Diagnosis and detection of dynamic eccentricity fault for permanent magnet transverse flux generator

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Abstract
The authors analyse no-load and full-load performance of a permanent magnet transverse flux generators (PMTFGs) in fully aligned condition as well as under different types of mechanical faults including static eccentricity (SE), dynamic eccentricity (DE), inclined rotor (IR) and run-out (RO) faults. An analytical model is developed to calculate the air-gap permeance. This permeance is used to estimate the flux density and back-embotive force in the healthy and faulty machine. Performance of the machine is predicted using the proposed analytical model and verified by comparing it with the results obtained using three-dimensional time stepping finite element method. Finally, the spectra of stator current in the PMTFG under SE, DE, IR and OR faults are determined through which the amplitude of side-band components with a specific frequency pattern is extracted. It can detect the eccentricity fault precisely, recognise its type and determines its severity.

1 | INTRODUCTION
In a magnet transverse flux machines (PMTFMs), direction of magnetic flux will be transverse to the direction of PMs rotation. In addition, the stator winding includes a ring-shaped coil placed into the segmented cores.

Various transverse flux machine structures have been proposed so far can be classified into synchronous type and reluctance type [1,2]. If the PMs are mounted on the rotor core surface or buried into the rotor core, then the machine is called as PMTF synchronous machine [3,4]. If there is no PM on the rotor, then the machine is called as a reluctance transverse flux machine (RTFM) [5]. The PMTF motor develops larger torque density than the RTFM. Meanwhile, manufacturing cost of the RTFM is lower while its reliability is higher. Thus, the cost and characteristics of machines should both be considered.

Applications of transverse flux machines usually include traction motors, propulsion systems and direct drive wind generators where low speed and high torque are needed, particularly, its application in wind power generator is of great interest. In PMTFG, the flux produced by PMs travels across the air gap and complete its path through the segmented stator core, which in turn induces voltage in the stator winding [6]. The electromagnetic energy conversion takes place in the air gap. Therefore, any factor disturbing the air gap balance leads to non-uniform magnetic flux distribution and this adversely affects the performance of the machine. The disturbance can be attributed to the faults, design errors, coupling eccentricity and bearing faults. The eccentricity faults fluctuate the air gap, which in turn disturbs the uniform air gap flux. Then, it is important to introduce an effective eccentricity fault diagnosis method to prevent further damages to the wind generator.

Many eccentricity fault diagnosis methods in electrical machines have been introduced so far [7–16]. Depending on the rotor axis position relative to the stator, the eccentricity faults are mainly divided into static eccentricity (SE), dynamic eccentricity (DE), run-out (RO) and inclined rotor (IR) faults [17–19]. Generally, the air gap permeance is estimated and then performance parameters such as induced voltage and winding current for different types of eccentricity are determined using the air gap flux density. Finally, the frequencies corresponding to each eccentricity fault is detected using spectrum analysis [20–22].

When compared to longitudinal flux machines, the eccentricity fault analysis in transverse flux machine becomes even more prominent since PMTFM enjoys two air gaps in its structure. Otherwise it can be stated that any eccentricity faults in PMTFM develops two non-uniform air gaps, and therefore, when compared to longitudinal flux machines, the non-uniformity of the magnetic flux distribution in PMTFM more adversely affects the performance of the machine. However, it
seems there is no direct research work addressing the eccentricity fault analysis in transverse flux machine. Therefore, the main contribution of this work is to investigate the impact of eccentricity faults on the performance of transverse flux machines. For this purpose, different types of mechanical faults are first addressed and eccentricity index corresponding to each fault is determined. Then, the index is used to predict the permeance of the air gap and as a result the magnetic flux density. The authors analytically investigate the 5 types of faults in their experiments. However, more common eccentricity fault has been simulated analytically, numerically and experimentally verified. A similar procedure may be followed to detect other four faults. This paper has studied these three faults only using finite element method (FEM). Finally, since harmonic components produced by the magnetic flux density in faulty condition appears in stator winding current, the current and its signature can be used to detect frequencies corresponding to dynamic eccentricity fault.

