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Original scientific paper

ANALYSIS OF ROTOR ASYMMETRY FAULT IN THREE-PHASE LINE START PERMANENT MAGNET SYNCHRONOUS MOTOR

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Abstract. *This article proposed a detection scheme for three-phase Line start permanent magnet synchronous motor (LSPMSM) under different levels of static eccentricity fault. Finite element method is used to simulate the healthy and faulty LSPMSM with different percentages of static eccentricity. An accurate laboratory test experiment is performed to evaluate the proposed index. Effects of loading condition on LSPMSM are also investigated. The fault related signatures in the stator current are identified and an effective index for LSPMSM is proposed. The simulation and experimental results indicate that the low frequency components are an effective index for detection of the static eccentricity in LSPMSM.*

Key words: *Line start permanent magnet synchronous motor, static eccentricity, current signature analysis, finite element method, fault detection*

1. INTRODUCTION

Line start permanent magnet synchronous motor (LSPMSM) is a hybrid electric motor uses the combination of induction motor (IM) and permanent magnet synchronous motor (PMSM) structure through a rotor bar to provide the starting torque that conducts the motor into synchronism and permanent magnets for the generation of synchronous torque at steady state. LSPMSM starts with the induction characteristic using rotor bar torque and permanent magnet opponent torque (breaking torque). So long as the velocity attains near synchronous speed, a synchronization process commences and the motor pulls to synchronous state whenever no eddy current generates into the rotor bars except harmonics field currents. LSPMSMs is introduced as a viable alternative to IMs [1-3]. Environmental considerations such as pollutions, greenhouse gases and landfills are the major issues in recent years [4] which has attracted a lot of attention for efficiency improvement of power

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systems and electrical machines [5,6]. Unpredictable faults always create unexpected problems in electrical motors because of many stress mechanisms such as thermal, electrical, mechanical and environmental effects during the operation, that ultimately result in efficiency reduction, serious damage and breakdown. The consequent economic and security reasons justify the importance of fault detection techniques for preventive maintenance [7]. Faults in LSPMSMs can be classified in different types as indicated in Fig. 1. The mechanical faults are much possible in electrical motors which earmark 60% of the faults, while 80% of mechanical faults are due to eccentricity between stator and rotor that encourage many research efforts still devoted to the eccentricity in electrical motors. Eccentricity in the LSPMSM could cause a type of fault cycle proportional to eccentricity percentage lead to decrease the motor efficiency. Despite the significance of eccentricity exploration in electrical motors, few researches has been reported on eccentricity fault detection in LSPMSM. It is worth mentioning that type of electrical motors has significant influence on the fault detection procedures [8] and hence precise eccentricity fault diagnosis in LSPMSM can guarantee their lifetime as well as keep their high efficiency performance.

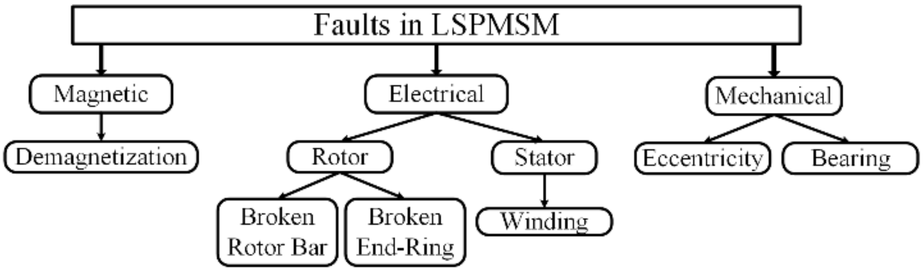


Fig. 1 Fault classification in LSPMSM

The initial study on static eccentricity detection in LSPMSM is reported in [3]. A three-phase LSPMSM is modeled using the finite element method (FEM). The stator current signal of LSPMSM under static eccentricity condition is analyzed in frequency domain and the fault index is determined. However, the loading effect on fault detection is not considered. The investigation then continued and a cost-effective, non-invasive detection strategy is proposed for mixed eccentricity fault diagnosis in LSPMSM. Examination is executed through simulation and experimental works and an efficient frequency pattern as well as detection criterion is specified [9]. A mathematical model of LSPMSM under static eccentricity condition is developed in [10]. The proposed model is verified using FEM. The performance of eccentric LSPMSM is analyzed and the time variations of stator current, speed and torque are investigated. PMSM has been simulated with eccentricity using FEM to calculate the stator current signal in addition to experimental investigation [11]. Barbour and Thomson [12] analyzed the influence of rotor shapes on static eccentricity in IM using MCSA method. FEM has been employed to simulate the stator current. It was concluded that the rotor slot design has a remarkable impact on the harmonic components of stator current with static eccentricity, while semi-closed slots indicate higher increase in the presence of static eccentricity. These researchers then proved that rotor slot skewing reduces the static eccentricity harmonic components of stator current signal in IM [13]. Nandi et al. work on the detection of eccentricity fault in three-phase IM by measuring the high frequency harmonic components in the stator current signal [14]. The amplitude of sideband components around principle slot harmonics (PSH) is examined for eccentricity detection. These researches proposed two feature formulas for detection of eccentricity fault in PMSM using MCSA. In [15] the same index as proposed in [16] has been evaluated for static eccentricity recognition in reluctance synchronous motor by predicting a proper harmonic component in the stator current signal through modeling and experimentation concepts. According to the resultant of aforementioned topics as well as the easiness and accessibility of measuring current spectrum via a current clamp, MCSA is the most accepted noninvasive technique which depends on exploring the variation of eccentricity related harmonics in the current signal of the motor.

