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Authors: **BOUCHAREB CHOUROUK, NAIT-SAID MOHAMED-SAID ,LAHMER FETHI**
Affiliations:
Department of Electrical Engineering, Batna University, Laboratory LSPIE' Batna 2000
Training Institute of Electricity and Gas, Aïn M'lila, Algeria
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Laboratory of Signals and Systems
Address : IGEE (Ex-INELEC), Boumerdes University, Avenue de l'indépendance, 35000, Boumerdes, Algeria
Phone/Fax : 024 79 57 66
Email : lss@univ-boumerdes.dz ; ajsyssig@gmail.com

Modeling and Diagnostic of Permanent Magnet Synchronous Machine under Insulation Failure Condition

BOUCHAREB CHOUROUK(1)*,NAIT-SAID MOHAMED-SAID (2),LAHMER FETHI (3)
(1) Department of Electrical Engineering, Batna University, Email: c.bouchareb@live.fr
Laboratory LSPIE' Batna 2000
(2) Department of Electrical Engineering, Batna University, Email: medsnaitsaid@yahoo.fr
Laboratory LSPIE' Batna 2000
(3) Training Institute of Electricity and Gas, Aïn M'lila, Algeria:Email: lahmer.fethi@ifeg.dz

Abstract: One of the most frequent faults in PMSM stator is the turn-to-turn short-circuit fault. So, the aim of this paper is to present a dynamic model for PMSM with turn-to-turn short-circuit fault based on equivalent electric circuit model. Two simple and useful diagnostic techniques ESA an EPVA based on frequency analysis are applied to detect this kind of fault. The accuracy of diagnosis is based on adding the real waveform **of back-**EMF.

Keywords: PMSM, inter-turn, short-circuit, modeling, ESA, EPVA.

1. INTRODUCTION

In recent years, Permanent Magnet Synchronous Motors (PMSM) are one of most important electric machines widely used in industries such as traction, automobiles, robotics and aerospace. Besides, they can be used in electric vehicles and ship propulsion systems due to the inherent important advantages of high power density, high efficiency, small weight, high reliability and easy control of external torque by stator's current control [1-4].

The fault diagnosis of electrical machines has received an intense amount of research interest during 30 years. Reducing maintenance costs and preventing unscheduled down-times, which result in losses of production and financial incomes and due to their utility in safety-sensitive applications, are the priorities of electrical drives manufacturers and operator [5-7]. In fact, correct diagnosis and early detection of incipient faults requires the development of an accurate model for electrical machine, able to simulate electrical faults and the application of an effective diagnosis technique.

However, model accuracy and computation time represents two opposite criteria. Conventional model (electric equivalent circuit or magnetic equivalent circuit) obtained with Park transformation for instance is based on restrictive assumptions and does not require much computation time [8], [9]. However, model obtained using the finite elements method is based on minimal assumption and requires much computation time[10], [11] There is a real need to establish an alternative model which offers a good balance between accuracy and computation time.

One of the most common faults in the electrical motors is the inter-turn short circuit in the one of the stator coils it is called insulation failure. Since the coil insulation material is under the high voltage and temperature stress, it degrades gradually and finally looses the insulating characteristic which is called inter-turn short circuit fault [7]. The inter-turn fault is mostly caused by mechanical stress, moisture and partial discharge, which is accelerated for inverter supplied electrical machines [12].

This paper is an extension of work originally presented in the 4th International Conference on Electrical Engineering (ICEE 2015) [1].So, the aim of this work is to exploiting the dynamic model of a stator surface mounted PMSM with turn-to-turn short-circuit fault of stator winding presented in [1] in order to extract faults signatures diagnosis and to predict the insulation failure, breakdown when the fault is not high developed in order to avoid the machine winding damages. To detect this fault we choose two simple and useful techniques based on frequency analysis these techniques are Electric Spectral Analysis (ESA) and Extend Park's Vector Approach (EPVA). The original in this work is added the real waveform of EMF of healthy machine which contains a third harmonic, because if the model does not take the uncertainties like real back-EMF, the indicator will give a wrong diagnostic.

2. PMSM INTER-TURN FAULT DYNAMIC MODEL

An inter-turn fault denotes insulation failures between two windings in the same phase of the stator. The insulation failure is modeled by a resistance, where its value depends on the fault severity. The stator winding of a PMSM machine with inter-turn fault is illustrated in "Fig.1". In this figure, the fault occurs in the phase a_s [1],[3], [13] and [14].

rf represents the fault insulation resistance. The sub-windings (a_{s1}) and (a_{s2}) represent the healthy and faulty part of the phase winding *a* respectively.

