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PERFORMANCE ANALYSIS OF SINGLE PHASE INTERIOR PERMANENT MAGNET SYNCHRONOUS GENERATOR

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ABSTRACT

This work presents the performance analysis of a single phase interior permanent magnet synchronous generator. The stator magneto motive force (MMF) waveform of the single phase winding function was developed. The mathematical model in phase variables by which the performance of the generator can be investigated under various operating conditions was developed. Self-excitation of the generator was achieved through pre-excitation by the permanent magnet in the rotor, and then regulated by connecting 30μF capacitor across the terminals of the stator winding. The performances of the generator under constant speed, constant capacitor value and varying power factor loads was investigated. The voltage build-up characteristics and dynamic loss of load performance was studied. The magnitudes of the output power, real power, load voltage and load current increases with increase in load power factors while the phase voltage, phase current, capacitor current and the reactive power decreases with increase in power factor loads. The generator has shown to be capable of stand-alone power source. Simulations were carried out using the Simulink® toolkit in MATLAB® software.

Keywords: *Interior permanent magnet, phase variable model, single phase, load characteristic, dynamic loss of load*

1. INTRODUCTION

Over the years, research into the use of renewable energy sources, such as wind, photovoltaic and hydro power plants for electricity generation has been the subject of increased attention as stated in [1-3]. The interest is also focused on small units used to provide electricity supply in remote or isolated areas that are beyond the reach of an electric power grid or cannot be economically connected to the grid. Known conventional generators are used for electricity generation and supply at the moment, each of which presents different advantages and disadvantages. However, permanent magnet synchronous generators are becoming alternative for generating electricity in stand-alone cases due to their advantages over others.

A number of previous studies were carried-out in [2-9] which investigated the performances of some other well-known conventional single phase generators. Although the research in [10] considered the performance of three-phase permanent magnet generator operating as standby power generating unit, it has also been noted that, relative to permanent magnet synchronous machines, papers have appeared dealing mostly with the electrical motors unlike the generators. It is further evident that the performance of single phase interior permanent magnet synchronous generators (SPIPMSG) has not received sufficient analytical attention. In this work, the developed phase variable model is used to investigate the performance of a single phase interior permanent magnet synchronous generator (SPIPMSG) feeding variable load.

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2. DESCRIPTION OF THE MACHINE

The machine under study is an AC single phase interior permanent magnet synchronous generator (SPIPMSG); the generator consists of a four pole single phase stator winding. The rotor consists of rare earth Neodymium Iron Boride (NbFeB) permanent magnets mounted on the rotor shaft and is arranged in opposite direction for production of a sinusoidal-distributed flux density in the air gap. The stator comprises of a laminated core with 36-slots, four-pole single layer winding with six coils on each pole. There are no moving conductors on the rotor. The rotation of the rotor causes magnetic fluxes changes in the stator core and voltage induction in the armature winding, the induced voltage and current are oscillating with time, and the output is connected to the load through a conductor. The connected load impedance Z_L consists of a resistive load, R_L in series with an inductive reactance load, X_L. A shunt capacitance C is also connected at the terminal of the generator for voltage regulation as shown in Figure 1. The schematic diagram of the machine is shown in Figure 2. The internally generated voltage E_a depends on the mechanical rotational speed and permanent magnet flux induced in the stator winding.

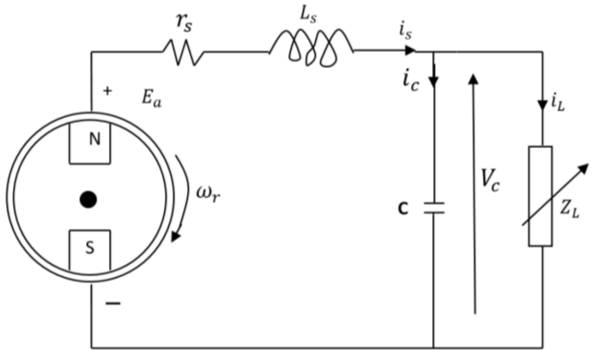

Figure 1: Connection diagram of SPIPMSG supplying load with a shunt-connected capacitance.

