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DEVELOPMENT OF MODEL FOR STATOR WINDING INTER-TURN FAULT IN PERMANENT MAGNET SYNCHRONOUS MOTOR

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ABSTRACT

This Paper develops and analyzes a model for simulating healthy and faulty surface mounted permanent magnet synchronous motor for stator winding inter turn fault. The presented model can be conveniently used for studying the effects of stator winding failure in the permanent magnet synchronous motor using MATLAB Simulink. The PMSM is finding list of applications nowadays to meet random specialized purpose like torque requirement and longetivity. The condition monitoring of electrical machines is generating lot of interest amongst the researchers. The proposed model shall serve the purpose of initial requirements towards on-line condition monitoring of PMSM.

KEYWORDS

Inter turn short circuits,Inter turn short circuit model,simulations,fault detection,fault diagnosis, permanent magnet synchronous motor.

NOMENCLATURE

a,b,c	Stator reference axis.
Va,Vb,Vc	Stator phase to neutral voltage .
Ia,ib,ic	Stator current in phase a,b,c.
Ra,Rb,Rc	Stator three phase resistance.

[Rsh]	Stator resistance matrix of a healthy machine.
λa,λb, λc	Magnetic flux linkage of each stator phase.
Laa,Lbb,Lcc	Self-inductance of stator winding.
Lab,Lba,Lca	Mutual inductance between stator winding.
[Lsh]	Stator inductance matrix of a healthy machine.
λpm	Permanent magnet flux.
Θe	Rotor electrical position.
Θmech	Rotor mechanical position.
P	Number of poles pair.
Np	Number of pole pair of the motor.
Θd	Angle by which d-axis leads the magnetic axis of phase a winding.
ωr	Rotor angular velocity.
Ns	Number of turns in each stator winding.
Tdq0	Park's transformation.
μ	Ratio between the number of shorted turns and total turns per phase.
Vd	Voltage in d axis.
Vq	Voltage in q axis.
Ld	d axis inductance.
Lq	q axis inductance.

INTRODUCTION

Nowadays electric motors are playing an important role in industry, public life, domestic life, automobiles and combustion engine, transportation and defense force, aerospace, medical and health case equipments. The Permanent Magnet Synchronous Motor (PMSMs) are currently being widely applied. The use of permanent magnet (PMs) in constructions of electrical machines brings following benefits.

1. No electrical energy is absorbed by the field excitation system and thus there are no excitation losses which means sustainable increase in the efficiency.
2. Higher torque and output power per volume than when using electromagnetic excitation.
3. Better dynamic performance than motors with electromagnetic excitation (higher magnetic flux density in the air gap).
4. Simplification of construction and maintenance.

With the aforementioned features Permanent Magnet Synchronous Motors (PMSMs) are widely used.[1,2] Resent development in rare-earth PM materials and power electronics have opened new prospects on the design, construction and application of Permanent Magnet Synchronous motor and are object of an research. Failure of machine has an impact on the operation of system, loss of production and jeopardize on human safety. Therefore early fault detection and diagnosis helps in reducing the machine wear and tear, machine down time and maintenance cost.[3] In the past research work different fault detection techniques have been applied for electric motors such as temperature measurement, motor current signature analysis (MCSA),Vibration analysis, fourier transform based method, frequency based method andharmonic analysis.[4,5]

Faults in PMSMs are classified into three parts, Electrical, Magnetic and Mechanical faults. Electrical faults is viewed as stator faults in which winding faults and external drive faults are most common.[1,6] Mechanical faults involves eccentricity faults and bearing faults. Eccentricity faults consists of static eccentricity (SE),dynamic eccentricity (DE), and mixed eccentricity (ME).These occurs due to manufacture impression such as unbalance mass, shaft bent and bearing tolerance. Eccentricity may cause magnetic and dynamic problem with additional vibrations, noise and torque production.[7,8]

In this paper, the mathematical model development and simulation study of stator short circuit interturn faults in surface mounted permanent magnet synchronous motor(SPMSMs) is carried out To meet this requirement a set of equations is formed for both healthy and faulty surface mounted permanent magnet synchronous motor. The MATLAB simulation is carried out for both healthy and faulty SPMSMs.

