_d P & 0 & 0 & 0 \\ 1 & 0 & R_s + L_{ls} & 0 & 0 \\ 0 & 0 & 0 & R_s + L_{ls} & 0 \\ 0 & 0 & 0 & 0 & R_s + L_{ls} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_x \\ i_y \\ i_0 \end{bmatrix} + \begin{bmatrix} \omega \lambda_m \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{11}$$

The output torque T can be expressed as:

$$\mathrm{T} = \frac{5}{2}\frac{P}{2}\left[\lambda_{\mathrm{m}} i_{qs}\right] \tag{12}$$

$$T = \frac{5\mathrm{P}}{4}\left[\lambda_{ds}\mathrm{i}_{\mathrm{qs}} - \lambda_{\mathrm{qs}} i_{ds}\right] \tag{13}$$

Simulink implementation of PMSM electrical part can be shown as in Figure 2.

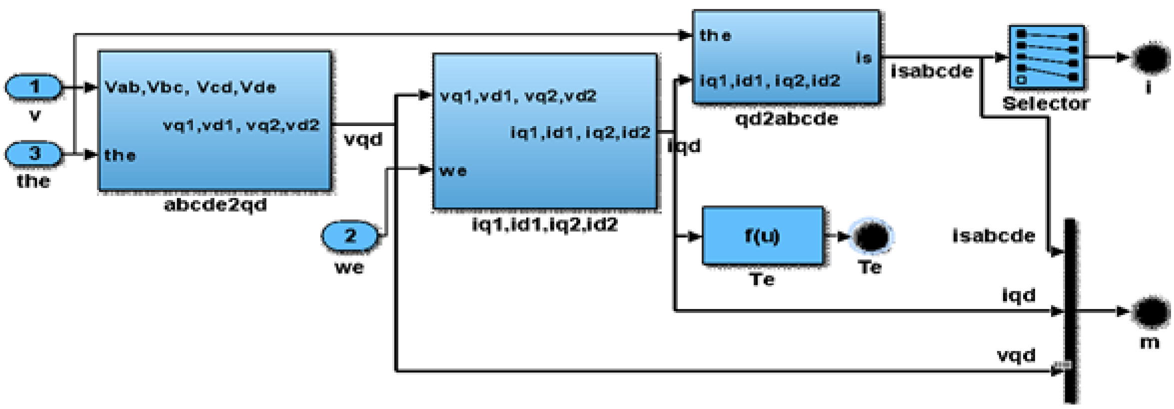

Figure 2. Electrical part of the PMSM

The mechanical part of the PMSM can be drived from the torque Te which is a function of the stator fluxes and currents. As in the electrical part, the mechanical part of the PMSM can be shown as in Figure 3.

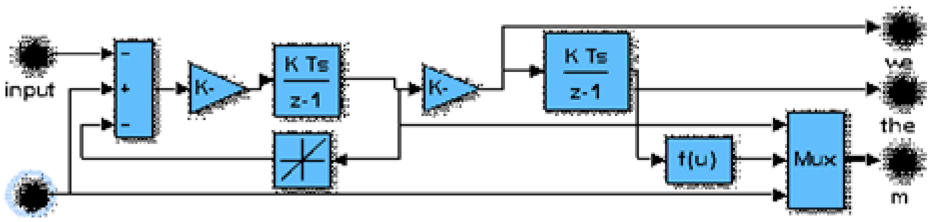

Figure 3. Mechanical part of the PMSM

The ploynimail faulty and healthy modes of the control system are implemented by Identification Matlab toolbox.

3. VECTOR CONTROL TECHNIQUE

Vector control in industrial applications are very popular. The basic principles of vector control, with the help of the phasor diagram is shown in Figure 4 [30].In order to control the output torque of the machines,the vector control isolates linear and nonlinear PMSM flux and torque undividauly and operates as a separately excited DC machine. The three phase voltage and current are converted to two phase wire d and q axis. Synchronization with the d-q frame rotating rotor magnetic flux vectors [31].