3. MAGNETO MOTIVE FORCE (MMF) OF THE STATOR SINGLE-PHASE WINDING

The winding function is the mmf per unit current and represents the winding distribution as it appears in slots around the stator periphery as shown in Figure 2. The concentric stator winding per pole of the single phase generator occupies 8/9 of all the stator slots along the circumference of the machine. The turns and windings function of the phase winding was obtained by summing turns and winding functions of the individual coils. The number of conductors in slots per pole is shown in Table 1. The resultant mmf profile of the distributed winding has a stair-case-like shape which is much closer to the sinusoid as shown in Figure 3. When a single magnet of a 4-pole generator complete one mechanical rotation, it crosses the four poles of the stator thereby giving the induced mmf with two positive half cycles and two negative half cycles which gives two complete cycles of induced mmf. The induced mmf is maximum when the magnet is at the center of the pole and the mmf induced is minimum when the magnet is at the middle of the two gap between the poles.

Table 1: Number of conductors per slot for one pole

Slot	Number of conductors
1	178
2	84
3	146
4	32
5	
6	32
7	146
8	84
9	178

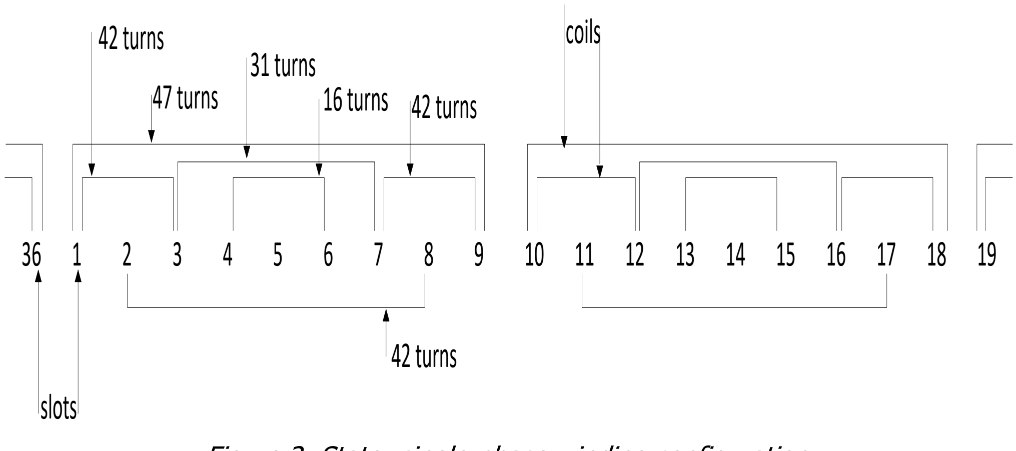

Figure 2: Stator single-phase winding configuration.

