

Performance Analysis of Permanent Magnet Vernier Generator under Mechanical Faults

Mehrage Ghods,^a Zahra Nasiri-Gheidari,^b and Hashem Oraee^c

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In this paper no-load and full-load performance of Permanent Magnet Vernier Generators (PMVGs) is investigated in fully-aligned condition and under different types of mechanical faults. The studied mechanical faults are Static Eccentricity (SE), Dynamic Eccentricity (DE), Inclined Rotor (IR), and Run-out (RO). Furthermore, an analytical model is developed to calculate the permeance of the air-gap and the induced voltages in the health machine and under studied mechanical faults. Then, 2-D and 3-D time stepping finite element method is utilized for performance evaluation of the generator. Some discussions are made on the quality of induced voltages, torque ripples, variations of axial and radial forces and the output power of the generator under the mechanical faults considering resistive, inductive and capacitive loads connected to the terminals of the generator. Finally, the performance of an outer rotor conventional permanent magnet generator (CPMG), considering constant dimensions, constant PM, copper and iron usage is compared with the studied PMVG. The performance of two generators is studied in fully-aligned condition as well as under SE and DE.

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I. INTRODUCTION

Low-speed, high-torque density permanent magnet (PM) machines are desirable for direct-drive systems in many applications such as electrical vehicles and wind turbines. Since these machines need to operate at low speed, they usually have a high pole numbers, high slot numbers and hence they suffer from huge dimension. Vernier machines, flux-modulated magnetic gears and magnetically geared machines are very similar in terms of their operating principles. As shown in Fig. 1 PM Vernier machines (PMVMs) are composed of the inner stator with Flux Modulation Poles (FMPs) and outer rotor with PMs. The output windings that are wound on

the stators main teeth generate a high frequency magnetic field and the Vernier teeth are used to perform the flux modulating function. The rotors PMs generate a low frequency magnetic field, which interacts with the modulated stator space harmonic to produce useful torque. The relationship between the number of rotor pole pairs, the number of stator teeth and the number of winding pole pairs P_s is given as¹:

$$P_r = N_{FMP} - P_s \quad (1)$$

Accordingly, the high-to-low speed ratio, G_r , is given by¹:

$$G_r = \frac{\omega_s}{\omega_r} = \frac{|mP_s + kN_{FMP}|}{mP_s} \quad (2)$$

where $m = 1, 3, 5, \dots$ and $k = 0, \pm 1, \pm 2, \dots$.

There are lots of works on performance prediction of the PMVMs as high power density electric motors²⁻⁸. In² merits and challenges of using distributed winding and fractional-slot concentrated winding in PM Vernier motors are studied. In⁷ a PM Vernier motor with a modular stator and a consequent pole rotor is designed. Using PMVMs as permanent magnet Vernier generators (PMVGs) is proposed in¹. Although no-load performance of the PMVGs is discussed in¹, the authors did not discuss on the output characteristic of the generator under load condition. In³ an effort to reduce the material and manufacturing costs of PM motors by using the soft magnetic composite is proposed. In⁴ design Improvement of a small, outer rotor, permanent magnet Vernier generator for supplying traffic enforcement camera is proposed. The no-load and full-load performance of the generator is discussed and a prototype of the machine is built and tested. Different topologies of PM Vernier machines are introduced in⁵. Authors of⁷ proposed a new PMVM that has fault tolerant capability and suppresses the magnetic unbalance caused by the consequent pole rotor. Based on the best knowledge of the authors there is no research on performance prediction of PMVGs under mechanical faults. However, mechanical faults have detrimental effects, such as increased

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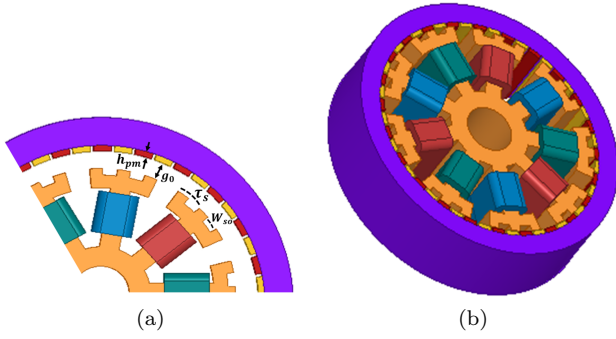


FIG. 1. The schematic of the PMVM.

vibration, higher electromagnetic stress, increased unbalanced magnetic pull, increased bearing wear, and stator-rotor rub. Furthermore, about 40 to 50 percent of faults in large electrical machines are due to mechanical faults⁸. So, it is vital to monitor mechanical faults and diagnose them at the early stage.

So, in this paper an accurate analytical model is developed to investigate the performance of the PMVGs under different types of mechanical faults and the quality of the induced voltages under these faults is discussed. The variations of axial and radial force densities under mechanical faults are studied. Then to justify the preference of the studied generator over the conventional PM generators, the performance of the studied PMVG under mechanical faults is compared with that of conventional PM generators. Furthermore, the full load characteristic of the PMVG in fully aligned and under fault conditions is presented considering three type of loads include resistive, capacitive, and inductive loads. Finally, 2-D and 3-D time stepping finite element method is used to validate the proposed analytical results.

II. OPERATION PRINCIPLE OF FLUX MODULATION MACHINES

Based on the theory, Vernier machines are classified as flux modulating machines. In this type of electric machines due to use of flux modulators the rotors speed is much smaller than that of electromagnetic field of stator. To explain this characteristic, the performance of flux modulators is explained using an example. An outer rotor with 48-pole PM is assumed. Two stators are considered for the mentioned rotor: the first one is a slot less stator without modulating poles (Fig. 2a), and the next one is an inner stator with flux modulators (Fig. 2b). The amplitude of radial component of magnetic flux density in the middle of the air-gap length is plotted for both machines. As shown in Fig. 2c, for machine without flux modulators, the dominant harmonic is related to 48-pole and the amplitude of the other harmonics is negligible. However, using flux modulators the dominant harmonics are related to 3th, 24th, and 51th pole-pairs. So, the stator can be found to have 3-pole pairs. In other words,

the pole number of armature winding and the excitation MMF in the flux modulating machines can be different.