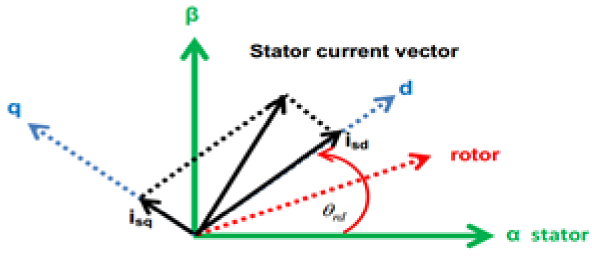

Figure 4. Stationary reference of vector control

This making PMSM to work as a high-performance during all the operating area.The Simulink unit of vector control to produce control gates for the five phase inverter can be shown in Figure 5.

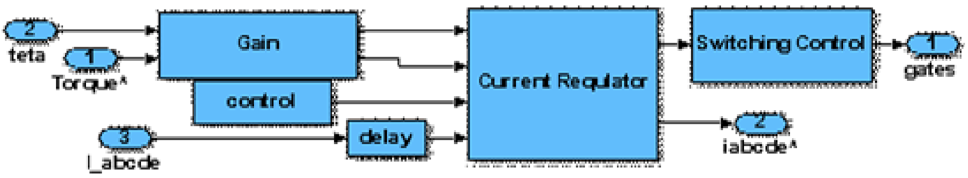

Figure 5. Vector control simulink implementation

The decoupled control of torque and flux, the higher efficiency for each operation point in a wide speed range, and the better dynamic behavior are the main advantages of the vector control.

4. SPWM INVERTER

The three-phase conventional sine wave PWM is easier in implementation compare to any other topology [35], produces a lower amount of heat during the period of switching, consumes less power and operate with higher frequencies. In this paper five phase ten switch inverters are used in five phase voltage source inverter (VSI) [32]. Many researches have been investigating VSI and CSI types of faults inverters. The output waveform and reduce harmonic distortion is very important to improve the inverters. In multilevel inverters, the cost, size, complexity of control scheme and reliability are depends on the number of devices needed [33]. Multilevel inverters with the number of switches needed for each configuration can be shown in Table 1.

Table 1. Multilevel Inverters with the Number Needed

	Diode clamp	Flying capacitor	cascaded
Main switching devices	(N-1)*2	(N-1)*2	(N-1)*2
Main diodes	(N-1)*2	(N-1)*2	(N-1)*2
Clamping diodes	(N-1)*(N-2)	0	0
DC bus capacitors	(N-1)	(N-1)	(N-1)/2
Balancing capacitors	0	[(N-1)*(N-2)]/2	0

The Space Vector Pulse Width Modulation (SVPWM) makes the motor drives more reliable in terms of system parameters. This method generates less Total Harmonic Distortion (THD) in the output voltages and currents, which provides more efficient use of the DC supply voltage (90.7%) in comparison to sinusoidal PWM techniques [34]. Though it has higher utilization and efficiency, the application of SVPWM is limited in five-phase system, as it needs to control 32 switching states. The sinusoidal pulse width modulation (SPWM) and its control circuit shown in Figure 6.