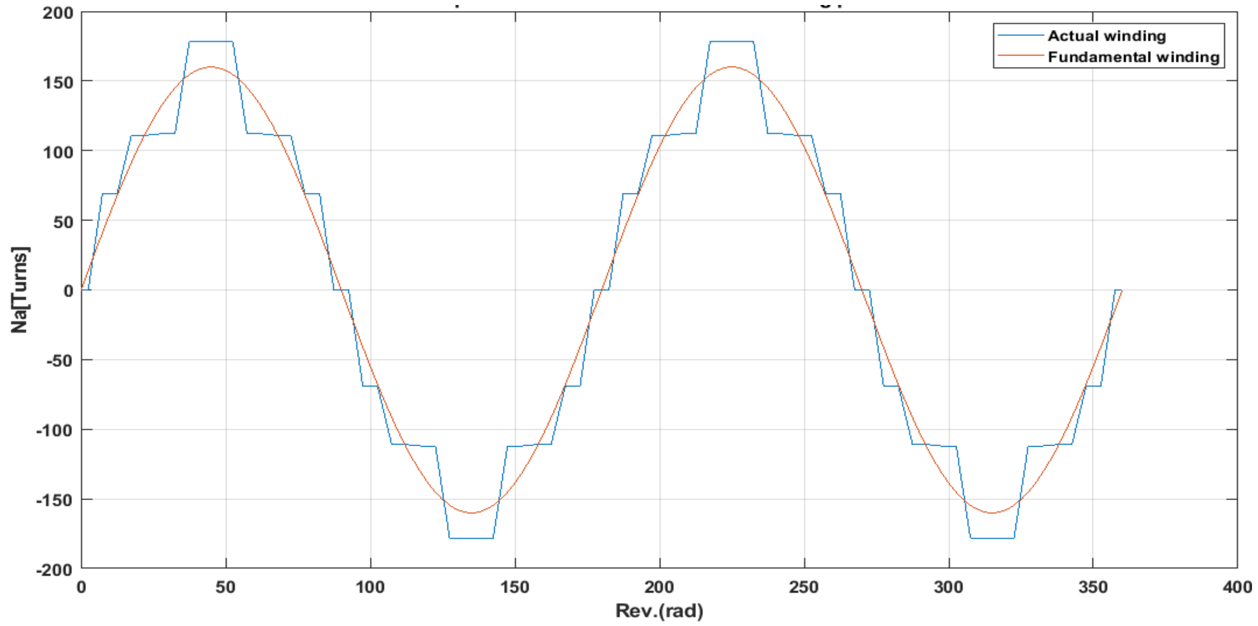

Figure 3: Stator single-phase winding function

4. MATHEMATICAL MODEL

The machine can be described by a set of equations governing the electrical behavior as follows:

4.1 Voltage equations

For unloaded generator, the terminal voltage corresponds to the voltage across the shunt capacitor. From Figure 1, the voltage equation can be written as:

$$E_a = v_c + \frac{d}{d_t}(L_s(\theta_r)i_s) + r_s i_s \tag{1}$$

or

$$v_c = E_a - L_s(\theta_r)pi_s - i_s\left(\omega_r \frac{dL_s(\theta_r)}{d\theta_r} + r_s\right) \tag{2}$$

Where $p = \frac{d}{dt}$ and $\omega_r = \frac{d\theta_r}{dt}$

$$E_a = \omega_r \lambda_{pm} \sin\theta_r \tag{3}$$

where λ_{pm} is the permanent magnet flux linkage

4.2 Inductance of the machine

The self-inductance of the winding associated with flux crossing the air-gap is given by the integral expression [11].

$$L_s = \mu_o r l \int_0^{2\pi} g^{-1}(\varphi, \theta_r) N_A^2(\varphi) d\varphi \tag{4}$$

The inverse air gap of the machine can be approximated by Fourier series according to Lawrenson and Agu as [12]:

$$g^{-1}(\varphi, \theta_r) = A - B\cos 2p_r(\varphi - \theta_r) \tag{5}$$

where $A = \frac{1}{2}\left(\frac{2}{g_1} + \frac{1}{g_2}\right)$, $B = \frac{2}{\pi}\left(\frac{1}{g_1} - \frac{1}{g_2}\right)\sin\pi\beta$ and $N_A = N_P\cos(p_r\theta_r)$. We note that g_1 is the airgap at pole face, g_2 is the interpolar slot space, N_P is the peak value of winding mmf, p_r is the number of pole pairs and β is the pole arc pole pitch ratio.

Substituting the constituents into (4) and performing the integration, we have:

$$L_s(\theta_r) = L_{sl} + L_0 - L_1\cos 2\theta_r \tag{6}$$

Where, $L_0 = \mu_o r l N_A^2 \pi\left(\frac{2}{g_1} + \frac{1}{g_2}\right)$ and $L_1 = \mu_o r l N_A^2 \pi\left(\frac{2}{g_1} - \frac{1}{g_2}\right)$ and L_{ls} is an added leakage inductance estimated to be 10% of L_0 [13].

4.3 The current equations

At open circuit, $i_c = i_s$ while at load, $i_c = i_s - i_L$. The capacitor current is given by:

$$pi_c = C\frac{dv_c}{dt} \tag{7}$$

The differential of the winding inductance with respect to θ_r is needed in (2) and is obtained which modifies it to:

$$pi_s = \frac{1}{L_s(\theta_r)}[E_a - v_c - i_s(\omega_r 2L_l\sin(2\theta_r) + r_s)] \tag{8}$$

4.4 Load model equations

Most of the sudden changes in the generator performance are as a result of load application on the generator while in operation. The load impedance Z_L is written as:

$$Z_L = R_L + j\omega_r L_L \tag{9}$$

The variables R_L and L_L represent the load resistance and inductance respectively. The power factor angle φ is given by:

$$\cos\varphi = \frac{R_L}{\sqrt{(R_L)^2 + (\omega L_L)^2}} \tag{10}$$

The associated output voltage variation with load current can be expressed as:

$$pi_L = \frac{V_c - R_L i_L}{L_L} \tag{11}$$

where

$$L_L = \frac{R_L}{\omega_r}\sqrt{\left(\frac{1}{\cos\ \varphi}\right)^2 - 1} \tag{12}$$

4.5 The power output

The apparent power, S is written as:

$$S = vi_L^* \tag{13}$$

Therefore, the real and reactive powers are expressed as:

$$P = V_c i_L \cos\varphi \ \ and\ Q = V_{out} i_L \sin\varphi \tag{14}$$

5. BUILD-UP CHARACTERISTICS

The voltage build-up characteristics of the machine at no-load shows that the generator voltage at no load starts then build-up maintaining a steady-state at 0.08sec to 0.5sec in the simulation, the generator attains its peak voltage value of 220volts as shown in Figure 4 using 30μF capacitor value. The phase and capacitor currents at no-load starts then build up maintaining steady-state values at 0.08sec with a peak of 2.25Amps as shown in Figure 5.