Air-gap magnetic flux density in permanent magnet machines can be calculated as PM magneto motive force multiplied by magnetic permeance²:

$$B(\theta_s, \theta_r) = \Im(\theta_s, \theta_r) \times \Lambda(\theta_s) \quad (3)$$

where $\Lambda(\theta_s)$ and $\Im(\theta_s, \theta_r)$ represent the permeance function and PM magneto motive force, respectively. θ_s and θ_r are mechanical angle on the stator and the rotor, respectively. The permeance of air-gap can be written as⁹:

$$\Lambda(\theta_s) = \Lambda_0 + \Lambda_1 \cos(N_{FMP}\theta_s) \quad (4)$$

Where Λ_0 and Λ_1 are two constant values and can be calculated as¹⁰:

$$\Lambda_0 = \mu_0(1 - 1.6\delta k_0)/g \quad (5)$$

$$\Lambda_1 = \frac{\mu_0}{g} \frac{4\delta}{\pi} \left(0.5 + \frac{k_0^2}{0.78 - 2k_0^2}\right) \sin(1.6\pi k_0) \quad (6)$$

where

$$g = g_0 + h_{PM}/\mu_{PM} \quad (7)$$

$$k_0 = W_{so}/\tau_s \quad (8)$$

$$\delta = 0.5 - \left(2\sqrt{1 + \left(\frac{W_{so}}{2g}\right)^2}\right)^{-1} \quad (9)$$

where W_{so} is the slot opening width, τ_s is the slot pitch, k_0 is the space ratio of modulation steels, μ_{PM} is the permanent magnet recoil permeability which can be assumed to be 1, and δ is the nonlinear coefficient related to $g_0 + h_{PM}$ and α . Where α denotes the ratio of pole arc to pole pitch, and h_{PM} the PM length. The mentioned geometrical dimensions are shown in Fig. 1.

The magneto motive force produced by PMs of the rotor can be written as²:

$$\Im(\theta_s, \theta_r) \approx \Im_1 \cos(P_r(\theta_s - \theta_r)) \quad (10)$$

where

$$\Im_1 = \frac{4h_{PM}}{\pi\mu_{PM}} B_r \quad (11)$$

where B_r is the residual flux density of PMs. Then, substituting (4) and (10) into (3) air-gap flux density of PM modulated by FMPs can be obtained as:

$$\begin{aligned} B(\theta_s, \theta_r) = & \Im_1 \cos(P_r(\theta_s - \theta_r)) (\Lambda_0 \\ & + \Lambda_1 \cos(N_{FMP}\theta_s)) \\ = & B_0 \cos(P_r(\theta_s - \theta_r)) \\ & + B_1 \cos[(P_r \pm N_{FMP})\theta_s - P_r\theta_r] \end{aligned} \quad (12)$$

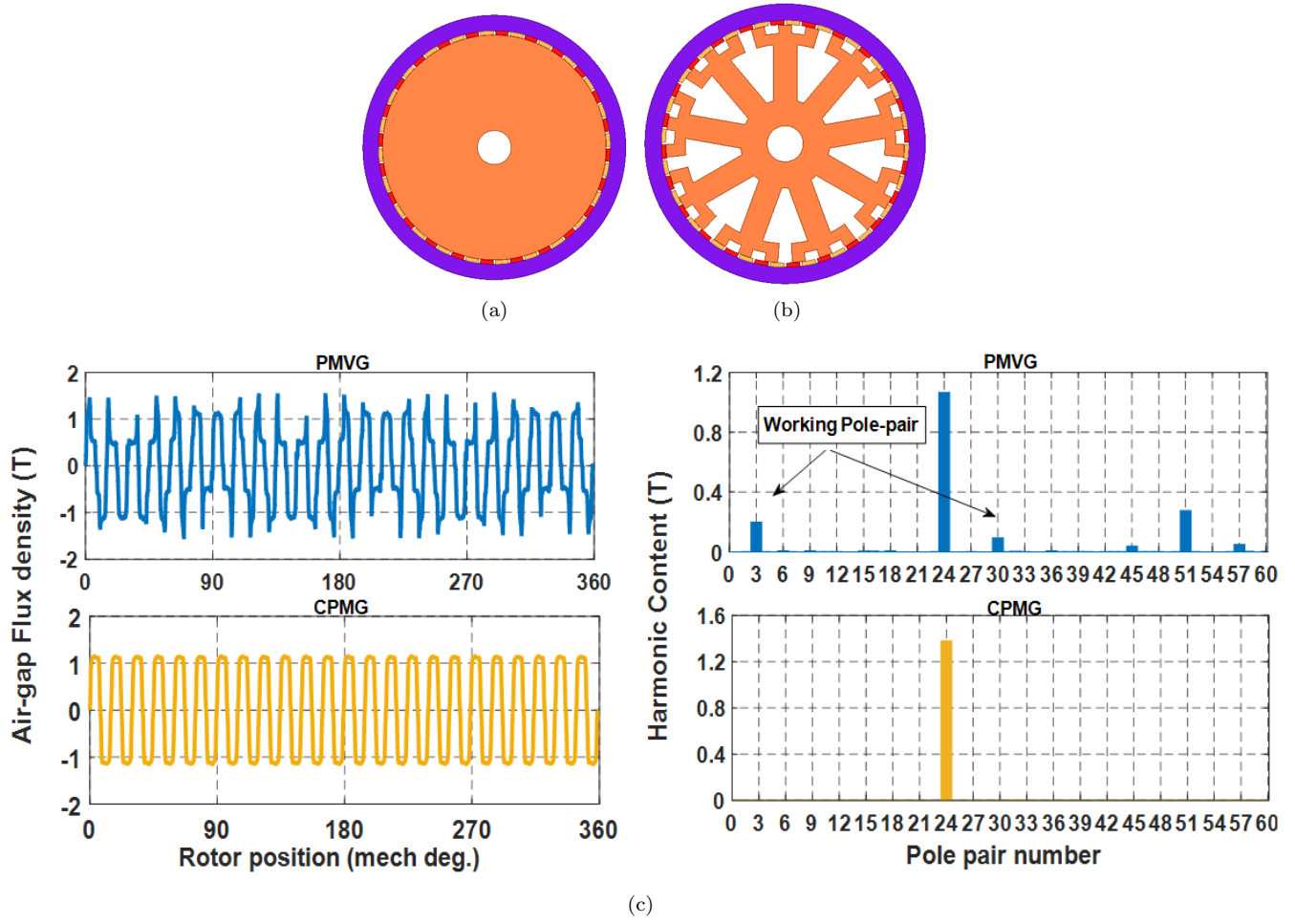


FIG. 2. The effect of pole modulators on the distribution of magnetic flux density in the middle of air-gap length: (a) the schematic of machine without modulators, (b) the schematic of machine with modulators (PMVG), (c) the distribution magnetic flux density and its harmonic content for both machines.