When the fault resistance (*rf*) decreases toward zero, the insulation fault evaluates toward an inter-turn full short-circuit [3]. It would be very help-full to predict the insulation failure, breakdown when the fault is not high developed in order to avoid the machine winding damages [15].

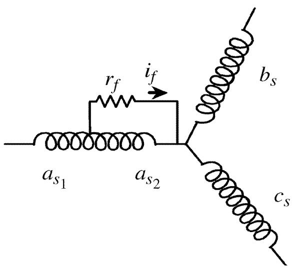


Fig.1 Three-Phase Winding With Inter-Turn Fault In The Phase *a.*

A. PMSM HEALTY MODEL IN ABC-COORDINATE

The voltage equations for the circuit of Fig.1 without fault are [1], [3]:

$$[V_s] = [R_s][I_s] + [L_s]\frac{d}{dt}[I_s] + [E_s], \tag{1}$$

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \tag{2}$$

Where:

$v_{as,bs,cs}$: stator voltages,
$I_{as,bs,cs}$: stator currents,
$e_{as,bs,cs}$: back EMF,
R_s: stator phase resistances,
L: self inductances of healthy machine,
M: mutual inductances of healthy machine.

B. PMSM INTER-TURN FAULTY MODEL IN ABC–COORDINATE

The global equation governing the behavior of the machine in the presence of short circuit [1],[3]:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & -R_{a2} \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ -R_{a2} & 0 & 0 & R_{a2}+r_f \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \\ I_f \end{bmatrix} + \begin{bmatrix} L & M & M & -L_{a2-M_{a1a2}} \\ M & L & M & -M_{a2b} \\ M & M & L & -M_{a2c} \\ L_{a2}-M_{a1a2} & -M_{a2b} & -M_{a2c} & L_{a2} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_{AS} \\ I_{bs} \\ I_{cs} \\ I_f \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \\ -e_f \end{bmatrix} \quad (3),$$

Where:
R_{as1}: stator phase resistance of healthy part of phase a
R_{as2}: stator phase resistance of faulty part of phase a
σ : is the ratio of fault turns (N_f) over the phase winding turn (N_s).
The self-inductances of the faulty and healthy parts of winding (a_{as1}, a_{as2}) are proportional to the square of the turn number(σ). Also the mutual inductance is proportional to this number of both parts:

$$L_{as1} = (1-\sigma)^2 L_{as}\,, \qquad L_{as2} = (\sigma)^2 L_{as}\,,$$
$$M_{as2b} = \sigma M, \qquad M_{as2c} = \sigma M,$$
$$M_{as1as2} = \sigma(1-\sigma)L \quad (4)$$

Where, L_{as1}: stator phase inductance of healthy part of phase a,
L_{as2}: stator phase inductance of faulty part of phase a,
I_f : is the additional current engendered by the short circuit,
r_f : is the faulty loop resistance,
v_f : is the faulty loop voltage.

The machine equations with inter-turn fault in two axis stationary $\alpha\beta$ reference frame are:

PMSM INTER-TURN FAULTY MODEL IN αβ –COORDINATE

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 & -R_{a2} \\ 0 & R_s & 0 \\ -R_{a2} & 0 & R_f \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \\ I_f \end{bmatrix} + \begin{bmatrix} L_s & 0 & M_{f\alpha} \\ 0 & L_s & M_{f\beta} \\ M_{f\alpha} & M_{f\beta} & L_{a2} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_\alpha \\ I_\beta \\ I_f \end{bmatrix} + \begin{bmatrix} e_\alpha \\ e_\beta \\ -e_f \end{bmatrix}, \quad (5)$$

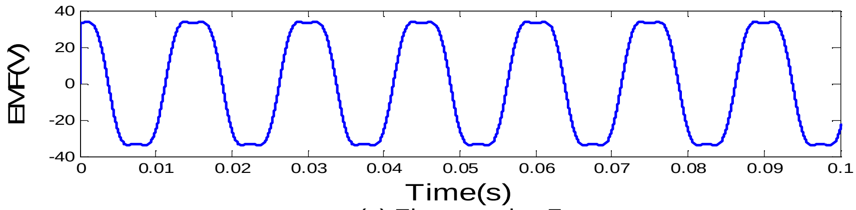
Where: $R'_{a2} = \sqrt{\frac{2}{3}} R_{as2}$, $R'_f = R_{as2} + r_f$, $e_f = e_{as2}$

$$M_{f\alpha} = -\sqrt{\frac{2}{3}}\left(L_{as2} + M_{as1as2} - \frac{M_{as2b} + M_{as2c}}{2}\right) \quad M_{f\beta} = -\sqrt{\frac{1}{2}}\left(M_{as2b} - M_{as2c}\right) \quad L_s = L - M$$