The Matlab simulation presented in the paper allows improving the algorithms for online fault diagnosis based on monitoring the stator current spectrum when such fault occurs. This will also help in overall condition monitoring of PMSM.

SPMSM Model in abc phase frame

The SPMSM are brushless machine with sinusoidally distributed stator winding. The excitation flux of motor is produced by the permanent magnet rotor. Kirchhoffs law are used to develop the electric model of the motor.

The following assumptions are made in developing the model.

1. The magnetic permeability of iron is considered to be infinite.
2. The operation is far from magnetic saturation.

3. The magnetic motive force and the flux profile are considered sinusoidally distributed.
4. Higher harmonics are neglected.

Healthy SPMSM Model

The stator equation for symmetrical healthy SPMSM in the abc reference frame are as follows.[1,4]

$$V_a = R_a . i_a + \frac{d\lambda_a}{dt} \ldots\ldots\ldots\ldots\ldots (1)$$

$$V_b = R_b . i_b + \frac{d\lambda_b}{dt} \ldots\ldots\ldots\ldots\ldots (2)$$

$$V_c = R_c . i_c + \frac{d\lambda_c}{dt} \ldots\ldots\ldots\ldots\ldots (3)$$

The stator phase voltages are composed of two parts a resistive part representing the voltage drops across the stator resistance and a magnetic part resulting from the changing of the stator magnetic flux linkage. For SPMSM the stator magnetic flux are generated by two different sources one form the flux created in the stator self-inductances and mutual inductances between different phase winding and other from the flux created due to rotor permanent magnet as expressed in.

$$\lambda_a = L_{aa}.i_a + L_{ab}.i_b + L_{ac}.i_c + \lambda_{PM.a} \ldots\ldots (4)$$

$$\lambda_b = L_{ba}.i_a + L_{bb}.i_b + L_{bc}.i_c + \lambda_{PM,b} \ldots\ldots (5)$$

$$\lambda_c = L_{ca}.i_a + L_{cb}.i_b + L_{cc}.i_c + \lambda_{PM,c} \ldots\ldots (6)$$

Where $R_{sh} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix}$ and Lsh=

$$\begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix}$$

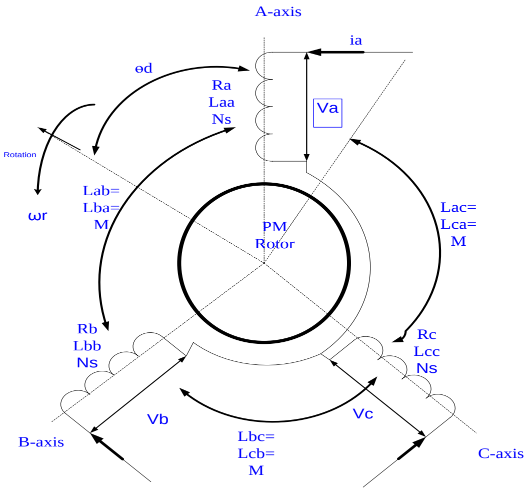

Fig. 1: Equivalent circuit of SPMSM.

Rsh are the resistance of stator healthy phase winding and Lsh are inductance of the stator healthy phase winding.The diagonal elementsLaa=Lbb=Lcc=L are the self-inductances of each winging and the off diagonal elements Lab=Lba=Lca=Lac=M are the mutual inductances between different phase winding.Since the magnetic field of SPMSM is dominated by the rotor permanent magnet.

The flux linkage [$\lambda_{PM.abc}$] expressed in the abc reference frame generated by rotor permanent magnet, relates to the rotor electrical angular position θr.where [θr = p θmech]

Assuming that the stator windings are placed evenly with a relative phase angle of 120 degree and the flux linkage distribution obeys the sinusoidal law.[$\lambda_{PM.abc}$] can then be expressed as periodic function of θr.where λ_{PM} the peak strength.[1]

$$\lambda_{PM,abc} = \begin{bmatrix} \lambda_{PM,a}\,(\theta r) \\ \lambda_{PM,b}\,(\theta r) \\ \lambda_{PM,c}\,(\theta r) \end{bmatrix} = \lambda_{\mathrm{PM}} \begin{bmatrix} \sin\,(\theta r) \\ \sin\,(\theta r - \frac{2\pi}{3}) \\ \sin\,(\theta r + \frac{2\pi}{3}) \end{bmatrix}$$