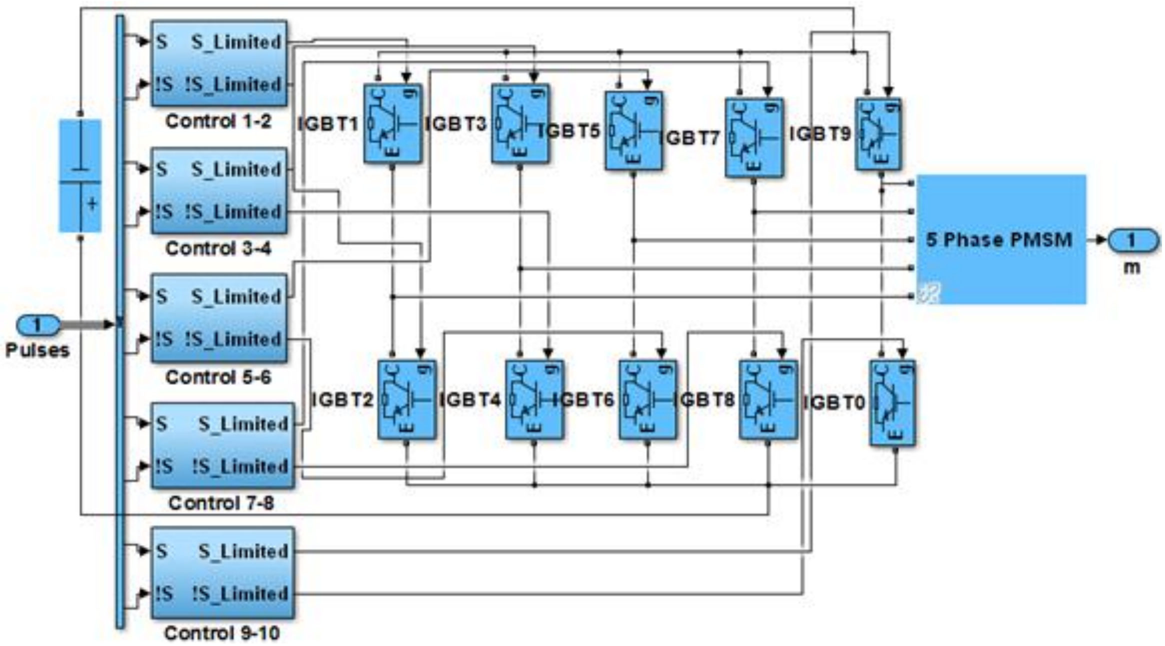

Figure 6. SPWM inverter complete circuit

In [36], [37], the efficiency of SPWM was measured and estimated to prove a lower DC link voltage utilization. In this study, a five phase PMSM motor is being considered to extend the operational range of SPWM for a five-phase inverter and maintain a sufficient output response during the occurrence of faults.

5. SIGNAL PROCESSING TECHNIQUES

Signal processing and intelligent systems have gained importance in many tasks, such as fault location and estimation, load estimations, reactive power compensation, the risk of blackouts. HVDC systems for many application with a fast, accurate and reliable protection algorithms have a major interest[38].The wavelet used signal processing system objects such as the dyadic analysis filter bank and dyadic synthesis filter bank to de-noise a noisy signal using soft thresholds.

The Discrete Wavelet Transform (DWT) decompose the signals at numerous scales of time and frequency resolution. DLPF with impulse response begins with DWT, pass the discrete original noisy signal signal, wavelet coefficients, output response through filter with impulse response.

The residue signal displays the error between the original and de-noised signal and can be used for the switching mechanism between the healthy and faulty PMSM control system. Several signal processing mathematical techniques such as small signal state space averaging, Fourier technique, time domain methods, short time Fourier transform (STFT), is used to analyse the performance of switching power converters. The finite energy is the most powerful tool in signal time-wavelet frequency characteristics.

The admissibility and regularity condition are important properties of the wavelet as can be expressed in the following formula [39].

$$\int \frac{|\psi(\omega)|^2}{|\omega|} d\omega < +\infty \quad (14)$$

ψ (ω) is used to perform the signal with Fourier transform using the wavelet function. The losing function of the information can checked in (15).

$$|\psi(\omega)|^2 = 0 \tag{15}$$

The wavelet can be used in many applications such as a compression signal processing, image analysis, statistics, nonlinear dynamic process modelling. It also has wide range of applications in electrical engineering fields such as measurement of harmonics in power lines under non-steady state conditions, disturbance evaluation, de-noising in signal processing, fast transient analysis like lightening induced disturbances, fault identification & diagnostics in electrical machine, electronic issues of power harmonic analysis of switching power supply noise.

The detection of the any faulty signal can be either through switching measurement or output waveform analysis [40].

The wavelet transform by using a 3-level wavelet db10 depending on a positive level, signals of PMSM motor are analysed with the above type of wavelet.

Simulink implementation of the noise reconstruction and noise reduction wavelet to generate the failures symptom can be shown in Figure 7 and Figure 8 respectively.