where

$$B_0 = \frac{4h_{PM}}{\pi\mu_{PM}} B_r \Lambda_0 \quad (13)$$

$$B_1 = \frac{2h_{PM}}{\pi\mu_{PM}} B_r \Lambda_1 \quad (14)$$

In addition, the flux linkage through a coil can be written as:

$$\varphi(t) = \frac{D_g l_{stk}}{2} \int_0^{\pi/P_r} B(\theta_s, \theta_r) d\theta_s \quad (15)$$

Then by substituting (12) into (15):

$$\begin{aligned} \varphi(t) = & \frac{D_g l_{stk}}{2} \left(\frac{2B_0}{P_r} \sin(P_r \theta_r) \right. \\ & + \frac{B_1}{P_r \pm N_{FMP}} \left(\sin\left(\frac{P_r \pm N_{FMP}}{P_r} \pi - P_r \theta_r\right) \right. \\ & \left. \left. + \sin(P_r \theta_r) \right) \right) \end{aligned} \quad (16)$$

The induced voltage in coils can be written as follows:

$$e(t) = -N_{ph} \frac{d\phi(t)}{dt} \quad (17)$$

Substituting (16) into (17):

$$\begin{aligned} e(t) = & -k_w D_g l_{stk} \omega_m N_{ph} \left(B_0 \cos(P_r \omega_m t) \right. \\ & + \frac{B_1}{2} \left(\frac{P_r}{N_{FMP} + P_r} + \frac{P_r}{N_{FMP} - P_r} \right) \cos(P_r \omega_m t) \\ & - \frac{B_1}{2} \left(\frac{P_r}{N_{FMP} + P_r} + \frac{P_r}{N_{FMP} - P_r} \right) \cos\left(\frac{N_{FMP}}{P_r} \pi - P_r \omega_m t\right) \end{aligned} \quad (18)$$

Assuming $N_{FMP} = P_r$, leads to:

$$\cos(P_r \omega_m t) = -\cos\left(\frac{N_{FMP}}{P_r} \pi - P_r \omega_m t\right) \quad (19)$$

So, the root-mean-square no-load phase back-EMF of the

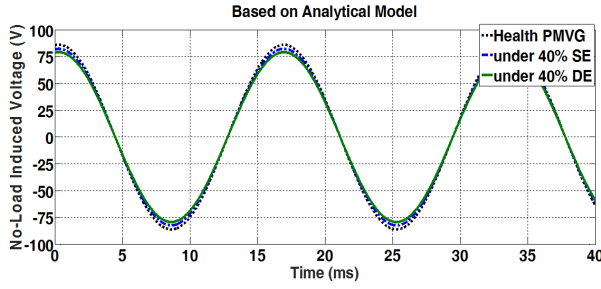


FIG. 3. The no-load induced voltage of the studied PMVG under eccentricities.

external rotor PMVG can be expressed as:

$$E_{ph} = \frac{k_w}{\sqrt{2}} D_g l_{stk} \omega_m N_{ph} (B_0 + B_1 \left(\frac{P_r}{N_{FMP} + P_r} + \frac{P_r}{N_{FMP} - P_r} \right)) \quad (20)$$

Where N_{ph} is the number of turns in series per phase, k_w is the winding factor, l_{stk} is the stack length, D_g is the air-gap diameter and ω_m is the mechanical speed. For sake brevity, the wave form of induced voltages in health generator is given along with that of eccentric machine in Fig. 3.

III. MECHANICAL FAULTS

Mechanical faults can be classified into torque oscillations and eccentricity faults. Torque oscillations are mainly caused by a fault outside the machine (the load or prime mover side) while the eccentricity fault is more related 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 fault⁴. Rotor eccentricity is a common fault that can happen even before electric machine installation. This may occur during manufacturing process or shipping. Moreover, load unbalance, misalignment coupling, inappropriate assembling and bent rotor shaft can cause rotor eccentricity¹⁰. Eccentricity can cause problems such as vibration, noise, unbalanced magnetic pull and torque pulsation¹¹. There are two types of rotor eccentricities: static eccentricity (SE) and dynamic eccentricity (DE). In both types, the air gap lengths in different rotor angles are not equal anymore. The first consequence of this phenomenon is non-uniform distribution of magnetic flux in air gap which may affect phase back-EMF waveforms. Eccentricity also affects air gap magneto-motive force (MMF) which may lead to change in phases winding inductances^{12,13}.

A. Static and Dynamic Eccentricities

In the case of SE, the rotational axis of the rotor coincides with the symmetrical axis, but it displaces from the stator symmetrical axis^{13,14}. So, the point of minimum

air-gap length remains fixed in the space. DE occurs when the point of the minimum air-gap length rotates along with the rotor. In the other words, in DE, the stator symmetrical axis coincides with the rotor rotational axis, but the rotor symmetrical axis is displaced^{13,14}.

In none of the mentioned eccentricities, the distribution of air-gap length is uniform around the rotor. In general the eccentricity factor can be defined as¹⁴:

$$\gamma = \left| \frac{g - g_0}{g_0} \right| \times 100 \quad (21)$$

where g is the air gap length under eccentricity fault condition, and g_0 is the air gap length in fully-aligned condition. Depending on different eccentricity conditions, the $(g - g_0)$ is different. For example in the case of SE, the static eccentricity factor (γ_{SEF}), can be defined as¹⁴:

$$\gamma_{SEF} = \frac{g_{\max} - g_{\min}}{2g_0} \times 100 \quad (22)$$

The air-gap length of PMVG under eccentricities depends on the rotor mechanical angle and is defined as:

$$g = g_0(1 - \gamma \cos(\omega_r t - \xi_M)) \quad (23)$$

where ω is static/dynamic eccentricity factor, $\omega_r = P_s \omega_s / P_r$ and ξ_M under SE is equal to zero and under DE is equal to ζ_s (the rotor mechanical angle). Finally, the induced voltage can be calculated as:

$$E_{ph,Ecc.}^{rms} = \frac{4B_r h_{PM} k_w}{\sqrt{2} \pi \mu_{PM}} D_g l_{stk} \omega_m N_{ph} \times (\Lambda_{0,Ecc.} + \frac{\Lambda_{1,Ecc.}}{2} \left(\frac{P_r}{P_s} + \frac{P_r}{N_{FMP} + P_r} \right)) \quad (24)$$

where E_{ph} is the induced voltage in fully-aligned PMVG that is presented in (20). The no-load induced voltages of the generator that is calculated based on the proposed analytical method in fully-aligned condition and under SE and DE are shown in Fig. 3. It can be seen that the amplitude of the induced voltage in health machine is 89 V while its value under 40% SE and 40% DE is decreased to 85 and 82 V, respectively. In section V, the results of analytical model are validated using finite element analysis.