Where,

$$\frac{d\lambda_{PM,abc}}{dt} = \lambda_{\mathrm{PM}}\,.\omega r \begin{bmatrix} \cos(\theta r) \\ \cos(\theta r - \frac{2\pi}{3}) \\ \cos(\theta r + \frac{2\pi}{3}) \end{bmatrix}$$

In this, the rotor position angle θrand the electrical angular velocity ωr,are two unknown variables are to be calculated.From the above equations the general equation of a healthy SPMSM is.[1,4]

$$[V_{abc}]=[\mathrm{R_{sh}}][\mathrm{i_{abc}}]+[\mathrm{L_{sh}}].\frac{\mathrm{d}}{\mathrm{dt}}[\mathrm{i_{abc}}]+\frac{\mathrm{d}}{\mathrm{dt}}[\lambda_{PM,abc}]\ldots(7)$$

SPMSM Model With Stotor Interturn Faults

Many works have been reported in the literature on both detecting and diagnosis in stator winding. Severalmodel have been created to describe an ac machine with interturn short circuit faults.

Fig. 2 shows the Equivalent circuit model of SPMSM with interturnfault.phase a is divided into two parts healthy and faulty. Where $\mathrm{i_f}$ is the short circuit current, and$R_f$is the resistance that models the short circuit, its value depending on the fault severity. When$R_f$decreases towards zero, the fault evolves to a full interturn short circuit.

Similarily to equation (7) stator equation for a interturn fault in phase a is given as.[1,4]

$$[V_{abcf}]=[\mathrm{R_{sf}}][\mathrm{i_{abcf}}]+[\mathrm{L_{sf}}].\frac{\mathrm{d}}{\mathrm{dt}}[\mathrm{i_{abcf}}]+\frac{\mathrm{d}}{\mathrm{dt}}[\lambda_{PMf,abc}].(8)$$

$$\text{Here } [V_{abcf}]=[V_a \quad V_b \quad V_c \quad 0]^t \; [\mathrm{i_{,abcf}}]=$$

$$[\mathrm{i_a} \quad \mathrm{i_b} \quad \mathrm{i_c} \quad \mathrm{i_f}]^{\mathrm{t}}$$

$$R_{sf}=\begin{bmatrix} \mathrm{R_{a1}+R_{a2}} & 0 & 0 & -\mathrm{R_{a2}} \\ 0 & \mathrm{R_b} & 0 & 0 \\ 0 & 0 & \mathrm{R_c} & 0 \\ -\mathrm{R_{a2}} & 0 & 0 & \mathrm{R_{a2}}+R_f \end{bmatrix}$$

$$L_{sf}=\begin{bmatrix} \mathrm{L_{aa}} & \mathrm{L_{ab}} & \mathrm{L_{ac}} & -\mathrm{L_{aa2}}-M_{aa1aa2} \\ \mathrm{L_{ba}} & \mathrm{L_{bb}} & \mathrm{L_{bc}} & -M_{\mathrm{aa2bb}} \\ \mathrm{L_{ca}} & \mathrm{L_{cb}} & \mathrm{L_{cc}} & -M_{\mathrm{aa2cc}} \\ -L_{\mathrm{aa2}}-M_{aa1aa2} & M_{\mathrm{aa2bb}} & M_{\mathrm{sa2cc}} & -L_{aa2} \end{bmatrix}$$

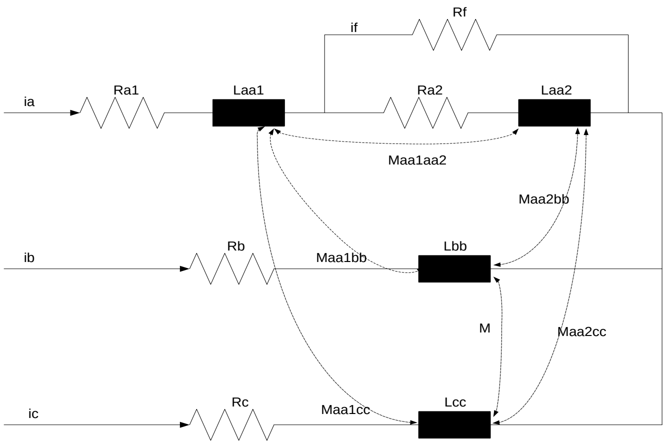

Fig. 2: Equivalent circuit of SPMSM with interturn fault.