This article proposed a method to identify the static eccentricity fault signature for three-phase LSPMSM. The main contribution is to examine the proposed index through the simulation and experimental analyses and determine its effectiveness. The stator current spectrum at steady state operation is used as a reference signal. A laboratory test setup is developed to measure the current signal of motor non-invasively for both healthy and faulty conditions with different degrees of fault and loading level. By the way, the stator current signal of LSPMSM is calculated using FEM. The simulated and measured current signals are processed in frequency domain using power spectral density (PSD) technique. It is indicated that the amplitudes of fault-related components increased proportional to fault severity while they decreased at higher levels of load.

2. ECCENTRICITY FAULT

The non-uniform air-gap distribution between stator and rotor due to displacement of one or all the rotor symmetry, stator symmetry and rotor rotation axes from the center of motor, so called eccentricity fault in electrical motors that classifies in three types as static, dynamic and mixed eccentricity. Static eccentricity defines as a condition when the rotor symmetrical axis (C_r) concentric with the rotor rotational axis (C_g) but they are displaced with respect to the stator symmetrical axis (C_s) result in a non-uniform air-gap distributes between stator and rotor where the position of minimum (and maximum) air-gap versus stator is motionless and time-independent.

Several stresses of forces and conditions lead to static eccentricity fault in electric motor such as shaft deflection, motor housings imperfection, wrong placement of the rotor or stator at the setup or subsequent of maintenance, elliptical stator core, incorrect bearing positioning, bearing deterioration, end-shield misalignment, excessive tolerance, rotor weight or pressure of interlocking ribbon. The consequences of static eccentricity could seriously damage the motor, specially the advanced degrees of fault. Static eccentricity fault causes static unbalanced magnetic pull (UMP) in the radial route across the motor, rub between rotor and stator, abnormal noise and vibration, harm the rotor and stator laminations, destroy the windings, rotor deflection, bent shaft and bearing defect.

The magneto motive force (MMF) of stator shapes the non-uniform air-gap due to eccentricity by permeance harmonics into the electromotive force (EMF) that induced in the rotor. The same procedure pursued for EMF which is induced in the stator on the basis of the rotor MMF. Thus, the air-gap flux results from permeance and MMF generates an air-gap magnetic field which composes of fundamental components, stator and rotor MMF harmonics, stator and rotor slot permeance harmonics, eccentricity permeance harmonics and permeance harmonics of saturation.

LSPMSM starts to run by rotor bar torque and permanent magnet breaking torque. While the rotor rotates close to the synchronous speed, the motor is driven to synchronization and steady state operation [3]. The air-gap permeance including stator slotting permeance and smooth rotor can be calculated for LSPMSM at steady state operation as follows:

$$P_{sl} = \sum_{k_{sl}=0}^{\infty} P_{k_{sl}} \cos(k_{sl} S_1 \theta) \tag{1}$$

where k_{sl} is an integer value, $P_{k_{sl}}$ is the stator slotting permeance, S_1 is the stator slots and θ is the space variable. The saturation permeance of this machine is expressed as:

$$P_{sat} = \sum_{k_{sat}=0}^{\infty} P_{k_{sat}} \cos[k_{sat}(2\omega t - 2P\theta)] \tag{2}$$

where k_{sat} is an integer number, $P_{k_{sat}}$ is the specific permeance of saturation, P is the main pole pairs, ω is the angular supply frequency and t is time variable.

Since the non-concentric air-gap in static eccentricity is time invariant the permeance due to this fault considering smooth rotor and stator will be:

$$P_{SE} = \sum_{k_{SE}=0}^{\infty} P_{k_{SE}} \cos(k_{SE}\, \theta) \tag{3}$$

where k_{SE} is an integer number and $P_{k_{SE}}$ is the specific permeance related to static eccentricity. Accordingly, the total permeance can be computed with the following expression:

$$P_T(t) = \sum_{k_{sl}=0}^{\infty} \sum_{k_{sat}=0}^{\infty} \sum_{k_{SE}=0}^{\infty} P_{k_{sl},k_{sat},k_{SE}} \cos[\pm(\frac{2k_{sat}}{P})\omega t + (k_{sl}S_1 \pm 2k_{sat}P \pm k_{SE})\theta] \tag{4}$$