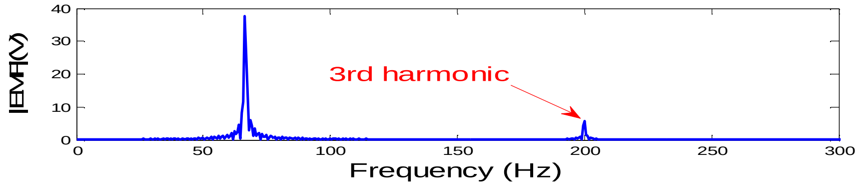
$I_{\alpha,\beta}$: α-and β-axis components of stator current,
$e_{\alpha,\beta}$: α-and β-axis components of stator back FEM.
The electromagnetic torque expression became:

$$T_e = \frac{e_\alpha I_\alpha + e_\beta I_\beta - e_f I_f}{\Omega}, \quad (6)$$

We consider for the all studies that the electromotive force of the healthy motor has a known sinusoidal form as shown on figure 2-a and contains a third harmonic as seen in Fig. 2- b.



(a) Electromotive Force.



(b) Spectrum Analysis.

Fig. 2 Electromotive Force and its Spectrum Analysis.

3. Dynamic Faulty Model Simulation Results

The study of the behavior of PMSM under fault conditions using proposed fault dynamic inter-turn model, requires an accurate knowledge of circuit parameters like the self inductances of the faulty part (*Las2*) and the healthy part (*Las1*) and the mutual inductance between them. For this purpose, a four pair-pole PMSM is considered, the fraction of shorted turns is fixed at 50% in the phase winding *a* . The machine parameters are given in Table.I [3]. The machine is supposed to be supplied by a 3-phases sinusoidal voltage source and to operate at synchronous speed (speed and supply frequency are 1000 *rpm* and 66.67 *Hz* respectively).

The Simulation of the proposed model is realized using Matlab environment. Figure 3 shows the characteristics (phases currents (*abc*), faulty current (I_f), electromagnetic torque and absorbed power) for different values of fault insulation resistance: *rf*=100Ω, 0.5Ω and 0.05Ω.The fraction of shorted turns is fixed at 50% in the phase winding' a'.

Figure 4 shows the characteristics (phase currents (*abc*), faulty current (I_f), electromagnetic torque and absorbed power) for different values of the fraction of shorted turns (σ=10%, σ=50%, σ=80%), the fault insulation resistance is fixed at *rf*= 0.1Ω, it means that the machine is working in faulty case.

TABLE I MACHINE PARAMETERS

Description	Value
Number of pole pairs	4
Stator phase resistance	0.44Ω
Back EMF at 1000 RPM	34V
Frequency	66.67HZ

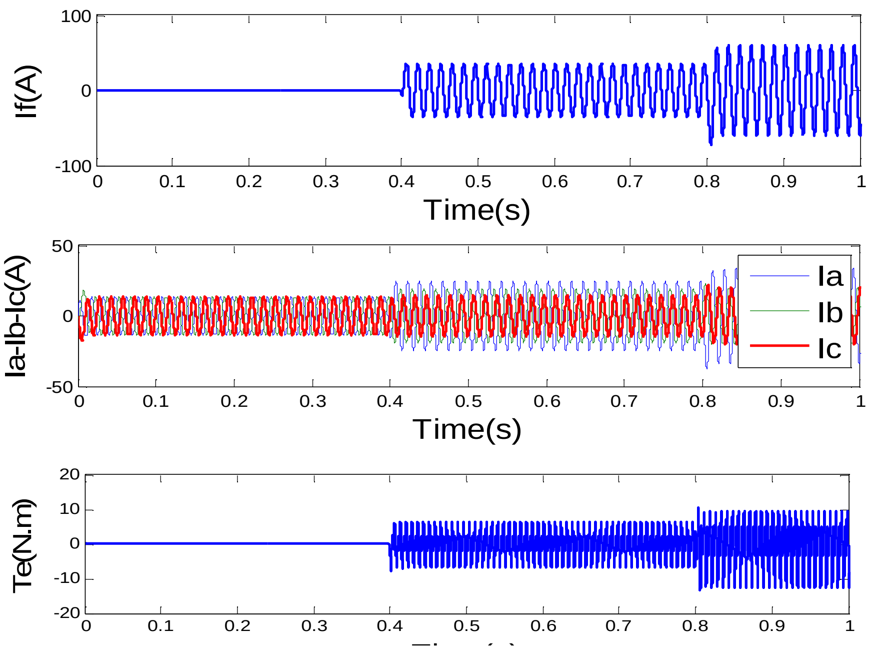


Fig. 3 Phase Currents, Faulty Current, Electromagnetic Torque and Absorbed Power for three values of fault resistances: *rf* =100Ω, *rf* =0.5Ω and *rf* =0.05Ω.

