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DESIGN, CONTROL AND EXPERIMENTAL INVESTIGATION OF FAULT-TOLERANT FIVE PHASE PMSG FOR WIND POWER APPLICATION

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ABSTRACT

Fault-Tolerant, small-scale wind energy conversion (WEC) system often utilises permanent magnet synchronous generator coupled with an uncontrolled diode rectifier. To enhance the electromagnetic performance and fault-tolerant capability over classical three-phase generator, a five-phase permanent magnet synchronous generator (FP-PMSG) has been opted here. The design and optimisation are carried out using finite element method (FEM). The rectified DC link voltage and its ripple factor is considered as the two basic performance parameters for the overall system. Furthermore it is compared with conventional 3and 5-phase PMSGs both under healthy and faulty conditions. The simulated and FEM results of the proposed generator is further validated with experimental results of the prototype of 60 slots eight poles fractional slot double layer winding surface mounted PMSG.

KEYWORDS: Wind Energy, Five Phase, PMSG, Fault-Tolerance, Open Circuit Fault & Control

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Original Article

1. INTRODUCTION

The nuclear catastrophe at Fukushima in Japan in 2011 has compelled the world to consider renewable energy as a safe reliable and cost effective alternative to nuclear energy [1],[2]. Renewable energy sources like solar, biomass and wind are locally available sources of energy, which are safe and reliable for the environment [3]. Wind energy is quite popular because it is cheap, clean, emission-free and eco-friendly resource of energy [4]. There are many conventional generators namely squirrel cage induction generator, doubly fed induction generator and electrically excited synchronous generator used to harness energy from the wind but they either require the slip rings or gearbox or in some cases both due to which system becomes less reliable and complex [5]. In this context, permanent magnet synchronous generator (PMSG) is quite suitable for wind application as it does not require any gearbox, slip ring, or winding on the rotor. It also has the advantage of compact size, high efficiency, high reliability and high power density over conventional generators [6], [7]. The power density and reliability can be further be enhanced using multi-phase (higher than three phase) PMSG. It reduces the torque ripple in the machine and size of DC link capacitor and also the rating of power electronic switches. Multiphase system poses an additional degree of freedom during the fault-tolerant operation [8]. Figure 1 depict general wind power turbine scheme with components like wind-mill, generator, rectifier, inverter, transformer and grid or stand-alone load system. Reliability and the cost are the two main factor of the wind turbine. In [9],[10] authors have reported that the component of power electronic converter and their control units are contributor of faults in majority of the cases. In particular the open circuit faults due to converter switches are common cause of faults.

To improve the fault tolerance of wind turbine many control strategies and converter topologies are suggested. In [11] authors used neutral-point-clamped (NPC) topology converter. From control aspect [12] opted for a new direct control technique of the converter to improve the fault tolerance of wind energy conversion (WEC) system. Presence of more power switches and their control scheme makes the system less reliable, more expensive and complex. Authors in[13] have considered a simple, low cost, robust and high fault tolerant WEC system which includes three phase PMSG, three-phase diode rectifier with DC to DC boost converter and voltage source inverter (VSI) for small-scale wind farms. In [14] authors reported a five-phase PMSG based WEC system which has better performance and fault tolerance capability compared to classical three phase PMSG system. According to above studies, it seems that a system comprising five phase PMSG, a five-phase diode rectifier with DC to DC boost converter and voltage source inverter (VSI) is a good solution for WEC system. The PMSG with connected rectifier is the building block of WEC system. So its performance under healthy and faulty conditions needs to be explore. In this paper, authors have designed and optimised the FP-PMSG using finite element method. The electromagnetic performance analysis of generator is carried out under healthy and faulty conditions. To investigate the fault-tolerant capability of the proposed generator connected with a five-phase rectifier, DC link voltage and its ripple factor is accounted as the performance parameters. These performance parameters for a proposed 5-phase PMSG are compared with a conventional 3-phase and 5-phase PMSG under healthy and faulty conditions are carried out with MATLAB/SIMULINK. The simulated and FEM results of the proposed generator are further validated with experimental results of prototype generator.

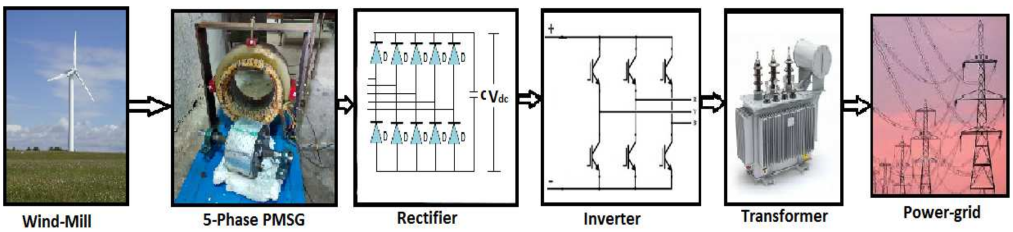

Figure 1: Wind Power Turbine Scheme

This Paper is organised in the following manner. Section-2 introduces the topology, winding detail and the design parameter of PMSG. Section-3 elaborates the mathematical modelling and the electromagnetic performance parameters. Section-4 describes the generator and experimental set-up. The simulated and experimental results, under healthy and faulty conditions of the generator are discussed in section-5. Finally, section-6 present the concluding remarks.