2 | STUDIED MACHINE CONFIGURATION

Figure 1 shows the overall structure of the proposed PMTFG [5]. The stator core of the PMTFG is made of steel lamination with a semi-closed structure. The segmented cores, then, are embedded in a non-ferromagnetic housing. It is preferable to use a non-conductive material for housing to eliminate eddy current losses; however, aluminium housing is used here for its manufacturing ease, light weight and improving the output power density. Also, the armature winding consists of a ring-shaped coil placed in the stator core. The rotor of the machine, unlike the conventional PMTFG, consists of a single row of PMs rotating between the two poles of each stator core. As the number of PMs is reduced by half, the PMs cost is reduced and as a result the overall cost of the generator is decreased. Table 1 presents the specifications and geometrical dimensions of the generator.

### Table 1 Geometrical dimensions and specifications of proposed PMTFG

| Parameter                  | Symbol | Unit | Value |
|----------------------------|--------|------|-------|
| Speed                      | \(n_s\) | rpm  | 200   |
| Frequency                  | \(f_s\) | Hz   | 40    |
| No. of stator poles pairs  | \(P_s\) |      | -     |
| No. of rotor poles pairs   | \(P_r\) |      | -     |
| No. of coil turns          | \(N\)  |      | 192   |
| Stack length               | \(h_s\) | mm  | 30    |
| PM diameter                | \(l_{pm} \times h_m\) | mm \(\times\) mm | 11.3 \(\times\) 5 |
| Stator inner/outer diameter| \(D_i/D_o\) | mm \(\times\) mm | 97/155 |
| Air gap length             | \(G\)  | mm  | 1     |
| Remanence of PM            | \(B_r\) | T   | 1.3   |
| Core window size           | \(W_p \times h_k\) | mm \(\times\) mm | 15 \(\times\) 14 |
| Stator tooth size          | \(W_p \times l_p \times h_k\) | mm \(\times\) mm \(\times\) mm | 10 \(\times\) 10 \(\times\) 3.5 |
| Wire diameter              | \(D_w\) | mm  | 0.45  |
| Current density            | \(J\)  | A/mm\(^2\) | 6     |

3 | MECHANICAL FAULT

Mechanical faults can be divided into eccentricity faults and torque oscillations. Torque oscillations are mainly caused by a fault outside the machine (the load or prime mover side) while the eccentricity fault is more pertinent to the defects inside of machine. The major origins of torque oscillations are: unbalance load (unbalance input torque in generator), shaft misalignment, gearbox fault and bearings fault [15]. Rotor eccentricity is a common fault occurring even before installation of electric machine. This may happen during manufacturing process or shipping. Moreover, unbalanced load, misalignment coupling, inappropriate assembling and bent rotor shaft can cause rotor eccentricity [25]. Eccentricity fault can cause some problems such as noise, vibration, unbalanced magnetic pull and torque pulsation [8]. In both SE and DE faults, the air gap lengths in different rotor angles are not equal anymore. This leads to non-uniform magnetic flux distribution in the air gap.
which may affect back-EMF waveforms. Eccentricity also impacts the air gap magneto-motive force (MMF), which in turn leads to change in winding inductance [26].

3.1 Static, dynamic and mixed eccentricity faults

For the SE fault, the rotational axis of the rotor coincides with the symmetrical axis, but it displaces from the stator symmetrical axis [10, 11]. So, the point of minimum air gap length remains fixed in the space. The DE fault occurs when the point of the minimum air gap length rotates along with the rotor. In the other words the stator symmetrical axis coincides with the rotor rotational axis in the DE fault, but the rotor symmetrical axis is displaced [10-15].