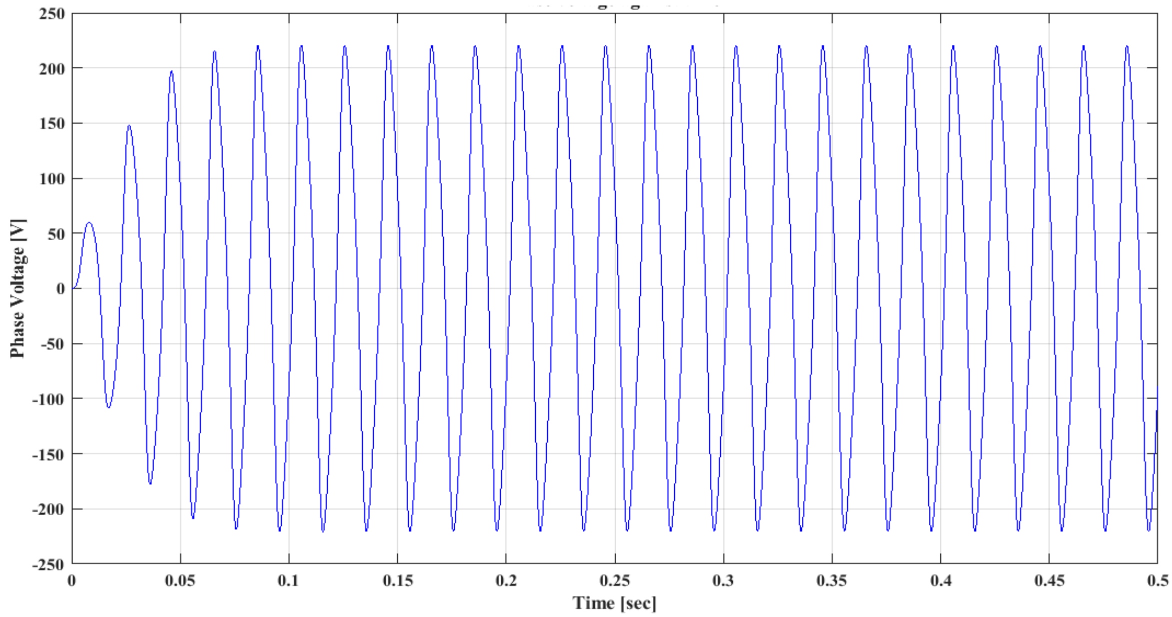

Figure 4: The build-up voltage of SPIPMSG

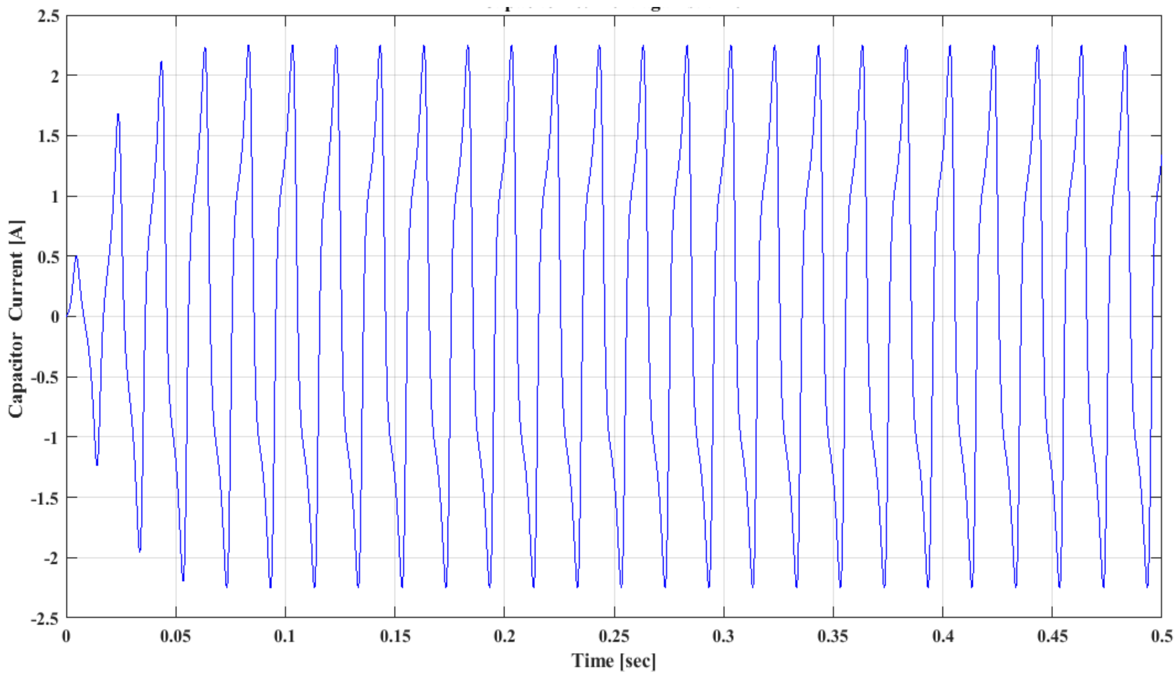

Figure 5: The build-up stator winding current at no load

6. THE DYNAMICS OF CHANGE OF LOAD

To determine the transient loading and the loss of load behavior of the generator at different power factor conditions, the object of observation is the envelope of the terminal wave form. The generator was operating under a no-load condition at terminal voltage of 220V when suddenly a load was added at $time, t = 1sec$. The Load was suddenly removed at $t = 1.4sec$. The added load was $2k\Omega$, for different power factors. The value of the resistive load (R_L) is constant and the corresponding values of inductive load (L_L) needed for the particular power factor are calculated from equation (12). The results are shown in Figure 6.