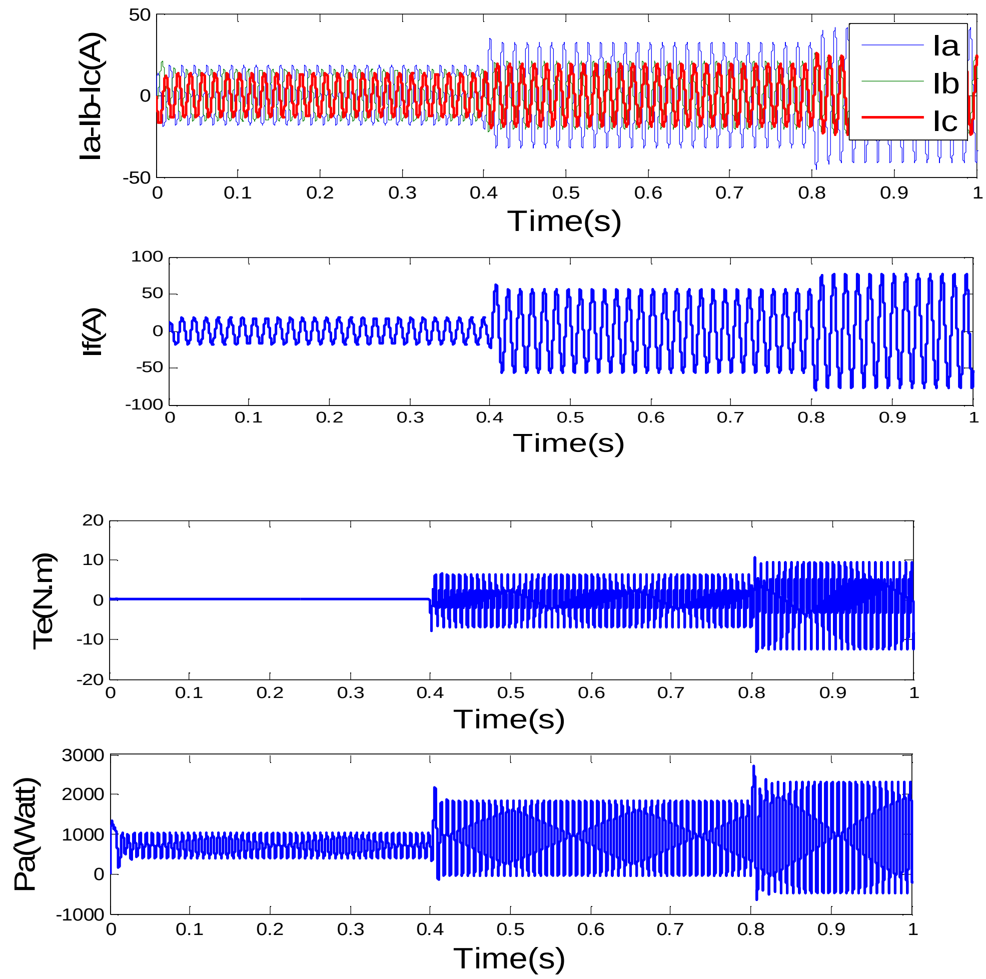


Fig. 4 Phase Currents, Faulty Current, Electromagnetic Torque, Absorbed Power at three values of the fraction of shorted turns:
(*rf* =0.1Ω ,σ=0.1, σ=0.5, σ=0.8).

Figure 3 shows that for three different values of fault resistances. For *rf*=100Ω means that the proposed model is working in healthy case. However, for *rf* =0.5Ω and *rf* =0.05Ω, the proposed model is valid for faulty case. When the fault resistance decreases, the three- phase currents increase to compensate the negative effect of the short-circuit fault. Especially in phase 'a', where the fault happens, the current increases more as shown in figure 3. It can cause a current unbalanced in the power supply and the power increase too. We can observe a torque ripple at a moment when the fault is applying.

Changing the fraction of short-turns means the changing severity of applying fault. In Fig.4, it's clear that the magnitude of the torque ripple is mainly determined by the severity of the fault. The phase and fault currents, power change obviously in the magnitude proportionally with the severity of the fault and becomes unbalanced.
It would be very help-full to predict the insulation failure "breakdown" when the fault is not high developed in order to avoid the machine winding damages [15].