The eccentricity fault factor is defined as follows [12]:

\[
\gamma = \left| \frac{g - g_0}{g_0} \right| \times 100, \text{ ForSEF} = \left\{ \begin{array}{l}
\frac{|O_1 O_w|}{g_0} \\
\frac{|O_r O_w|}{g_0} \\
\frac{|O_1 O_r|}{g_0}
\end{array} \right\} \times 100, \text{ ForDEF}
\]

\[
O_r, O_s, \text{ and } O_w \text{ are the rotor, stator and rotation symmetry centres, respectively. The } |O_1 O_w|, |O_r O_w| \text{ and } |O_1 O_r| \text{ are called the static, dynamic and mixed transfer vectors. Figures 2 and } 4 \text{ show the centre positions of stator, rotor and rotor rotation under the SE, DE and ME where } g \text{ is the gap length under eccentricity fault, and } g_0 \text{ is the air gap length in the fully-aligned condition. The } \left| \frac{g - g_0}{g_0} \right| \text{ value depends on the eccentricity fault type. For example, in the SE fault, the SE factor } (\gamma_{SEF}) \text{ can be defined as follows [23]:}
\]

\[
\gamma_{SEF} = \frac{|O_1 O_w|}{g_0} = \frac{g_{\text{max}} - g_{\text{min}}}{2g_0} \times 100
\]

and the DE factor } (\gamma_{DEF}) \text{ as:}

\[
\gamma_{DEF} = \frac{|O_r O_w|}{g_0}
\]

where } \gamma_{SEF} \text{ is the SE factor, } \omega_r = P \omega/P_r, \text{ and } \xi_M \text{ for SE-fault case is zero and under the DE fault is } \xi_s \text{ (the rotor
mechanical angle. The eccentricity in actual machinery often exhibits a combination of both types of eccentricity [16,17] and is defined as mixed eccentricity (ME). These types of faults could be formulated by following equations based on their geometrical behaviour.

### 3.2 | Inclined rotor fault

Bearings wear causes IR fault in which the axis of the rotor and that of stator inclines against each other. Figure 4a shows the schematic of the proposed machine under the IR fault. It is noted that because of the high value of the ratio of diameter to the length and horizontal installation of the proposed PMTFG, it is strongly exposed by the IR fault.

Although the distribution of air gap length through rotor circumference is non-uniform under the IR fault, it is time-independent. So, IR factor \( \gamma_{IRF}(z) \) is defined as follows:

\[
\gamma_{IRF,0} = \frac{(R_r - r)}{g} \times 100
\]

where \( R_r \) is the outer radius of the rotor and \( r \) is calculated as follows:

\[
r = R_r \cos \theta
\]

Therefore, \( \gamma_{IRF,0} \) can be written as a function of the deviation angle as follows:

\[
\gamma_{IRF}(z) = \begin{cases} 
-2\gamma_{IRF,0} \times z/W_p + \gamma_{IRF,0} & 0 < z < W_p/2 \\
(2z - W_p)\gamma_{IRF,0}/W_p & W_p/2 < z < W_p
\end{cases}
\]

### 3.3 | Run-out fault

Note that the stator axis, rotor axis and the rotational axis coincides under RO fault. But, the rotor or stator displaces axially against the stator/rotor. Figure 4b shows the proposed generator under exaggerated level of the RO fault. In bearings, the RO causes vibration of the machine and increases the load on the bearings. The level of the RO fault is usually defined as a percentage of the machine length. So, the RO factor, \( \gamma_{ROF} \), can be defined as follows:

\[
\gamma_{ROF} = z/W_p \times 100
\]
following detection.

Theorem and teeth, for example, air flux side view material faulty ideal the No on the magnets rotor full the of used wax density e yok, moni- for air motor of machine: crosses. in meanance line that stator ap The the flux is g distribution, line equal. provides e produced thic the magnets re ∞, The, are stator in magnets field flux air hav gap the and density mechanic no to in the the shape magnetic the density flux set the in minimum assumptions magnets are relativ to tooth. mined model. is analysed of abov al from The corner air assumed be The a apkness µi be the a a and iron the fault estimation be. Then, its density the crosses the continuous in the is magnet the circular of about is meance. Magnetic fluxes is i.e. flux air should flux the g gap mac yok e the g density the continuous can The the proposed faults the teeth The the assumed magnetic follow air assumed the rotor leakage dicularly a and considered. in circuit. ap just g infor flux are product to tooth. The proposed diagnostic technique is based on the airgap magnetic field characteristics. The airgap magnetic flux density is defined as the difference between the flux density at the surface of the airgap and the flux density at the surface of the yoke. The airgap magnetic flux density is given by the expression:

\[ B_{gap} = B_{yoke} - B_{airgap} \]

where \( B_{yoke} \) is the flux density at the yoke surface and \( B_{airgap} \) is the flux density at the airgap surface.