Then, the air-gap flux density of LSPMSM at steady state can be calculated utilizing Ampere's circuital principle as:

$$B(t) = P_T(t) \int \mu_0 j_s(\theta, t) d\theta \tag{5}$$

where μ_0 is the vacuum permeability and j_s is the current density of stator interior surface.

$$j_s(\theta, t) = \sum_{k_j=1}^{\infty} J_s \sin(k_j \omega t - P\theta)] \tag{6}$$

where k_j is an integer number. Substituting Expression (4) and (5) results in:

$$B(t) = \frac{\mu_0 J_s}{P} \sum_{k_j=1}^{\infty} \cos(k_j \omega t - P\theta) \sum_{k_{sl}=0}^{\infty} \sum_{k_{sat}=0}^{\infty} \sum_{k_{SE}=0}^{\infty} P_{k_{sl},k_{sat},k_{SE}}$$

$$\times \cos[\pm(\frac{2k_{sat}}{P})\omega t + (k_{sl}S_1 \pm 2k_{sat}P \pm k_{SE})\theta] \tag{7}$$

Expression (7) can be rewritten in the following form:

$$B(t) = \frac{\mu_0 J_s P_{k_{sl},k_{sat},k_{SE}}}{P} \sum_{k_{sl}=0}^{\infty} \sum_{k_{sat}=0}^{\infty} \sum_{k_{SE}=0}^{\infty} \cos[(k_j \pm (\frac{2k_{sat}}{P}))\omega t$$

$$+ (\pm k_{sl}S_1 \pm 2k_{sat}P \pm k_{SE} - P)\theta] \tag{8}$$

Eventually, Expression (8) can be finalized as follows:

$$B(t) = \sum_{\lambda,\xi} B_{\lambda,\xi} \cos[(k_j \pm \left(\frac{\lambda}{P}\right))\omega t \pm \xi\theta] \tag{9}$$

$$\lambda = 2k_{sat}$$

$$\xi = \pm k_{sl}\theta \pm 2k_{sat}P \pm k_{SE}\theta - P\theta$$

The MMF of the stator is expressed as:

$$F_s = \frac{B(t)}{P_T(t)} \tag{10}$$

The stator current involving space and time harmonics is as follows:

$$i(t) = \sum_{\lambda,\xi} I_{\lambda,\xi} \cos[(k_j \pm (\frac{\lambda}{p}))\omega t \pm \xi\theta] \tag{11}$$

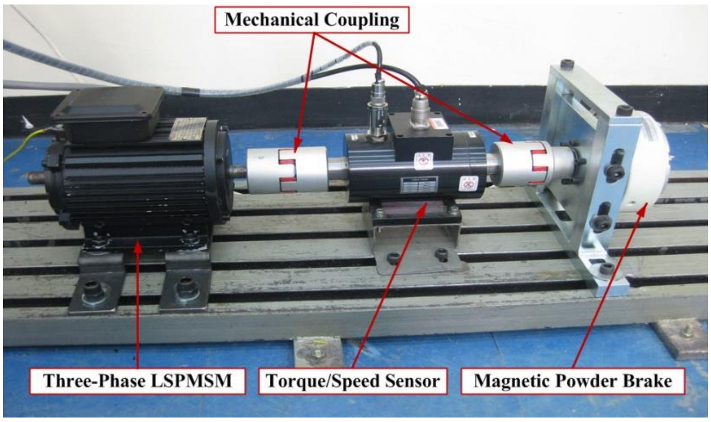
Expression (11) is simplified for sinusoidal supply voltage as:

$$i(t) = \sum_{\lambda,\xi} I_{\lambda,\xi} \cos[(1 \pm (\frac{\lambda}{p}))\omega t \pm \xi\theta] \tag{12}$$

where λ = 1, 3, 5, ...

3. Experimental Setup

The experimental test rig is shown in Fig. 2(a). The characteristics of LSPMSM for both healthy and faulty cases is a 1-hp, 4-pole, three-phase LSPMSM with the specification as mentioned in Table 1. The motor is directly fed by the grid power supply while the stator windings are Y connected and the current nominal value is 1.28 A. The LSPMSM is coupled to torque/speed sensor in order to measure the torque value in different operation condition. On the other side, a mechanical load has been provided by a DC-excited magnetic powder brake (MPB) coupled to torque/speed sensor. The specific load torque level could be furnished to the motor shaft by controlling the input dc voltage of MPB. There are some advantages to use MPB instead of generator for mechanical load such as stability of load torque value. The schematic of test rig is displayed in Fig. 2(b). This shows a brief information about the LSPMSM, MPB, current transducer and data acquisition system. This system is used to sample the stator current noninvasively while the motor operated in the steady state condition. The stator current is measured using current probe model Pico-PP264 and data acquisition carried out by PicoScope 4424 which is a high resolution USB-connected system including an industry-leading signal acquisition path, provides 80 MS/s ADC on each channel with 1% accuracy. Only one phase current signal is required to be recorded for detection process. The recorded signals are analyzed by a computer-based signal processing program.