4. DIAGNOSTIC OF STATOR FAULT BY ESA AND EPVA TECHNIQUES

Two techniques based on frequency analysis are applied to detect fault in the stator. These two techniques are:
Electric Spectral Analysis (ESA) based on the fast Fourier decomposition of the phases currents of the winding, the electromagnetic torque and the absorbed power. Extend Park's Vector Approach

(EPVA) is based on the frequency analysis of the module of the Park's Vector of currents as discussed below [16- 18].

A.ELECTRIC SPECTRAL ANALYSIS ESA

We applied this technique on the phase stator currents, the instantaneous absorbed power and on the electromagnetic torque. The instantaneous absorbed power is given by the following equation [19]:

$$p(t) = v_{as}(t)i_{as}(t) + v_{bs}(t)i_{bs}(t) + v_{cs}(t)i_{cs}(t) \quad (7)$$

The phase stator current of the winding 'a', the instantaneous absorbed power and electromagnetic torque spectrum analysis results of both healthy and faulty conditions with different values of faulty resistance(*rf* =100Ω, *rf* =0.5Ω and *rf* =0.05Ω of simulation machine are illustrated respectively on figures 5-6-7.

A.1 CURRENT SPECTRAL ANALYSIS

The ESA signature reveals the existence of a spectral component, with a small amplitude at the third harmonic due the existence of an inter-turn short circuit in stator winding as seen in figure 5-b_{1-} b_2, the existence of this harmonic is due to the third harmonic of the electromotive force presented in figure 2-b. We can observe the now existence of this harmonic at healthy conditions although if the electromotive force has this component (third harmonic), as seen in figure 5-a.

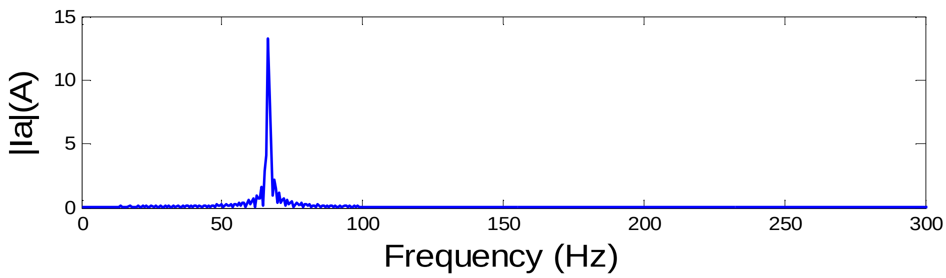
A. 2 ELECTROMAGNETIC SPECTRAL ANALYSES

It's clearly noticeable from figure 6, that under healthy conditions there is only the zero frequency components but when the fault happens we notice the appearance of second harmonic. The increase of the harmonic amplitude is inversely proportional to values of fault resistance it means when the fault increases the amplitude of harmonic increases too.

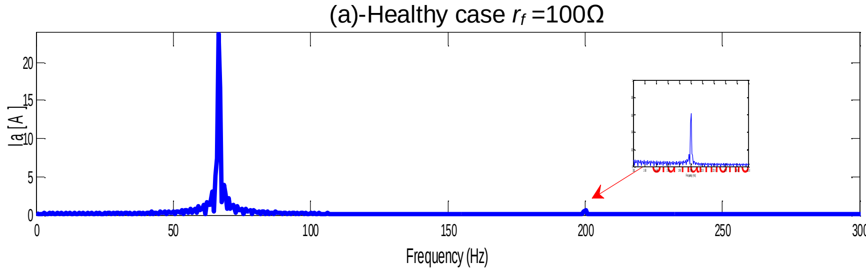
A. 3 ABSORBED POWER SPECTRAL ANALYSIS

Figure 7 shows the absorbed power spectrum with and without fault. The same analysis as that of the electromagnetic torque is noted.

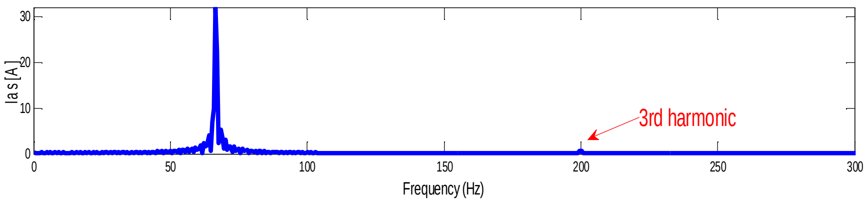
So, the comparative analysis results under healthy and faulty conditions show that the fault manifest in the ESA signature by the appearance of harmonic of rows even on the spectrum analysis of electromagnetic torque and absorbed power and by the appearance of harmonic of odd rows on the spectrum analysis of phases currents. The appearances of these harmonics are directly related to the existence of asymmetries caused by the short- circuit in stator winding with the supposition that we have a balanced voltages source.