7. LOAD CHARACTERISTICS

The load characteristics here is deduced by loading the generator gradually from no-load to full load until it reaches pull-out. For each power factor loading, only the value of the load resistance is adjusted, and the corresponding load inductances needed for that particular load power factor are calculated according to equation (12). Figures 7 through 10 show the characteristics obtained. The key information in the plots shown here is that the loading at different power factors do not yield a substantial change, implying that unlike other single-phase generators, the SPIPMSG shows a promising governing characteristics even for very low power factor loads.

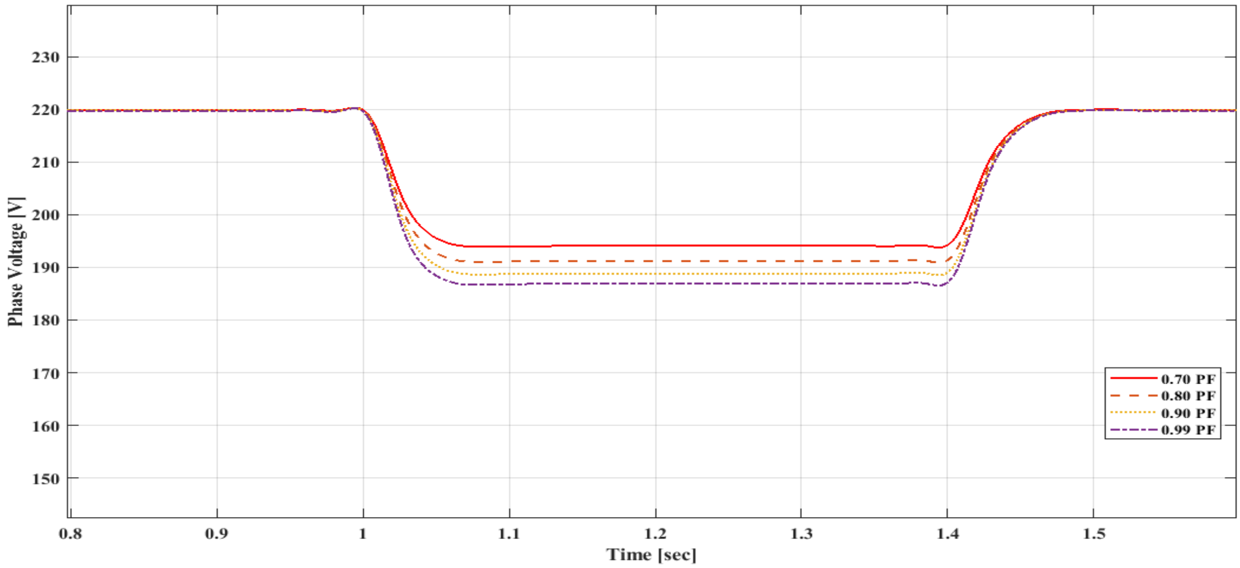

Figure 6: Phase voltage against time due to sudden addition and removal of different power factor loads.