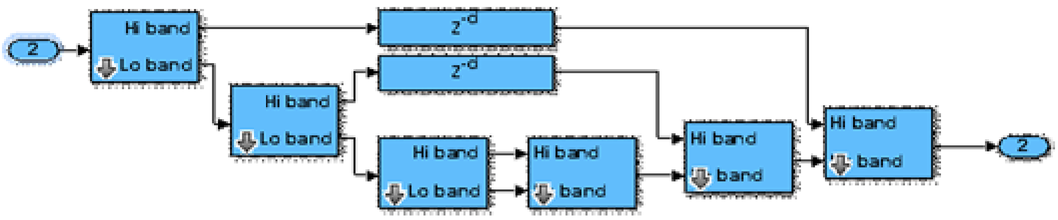

Figure 7. Noise reconstruction wavelet unit

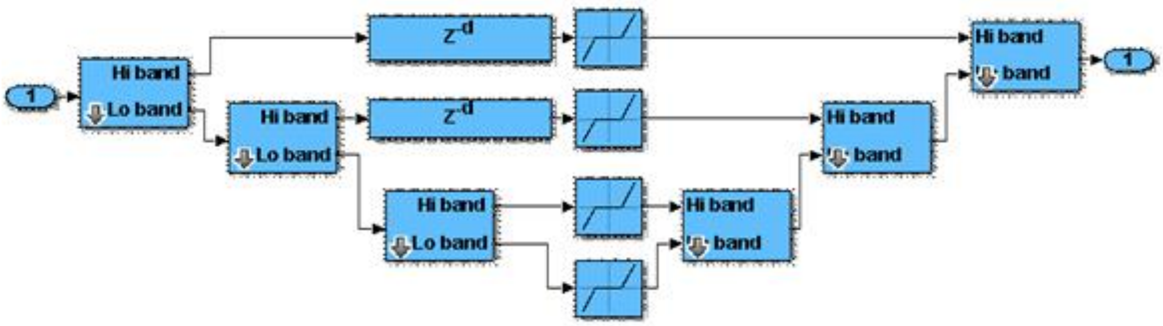

Figure 8. Noise reduction wavelet unit

The discrete wavelet transforms is used for the feature extraction system. The discretized mother wavelet function can be defined as:

$$\psi_{m,n}(t) = a_0^{-m/2}\psi\left(\frac{t - nb_0 a_0^{m}}{a_0^{m}}\right) \tag{16}$$

The corresponding DWT can be defined:

$$\mathrm{DWT}_{\psi}\,\mathrm{x(m,n)} = \int_{-\infty}^{\infty}\left(x(t)\psi^{*}_{m,n}(t)dt\right) \tag{17}$$

Where, a0 and b0 are the fixed constants with: a0>1,b0>0, (m, n ∈ N). Here N is the set of positive integers [36].

During a fault condition inverter multiple level current signal is known from the DWT fault value output time and frequency in time and frequency. The dependence of the flux and torque of the motor speed is used as a basis to detect faults.

d3 detailed decomposition is the information about the current state of the stator can be derived from the frequency and high pass filter.

The best wavelet decomposition levels can be obtained according to the following criteria:

$$W_{decomp} = \frac{\log(fs / f)}{\log(2)} \pm 1 \tag{18}$$

Where *f*s is the sampling frequency and *f* is the nominal frequency.

The wavelet high pass and low pass filters coefficient in both decompostion and recontructed stages are illustrated as in Figure 9.