$$\frac{d\lambda_{PMF,abc}}{dt} = \lambda_{\mathrm{PM}} .\omega r \begin{bmatrix} \cos(\theta r) \\ \cos(\theta r - \frac{2\pi}{3}) \\ \cos(\theta r + \frac{2\pi}{3}) \\ \mu \cos(\theta r) \end{bmatrix}$$

SPMSM Model in dq0 Frame

Park’s dq-transformation is a coordinate transformation that converts the three-phase stationary variables into variables in a rotating co-ordinate system. In dq0 transformation, the rotating coordinate is defined relative to a stationary reference angle. The stationary reference can be selected arbitrarily. forsimplicity, this reference is usually selected at the location of the phase ‘a’ axis. Thus the transformation angle has the same value as that of the rotor electrical position and θr. Denoting the variables in the rotation reference frame as direct (d), quadrature (q) and zero (0) sequence.3

The dq0 reference frame is fixed to the rotor, with the positive d-axis is aligned with the magnet flux vector. The positive q-axis is defined as leading the positive d-axis by л/2.ThePark transform allows converting magnitudes from the stationary abc frame to the rotor fixed dq0 frame.[1]

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta r) & \cos(\theta r - \frac{2\pi}{3}) & \cos(\theta r + \frac{2\pi}{3}) \\ \sin(\theta r) & \sin(\theta r - \frac{2\pi}{3}) & \sin(\theta r + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$V_d = R_s i_d + \omega L_s i_q + L_s \frac{di_d}{dt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

$$V_q = R_s i_q - \omega L_s i_d + L_s \frac{di_q}{dt} + \omega\lambda_{PM} \ldots\ldots\ldots\ldots\ldots(10)$$

The voltage equation in the shorted turns results is as follows

$$\begin{aligned} V_f' &= V_f - i_f R_f \\ &= \frac{2}{3}\mu\left[R_s(i_d \cos\theta r - i_q \sin\theta r) - (2R_s + \frac{R_f}{\mu})i_f\right] \\ &- \left[\omega L_s(i_d \sin\theta r + i_q \cos\theta r)\right] \\ &+ \frac{2}{3}\mu\left[L_s(\cos\theta r \frac{di_d}{dt} - \sin\theta r \frac{di_q}{dt})\right] \\ &+ \frac{2}{3}\mu^2 L \frac{di_f}{dt} - \mu\omega\lambda_{PM} \sin\theta r = 0 \ldots\ldots\ldots\ldots\ldots(11) \end{aligned}$$

Being Ls=Ld=Lq=L

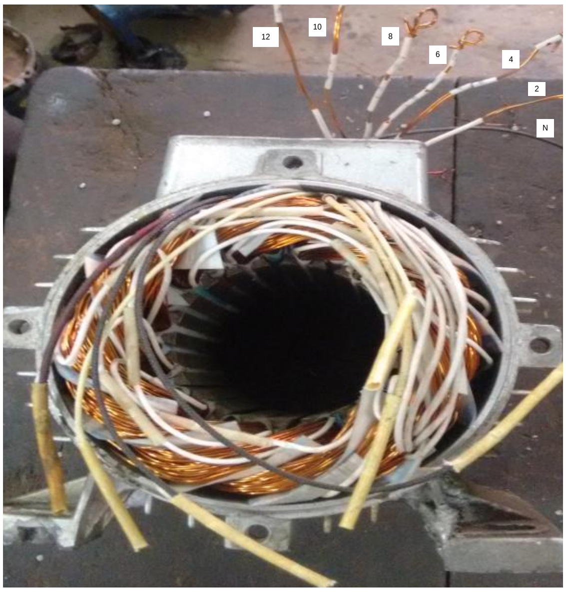

Fig. 3: Stator of PMSM to create inter-turn fault.