B. Inclined Rotor Fault

Bearings wear causes inclined rotor fault in which the axis of the rotor and that of stator inclines against each other. Fig. 4a shows the schematic of studied machine under IR fault. It should be mentioned, due to high value of diameter to length ratio and horizontally installation of the studied PMVG, it is strongly exposed by IR fault.

Although under IR fault the distribution of air-gap length through rotor circumference is not uniform, it is time-independent. So, inclined rotor factor ($\gamma_{IRF}(z)$) can be written as:

$$\gamma_{IRF,0} = (R_s - r)/g \times 100 \quad (25)$$

where R_s is the outer diameter of the stator and r can be calculated as:

$$r = R_s \cos \beta \quad (26)$$

Therefore, $\gamma_{IRF}(z)$ can be written as a function of deviation angle:

$$\gamma_{IRF}(z) = \begin{cases} -2\gamma_{IRF,0} \times z/l_{stk} + \gamma_{IRF,0}, & 0 < z < l_{stk}/2 \\ (2z - l_{stk})\gamma_{IRF,0}/l_{stk}, & l_{stk}/2 < z < l_{stk} \end{cases} \quad (27)$$

Then the no-load induced voltage of the studied PMVG under IR fault can be expressed as:

$$E_{ph,IR}^{rms} = \frac{k_w}{\sqrt{2}} D_g l_{stk} \omega_m N_{ph} \times (B'_0 + B'_1 \left(\frac{P_r}{N_{FMP} + P_r} + \frac{P_r}{N_{FMP} - P_r} \right)) \quad (28)$$

where

$$B'_0 = \frac{4h_{PM}}{\pi\mu_{PM}} B_r \Lambda'_0 \quad (29)$$

$$B'_1 = \frac{2h_{PM}}{\pi\mu_{PM}} B_r \Lambda'_1 \quad (30)$$

$$\Lambda'_0 = \frac{\mu_0}{g_{IRF}} (1 - 1.6\delta k_0) \quad (31)$$

$$\Lambda'_1 = \frac{\mu_0}{g_{IRF}} \frac{4\delta}{\pi} \left[0.5 + \frac{k_0^2}{0.78 - 2k_0^2} \right] \sin(1.6\pi k_0) \quad (32)$$

$$g_{IRF} = \begin{cases} g(1 - \gamma_{IRF}(z) \cos(\omega_r t - \xi_s)), & 0 < z < \frac{l_{stk}}{2} \\ g(1 - \gamma_{IRF}(z) \cos(\omega_r t - \xi_s + \pi)), & \frac{l_{stk}}{2} < z < l_{stk} \end{cases} \quad (33)$$

The no-load induced voltage of the studied PMVG under different levels of IR faults are presented in Fig. 4b. It can be seen that by increasing fault percentage the amplitude of the induced voltage is decreased.

C. Run-out Fault

Under run-out (RO) fault the axis of stator, that of rotor and the rotational axis is coinciding. But, the rotor/stator is displaced axially against the stator/rotor. Fig. 4c shows the studied generator under exaggerated level of run out error. In the case of bearings, run-out will cause vibration of the machine and increased loads on the bearings. The level of run out fault is usually defined as a percentage of the machine length. So, the run out factor, γ_{ROF} , can be defined as:

$$\gamma_{ROF} = z/\ell_{stk} \times 100 \quad (34)$$

where z is the longitudinal displacement of the rotor axis versus that of stator. Then the no-load induced voltage of the studied PMVG under RO fault can be calculated

as:

$$E_{ph,RO}^{rms} = E_{ph}^{rms} (1 + \gamma_{ROF}) \quad (35)$$

The no-load induced voltage of the studied PMVG under different levels of RO faults are presented in Fig. 4d. It can be seen that by increasing fault percentage the amplitude of the induced voltage is decreased.

IV. FINITE ELEMENT ANALYSIS

2-D and 3-D non-linear time-stepping finite element method (TSFEM) is employed to analyze the performance of the studied PMVG in fully-aligned condition and under different types of mechanical faults. The geometrical dimensions of the studied machine along with those of conventional PM generator (CPMG) are presented in Table I¹. To study the full load condition, three type of loads were studied: 3-phase resistive load, 3-phase inductive load and 3-phase capacitive load that are connected to the terminals of the generator.

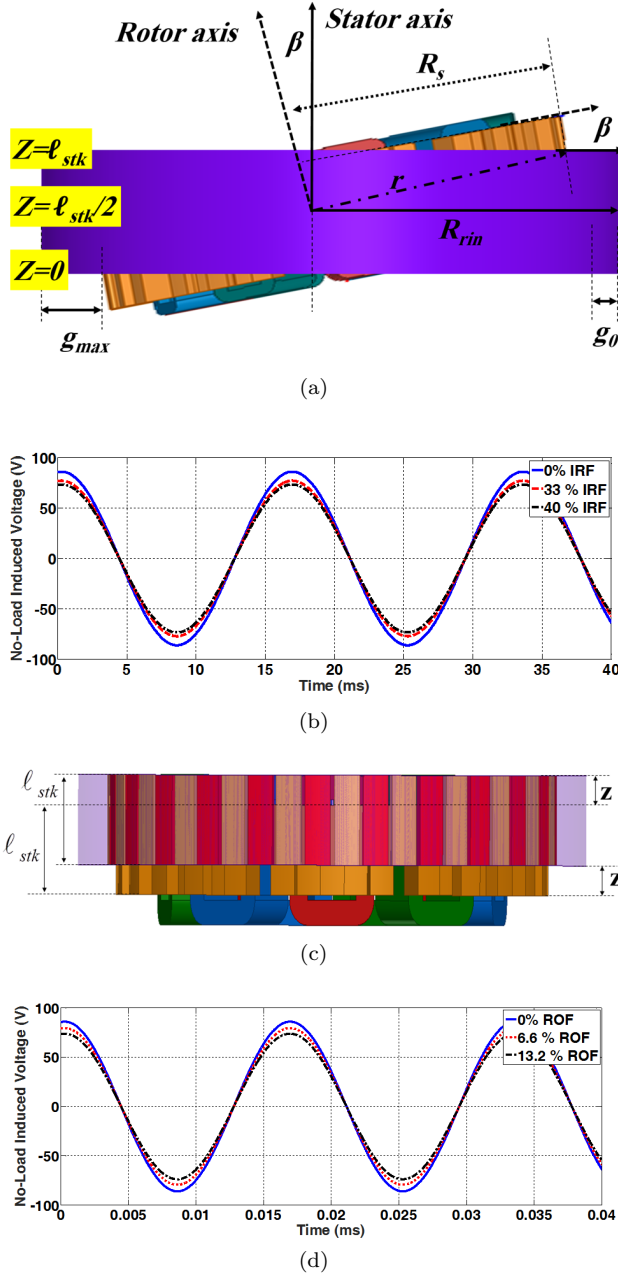


FIG. 4. The studied generator under IR/RO fault: (a) the schematic of the generator under IR, (b) no-load induced voltage for different percentage of IR fault, (c) the schematic of the generator under RO, and (d) no-load induced voltage for different percentage of RO fault.