2. TOPOLOGY FOR INVESTIGATION

The proposed five-phase Permanent magnet synchronous generator is shown in Figure 2. This generator consists of a stator having 60 slots, five phase, double layer fractional slot winding and a rotor having four pairs of surface-mounted permanent magnets, each short-pitched by 36^{O} E. Each phase of the winding are mutually 72^{o}E apart and 12 coils composing each phase short-pitched by 12^{O} E. Due to short-pitching of coil harmonic with multiple of 15 are eliminated from the generated voltage in the coils. Figure 3 shows the winding connection of phase A, where the 12 coils are distributed around the stator. The rating of the machine is listed in Table 1 and correspondingly to which it is designed and optimised using FEM analysis. The FEM model consists of two flux sources namely five phase eight pole fractional slot double layer armature winding and four pairs of permanent magnets. Figure 4 shows the flux line plot due to 8 poles PMs mounted on the surface of the rotor. As the rotor rotates at 400 rpm the generated voltage in the armature winding has

26.667Hz frequency. When rated load is connected to the terminals of the generator, the five-phase current are drawn by the generator. Due to the armature magneto motive force (MMF), 8 poles are flux is set up which is shown in Figure 5. The machine is designed such that it is not saturated due to the combined effect of these fluxes. The armature flux depends on the load due to which it either supports or opposes the PM flux. In terms of saturations the stator teeth are the most sensitive part of the generator. Figure 6 and Figure 7 show that the peak flux density due to PM and winding are around 1.45 and 0.10 tesla, respectively. It is clear that their combined effects of the two is lesser than the peak saturated flux density of 1.8 tesla in the stator teeth. The design details corresponding to the rating of the generator are listed in Table 2.

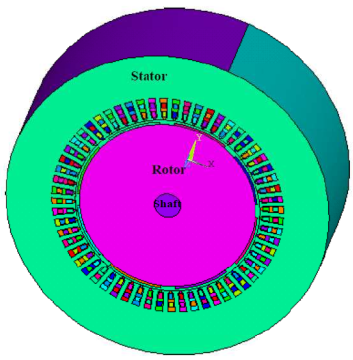

Figure 2: Proposed Model of Five Phase PMSG

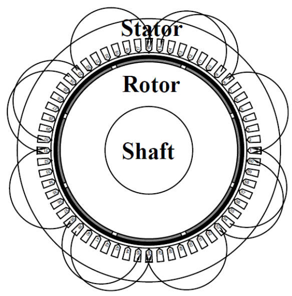

Figure 3: Five Phase

Table 1: Generator Rating

Parameter	Value
Power(kva)	3.42
Voltage(Volt.)	171.0
Current(Amp.)	4
Speed(rpm)	400