The airgap magnetic flux density is calculated using the finite element method (FEM) and the results are compared with the analytical approach.

The magnetic field provides full information on the stator, rotor and mechanical faults of the motor. Then, continuous monitoring of the air gap magnetic field can be used for fault detection. To analyse the air gap magnetic flux density, its permeance in the faulty machine should be calculated. The following assumptions are considered in the proposed model:

- The iron material is assumed to be ideal i.e. \( \mu = \infty \).
- The flux density distribution, on the side of the tooth is determined from the product of the flux density produced by the magnets and the relative permeance.
- The flux density in the air gap is assumed to have a trapezoidal wave shape.
- The flux that crosses the air gap is assumed to follow a straight line just above the magnet and a circular line centred about the corner of a tooth.
- The flux density crosses the magnets and the air gap perpendicularly.
- There is no leakage flux in the circuit.
- The fluxes in the air gap, the magnets, the rotor yoke, the stator teeth and the stator yoke are equal.
- No minimum thickness for the teeth and magnets are set in the model.

### 4 | MATHEMATICAL ANALYSIS OF MAGNETIC FIELD

Magnetic field provides full information on the stator, rotor and mechanical faults of the motor. Then, continuous monitoring of the air gap magnetic field can be used for fault detection. To analyse the air gap magnetic flux density, its permeance in the faulty machine should be calculated. The following assumptions are considered in the proposed model:

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- There is no leakage flux in the circuit.
- The fluxes in the air gap, the magnets, the rotor yoke, the stator teeth and the stator yoke are equal.
- No minimum thickness for the teeth and magnets are set in the model.

\[ E_{ph,R}^{m} = E_{ph}^{m} (1 - \gamma_{ROF}) \quad (12) \]

### 4.1 | Air gap permeance and flux density

Figure 5a shows the inverse air gap function \( g'(x, y) \). It means that there is an alternative expression for the air gap in the
asymmetrical case. The inverse air gap function can be demonstrated as follow:

\[
\Lambda_{ag}(x,t) = \mu_0 g^{-1}(x,t) = \mu_0 \left[ \frac{I_p}{l_p + l_c} \left( \frac{b_{pm}}{2g + \frac{b_{pm}}{\mu_{pm}}} \right) \right]
\]

+ \sum_{m=1,3,5,...} \left( \frac{2}{m\pi} \right) \left( -\frac{1}{2g + \frac{b_{pm}}{\mu_{pm}}} \right) \sin \left( \frac{l_p}{l_p + l_c} \pi \right) \cos \left( \frac{2m\pi}{l_p + l_c}(x) \right)

(13)

The air gap flux density generated by surfay the PMs can be estimated by a rectangular waveform, that is, it is non-zero over the length of the PM, otherwise, it takes a value of zero. However, to achieve a more realistic waveform for the flux density, the concept of fringing effect is employed to make the approximation closer to the actual waveform. Assuming that fringing length \( l_{frig} \) is half the length of the air gap, flux density produced by the PMs can be approximated as in bellow (Figure 5b):

\[
B_{pm}(x, t) = \sum_{m=1,3,5,...} \left[ \frac{16B_r}{\pi^2 m^2 l_{frig}^2} \sin \left( \frac{m l_{frig}}{4} \right) \cos \left( \frac{m (l_{frig} + l_w)}{4} \right) \right]
\]

\[
\cos \left( \frac{m\pi}{l_{pm} + l_w}(x) \right)
\]

(14)

The analysis is expanded to cover the on load case. In this case, the air gap flux density distribution \( B_{sw}(x) \) produced by the phase current in the stator windings is evaluated by the Fourier series:

\[
B_{sw}(x, t) = \Lambda_{ag}(x,t) \int j_{sw}(x,t) dx
\]

(15)

Assuming a stator sinusoidal MMF, the surface density of the stator current is as follows:

\[
j_{sw}(x, t) = f_{sw} \sin \left( \omega_t - \frac{2\pi}{l_p + l_c}x \right)
\]