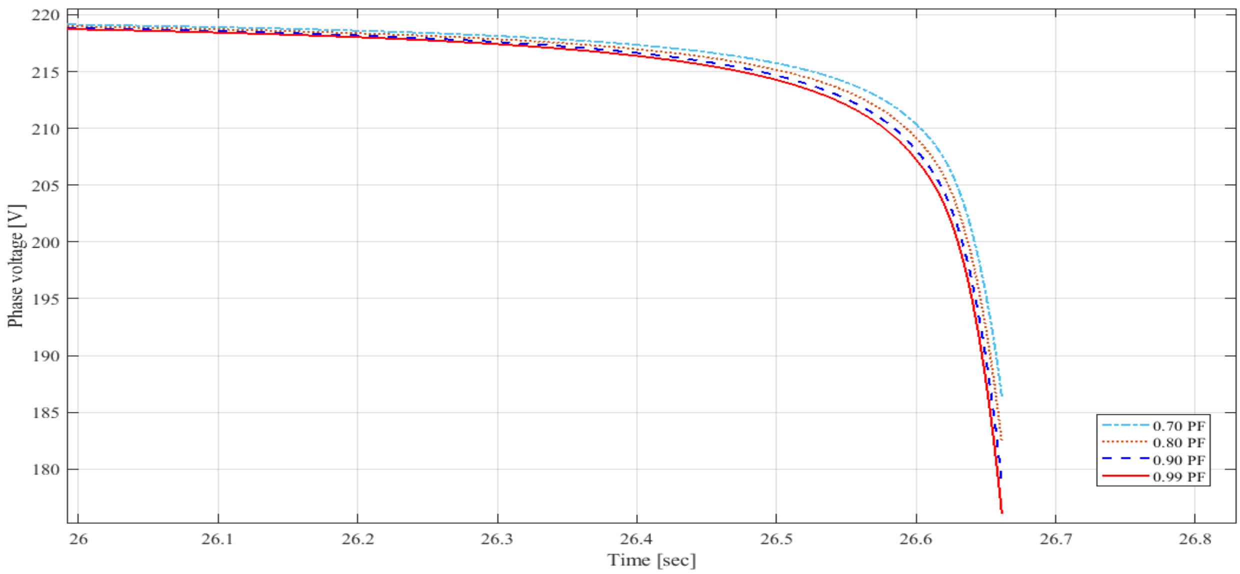

Figure 7: Phase voltage against time on loading condition.

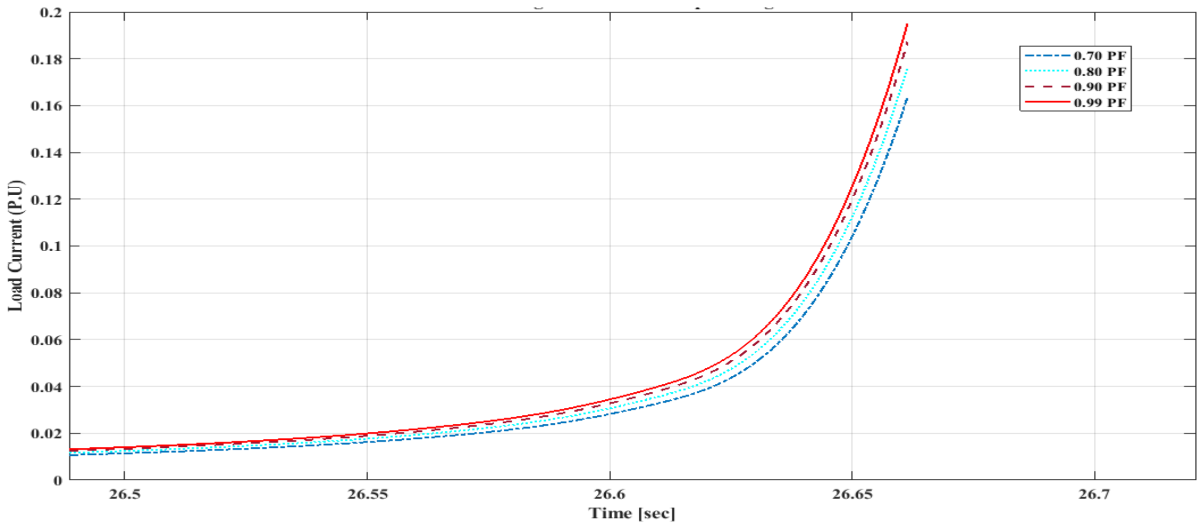

Figure 8: Load current against time on loading condition.