RN	**0-2**	**0-4**	**0-6**	**0-8**	**0-10**	**0-12**
R	0.0734Ω	0.1474	0.1902	0.2598	0.4454	0.6482
L	4.5µH	15.8	34.4	54.8	128.3	156.8
Z	0.0783 Ω	0.1643	0.2879	0.4291	0.9213	1.6625
ϴ	+21.06	+36.12	+45.82	+53.06	+61.07	+68.31

Experimental Setup

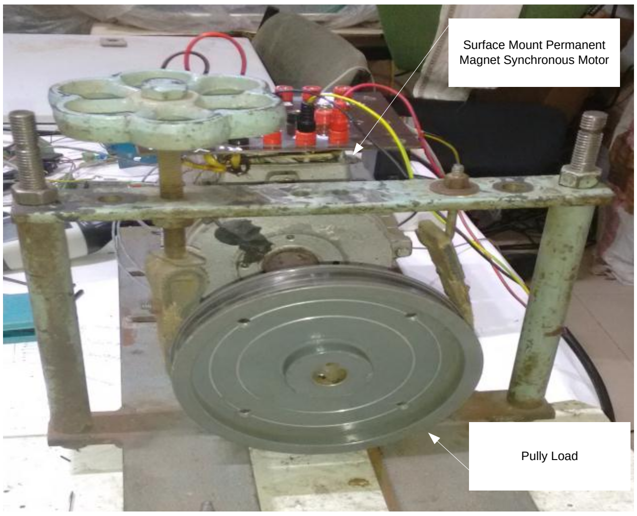

Fig. 4: Experimental Setup to create inter-turn fault.

The parameters used for Matlab simulation of Surface Mounted Permanent Magnet Synchronous Motor is having following specification.

Table 1: Key specification of SPMSM

Item	***value***
Rated Voltage (Volt)	415
Capacity in hp	1
Pole number	4
Rated speed (rpm)	1500
Rated current (Amp)	1.5
Frequency in (Hz)	50
Total no of slots	24
Turns of stator winding	500
Length of stator winding in (mm)	310
Lamination thickness (mm)	0.18
Air gap (mm)	0.6
Coils per phase winding	Single layer lap winding
Torque at noload (N-m)	4.78
Torque at Full load (N-m)	5.11
Stator resistance (ohm)	0.0378
Stator inductance (µH)	220
Gauge of winding	21
Double ball bearing	6205ZR
PM flux linkage (wb)	0.0543

Simulation Result

In this section, simulation of healthy and faulty SPMSMs have been carried out by means of Matlab Simulink. The decrease in winding equivalent turns will increase the stator –winding current, thus causing increase in heating due to additional I^2R losses. The increase in heating will cause a corresponding temperature rise in stator, thereby decreasing the life expectancy of the stator winding insulation.

The stator winding insulation failure will cause additional shorted turns and further increase in temperature. This effect increases the rate of deterioration of the stator winding insulation

If the machine bearing is healthy in that case, motor intake current is normal. But as the bearing deteriorates, to fulfill the required load demand, the electrical torque increases. Therefore, the input current also rises.

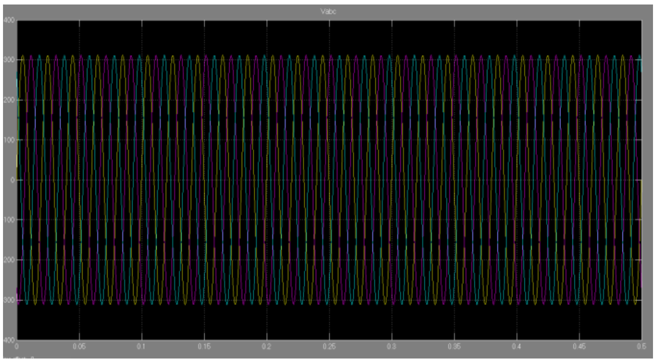

Fig. 5: Three phase voltages.