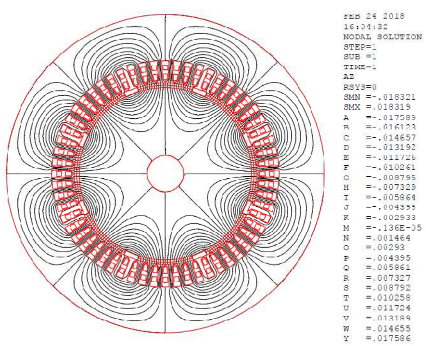

Figure 4: Flux Line Plot due to Four Pairs of Rotor PMs

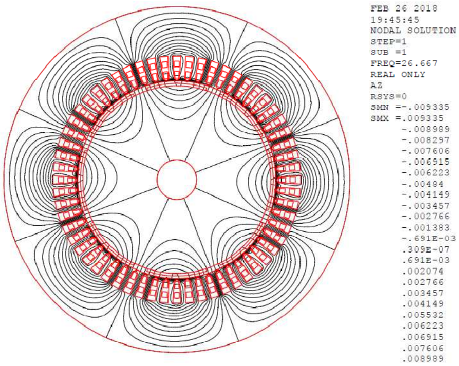

Figure 5: Flux Line Plot due to MMF of Five Phase Winding

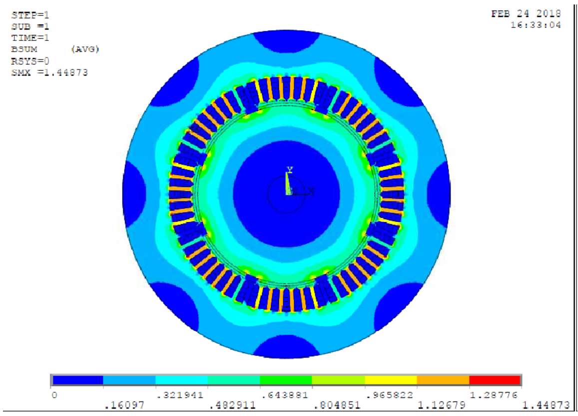

Figure 6: Flux Density Plot due to PMs Only

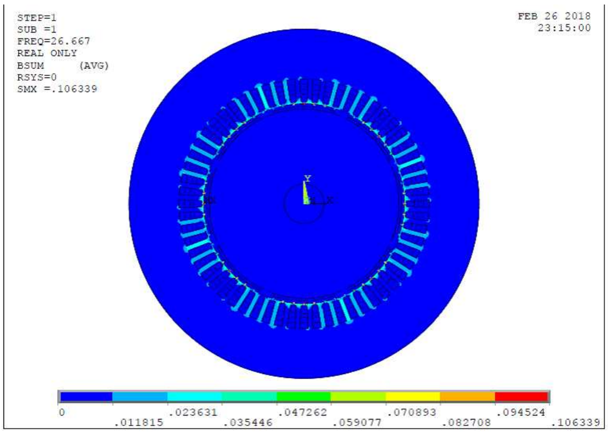

Figure 7: Flux Density Plot due to Winding MMF

Table 2: Design Parameter

Design Parameter	Value
Diameter of shaft	40 mm
Diameter of rotor	190 mm
Magnet Thichness	2.5 mm
Air gap length	2.3 mm
Thickness of rotor sleeve	0.2 mm
Inner Diameter of stator	200 mm
Outer Diameter of stator	350 mm
Area of slot	123.27 mm^2

3. FP-PMSG MODELLING

The fault-tolerant five phase PMSG is to be used for small-scale WEC system. Keeping the system simple and reliable, a five-phase diode rectifier is used on generator side and a three phase VSI should be used for the grid /load. It is clear that the output of the rectifier is the fundamental building block of this system. The analysis of rectified DC voltage under healthy and unhealthy condition is required to fix the size of the DC-link capacitor and to know the system fault-tolerant capability. For this analysis, MATLAB/Simulink is considered for modelling the generator connected with five phase rectifier, as shown in Figure 8. It consists of five phase trapezoidal source with equal phase resistance and inductance. The generator is connected to load through rectifier and DC link-capacitor. The open circuit fault like single phase/leg or two-phase of rectifier hampers the quality of output DC voltage and power transfer to load. In this context, modelling is required to analyze the performance of rectifier and the fault tolerance capability.

The generated voltage, corresponding to the five-phases with notations a, b, c, d, e can be expressed by equation 1, this includes generated voltage $E_m(t)$ of 5x1 matrix, terminal voltage $V_m(t)$ of 5x1 matrix, phase current $I_m(t)$ of 5x1 matrix, flux linkage $\wedge_m(t)$ of 5x1 matrix, phase resistance R_m of 5x5 matrix and phase inductance L_m of 5x5 matrix.

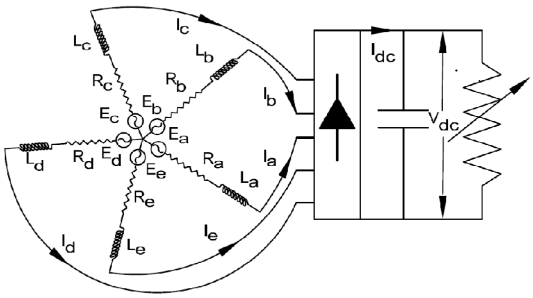

Figure 8: Simulink Block diagram for FP-PMSG

Generalised generated voltage can be expressed as

$$[E_m(t)] = [V_m(t)] + [I_m(t)][R_m] + \frac{d([\wedge_m(t)])}{dt} \tag{1}$$

Where,

$$[E_m(t)] = [E_a(t)\, E_b(t)\, E_c(t)\, E_d(t)\, E_e(t)]^T \tag{2}$$

$$[V_m(t)] = [V_a(t)\; V_b(t)\; V_c(t)\; V_d(t)\; V_e(t)]^T \tag{3}$$

$$[I_m(t)] = [I_a(t)\, I_b(t)\, I_c(t)\, I_d(t)\, I_e(t)]^T \tag{4}$$

$$[\wedge_m(t)] = [L_m][I_m(t)] \tag{5}$$

$$R_m = \begin{pmatrix} R & 0 & 0 & 0 & 0 \\ 0 & R & 0 & 0 & 0 \\ 0 & 0 & R & 0 & 0 \\ 0 & 0 & 0 & R & 0 \\ 0 & 0 & 0 & 0 & R \end{pmatrix} \quad (6)$$

$$L_m = \begin{pmatrix} L & M_a & M_{na} & M_{na} & M_a \\ M_a & L & M_a & M_{na} & M_{na} \\ M_{na} & M_a & L & M_a & M_{na} \\ M_{na} & M_{na} & M_a & L & M_a \\ M_a & M_{na} & M_{na} & M_a & L \end{pmatrix} \quad (7)$$