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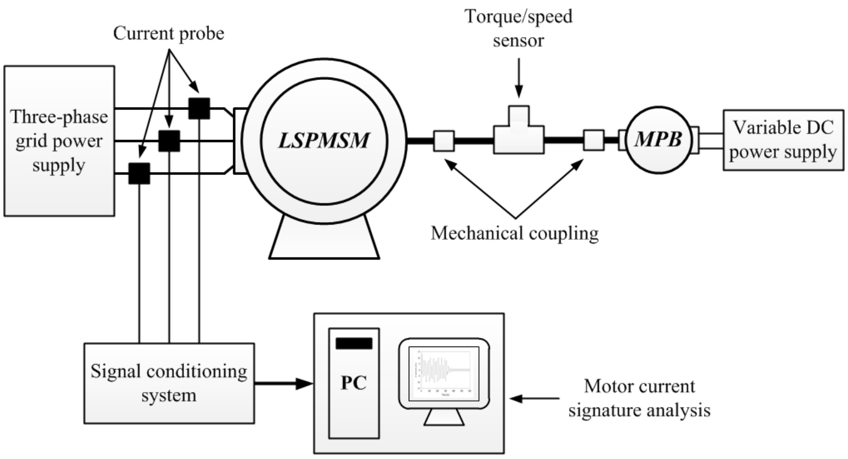


(b)

Fig. 2 (a) Experimental test rig (b) Schematic view of system

Table 1 Specification of three-phase LSPMSM

Rated output power (HP)	1
Rated voltage (V)	415
Rated frequency (Hz)	50
Number of Poles	4
Rated speed (RPM)	1500
Connection	Y
Air-gap length (mm)	0.30
Remanent flux density of magnets (T)	1.235

3.1. Noninvasive Implementation of Static Eccentricity in Three-Phase LSPMSM

Hitherto, different approaches have been proposed to beget eccentricity fault in IM and PMSM for the purpose of fault diagnosis. Some of the introduced approaches invasively modify the configuration of motor and damage it permanently. In some cases, changing the fault severity is impossible while others require accurate measuring device to specify the fault percentage. This noninvasive method makes the LSPMSM temporarily eccentric without any costly measuring device while the fault severity can be easily changed and after all, motor returned to the normal condition for further usage. Accordingly, the original bearings of LSPMSM are changed by a new set of bearing with larger inner diameter and smaller outer diameter result in creation of free space between the shaft and bearings and also between the bearings and the housing of end shields. The fault can be created by filling these free spaces with special-made concentric or non-concentric inner and outer rings. A specific screw is applied to prevent sliding of inner ring on the rotor shaft and inside the bearing. Meanwhile, a particular slot is made for outer ring to fix it properly in the housing. The protective layers are designed for inner ring to keep the outer ring inside the housing at any probabilistic misalignment and to avoid friction and scrubbing between the inner ring and bearing or outer ring. The prototype of eccentricity simulation strategy is shown in Fig. 3.

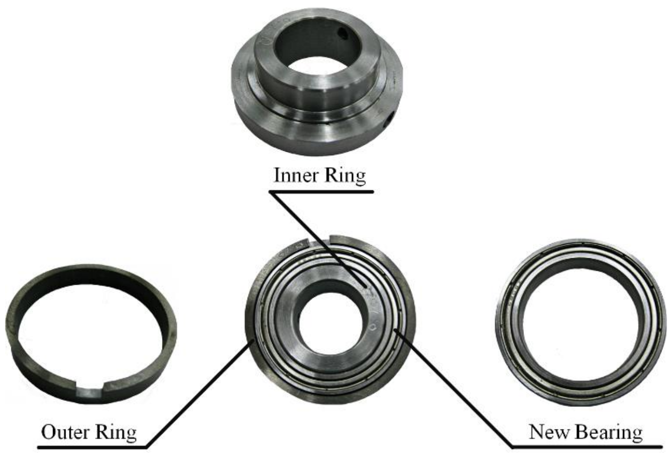


Fig. 3 Inner, outer rings and new bearing before and after assembly

Static eccentricity is created by fixing the concentric inner rings between the new bearings and shaft on both ends of LSPMSM and non-concentric outer rings between the new bearings and housings of both end shields. The non-concentric outer ring is made via offset the center of ring based on the specific measures, so the severity of static eccentricity can be varied by fixing the outer rings with different values of offset. This strategy is followed to create 20%, 35% and 50% static eccentricity in LSPMSM.

4. FEM BASED SIMULATION OF THREE-PHASE LSPMSM

FEM based analysis provides an accurate tool for modeling of electrical motors since it includes material characteristic, nonlinearity and complexities. The reliability and accuracy of FEM for analyzing the electric motor performance is more than other method such as winding function theory (WFT). FEM is a precise method because the inductances can be directly calculated by field analysis which leads to various conditions such as slot effects, saturation and etc. to be spontaneously taken into account [9].