(16)
The approach produces a stepping air gap flux density for the armature reaction field. Then, by assuming that the air gap flux density distributions due to the PMs and the stator currents are independent, the total air gap flux density distribution is obtained from adding the \( B_{PM}(x) \) to the \( B_{sw}(x) \)

\[
B_{ag}(x, t) \approx B_{pm}(x) + B_{sw}(x, t)
\]  

(17)

The magnetic flux amplitude of the proposed PMTFG actually depends on the difference of the air gap reluctance; the larger reluctance difference, the larger effective magnetic flux is. When one branch achieves the maximum PM magnetic flux, the other branch must have the minimum PM magnetic flux, which actually is regarded as magnetic leakage flux. The corresponding on-load back-EMF can be obtained as follows:
Figure 12 Proposed generator with IR/RO fault: (a) no-load induced voltage for IR fault and (b) no-load induced voltage for different severity of ROF

\[ e_{\text{ind}} = -k_w N_{\text{turn}} \frac{d\lambda_{\text{link}}}{dt} \] (18)

where \( N_{\text{turn}} \) is the number of coil turns, and \( k_w \) is the winding factor. In addition, the magnetic flux-linkage through a coil is as follows:

\[ \lambda_{\text{link}}(x, t) = W_p \int_0^{l_{\text{pm}}+l_{\text{a}}} B_{\text{al}}(x, t) dx \] (19)

5 | FINITE ELEMENT ANALYSIS

To analyse the performance of the proposed PMTGF in the fully-aligned condition with mechanical faults, 3D non-linear time stepping finite element method (TSFEM) is used. To study the full-load condition, three types of loads were considered: resistive load, inductive load and capacitive load. Figure 6 shows the schematic of the mesh and magnetic flux density of the PMTGF body.

5.1 | Proposed PMTGF under SE and DE fault

Figure 7 presents the analytically estimated no-load induced voltages of the generator in fully-aligned condition and under SE and DE faults. It is observed that the amplitude of the induced voltage in the healthy machine is 57 V while its value decreases to 51 and 48 V under 50% SE and 50% DE fault, respectively. Figure 8 shows the no-load induced voltage of the proposed PMTGF at the rated speed of 200 rpm using 3D FEM and the analytical model. It can be found that the amplitude of the induced voltages based on 3-D analytical model calculated is equal to 60 and 57 V, respectively.

The prediction of the analytical model has 5.26% error with respect to that of 3-D FEM. Recalculating the mentioned voltages using FEM shows less than 4.3% error. It means the no-load induced voltage under SE/DE fault was predicted using the proposed analytical model is 51/48 V, while it is 48.8/46.2 V using FEM. Furthermore, the induced voltage in resistive \( (R_{\text{load}} = 10.6 \, \Omega) \), inductive \( (0.8 \, \text{lag}) \) and capacitive \( (0.8 \, \text{lead}) \) loads is presented in Figure 9a. Considering the resistive load, the amplitude of the full load induced voltage is calculated and equal to 45 V using 3-D FEM; the value for inductive load is 34 V, while for capacitive load it is 56 V. Figure 9b shows the voltage versus current characteristic of the generator, calculated based on the 3-D FEM. It is observed from the figure that the voltage amplitude is reduced from 57V
in the no-load to 45 V in the full-load for the resistive load, while for inductive load the full-load voltage is 34 V and for capacitive load its value is 56 V. Considering different types of loads, the result of 3-D FEM at no-load and full-load conditions are presented in Table 2.

Furthermore, the effects of air gap variation in the generator with the SE and DE faults are investigated through harmonic analysis of back-EMF spectrum, rated output power and current waveforms.

In all simulations, a nominal resistive load is connected to the generator's terminals. Figure 10 presents the variations of the radial force density in the fully aligned machine and under SE and DE faults, based on the 3D FEM.

As seen, variations of unbalanced magnetic pull (UMP) under eccentricity faults are significantly increased. Table 3 summarises the output characteristics of the proposed PMTFG with SE and DE faults.