A. Fully-Aligned PMVG

Fig. 5, shows the no-load induced voltage of the studied PMVG at the rated speed of 150 rpm using 2D and 3D FEM and the analytical model. It can be found that the amplitude of the induced voltages based on analytical model and 2-D and 3-D analysis is calculated equal to 89 V, 89.2 V and 87.5 V, respectively. The prediction of

TABLE I. Designed PMVG dimension¹

Items	PMVG	CPMG
Rational speed (rpm)	150	150
Rated frequency (Hz)	50	50
Stator turns per phase	126	126
Stack length (mm)	60	60
Air-gap length (mm)	0.6	0.6
Total copper volume (cm ²)	530	530
Total iron volume (cm ²)	2200	2200
Total PM volume (cm ²)	502	502
Remanence of PM, B_r (T)	1.23	1.23
Tooth width (mm)	22	28.5
PM width $\times$ PM thickness (mm)	22 $\times$ 7.1	22 $\times$ 7.1
No. of stator pole	6	24
No. of stator slots (FMPs)	27	36
No. of rotor pole	48	48

TABLE II. The comparison between the results of 2-D and 3-D FEM in fully-aligned PMVG

Parameters	2-D	3-D
Rational speed (rpm)	150	150
No-load	Voltage (V)	89.2
	output power (W)	1824
	phase voltage (V)	72.5
	phase current (A)	16.8
	Efficiency (%)	96
	output torque (N.m)	116
	output power (W)	970
	phase voltage (V)	65
	phase current (A)	12
	Efficiency (%)	89
	output torque (N.m)	62
	output power (W)	2879
	phase voltage (V)	102.56
	phase current (A)	18.7
	Efficiency (%)	99
	output torque (N.m)	180

the analytical model has 0.22% error with respect to that of 2-D FEM and 1.71% with respect to that of 3-D FEM. It means the result of analytical model is closer to that of 2-D FEM. However, there is 1.94% error between the predictions of 2-D FEM with respect to that of 3-D FEM. The mentioned errors are related to considering the end winding lengths in 3-D analysis and ignoring them in 2-D analysis.

The average of full load electromagnetic torque of the studied generator for different loads is presented in Table II. It can be seen that for resistive load the average torque using 3-D FEM is calculated about 18% lower than that of 2-D FEM. The reason is related to considering end winding length, in 3-D analysis. Furthermore, the induced voltage in resistive ($R_{load} = 4.3\Omega/\text{phase}$), inductive ($Z_{load} = 4 + j3\Omega/\text{phase}$) and capacitive ($Z_{load} = 4 - j3\Omega/\text{phase}$) loads is presented in Figs. 6a. Considering the resistive load, the amplitude of the full load

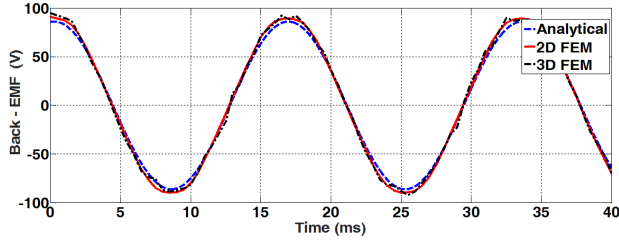


FIG. 5. The Finite Element Simulations of the studied PMVG in no-load condition: back-EMF waveforms.

TABLE III. The output characteristics of the studied PMVG under SE and DE based on the results of FEM (with resistive load)

Items	Healthy	Under SE	Under DE
NoLoad voltage (V)	89.2	85.5	82.2
Rated current (A)	16.8	15.9	15.4
Rated voltage (V)	72.5	70	66
Rated output power (W)	1824	1669	1527

induced voltage is calculated equal to 72.5 V using 2-D FEM and 65 V using 3-D FEM. Those values for inductive load are 65 and 61 V, and for capacitive load are 102.56 and 96 V, respectively. Fig. 6b shows the voltage versus current characteristic of the generator, calculated based on the 2-D FEM. It can be seen that voltage amplitude is reduced from 89.2 in no-load to 72.5 V in full-load, considering the resistive load. While, for inductive load the full load voltage is 65 V and for capacitive load its value is 102.56 V. The comparison between the results of 2-D and 3-D FEM in no-load and full-load conditions, considering different types of loads are presented in Table II.

B. The Studied PMVG under SE and DE

The no-load induced voltages under SE and DE were calculated based on analytical model in Fig. 3. Recalculating the mentioned voltages using FEM shows less than 1% error. It means the no-load induced voltage under SE/DE was predicted using the proposed analytical model equal to 85/82 V, while it is calculated using FEM equal to 85.5/82.2 V. Furthermore, this section investigates the effects of air gap variation under the static and dynamic eccentricities through harmonic analysis of back-EMF spectrum, rated output power and current waveforms.

In all simulations a nominal resistive load is connected to the generators terminals. Fig. 7a, indicates current amplitude in term of harmonic components. It can be seen that fundamental component under SE and DE faults is about 11.8% and 5.9% lower than that of health generator, respectively. Induced voltages in the output windings of the studied PMVG in fully-aligned condition and under SE and DE faults are shown in Fig. 7b. Fi-

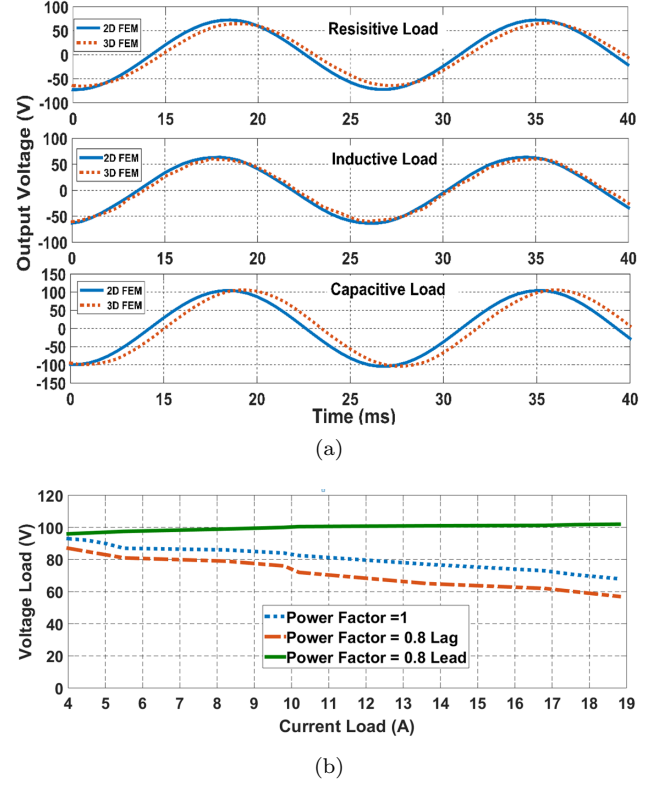


FIG. 6. Full-load characteristic of the studied PMVG considering different types of loads: (a) induced voltages, and (b) voltage-current characteristic.