The three-phase LSPMSM is simulated in 2-D environment based on FEM utilizing Maxwell 2-D software to calculate the stator current spectrum with eccentricity effect. The simulations are performed at the same condition of the experimental study such as motor specification, static eccentricity percentages, sampling frequency, sampling time and frequency resolution. The geometrical and physical complexities of LSPMSM like stator, hybrid rotor and shaft, stator winding distribution, non-uniform permeance of air-gap due to eccentricity, nonlinear characteristics of stator and rotor cores and permanent magnets materials are considered for modeling study. The 2-D model of LSPMSM is described in Fig. 4.

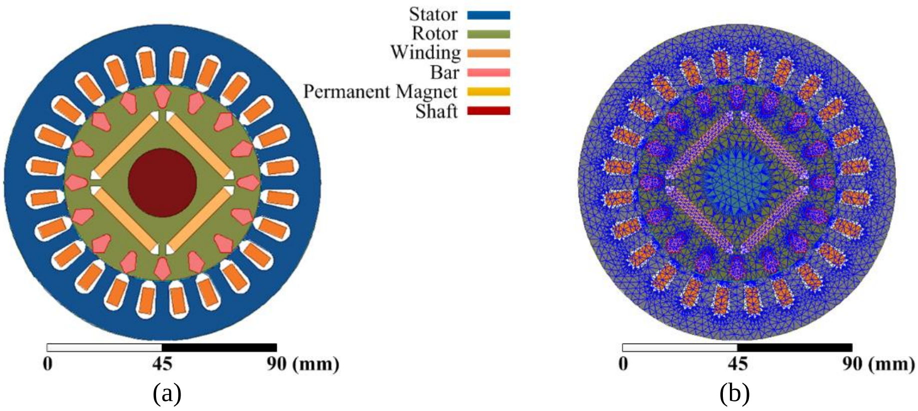


Fig. 4 Cross-section of three-phase LSPMSM: (a) geometric configurations and (b) plotting of the mesh

Three-phase sinusoidal voltage is injected to stator windings. A solver with time integration method based on backward Euler is employed to solve the steady state current of LSPMSM. Magnetic field distribution in LSPMSM is calculated by FEM and the stator current signal is computed. The proposed LSPMSM is simulated with different degrees of static eccentricity by shifting the center of rotor from the center of stator while the rotor rotates concentrically with its own center as mentioned in section 2. The non-uniform air-gap magnetic field due to static eccentricity in LSPMSM produces asymmetrical current, torque and speed. Several harmonic components will be manifested in magnetic flux, stator current of the motor. Detection of the harmonic components in stator current will nominate a precise fault signature for static eccentricity diagnosis in LSPMSM.

5. Stator Current Signature Analysis in Three-Phase LSPMSM

Investigation of static eccentricity fault detection in LSPMSM is pursued by analyzing the stationary spectrum of stator current in frequency domain applying power spectral density (PSD) technique. Current spectrum is stored with the sampling frequency of 5 kHz over a total sampling time of 6.5 s which allows the analysis of the signals with a minimum frequency of 0.15 Hz. In order to evaluate the static eccentricity at early stages, the lower degree of fault is also considered. The inherent eccentricity up to 10% normally disregards in electrical motors [2]. Flowchart of rotor asymmetry fault analysis is displayed in Fig. 5. In particular, two different configurations are tested in this study such as:

1. healthy LSPMSM (0% static eccentricity)
2. LSPMSM with 20, 35 and 50% static eccentricity

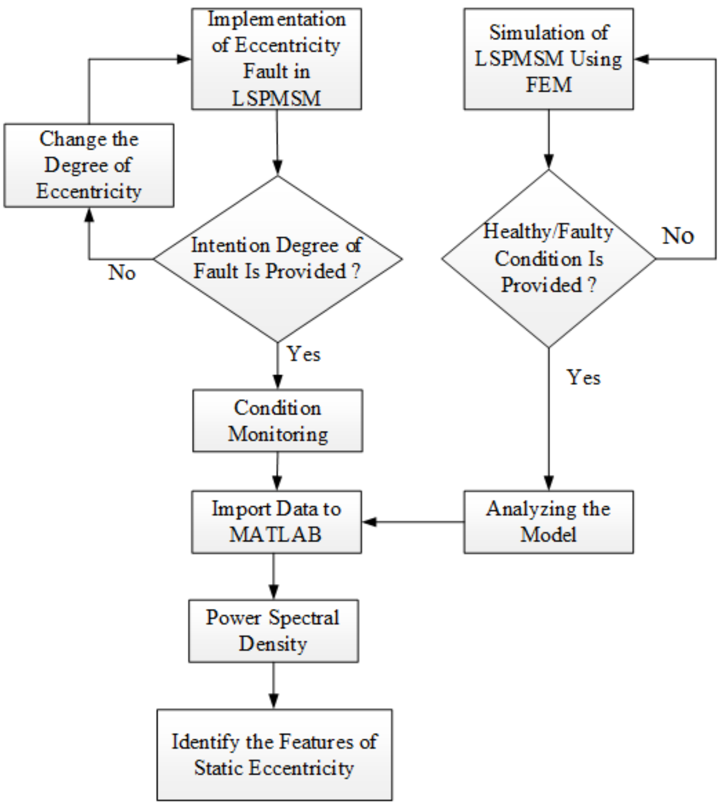
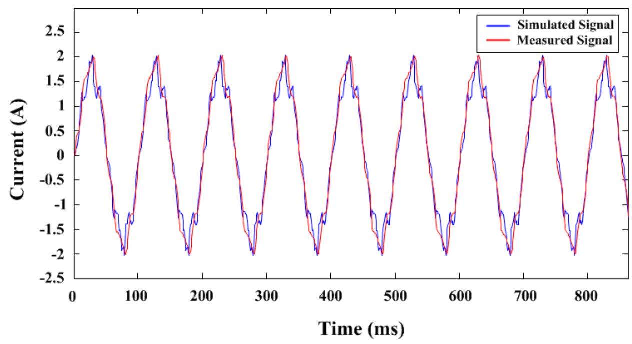