5.2 Proposed PMTFG with IR fault

The air gap length in the proposed machine is about 1 mm, the maximum rotation angle is $\beta = 3.5^\circ$ that leads to $\gamma_{IRF}$ max = 20%. So, the results of 3-D FEM are presented considering $\gamma_{IRF}$ max = 20%.

Variation of the radial and axial force density in the healthy generator and with IR fault is presented in Figure 11a,c based on the results of 3-D FEM. As excepted, the variations of radial force density with IR fault increase considerably. However, the variation of axial force density is slightly changed. The no-load induced voltage of the proposed PMTFG under different levels of IR faults is presented. It is seen that when increasing the fault percentage, the amplitude of the induced voltage is decreased.

5.3 Proposed PMTFG with RO fault

Figure 12b presents the no-load induced voltage of the proposed PMTFG under RO fault with different severities. It shows that when increasing the fault severity, the induced voltage amplitude decreases. Figure 11b,d indicate the proposed generator performance and the radial and axial force densities with 25% RO fault. It shows that the force density increases under RO fault compared to the healthy generator.

6 FAULT DETECTION

The mechanical faults in PM machines result in vibration, incidence of distortion in the speed and torque, increase in the loss and temperature rise depending on the type of the PM machine. When eccentricity faults occur, harmonic components are produced in the magnetic flux density of air gap. This in turn generates harmonic components in torque profile. Consequently, these harmonic components are observed in
stator winding current profile. In other words, harmonic components appeared in the stator current are in fact the components generated in the magnetic flux density of air gap. Hence, a method is introduced based on the of the current

signal monitoring. To this end, the stator current signal processing is used in which frequency spectrum of the stator current is generally utilised, and the amplitude of the harmonic components is introduced as the index and the frequencies desired for a frequency pattern. To start with, the fundamental component of air gap permeance function in the healthy condition is obtained by the following equation:

\[
\Lambda_{ag}(x, t) = \mu_0 \left[ \frac{l_p}{(l_p + l_c)(2g + h_{in})} \right] \cos \left( \frac{2\pi}{l_p + l_c}(x) \right) + \left( \frac{2}{\pi} \right) \frac{1}{h_{in}} \sin \left( \frac{l_p}{l_p + l_c} \pi \right) \cos \left( \frac{2\pi}{l_p + l_c}(x) \right)
\]

(20)

\[
\Lambda_{ag}(x, t) = \frac{1}{(g + \frac{h_{in}}{2\mu_{pm}})} \left[ K_1 + K_2 \cos \left( \frac{2\pi}{l_p + l_c}(x) \right) \right]
\]

To achieve the air gap permeance function in faulty condition, the uniform air gap should be replaced by the non-uniform air gap corresponding to each eccentricity faults. However, here, the dynamic eccentricity fault is thoroughly investigated. Therefore, by considering the changes in the air gap length in dynamic eccentric cases, the fundamental component of air gap permeance function in dynamic fault condition is determined by (21).
TABLE 4 Comparison of amplitudes of harmonic currents in healthy and faulty (DE fault) full-load generator – (FEM) results (with resistive load)

| Severity of eccentricity (%) | ASBC index | 0 | 25 | 50 |
|-----------------------------|------------|---|----|----|
| (1–5)/p_f       | 70        | 64 | 53 |
| (1–3)/p_f       | 73        | 65 | 55 |
| (1–1)/p_f       | 85        | 64 | 57 |
| (1–1)/p_f       | 80        | 68 | 60 |
| (1–3)/p_f       | 75        | 70 | 67 |
| (1–5)/p_f       | 80        | 73 | 69 |
| (1–7)/p_f       | 78        | 69 | 57 |

Since the ratio of $2g_0\mu_{pm}/b_m$ is much lower than 1, the terms with higher order than two can be neglected. Also, $\gamma_{DEF}$ and $\cos(\omega_l t, P_r, \xi_f)$ are bounded between $-1$ and $+1$, the above 2nd order terms can be neglected in Taylor's expansion and the air gap permeance with a good approximation is simplified as follows:

$$\Lambda_{ Ecc}(\varphi, t) = \left[ K_3 + K_4 \cos \left( \frac{1}{P_r} \omega_l t - \xi_S \right) \right] \quad (22)$$