In equation.(6) R is the phase resistance. In equation.(7) , L, M_a, M_{na} are the self inductance, mutual inductance between adjacent phases and mutual inductance between the non-adjacent phases, respectively.

Alternatively, the generated five phase voltage can be expressed as

$$E_a(\mathrm{t}) = \sum_{k=1,3,7..}^{\infty} E_k \sin(k w_e t) \quad (8)$$

$$E_b(\mathrm{t}) = \sum_{k=1,3,7..}^{\infty} E_k \sin(k w_e t + \frac{2\pi}{5}) \quad (9)$$

$$E_c(\mathrm{t}) = \sum_{k=1,3,7..}^{\infty} E_k \sin(k w_e t + \frac{4\pi}{5}) \quad (10)$$

$$E_d(\mathrm{t}) = \sum_{k=1,3,7..}^{\infty} E_k \sin(k w_e t + \frac{6\pi}{5}) \quad (11)$$

$$E_e(\mathrm{t}) = \sum_{k=1,3,7..}^{\infty} E_k \sin(k w_e t + \frac{8\pi}{5}) \quad (12)$$

Where E_k is the peak phase voltage and w_e is the electrical frequency.

The total electromagnetic power is the sum of power generated by each of the phases

$$\begin{aligned} \mathrm{P(t)} &= E_a(\mathrm{t})\,\mathrm{I}_a(\mathrm{t}) + E_b(\mathrm{t})\,\mathrm{I}_b(\mathrm{t}) + E_c(\mathrm{t})\,\mathrm{I}_c(\mathrm{t}) \\ &\quad + E_d(\mathrm{t})\,\mathrm{I}_d(\mathrm{t}) + E_e(\mathrm{t})\,\mathrm{I}_e(\mathrm{t}) \end{aligned} \quad (13)$$

The electromagnetic power is due to the electromagnetic torque ($P(t)/w_e$). Hence the total torque required to move the generator

$$T(t) = T_{cogg} + \frac{P(t)}{w_e} \tag{14}$$

Where T_{cogg} is the cogging torque which is present during entire operation of generator.

The %ripple factor torque can be expressed as

$$\%\text{Torque RF} = \frac{T_{\max} - T_{\min}}{T_{avg}} \times 100 \tag{15}$$

Where T_{max}, T_{min} and T_{avg} are the magnitude of maximum, minimum and average value of torque, respectively. on the other hand the rectifier DC output voltage can be expressed as,

$$V_{dc} = \frac{1}{T_p}\int_0^{T_p} V_o(t)\, d(w_e t) \tag{16}$$

where T_p is the time period of the generator output voltage and $V_o(t)$ is the output voltage of the rectifier.

$$\%DC\,Voltage\,\text{RF} = \left(\sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}\right) \times 100 \tag{17}$$

where V_{rms} and V_{dc} are the rms value and average value of rectified output voltage, respectively.

When electrical load is connected to the rectifier then current can be expressed as

$$I_{dc} = \frac{V_{dc}}{R} \tag{18}$$

Corresponding DC current Ripple factor is

$$\%DC\,Current\,\text{RF} = \left(\sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}\right) \times 100 \tag{19}$$

And power delivered to the load can be expressed as

$$P_{dc} = V_{dc}\, I_{dc} \tag{20}$$

4. EXPERIMENTAL SETUP

To investigate the fault-tolerant capability of FP-PMSG drive, an experimental setup is developed as shown in Figure 9. The main component of this drive system are prime-mover, FP-PMSG, Five phase rectifier (FP-Rectifier) and variable electric load. The prime-mover supplied the power to the PMSG at 400rpm speed. The generator speed decides the fundamental frequency of the output voltage. The five terminals of generator are connected with five phase diode rectifier. Due to which DC voltage is directly affected by the nature of generator voltage. The rectified DC link voltage is an important stage for grid-connected/stand-alone generators, so loading the generator using rectifier provides useful information. The quality assessment of rectified DC voltage is required for the size and rating of DC link capacitor. The experiment is performed under different terminal fault conditions of generator. The fault at the generator terminal influences the power transfer to the DC loads. Faults can be classified as: single phase open circuit, adjacent phase open circuit and non-adjacent phase open circuit. These faults do not only affect the loading capability but also enhances the ripple content in the DC voltage. The no-load phase voltage and corresponding rectified output DC voltage at 26.67 Hz are 193.92 volt and 387.8 volt, respectively as shown in Figure 10