Fig. 5 Flowchart of static eccentricity detection strategy for LSPMSM

The time variation of simulated and measured steady state current signal for three-phase LSPMSM in healthy condition and under static eccentricity at full load operation is indicated in Fig. 6. The effect of static eccentricity is intangible in time variation of current signal. The amplitude of sideband components around fundamental frequency which is extracted by signal processing of the stator current in frequency domain can be used for precise eccentricity fault detection. Harmonics of controllers always have influenced on the previous eccentricity detection methods in synchronous motors. Due to unique property of LSPMSMs, the purpose of this research is to study the motor behavior under the static eccentricity condition without any driver.



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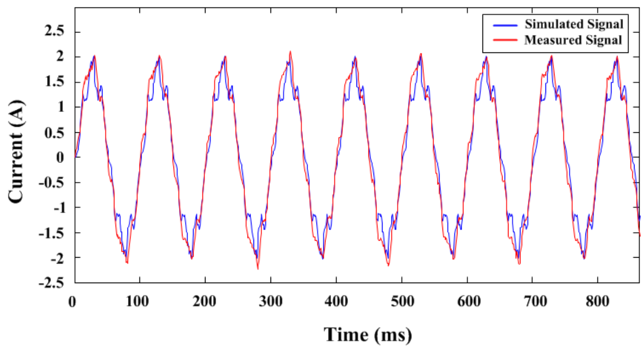


(b)

Fig. 6 The stator current signal of LSPMSM: (a) healthy condition (b) with 50% static eccentricity

This article is dedicated to identify an index for eccentricity fault detection based on MCSA. The normalized line current spectra of LSPMSM at healthy condition and with 20% static eccentricity are displayed in Fig. 7. Comparison between healthy and faulty conditions with 20% static eccentricity shows increment in the amplitude of harmonic components around fundamental frequency.

Low percentage of static eccentricity generates harmonic components at frequencies of 25 Hz, 75 Hz and 125 Hz in the stator current. The visibility of these harmonics is prominent to nominate them as static eccentricity fault signature for incipient detection and maintenance procedure in LSPMSMs. Despite the eccentricity-related harmonics, the main field also generates harmonics because of associated rotating force wave at frequencies 50 Hz, 100 Hz, 150 Hz, 200 Hz and etc., while the amplitude of main field harmonics is superior to the eccentricity components so the eccentricity components at frequencies 50 Hz, 100 Hz, etc. is negligible.