(a)-Healthy case r_f =100Ω

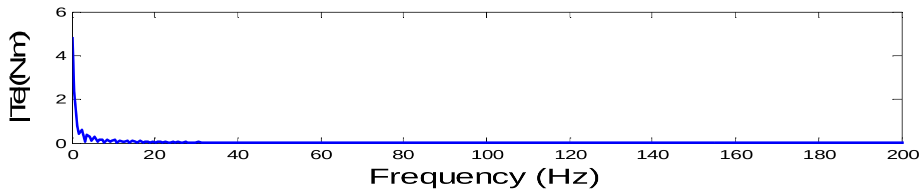


(b1)-Faulty case for r_f =0.5Ω.

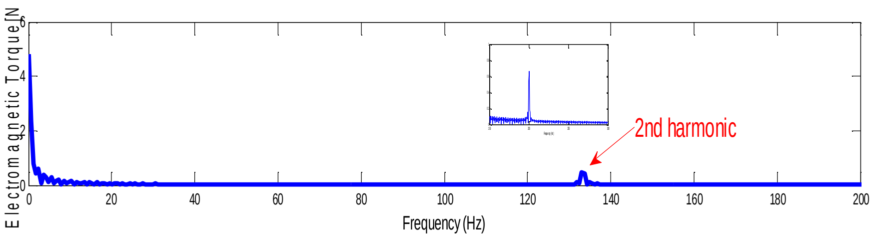


(b2)-Faulty case for r_f =0.05Ω.

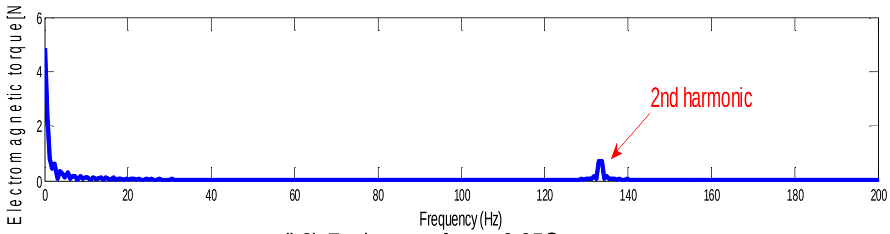
Fig. 5 Spectrum of phase current



(a)-Healthy case r_f =100Ω.

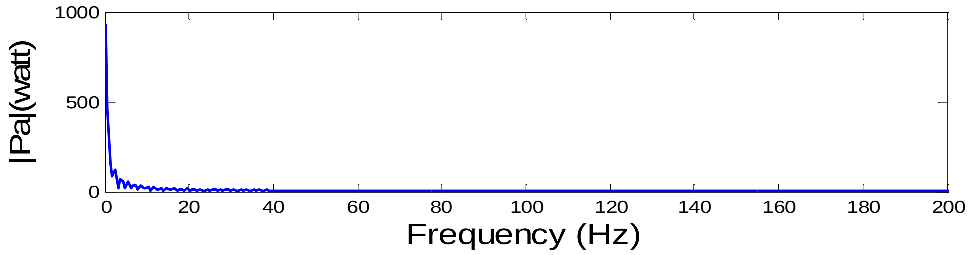


b1)-Faulty case for r_f =0.5Ω .

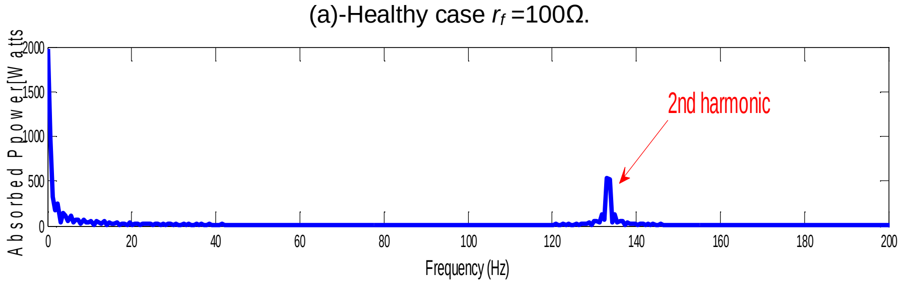


(b2)-Faulty case for r_f =0.05Ω .