nally, the variations of radial force density in fully aligned machine and under SE and DE are presented in Fig. 7c, based on the results of 2-D FEM. It can be seen that the variations of unbalanced magnetic pull under eccentricities is significantly increased. The output characteristics of the studied PMVG under SE and DE are summarized in Table III.

C. The Studied PMVG under IR Fault

In the proposed machine, because air-gap length is about 0.6 mm, the maximum rotation angle is $\beta = 1^\circ$ that leads to $\gamma_{IRF,max} = 40\%$. So, the results of 3-D FEM are presented considering $\gamma_{IRF,max} = 40\%$. The variation of radial and axial force density for the health generator and under IR fault, is presented in Figs. 8a, and 8b based on the results of 3-D FEM. As it was predictable the variations of radial force density under IR fault is significantly increased. However, the variation of axial force density is slightly changed.

D. The Studied PMVG under RO Fault

In this section, the performance of studied generator under 13% run out fault is studied. The radial force densities under run-out fault are presented in Fig. 8c. It

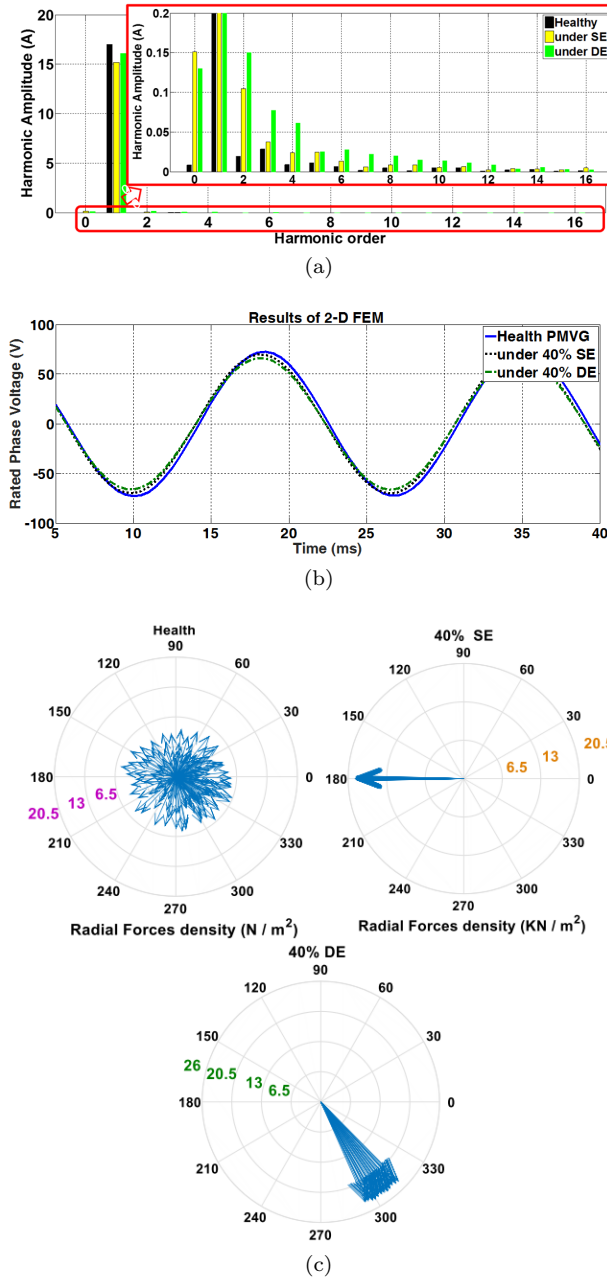


FIG. 7. Full-load characteristic of the studied PMVG considering resistive load, under 40% SE and 40% DE: (a) harmonic content of phase currents, (b) induced voltages, and (c) the variation of radial magnetic force density.

can be seen that the force density is increased under RO fault with respect to the health generator.

E. Evaluation of the proposed analytical model

The proposed analytical model is used to calculate the induced voltages. Figs. 9a, 9b show the harmonic content of the no-load induced voltages and the THD of voltages for the fully-aligned generator, the studied generator un-

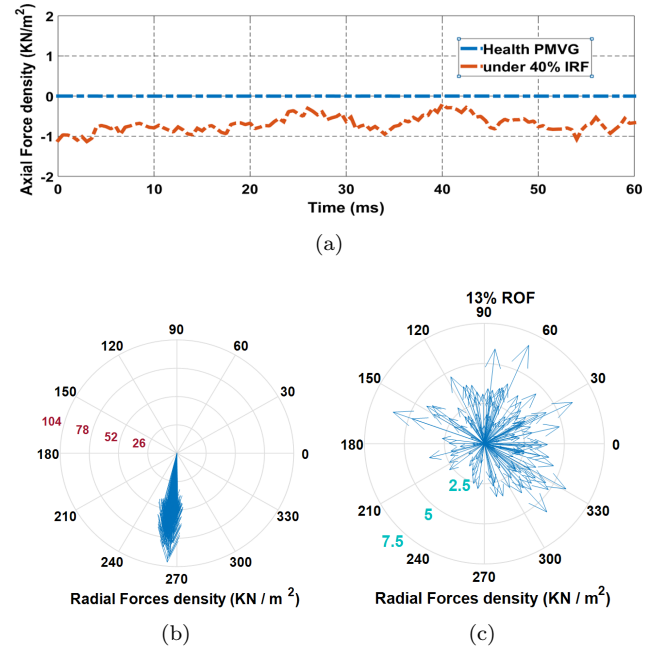


FIG. 8. The variation of axial and radial force density based on 3-D FEM: red(a) axial force density under 40% IR fault, red(b) the radial force density under 40% IR fault and red(c) the radial force density under 13% RO fault.

der SE, under DE, under IR and under RO faults using analytical model, and FEM. The amplitude of the no-load induced voltages is shown in Fig. 9c. It can be seen the error between the results of analytical model and those of FEM is less than 5%.