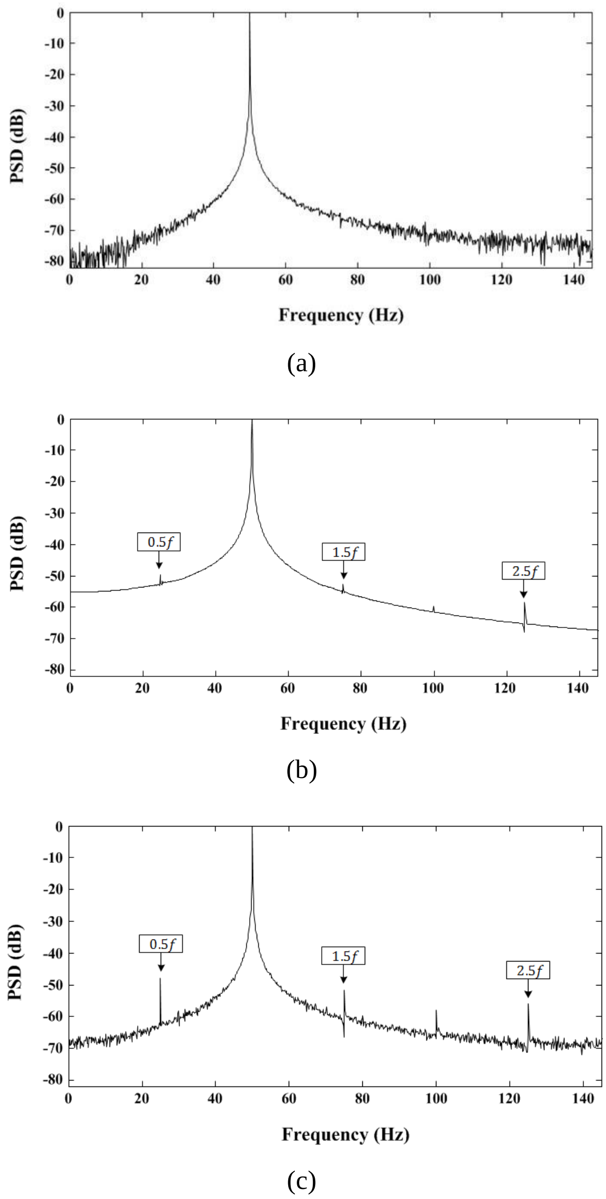


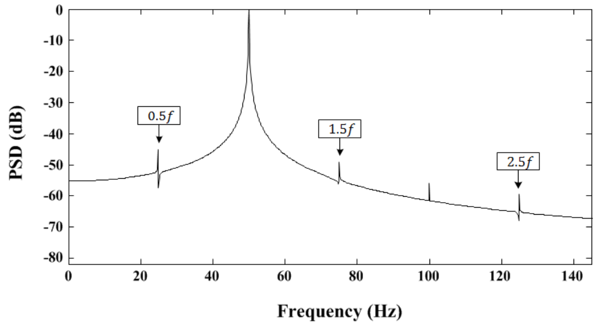
Fig. 7 PSD spectra of current signal for: (a) healthy LSPMSM (b) simulation result of 20% static eccentricity (c) experimental result of 20% static eccentricity

Accordingly, the nominated signatures can be effective for LSPMSM in order to detect the static eccentricity at early stages. It is derived from the results that the following index can be introduced as an appropriate frequency pattern to pinpoint the static eccentricity related signatures in three-phase LSPMSM.

$$f_{static} = \left[1 \pm \frac{\lambda}{p}\right] f \tag{13}$$

where f_{static} is the harmonic components due to static eccentricity in LSPMSM, λ is an odd integer value, p is the number of pole pair and f is the fundamental frequency. Proposed index can be used to detect the static eccentricity in LSPMSMs with different number of pole pairs due to variable p in expression (13).

Investigation on the influence of fault severity percentage in current signal is a significant issue in order to estimate the ability of proposed index. The PSD of stator current spectrum for LSPMSM with 35% and 50% static eccentricity are demonstrated in Fig. 8 and Fig. 9, respectively.



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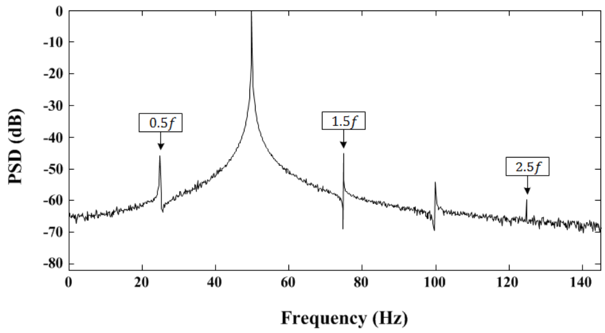

(b)

Fig. 8 PSD spectrum of current signal with 35% static eccentricity: (a) simulation result (b) experimental result

Fig. 8 exposes a remarkable rise of the amplitudes of harmonic components due to 35% static eccentricity at nominated frequencies. This incremental rate of amplitudes proofs the ability of Expression (13) to detect the static eccentricity and its degree. On the other hand, comparison between Fig. 7 and Fig. 8 illustrates that amplitudes of harmonic components are increased while the static eccentricity degree changed from 20% to 35%.

PSD spectrum of stator current in Fig. 9 indicates that the amplitude of harmonic components at low frequencies further increases due to 50% fault severity. The static eccentricity degree of 50% increases the amplitude of 25 Hz to -36 dB, 75 Hz to -40 dB and 125 Hz to -44 dB that are significantly far from the amplitudes of these components at healthy condition as well as faulty condition with 20% and 35% of static eccentricity. Thus, the amplitudes of harmonic components at frequencies which determined by Expression (14) are a suitable index for detection of static eccentricity fault in three-phase LSPMSM. By the way, the proposed feature is capable to be used for predicting the static eccentricity degree in this type of motor.