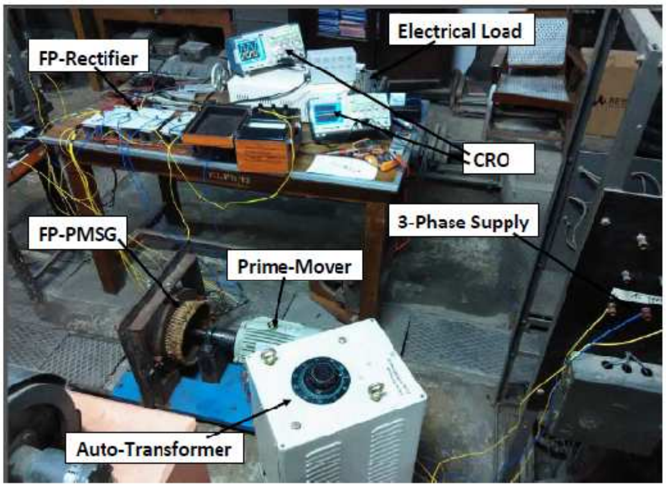

Figure 9: Experimental Setup

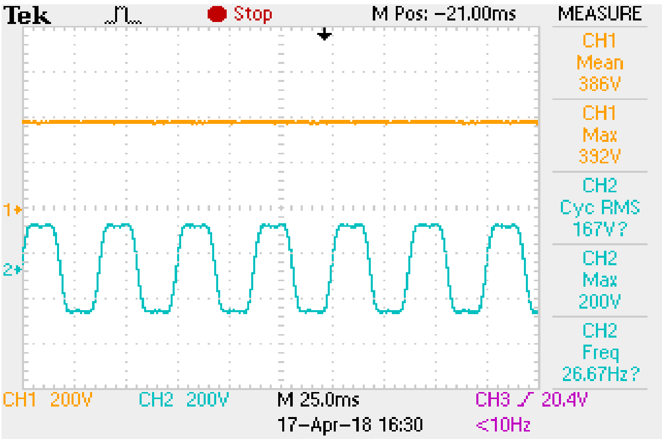

Figure 10: Generated Voltage and DC Voltage at 26.67Hz

5. RESULTS AND VALIDATION

The generated voltage is verified with experimental results. It is found that at 400rpm experimental result is 2.06% higher than the FEM result as shown in Figure 11.

For investigation of the fault-tolerant capability MATLAB/Simulink model is considered. The simulation under healthy and faulty condition is carried out. To investigate the effect on DC link voltage, three generating sources are considered.

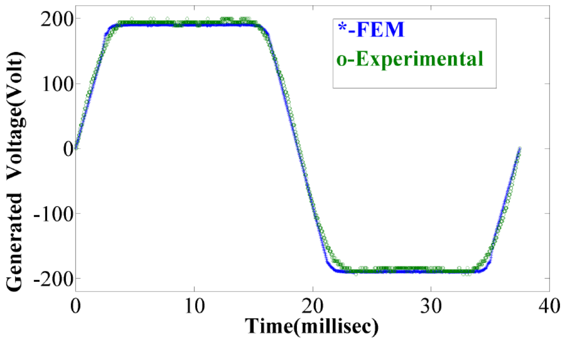

Figure 11: Generated Phase Voltage

The first is three phases PMSG with sinusoidal generated phase voltage, the second is five phase PMSG with sinusoidal generated phase voltage and the third is the proposed FP-PMSG with trapezoidal generated phase voltage. Figure12 shows simulated five phase generated voltages of the proposed generator which is of trapezoidal shape. The FFT analysis of generated voltage is carried out. It is observed that % THD is 16.08%, as shown in Figure 13. The higher THD in the generated voltage confirms the presence of multiples third order harmonics which makes the proposed generator advantageous than the other two generators. Due to the flat topped nature of generated voltage, the rectified voltage has less ripple content. A comparative study of these generators is carried out in the next subsection.