V. COMPARISON BETWEEN CONVENTIONAL PM GENERATORS AND PMVGs

In this section the performance of a conventional PM generator (CPMG) with outer rotor configuration is compared with that of studied PMVG. Both generators are considered with the same outer diameter and axial length. The volume of the iron, copper and permanent magnets are kept constant in both generators and they are rotated with the same speed. The design parameters of the generators are presented in Table I. It should be mentioned to fairly compare two generators both of them are designed to be used gearless and despite the different pole pairs of the stator winding and identical rotational speed, due to different stators teeth, the output frequency of them is the same. The explosion diagram and cross section of the studied CPMG is shown in Fig. 10a. the winding diagram of both studied generators are shown in Fig. 10b.

No-load induced voltage of both generators that is calculated based on based on 2-D FEM is shown in Fig. 11a.

Comparing the amplitude of the voltages shows consid-

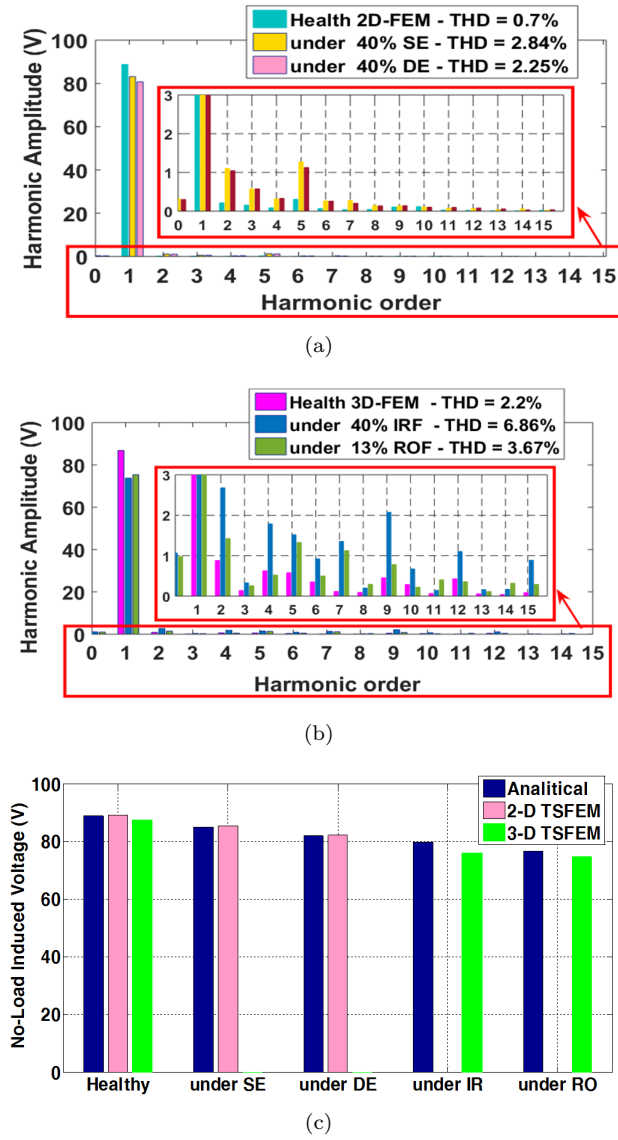


FIG. 9. The comparison of no-load induced voltage amplitude calculated based on the proposed analytical model and FEM in fully aligned generator and under different mechanical faults: (a) the harmonic content of the induced voltages under eccentricities, (b) the harmonic contents under 3-D faults, and (c) the amplitude of the voltages.

ering the same volume of the copper for two generators, the value of induced voltage in PMVG is higher than that of CPMG. Furthermore, harmonic content of the voltages in Fig. 11b shows the amplitude of harmonics for PMVG is higher than that of CPMG. However, due to higher main harmonic amplitude in PMVG, total harmonic distortion (THD) of the induced voltages in PMVG is less than that of CPMG. Furthermore, as shown in Fig. 11c, the cogging torque in the studied PMVG is significantly less than CPMG. Assuming a resistive load ($R = 4.3 \Omega$) in the terminals of the studied generators shows the full load voltage for the CPMG is 51.22 V while its value for

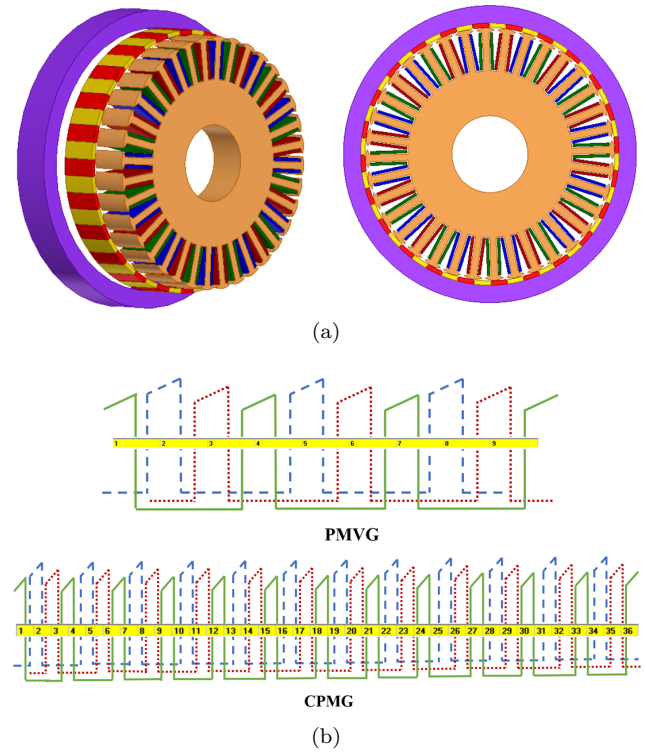


FIG. 10. Comparison between conventional PM generator and PMVG: (a) The schematic of CPMG and PMVG, and (b) winding diagram of both generators.

PMVG is 89.2 V. Fig. 12a shows the full load voltage for both generators. Comparing the full load voltage of two generators under 40% SE/DE shows the output voltage of the CPMG under the mentioned faults remains unchanged. However, the output voltage of the PMVG under SE/DE changes slightly. The output power of the generators is presented in Fig. 12b. It can be seen the output power of the PMVG is higher than the CPMG for constant value of PM, iron and copper. However, the effect of SE/DE on output power of PMVG is worse than CPMG.