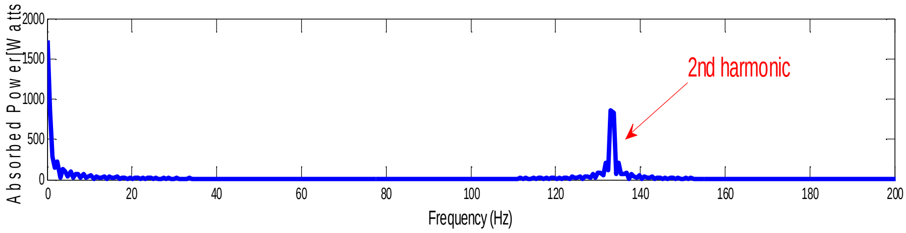
Fig. 6 Spectrum of electromagnetic torque.



(a)-Healthy case r_f =100Ω.



(b1)-Faulty case for r_f =0.5Ω



(b2)-Faulty case for r_f =0.05Ω.

Fig. 7 Spectrum of absorbed power

B. EXTEND PARK'S VECTOR APPROACH E EPVA

This technique is based on PVA approach.First: the PVA approach is based on the two equivalent currents in reference frame obtained by Park's transformation [19]:

$$i_d = \sqrt{\frac{2}{3}} i_{as} - \frac{1}{\sqrt{6}} i_{bs} - \frac{1}{\sqrt{6}} i_{cs}, \qquad (12)$$
$$i_q = \frac{1}{\sqrt{2}} i_{bs} - \frac{1}{\sqrt{2}} i_{cs},$$

Where, i_d and i_q are the instantaneous values of electric currents in direct and quadrature axis. i_d have always a sinusoidal form and i_q have a cosine form in healthy condition this two component have the same values and their locus is a circle like seen on figure 8-a.

When the inter-turn short circuit happens the current becomes unbalanced and it can be expressed as the sum of a positive sequence an a negative sequence components and us a result of this fault the Concordia's vector locus shape deviates and becomes elliptic as shown in figure. 8-b this technique is called Park's Vector Approach.

If the motor operates under healthy condition which means under symmetrical conditions, the three currents form a balanced system and constitute a positive sequence system .Hence, i_d and i_q can be written as below [19]:

$$i_d = \frac{\sqrt{6}}{2} i_+ \sin(\omega t)$$
$$i_q = \frac{\sqrt{6}}{2} i_+ \sin(\omega t - \pi/2) \qquad (13)$$
$$i_p = \sqrt{i_d^2 + i_q^2}$$

Where: i_+ is a maximum value of the current positive sequence;

ω: angular supply frequency.

t: time variable.

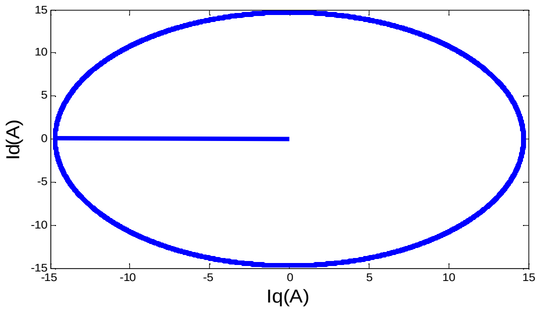
i_p: Park's equivalent current module.

When the system is balanced the current Park's modulus is constant as illustrated on figure 9-a.

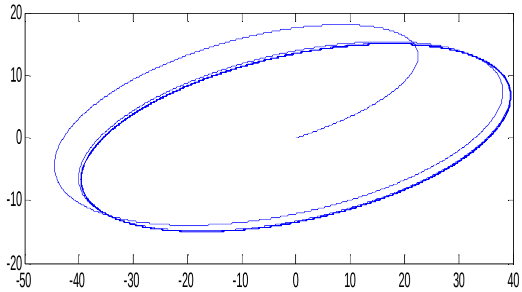
Under faulty conditions the currents will contain other components besides the positive sequence component and in this case the Park's Vector modulus will contain a dominant dc level and ac level of the motor current supply [16] and their existence is directly related to the asymmetries as we can see on figure 9-b.

The aim of EPVA technique is to apply the frequency analysis to the Park's vector modulus in order to obtain the EPVA signature when the unbalance system happens. After simulation and analysis we obtain results for healthy conditions (r_f =100Ω) and faulty conditions (r_f =0.5Ω and r_f =0.05Ω) as shown on figure 10.