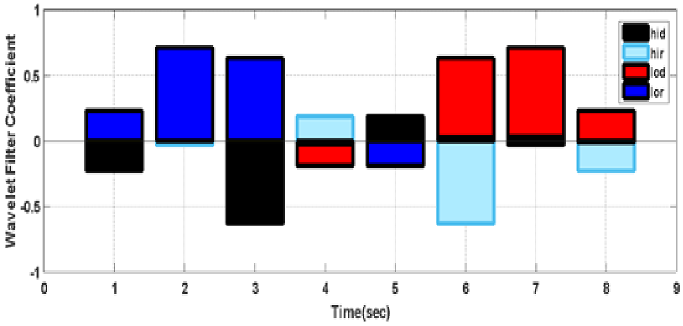

Figure 9. Wavelet Coefficient of high and low pass filters

6. COMPARTIVE STUDY

MATLAB/ Simulink is used to model all the individual units of the PMSM closed control system. A five-phase motor rated 4.4 kW fed by a SPWM inverter shown in Figure 10. The SPWM inverter outputs goes through controlled voltage source blocks before being applied to the PMSM block's stator windings. The load torque applied to machine's shaft is fixed to 12 N.m.

Two control loops are used, the first one is the inner loop to regulate the motor's stator currents. This is faster than the second speed control loop by ten times.

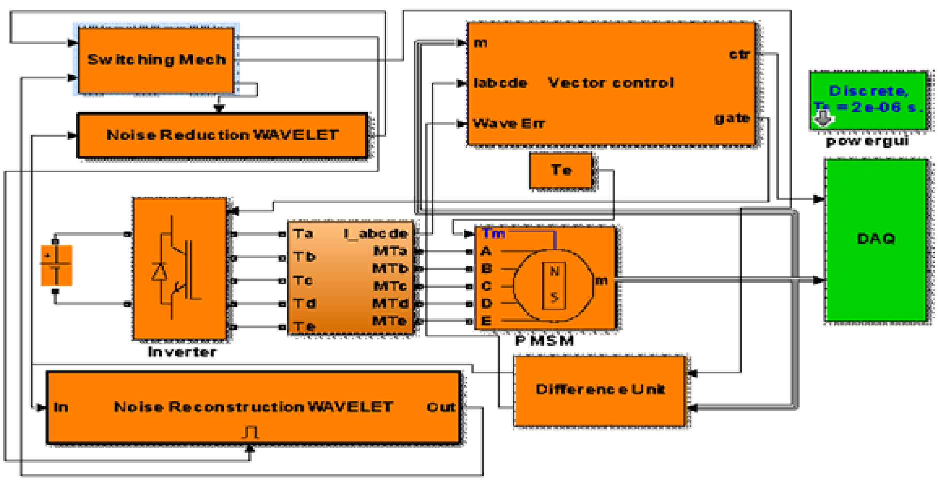

Figure 10. Simulink proposed circuit

The proposed comparative study is based on the following procedure:

6.1. Healthy case

The five-phase PMSM control performances in healthy conditions are shown in Figure 11 to Figure 13, respectively illustrating the PMSM currents, the rotor speed and motor torque. Smooth operation in all the three figures proves the healthy operation.