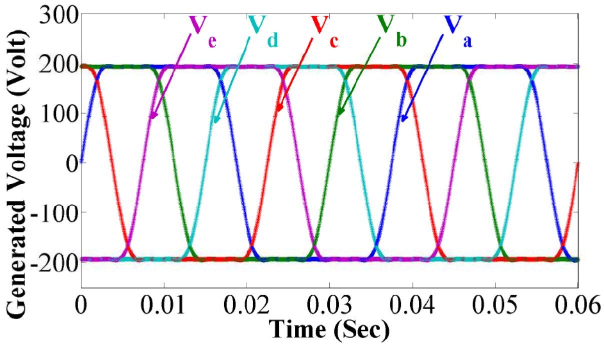

Figure 12: Five Phase Generated Voltage

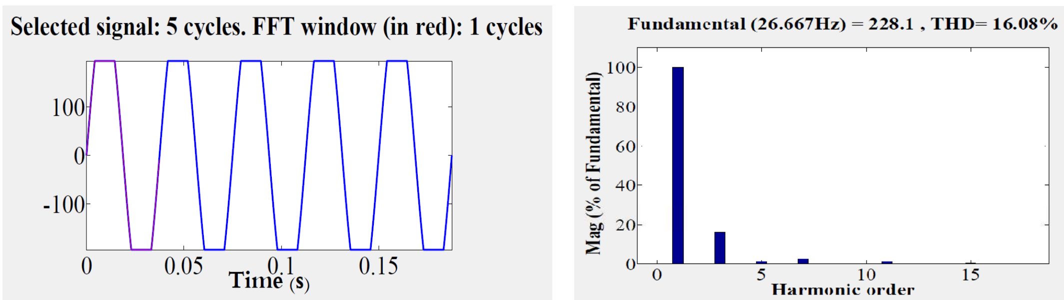

Figure 13: Generated Voltage and Harmonic Plot

The three type of generators are connected to a diode rectifier feeding a resistive load. The quality and the magnitude of their DC link voltages are investigated in terms of percentage ripple factor. In addition, PMSG operation under different fault condition is performed. Furthermore, the DC link voltage, current ripple, terminal voltage and electromagnetic torque are observed under loading condition with healthy and faulty condition operation of the proposed generator. Finally, simulated results are verified with experimental results.

5.1 No-Load Operation

The simulated result at no-load for three different generators, connected with diode rectifier are listed in Table 3. The DC voltage of the proposed generator is 22.097% higher and that of five phase PMSG is 12.45% higher compared to three phase PMSG at 400 rpm. The %ripple factor for six pulsed DC voltage of three phase generator as shown in figure 14 is 4.336% and ten pulses DC voltage as shown in figure 15 is 2.945% for five phase PMSG. In contrast the %ripple factor of proposed PMSG is found to be negligible. The experimental result of the %ripple factor of DC voltage of proposed PMSG is found to be 0.009% and is in good agreement with the simulated result. In this paper two kind of open circuit faults are considered, single phase open circuit(either phase B or C phase is open) and double phase faults(either of B and C or B and D is open). It is found that as diode of any leg is open circuited the output of DC voltage of the rectifier decreases and the % ripple factor increases. Under single phase fault, the % ripple factor is increased to 50.42% and DC voltage is decreased to 209.3 volts for three phase PMSG. In case of five phase PMSG, it is found that the rectified DC voltage of B phase under open circuit condition is found 0.030% lesser than the case in which C phase is open and a higher ripple factor 14.376% is found. Similarly, for the proposed PMSG it is found that the rectified DC voltage of B phase under open condition is found 0.053% lesser than the C phase under open and a higher ripple factor 7.686% is found. The experimental result of the magnitude of DC voltage of the proposed generator is found higher in both cases of the fault, whereas the ripple factor is lesser. In case of B and D open circuit fault, the DC voltage of the proposed generator is 4.569 % higher value than the five-phase generator and the ripple factor of it is found 4.510 which is lesser than five phase PMSG. The experimental result of DC voltage for B and D fault case is found higher and the %ripple factor is lesser in value than the simulated result of the proposed generator. In case of B and C open circuit fault, the DC voltage of the proposed generator is 6.9% higher in value than the five-phase generator and the %ripple factor is found 33.586% which is lesser than the conventional five phase PMSG. The experimental result of DC voltage for B and C fault case is found higher and the %ripple factor is lesser in value than the simulated result of the proposed generator.