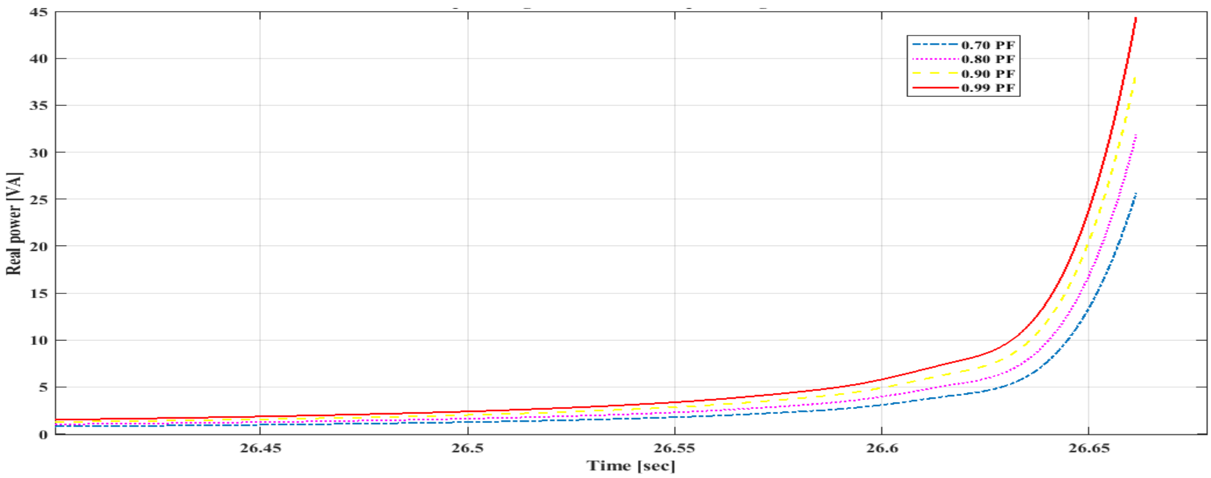

Figure 9: Real power against time on loading condition.

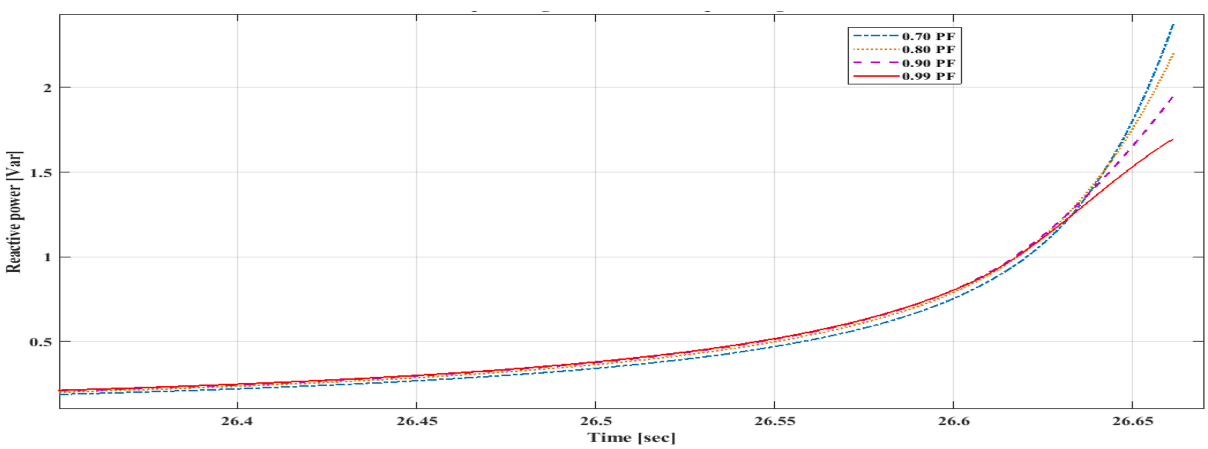

Figure 10: Reactive power against time on loading condition.