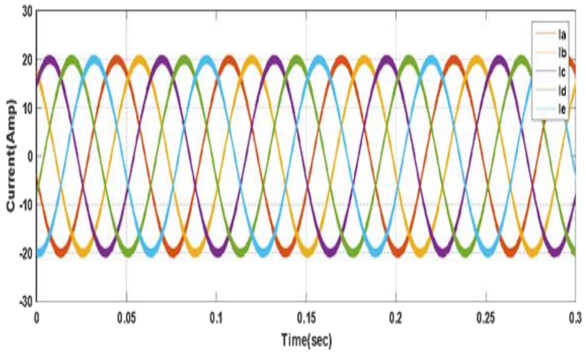

Figure 11. PMSM healthy current

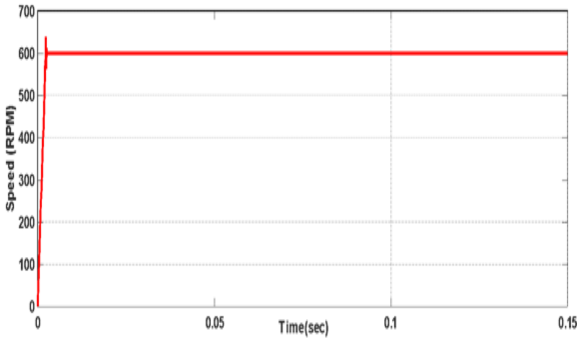

Figure 12. PMSM healthy speed

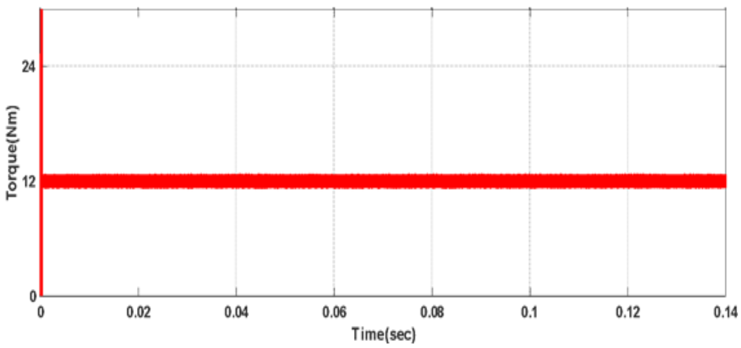

Figure 13. PMSM healthy Torque

6.2. Faulty Case without Proposed Algorithm

The operation of machine is tested under faulty condition. The open fault of one phase is introduced at 0.7 sec. Initially speed was set to 600 rpm until the occurrence of the fault. Reduction of operation speed is acceptable until the second fault at 3 sec. the speed decreased to 200 rpm with large ripple as can be shown in Figure 14.

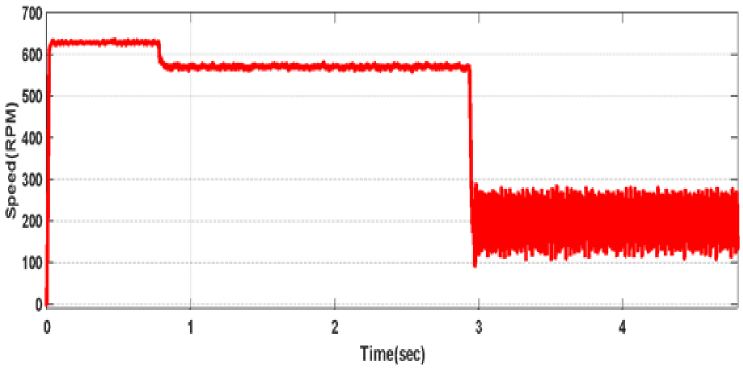

Figure 14. Actual speed PMSM faulty

The correspondent current waveform can be shown in Figure 15. We can see a large spikes of current during non-steady state modes.

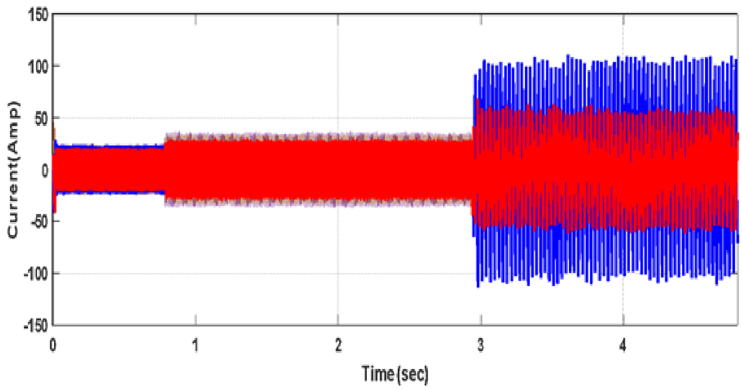

Figure 15. PMSM current under the system variation parameter

6.3. Faulty case with proposed algorithm

The proposed algorithm is tested with lose one and two phases at a time. Figure 16 illustrate Iabcde current waveform which is non-sinusoidal in the beginning due to open fault at observed that waveform amplitude is decreased during less load value.

Variation of amplitude indicates that for more torque more current is needed. In this situation, the currents in other phases get distorted which reduces the output torque. Figure 17 shows the torque at two-phase open faults and reference torque is changed between (12,-12) Nm.

It was observed that the torque at single phase open fault improved. The output torque can be maximized under fault condition by modifying the magnitudes and phases in the remaining phase currents.