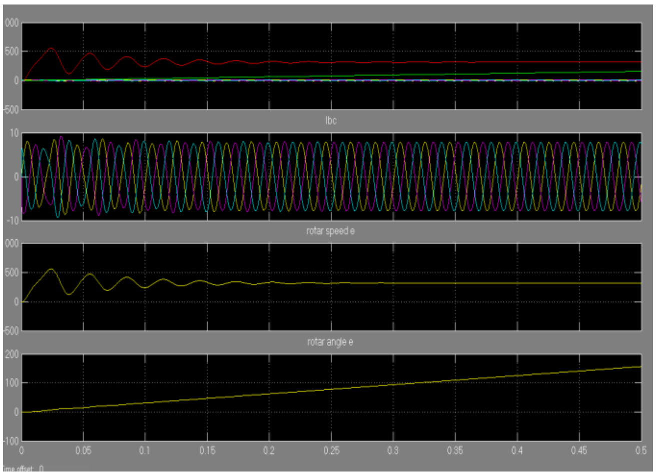

Fig. 6: Three phase current,rotor speed,rotor angle.

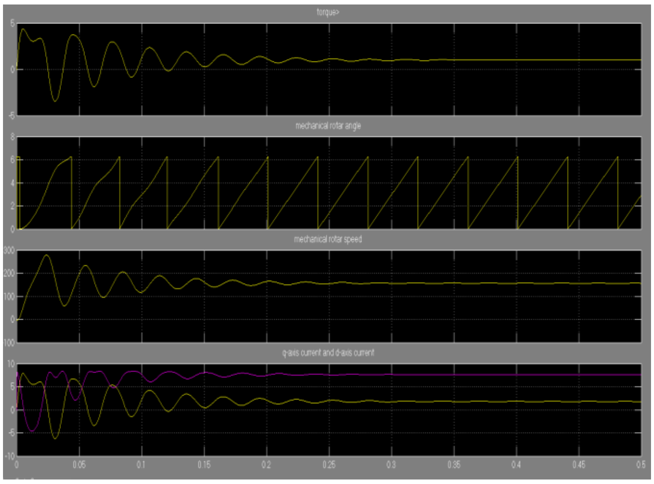

Fig. 7: Torque, Mechanical angle,Mechanical Speed, d and q axis current.

CONCLUSION

In this paper, a mathematical model that allows studying the effect of stator winding interturn faults have been developed. According to mathematics and logic analysis result, a series of dynamic simulation for these faults are established in simulink @MATLAB.The simulation result shows decrease in winding equivalent turns will increase the stator winding current of faulted phase and thereby increase in temperature.

The validation of the proposed model via experiments remains as the future research.

REFERENCES

1. Luis Romeral,Julio Cesar Urresty, Jordi Roger Riba Ruiz and Antonio Garcia Espinosa*"Modelling of Surface-Mounted Permanent Magnet Synchronous Motor with Stator Winding InterturnFaults"*.IEEE Transactions on Ind. Electronics, May 2011; 58(5): 1576-1585.
2. ZhengChen,Rang QI, and HuiLin,"Inter-turn short circuit fault diagnosis for PMSM based on complex Gauss Wavelet", proceeding of the 2007 International conference on wavelet analysis and pattern recognition,China, Nov, 2007; 2-4: 1915-1920.
3. Q.A.Mohammed,Z.liu,S.liu and N.Y.Abed,"Internal Short circuit fault diagnosis for PM Machines using FE-Based phase variable model and Wavelets Analysis",IEEE transactions on Magnetics, April 2007; 43(4): 1729-1732.
4. T. Boileau, B. Nahid-Mobarakh and F. Meibody-Tabar,"Back-EMF Based detection of Stator winding inter-turn fault for PM Synchronous motor drives", IEEE, 2007; 95-100.

5. J. Rosero, L. Romeral, J. A. Ortega and E. Rosero,"Short circuit fault detection in PMSM by means of Empirical Mode Decomposition (EMD) and Wigner Ville Distribution (WVD)",IEEE, 2008; 98-103.
6. J. Rosero, A. Garcia, J. Cusido, L. Romeral and J. A. Ortega ,"Fault detection by means of Hilbert Huang transform of the stator current in PMSM with demagnetization", IEEE, 2007.
7. J. Rosero, J. Ortega, J. Urresty, J Cusido and L. Romeral,"Stator Short circuit detection in PMSM by means of Higher Order Spectral Analysis (HOSA)", IEEE, 2009; 964-969.
8. J. Rosero, L. Romeral, J. Cusido, A. Garcia and J. A. Ortega, "On the Short- circuiting fault detection in PMSM by means of Stator Current Transformation", IEEE, 2007; 1936-1941.

X: BIOGRAPHIES

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