Based on the Ampere’s circuit law, stator air gap magnetic flux density is defined as follows:

$$B_{ag}(x, t) = \Lambda_{ Ecc}(\varphi, t) \cdot \int j_{wr}(x, t) dx$$

$$= \int j_{wr} \cos(\omega_l t - \beta x) \left[ K_3 + K_4 \cos \left( \frac{1}{P_r} \omega_l t - \xi_S \right) \right]$$

$$= \left( K_5 \cos \left( 1 + \frac{1}{P_r} \right) \omega_l t - \beta x - \xi_S \right) +$$

$$\left( K_6 \cos \left( 1 - \frac{1}{P_r} \right) \omega_l t - \beta x + \xi_S \right) \quad (23)$$

Finally, by neglecting the above 2nd-order terms in the Taylor’s expansion, a comprehensive frequency pattern detecting the DE fault by the stator current frequency spectrum is determined as follows:

$$f_{ Ecc} = \left[ 1 \pm m \frac{1}{P_r} \right] f_p = 1, 3, 5, \ldots \quad (24)$$

The current and signature of electrical machine are the most commonly used signals in the fault diagnosis, because its measurement is straightforward, and contains the most required information for the fault diagnosis. In addition, the corresponding measurement process is non-invasive. Although it is not the most sensitive signal for the diagnosis, it is generally appreciated in industry. The occurrence and enhancement of harmonic components in the stator current spectrum increase the importance of signal processors. Therefore, tools such as FFT and Wavelet are used to analyse and process the stator current signal.
TABLE 5 Comparison of amplitudes of harmonic currents in healthy and faulty (DE fault) 75%-load generator – (FEM) results (with resistive load)

| Severity of eccentricity (%) | ASBC index | 0 | 25 | 50 |
|------------------------------|------------|---|----|----|
| (1-5/p)f_s                  |            | -67 | -62 | -50 |
| (1-3/p)f_s                  |            | -71 | -64 | -53 |
| (1-1/p)f_s                  |            | -81 | -61 | -54 |
| (1+1/p)f_s                  |            | -78 | -65 | -57 |
| (1+3/p)f_s                  |            | -72 | -68 | -64 |
| (1+5/p)f_s                  |            | -77 | -71 | -66 |
| (1+7/p)f_s                  |            | -75 | -65 | -55 |

TABLE 6 Comparison of amplitudes of harmonic currents in healthy and faulty (DE fault) 50%-load generator – (FEM) results (with resistive load)

| Severity of eccentricity (%) | ASBC index | 0 | 25 | 50 |
|------------------------------|------------|---|----|----|
| (1-5/p)f_s                  |            | -63 | -60 | -48 |
| (1-3/p)f_s                  |            | -69 | -57 | -51 |
| (1-1/p)f_s                  |            | -81 | -58 | -52 |
| (1+1/p)f_s                  |            | -77 | -61 | -53 |
| (1+3/p)f_s                  |            | -72 | -65 | -61 |
| (1+5/p)f_s                  |            | -75 | -70 | -63 |
| (1+7/p)f_s                  |            | -74 | -62 | -52 |

Tables 4–6 summarise the amplitude of these frequencies in the harmonic spectrum at the loaded and healthy condition 25% and 50% DE severities. It shows that the behaviour of the index at the two cases is alike, so, this index is robust against the load changes.

In the following, the stator current is in the state of charge in a safe state under a 25% and 50% DE fault spectral analysis. For this purpose, the FFT transform is used to calculate the stator current spectrum in healthy and faulty cases.

The first step in calculating the current spectrum is sampling the current or converting analogue signal to digital signal. It is noted that the resolution and sampling rate in the frequency analysis are significant. In the simulation process, the higher sampling frequency leads to more realistic results.

These frequencies depend on the number of PMs of rotor obtained by (24). Figure 13 exhibits the power spectrum density (PSD) of the stator current of a healthy and faulty 12 pole pairs machine with nominal frequency of 40 Hz. These harmonics confirm the frequency pattern of (24).