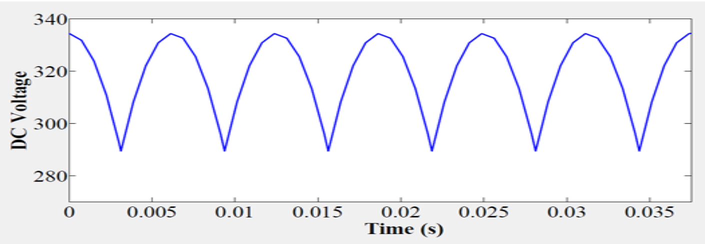

Figure 14: Three Phase Rectified DC Voltage

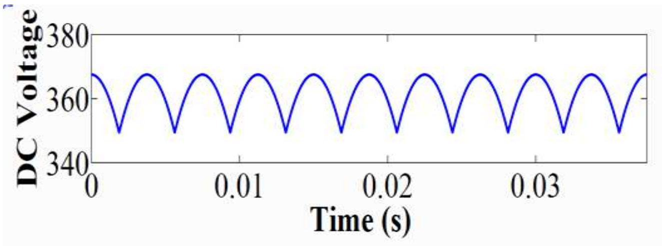

Figure 15: Five Phase Rectified DC Voltage

Table 3: Comparison DC Link Voltage and %Ripple Factor for different Generator

Condition	DC Voltage of Three Phase PMSG	% Ripple Factor of DC Voltage of Three Phase PMSG	DC Voltage of Five Phase PMSG	% Ripple Factor of DC Voltage of Five Phase PMSG	DC Voltage of Proposed Five Phase PMSG	% ripple Factor of DC Voltage of Proposed Five Phase PMSG	Experimental Result of DC Voltage of Proposed 5-Phase PMSG	Experimental Result of % Ripple Factor of DC Voltage of Proposed 5-Phase PMSG
Healthy	316.5	4.336	361.5	2.945	386	0	386	0.00977
B phase open	209.3	50.42	330.6	14.376	372.9	7.6866	378.96	4.982
C phase open	209.3	50.42	330.7	14.164	373.1	7.6846	382.53	4.7446
B& D phase open	....	....	303.7	19.637	359.8	10.015	376.24	4.51094
B &C Phase Open	....	....	259	29.589	287.8	33.9135	307.66	33.58647

Figure 16 shows the variation of rectified DC voltage with respect to speed of proposed PMSG and a linear relationship is observed between the two. The simulated DC Voltage is found in good accordance with the experimental result. This relationship can also be obtained under different open circuit fault conditions including B open, C open, B&D open and B&C open, which is shown in figure 17. At 400rpm the DC Voltage is found 0.898 % lesser in value for C phase fault, 1.823% lesser value for B phase fault, 2.528% lesser in value for B&D fault and 20.295% lesser in value for B&C phase fault in comparison to healthy conditions respectively.

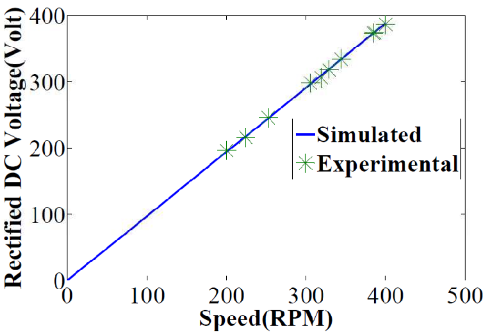

Figure 16: Rectified DC Voltage vs Speed

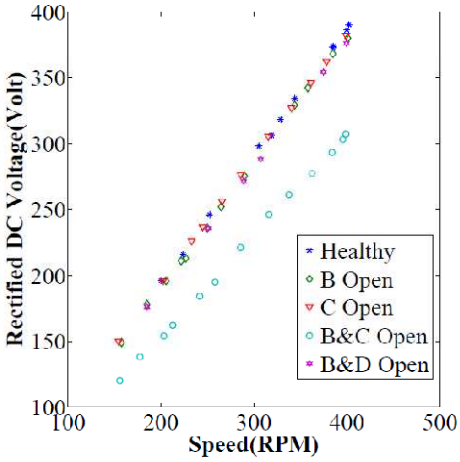

Figure 17: Generated Voltage Vs Speed

5.2 Load Operation

The loading of the proposed generator is performed using five phase diode rectifier and a graph is plotted between DC voltage and DC current as shown in Figure 18. At DC current of 10A, rectified DC voltage is found to be 18.134% lesser than the no-load voltage. The drop in voltage is due to the machine parameter and diode forward voltage drop. The simulated result is found in good accordance with the experimental result. Figure 19 shows the same relationship under different open circuit fault scenario. At 10A of DC current, as compared to healthy conditions, the DC voltage is reduced by 2.531% when C phase is at fault and by 3.164% when B phase is at fault. Additionally, a decrement of 3.481% and 25.949% is observed with respect to healthy DC voltage when phases B, D and B, C are under fault respectively.