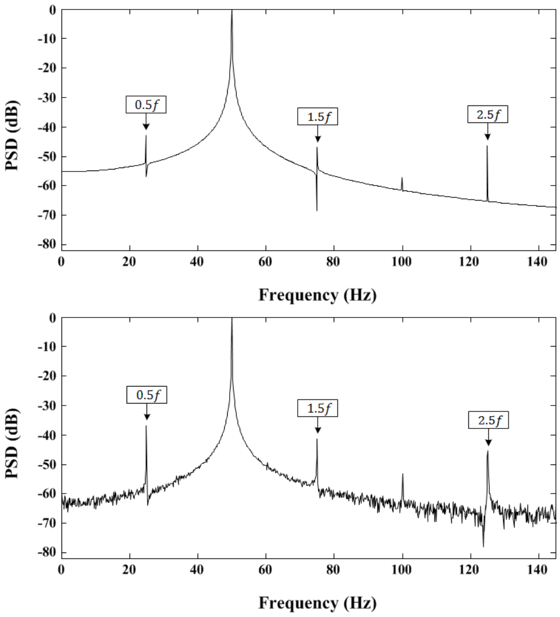

Fig. 9 PSD spectrum of current signal with 50% static eccentricity: (a) simulation result (b) experimental result

The evaluation of proposed index for various loading levels and fault severity are summarized in Table 2. These amplitudes increase as a function of fault severity and vary in a subtractive manner proportional to load level. Effect of load variation on amplitudes of eccentricity-related harmonics depends on the type of electrical motor. Amplitudes of eccentricity-related harmonics in PMSM remain constant versus load variation at fixed degrees of fault [8]. Despite the similarity of PMSM and LSPMSM as a synchronous motor but their reactions to static eccentricity fault are not the same due to their different configurations. This observation again demonstrates the importance of motor type in fault detection process. A comparison between the proposed method and previous techniques is summarized in Table 3.

Table 2 Amplitudes of harmonic components in current spectrum of LSPMSM

Index	Load (%)	Static Eccentricity Degree (%)							
		Simulation result (dB)				Experimental result (dB)			
		0%	20%	35%	50%	0%	20%	35%	50%
$\left[1-\frac{1}{p}\right]f$	0	-46	-42	-42	-40	-49	-44	-45	-41
	20	-47	-40	-39	-35	-44	-34	-32	-30
	60	-50	-45	-43	-40	-46	-42	-37	-35
	100	-55	-50	-45	-43	-68	-47	-43	-36
$\left[1+\frac{1}{p}\right]f$	0	-48	-44	-43	-40	-52	-48	-45	-42
	20	-50	-40	-37	-32	-53	-41	-39	-34
	60	-51	-49	-44	-42	-53	-46	-40	-46
	100	-54	-52	-49	-47	-57	-53	-46	-40
$\left[1+\frac{3}{p}\right]f$	0	-52	-46	-43	-41	-61	-48	-45	-44
	20	-55	-47	-40	-39	-63	-51	-42	-38
	60	-59	-50	-46	-43	-66	-55	-44	-41
	100	-63	-58	-59	-46	72	-56	-58	-44

Table 3 Comparison between eccentricity detection methods

Ref.	Monitoring Technique	Motor Type	Fault Type	Achievement
[3]	Current	LSPMSM	Static Eccentricity	▪ A simulation study has been done. ▪ An index has been proposed for fault detection. ▪ Loading condition is not considered. ▪ The method is not examined experimentally.
[10]	Current, Speed, Torque	LSPMSM	Static Eccentricity	▪ Motor performance has been analyzed under healthy and faulty condition. ▪ Mathematical and simulation studies are performed. ▪ No index has been proposed for detection.
[11]	Current	PMSM	Static and Dynamic Eccentricity	▪ A simulation and experimental examination has been done. ▪ Specific frequencies under different loading levels have been analyzed.
[12] & [13]	Current	IM	Static Eccentricity	▪ Effect of rotor shapes on fault related features in IM has been investigated. ▪ It has been shown that rotor slot skewing reduces the fault-related components.

6. CONCLUSIONS

The stator current spectrum of LSPMSM at both healthy and faulty condition during its steady state operation was examined to identify the features of static eccentricity and propose an index for precise fault detection at early stage. The stator current signal of motor was measured noninvasively. Different degrees of static eccentricity were created in the motor by a noninvasive method and then the motor returned to the healthy condition for continuing its normal operation. A three-phase LSPMSM was simulated using FEM with the same conditions of the laboratory test such as motor specification, static eccentricity percentages, sampling frequency, sampling time and frequency resolution. The effects of static eccentricity on the harmonic content of stator current spectrum were scrutinized in frequency domain utilizing PSD analysis to propose a criterion for fault detection in this hybrid type of electrical motors. It is concluded that the low frequency components are the accurate signatures for static eccentricity in LSPMSM which can be specified by frequency pattern $[1 \pm \lambda/p]f$ as an index for this fault. The higher degrees of fault increase the amplitude of these components which can be utilized to estimate the degree of static eccentricity. In an opposite manner, higher levels of load reduce the amplitudes of eccentricity-related components in the stator current. Accordingly, this frequency pattern is reliable for static eccentricity detection at early stage.

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