The mechanical eccentricity faults inject the harmonic to the stator current at the frequencies shown by (24). It can be noticed that the DE fault enhances the amplitude of side-bands components (ASBCs) at frequencies 23.33, 30, 36.46, 43.33, 50, 56.66 and 63.33 Hz. They are used as a competent criterion for the DE fault identification in the PMTFGs. Hence, the proposed frequency pattern and the index are valid for eccentricity fault diagnosis in any PMTFG. By increasing the eccentricity fault severity, the amplitude of the injected harmonic components can be increased.

7 | EXPERIMENTAL VERIFICATION

Figure 14 shows the stator, rotor and the assembled PMTFG. Figure 15a presents the experimental test setup of the generator. A three-phase inverter is employed to drive the generator at desired speed. The phase current sampled by a current sensor (LTS25) is converted into voltage signals using three resistors placed inside the current to voltage conversion box. Both voltage and current signals are the signals conditioned by an analog filter with 5 kHz cut-off frequency. The air-gap is varied at the free end. The sampling frequency acquire date is fixed at 4800 Hz. Also, one second of steady-state data is employed to plot the FFT in the healthy and faulty machine. Figure 15b shows the no-load induced voltage of the PMTFG. Figure 16a presents the nearly perfect sinusoidal waveform of the load current at 200 rpm. The measured THD of the load current is 1.65%. The experimentally measured and TSFEM estimated output power versus load currents of the PMTFG (before and after compensation) have been compared in Figure 16b. A good agreement between the predicted and experimental results has been achieved. Figure 17 depicts the efficiency and power factor of the generator at different loads. The measured full-load efficiency and power factor were 84% and 82.4%, respectively.

The simulation results based on the proposed method was further validated experimentally on a laboratory prototype. To create the DE fault, the bearing is fixed concentric with respect to the stator housing while the rotor housing is eccentric with regard to the shaft; thus, the centre of the rotation is varied when the rotor housing rotates. In this case, the minimum air gap rotates with the rotation of the rotor housing.

To start the fault detection process, the FFT is applied to the stator winding current signal in the steady-state condition. On the other hand, to obtain a high-resolution FFT for accurate detection of the eccentricity fault, a fixed-time interval for the stator current signal is considered.
Figure 18 demonstrates the high-resolution FFT for a long sampling time, covering all range of frequencies. First, the behaviour of healthy machine was analysed.

Then, the machine with 25% and 50% of eccentricity fault were tested at loaded condition. The band ranges from 0 to 65 Hz with a resolution of 0.2 Hz for the FFT analysis, was used to detect the harmonics produced by eccentricity fault.

The current harmonics spectra obtained from the test result in the healthy and faulty conditions is depicted in Figure 18, in which the harmonic orders of \((\pm m/p) f_s\) are generated by the non-uniform air gap between stator and rotor. A comparison between simulation results and those achieve by the test reveals that in both cases harmonics at frequencies \((\pm m/p) f_s\) appears in the current signal of the faulty machine. Therefore, the experimental results verify the simulation results. Table 7 summarises the amplitude of the excited frequencies in the harmonic spectrum at the full-load healthy condition, 25% and 50% DE severities. It indicates that the behaviour of the index of the two cases is similar. It means that this index is robust against the load change.

8 | CONCLUSION

At first, eccentricity index for each mechanical fault was introduced providing a criterion of the severity of the eccentricity fault. Then, the index was used to calculate the permeance of the air gap. Assuming a sinusoidal MMF in the stator, the permeance is employed to find the Fourier series of the air gap magnetic flux density generated by the phase current. After identifying the total air gap magnetic flux density, the performance parameters, such as induced voltage, was estimated. A method based on the stator current signal processing was then employed in which the frequency spectrum of the stator current was used to determine the amplitude of the harmonic components caused by the fault as well as the frequency pattern for the DE fault. To verify the simulation results, a prototype transverse flux generator was constructed and tested. The test was carried out under different DE fault severity to obtain the stator current signal. Then, FFT was applied to the signal for detection of frequencies and amplitude of the DE fault. The results showed that the fault index is robust against the change of load variations.

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