To explain why the output power and the voltage of the PMVG is higher than those of CPMG while, the same volume of the copper, iron and permanent magnets is used in two machines, it is required to compare the harmonic content of the air-gap flux density for two generators. Comparing the impact of mechanical fault on the field harmonics for both generators are given in Figs. 13a, and 13b. It can be seen the amplitude of the working harmonic (3rd pole pairs) of the health PMVG is higher than that of health CPMG (12th pole pair). Furthermore, the amplitude of the working harmonic in PMVG is affected by different mechanical faults, however considering the studied CPMG, the amplitude of the working harmonic is not changed during eccentricities.

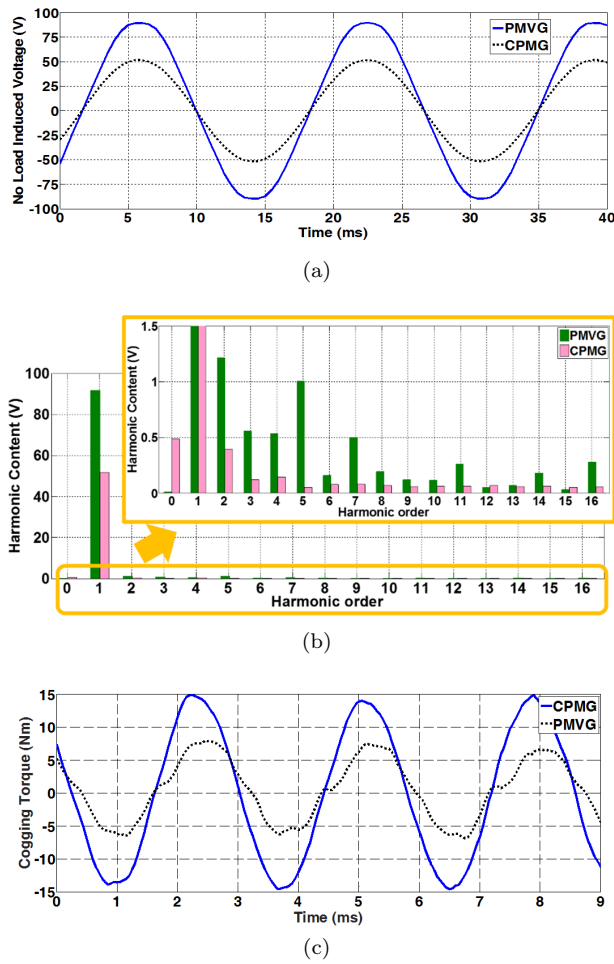


FIG. 11. No-load performance comparison of CPMG with that of PMVG based on 2-D FEM: (a) no-load induced voltages, (b) harmonic content of the voltages and (c) the cogging torque.

VI. CONCLUSION

In this paper no-load and full-load performance of an outer rotor PMVG under resistive, inductive, and capacitive loads was studied considering fully aligned machine and under different types of mechanical faults. In this regard, an analytical model was developed to predict the no-load induced voltage and air-gap permeance in the fully aligned generator and under different mechanical faults include static and dynamic eccentricities, inclined rotor and run-out fault. Then 2-D and 3-D time stepping finite element method were utilized to validate the results of proposed analytical model. Furthermore, the magnetic field and the transient output characteristic of the machine under resistive, inductive and capacitive loads under mechanical faults and in fully aligned condition were obtained based on finite element method. Finally, the performance of the studied PMVG was compared with that of conventional

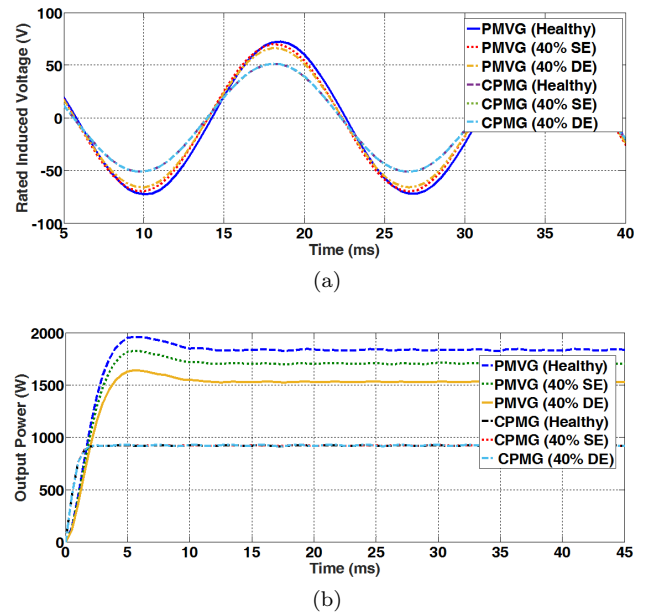


FIG. 12. Comparing the performance of PMVG and CPMG, considering resistive load: (a) output voltages, and (b) output power.

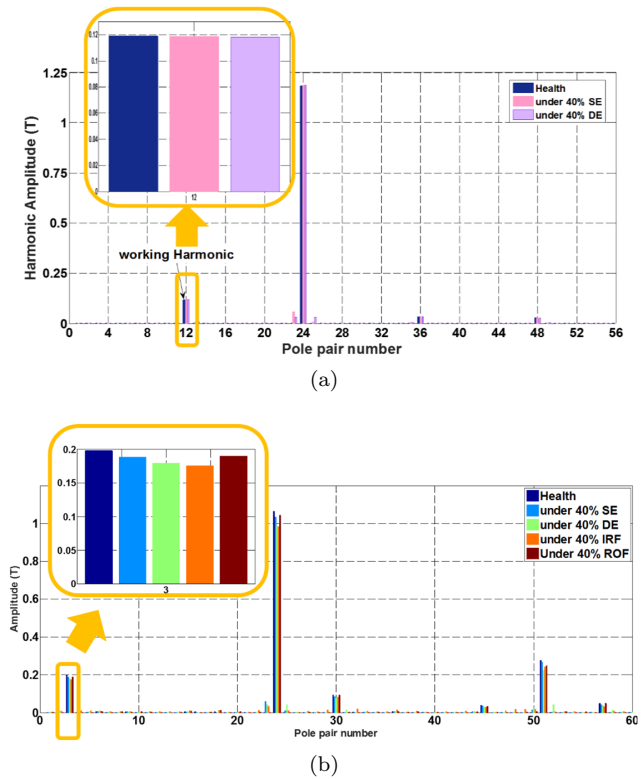


FIG. 13. The harmonic content of air-gap flux density under mechanical faults: (a) CPMG, and (b) PMVG.

PM machines. It was concluded considering a constant volume for PMs, iron, copper and prime-movers speed the no-load induced voltage and the output power of the studied PMVG was higher than those of studied CPMG. However, the influence of static and dynamic eccentricity on the performance of studied CPMG was less than studied PMVG.

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