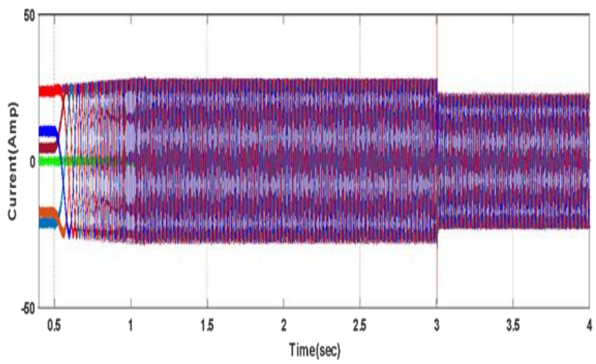

Figure 16. Reference and actual speed

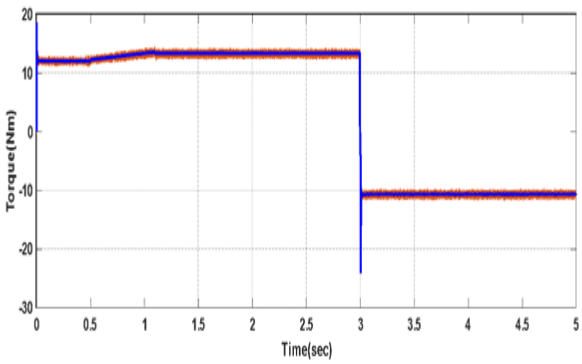

Figure 17. Torque actual and reference

The speed is gradually increased during the fault periods (0.5 and 3) sec and high torque needed until stability obtained as can be shown in Figure 18.

Apart from these large spikes, torque is kept constant at input load value of 12 Nm in steady states and flow the reference directly. Indeed, the torque remains quiet smooth.

The dq component of current is shown in Figure 19, its d- component is almost remain at zero as commanded throughout the graph.

But some distortion can be seen in the non-stable regions due to sudden introduce of a fault at 3 sec.

This algorithm can be activated in the system based on the type of fault. Wavelet decomposition of db10 with three levels during smooth switching operation between fault to healthy mode can be shown in Figure 20.

To get the gain margin and phase margin, the bode plot of the model process is shown in Figure 21.

The values of gain margin and phase margin which are below shows the stability of the system consideration due to their positive signs.

[GM=+2.2108e+08, PM=+93.9196]