From these results, the EPVA signature reveals the existence of a spectral component at a frequency of 66.67hz-twice the fundamental supply frequency , and it is so clear from results when the fault resistance decreases (the severity of fault increases) the amplitude of the spectral component increases, makes it a good indicator of the presence of the fault.

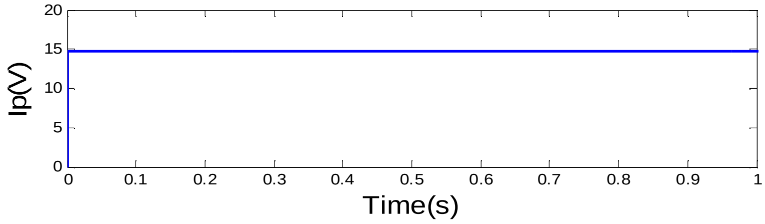


(a)-Healthy case.



(b)-Faulty case.

Fig. 8Locus of the d-q Currents



(a)-Healthy case.

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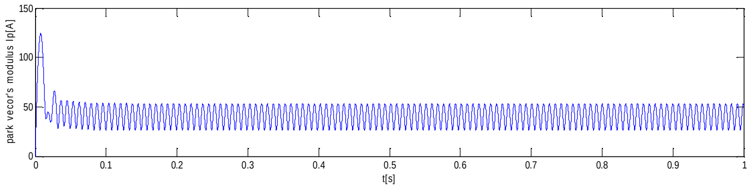
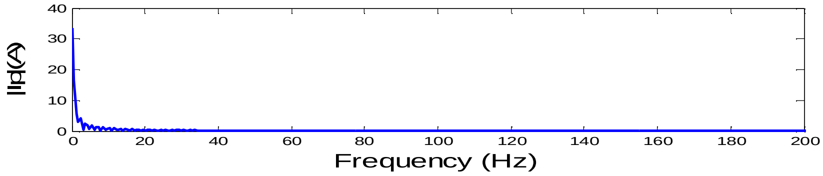
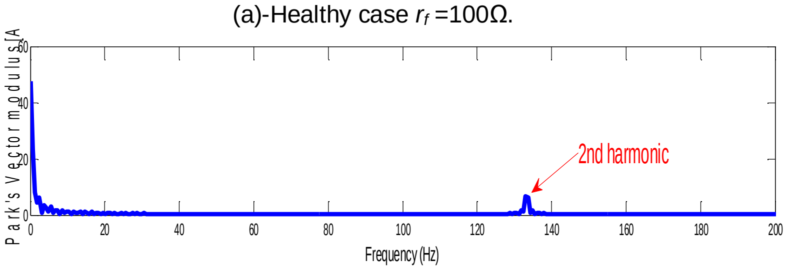


(b)-Faulty case.

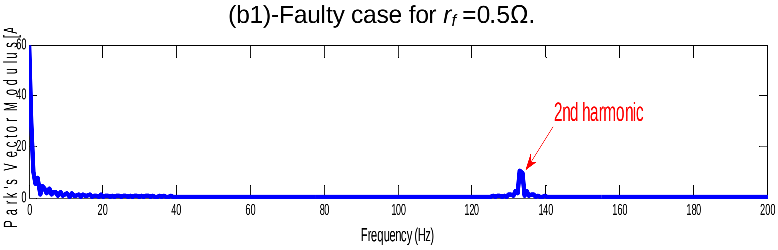
Fig. 9 Park's vector modulus



(a)-Healthy case r_f =100Ω.



(b1)-Faulty case for r_f =0.5Ω.



(b2)-Faulty case for r_f =0.05Ω.

Fig. 10 Spectrum of Park's Vector Modulus.

5. CONCLUSION

A through this paper a dynamic model for su*rf*ace mounted PMSM machine under turn-to-turn short-circuit in stator winding. This faulty model is used to study the behavior of a machine under various fault conditions and severity. From the analysis of the simulation results, turn-to-turn short-circuit fault causes high torque ripples and currents unbalance in the system. Higher circulating currents could be generated because of the motor winding short-circuit. More importantly, the detection of these kinds of fault should be aware in the design and development procedure of the motor, drive and diagnosis for this a simple and effective diagnosis methods ESA and EPVA based on frequencies analysis are used in the way to analyzed and indicate the presence of the short-circuit fault in the stator. Results show that stator winding short-circuit can be diagnosed by application of this technique, whose operating philosophy relies on the behavior of a spectral component at twice and third of the fundamental supply frequency and the amplitude of this spectral component is directly related to the severity of fault. The shape of concordia's currents vector locus is a good indicator of fault when its form change from circle to an elliptic one according to the associated fault where this ellipticity is proportional to the fault severity.

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