8. CONCLUSION

Performance analysis of single phase interior permanent magnet synchronous generator was presented. The mathematical model relating the parameters of the generator and the magnetic properties of the SPIPMSG were derived. The derived equations together with the generator parameters were simulated in MATLAB/ Simulink environment, the results obtained under no-load, dynamic change of load performance and loading conditions x-rayed the performance characteristics of the generator. The build-up time for phase voltage, phase current and capacitor current was very short because it was only armature time constant that were present in the stator winding, the build-up time was 0.08sec. Transients with near-zero oscillations were observed during the dynamic loss of load performance, the magnitudes of the output power increases with increase in power factor load but the drop during addition of load decreases with increase in power factor load. The transient was higher during removal of the load than addition of load. The drop in the phase voltage increases with decreasing power factor load while the drop in phase current decreases with increasing power factor load. The capacitor current on loading decreases with increasing power factor load. Finally, when SPIPMSG is fully developed it could be compared favorably with field-excited single phase synchronous generator of the same size for stand-alone applications.

9. REFERENCES

[1] Y. H. A. Rahim, A. I. Alolah and R. I. AI-Mudaiheem. "Performance of Single Phase Induction Generator", *IEEE Transactions on Energy Conversion,* Vol. 28, No.3, pp. 389-395, Sep 2003.

[2] T. Ahmed, K. Nishida and M. Nakaoka, "A novel stand-alone induction generator system for ac and dc power applications," *IEEE Trans. Ind. Appl.,* Vol. 43, No. 6, pp. 1465–1474, Dec. 2007.

[3] T. F. Chan, "Capacitance requirements of self-excited induction generators," *IEEE Trans. Energy Convers.*, Vol. 8, no. 2, pp. 304–311, Jun. 1993.

[4] T. Fukami, K. Nakagawa and Y. Kanamaru, "A technique for the steady-state analysis of a grid-connected permanent-magnet induction generator." *IEEE Trans Energy Conversion.* Vol.19, Issue.1, pp. 318–324, Jan.2004.

[5] T. Fukami and M. Yokoi, "Performance evaluation of a permanent-magnet induction generator," *IEEJ Trans IA*, Vol.123, pp.1065–1070, 2003.

[6] T. Tsuda, T. Fukami, Y. Kanamaru and T. Miyamoto. "Magnetic field analysis of a permanent magnet induction generator." *IEEJ Trans IA,* Vol.124, pp.1274–1280, 2004.

[7] T. Tsuda, T. Fukami, Y. Kanamaru and T. Miyamoto. "Performance analysis of a permanent-magnet induction generator connected to a single phase power grid." *IEEJ Trans IA,* Vol.125, pp. 666–672, 2005.

[8] J. Chen and P. Famouri, "Single-phase self-excited reluctance generator, part I: Steady state analysis," *Electric Power Components and Systems*, vol. 31, pp. 129–147, 2003

[9] T. Chan and L. Lai, "Steady-state analysis and performance of a single-phase self-regulated self-excited induction generator," *IEE Proc: Generation, Transmission and Distribution,* Vol.149, No. 2, pp. 233–241, 2002.

[10] S. Kahourzade, W. L. Soong and P. Lillington, 'Single-Phase Loading Behavior of the Isolated 3phase Permanent-Magnet Generator,' *IEEE Transactions on Industry Applications,* Vol. 53, no. 3, pp.1860-1869, 2017

[11] Obe, E. S. and Onwuka, K. I., "Modeling and Performance of a Self-Excited Two-Phase Reluctance Generator" *Nigerian Journal of Technology*, Vol. 30. No. 2, June 2011, pp. 55-66.

[12] Lawrenson P. J., Agu, L. A. Theory and performance of polyphase reluctance machines. *Proc. IEE,* 111(8):1435–45, 1964.

[13] S. J. Chapman, "*Electrical Machinery Fundamentals*." 4th edition, New York: McGraw Hill. 2005

[14] V. N. Mittle, A. Mittal. *Design of Electrical Machines,* 4th edition Delhi: Standard Publishers Distributors, 1996.

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APPENDIX: MACHINE PARAMETERS USED IN THE SIMULATION

Number of poles = 2, Frequency, f = 50Hz, Capacitance of the Capacitor, C= 30μF,
Stator Resistance R_s = 27.7Ω, Permanent magnet flux ϕ = 0.139Wb, Stator leakage inductance, L_{ls} = 0.067H.