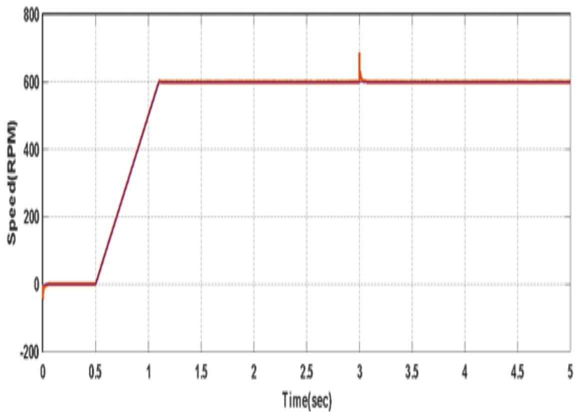

Figure 18. Reference and actual speed

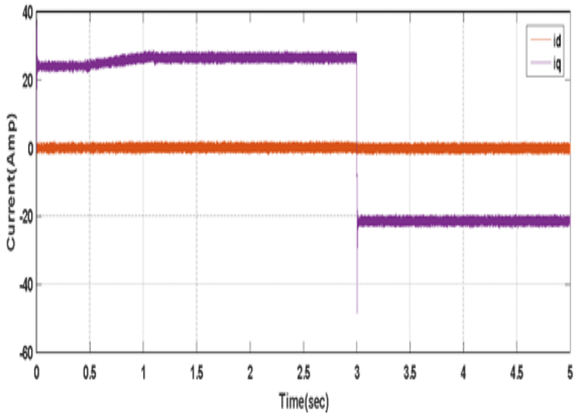

Figure 19. id and iq current components during proposed method

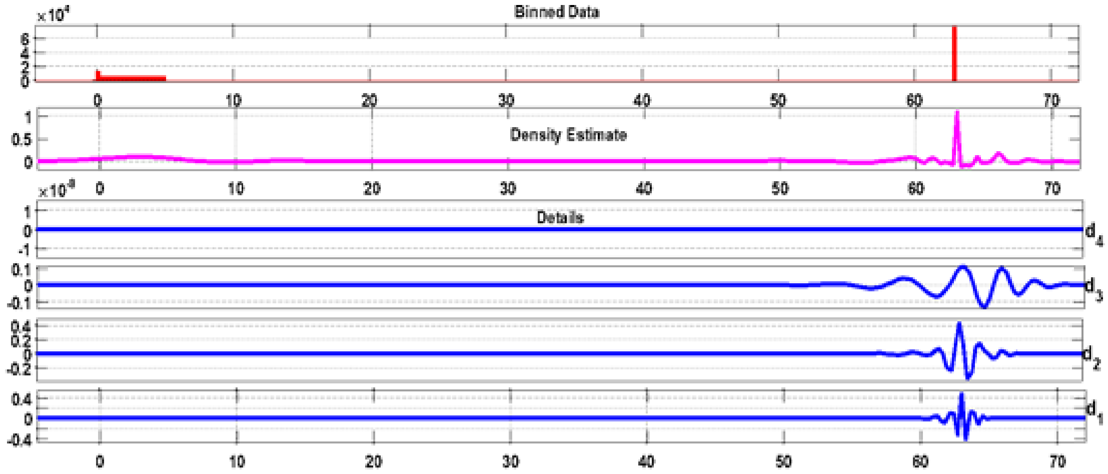

Figure 20. Wavelet decomposition during switching operation

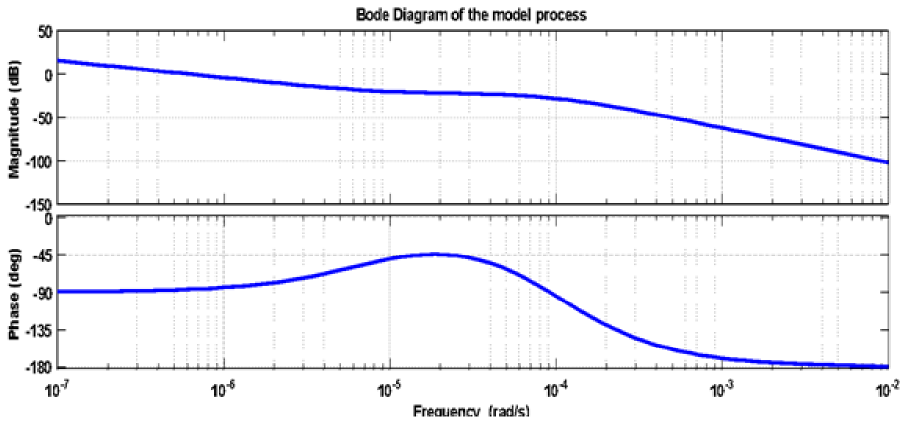

Figure 21. Bode plot of the Final process model

The final process healthy model transfer function can be found using Matlab/Simulink identification toolbox.

$$G(s) = \frac{6.4571\text{e-}07(1\text{-}125851.9673s)}{s(1+0.001069s)(1+10000s)^2} \tag{19}$$

7. CONCLUSION

Signal processing fast and low cost new algorithm for open phase FTC wavelet based in SPWM feeding five phase PMSM was proposed in this paper. The measurement of the output inverter currents that are already available for a closed-loop control of the electric drive is only needed.

The achievements of a reconfiguration for sufficient of PMSM motor operation, and avoid the propagation of the fault in the other parts are the most important finding in this paper.

The new wavelet based FTC approach is derived from the operating characteristics of the five-phase PMSM under one and two open phase faults. The switching between the vector control and the wavelet show the validity and the feasibility of the proposed method

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