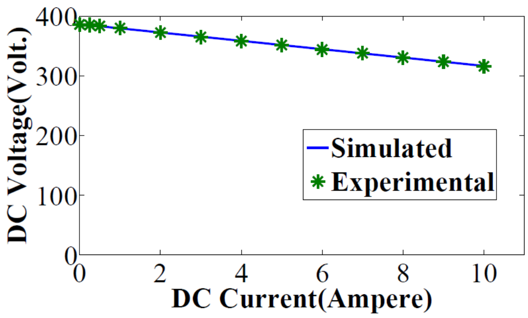

Figure 18: DC Voltage Vs DC Current

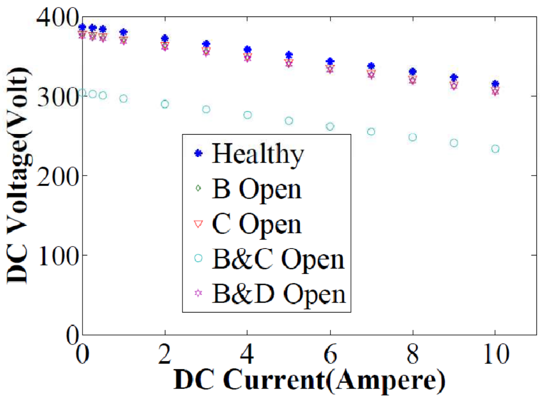

Figure 19: DC Voltage Vs Current under different Condition of Proposed Generator

5.3 Electromagnetic Torque

Figure 20 shows that the simulated result of electromagnetic torque of proposed generator at 400 rpm is 2.46% higher than the FEM results. The torque ripple is 8.62 % and 7.4% for simulated and FEM results, respectively. Figure 21 shows electromagnetic torque under healthy and faulty conditions. The magnitude of torque and its ripple under all these conditions is listed in Table 4. It is found that torque is 19.704% lesser for C phase fault, 19.725% lesser for B phase fault, 37.046% lesser for B&D phase fault and 39.075% lesser for B&C phase fault than the healthy condition. Therefore, ripple factor is found least under the healthy condition and highest under B&C phase fault.

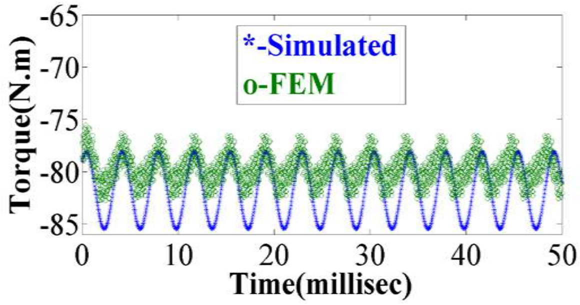

Figure 20: Torque of PMSG

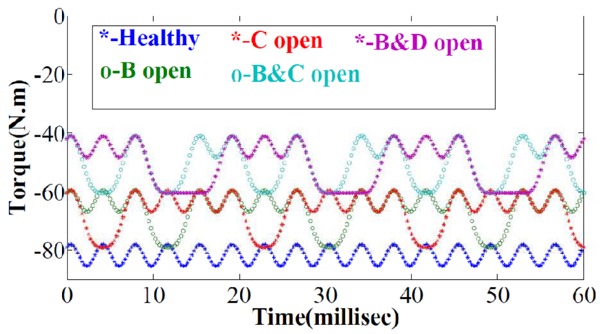

Figure 21: Torque Under Healthy and Faulty Condition

Table 4: Electromagnetic Torque at different Condition

Condition	Average Torque(N. m)	%Ripple Factor
Healthy	-81.8618	8.62429
B-phase open	-65.7142	29.5978
C-phase open	-65.7316	29.590
B and C phase open	-49.8743	39.2386
B and D phase open	-51.5348	37.974

6. CONCLUSIONS

This paper has presented a Fault-tolerant small-scale WEC system. For simplicity and high-reliability, WEC utilises five-phase permanent magnet synchronous generator coupled with an uncontrolled diode rectifier. The FP-PMSG is designed and optimised using FEM analysis in such a way that the model has no saturation under loading condition. The experimental result of electromotive force at 400 rpm is found to be 193.92 volts at 26.667Hz frequency, which is 2.06 % higher than the FEM result. The shape of EMF waveform is trapezoidal due to which THD of 16.08% is found. In particular the harmonics are 3rd, 7th, 9th. etc. To know the superiority of proposed generator, the output performance of coupled rectifier is compared with two conventional 3-phase and 5-phase PMSG under healthy and faulty conditions. It is found that ripple factor in DC link voltage for the proposed generator is least. Under single phase open circuit the DC-link voltage ripple fault for conventional 3 phase, 5 phase and proposed PMSG are found to be 50%, 14% and 7.5%, respectively. Similarly, for the adjacent and non-adjacent double phase open circuit fault, the conventional five phase PMSG has higher ripple factor as compared to the proposed FP-PMSG. Therefore, DC-link capacitor size for three phase PMSG will be higher than proposed FP-PMSG. Under loading condition of the proposed generator, the rectified output voltage shows a dip at rated current which is due to machine parameter and armature reaction effect. Similar, effect is found under faulty conditions. Furthermore, the electromagnetic torque of the proposed generator has been investigated and found that the %ripple factor is around 8.6 %, 29.6 %, 39 % under healthy, single open circuit fault and double phase open circuit fault respectively.

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