The American Journal of Engineering and Technology
ISSN 2689-0984 | Open Access

TYPE Original Research
PAGE NO. 102-114
DOI 10.37547/tajet/Volume07Issue06-11

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Direct-Phase Variables Performance Analysis of Concentrated Winding Permanent Magnet Synchronous Generator with Capacitive Assistance

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OPEN ACCESS

SUBMITED 19 April 2025
ACCEPTED 22 May 2025
PUBLISHED 14 June 2025
VOLUME Vol.07 Issue 06 2025

CITATION

Emmanuel C. Obuah, Uche C. Eze, & Benjamine Akinloye. (2025). Direct-Phase Variables Performance Analysis of Concentrated Winding Permanent Magnet Synchronous Generator with Capacitive Assistance. The American Journal of Engineering and Technology, 7(06), 102–114. https://doi.org/10.37547/tajet/Volume07Issue06-11

Abstract: The dynamic and transient performance analysis of a three-phase interior rotor concentrated winding permanent magnet synchronous generator (CW-IPMSG) with was presented. In this paper. The study was done in direct-phase variables concentering only the fundamental magneto-motive force (MMF). The machine's inductance was determined using winding function theory (WFT). The derived inductance was used to determine performance characteristics of the machine's variables such as phase current, load current and electromagnetic torque. The study was validated in MATLAB/Simulink to observe the performance of the characteristics of the generator. The study was carried out at no-load condition, under load perturb, as well as increase and decrease of capacitor. It was observed that the permanent magnet synchronous generator had slightly better output performance with capacitor assistance.

Keywords: Concentrated Winding; Direct-Phase Variables.; Inductance, Permanent Magnet; Winding Function Theory.

Introduction: Most electric machines have distributed winding (DW). Distributed windings were preferred over the concentrated winding (CW) because the distributed winding gives a sinusoidal uniform MMF [1-3].

In recent years electric machines with concentrated windings have become a competitive alternative to machines with distributed windings for certain applications. Machine with concentrated winding is easier and cheaper to manufacture because of the short ends winding feature. It has higher power density and good fault tolerance capabilities especially the fractional-slot concentrated winding machine. Again, machine with CW has higher slot fill factor and good efficiency compared to distributed winding permanent magnet (PM) machine [4]. A concentrated winding is preferred for a cost-effective application which requires higher power density.

The benefits of concentrated windings and dual-windings together have not been taken advantage of in the synchronous reluctance motor. Previous researches carried out on the synchronous reluctance motor considered the stator of the machine as having only distributed, or having distributed dual stator winding.

Performance characteristic of permanent magnet synchronous motor (PMGM) with CW and DW was carried out. The study compared the performance of the two arrangements using certain rotor parameters such as back EMF, resistance, efficiency, output torque etc with two identical rotor dimensions. Parasitic characteristics such as cogging torque, torque pulsation, unbalanced magnetic force, mechanical vibration and acoustic noise are always of significant concern during the machine design. The parasitic effects could be potentially more harmful in CW PMSM since there are additional space harmonic contents in the stator MMF distribution of the machine [5].

The synchronous reluctance generator with transversely limited rotor has been studied. It was reported that the generator is more robust, and has relatively lower core loss, and provides spaces for embedding cage, and can easily be skewed, and gives allowance for inserting magnet. [6].

Reference [7] carried out comparative analysis of synchronous reluctance machines (SynRM) with 6, 8 and 12 poles. The effect of different pole numbers on average torque, loss, torque-ripple, d and q inductances is investigated. It was shown that the 8-pole machine has similar performance to the 6-pole machine but the 12-pole machine has worse performance.

Reference [8] developed an analytical model in the d-q reference frame to recognize the steady-state of the self-excited reluctance generator, considering no-load and resistive load conditions. A fast method to estimate the minimum capacitance requirements was also proposed, and experiments were carried out to verify the analytical results. After that, attention was paid on the capability of self-excitation in reluctance generator with different residual magnetisms in the rotor. Different levels of residual rotor magnetism are achieved by different magnetizing DC currents. An indicative value of phase current was defined to determine the self-excitation, and the required minimum residual rotor magnetism for self-excitation in the reluctance generator connected with different capacitances was discussed. At last, the capability of self-excitation in reluctance generators by connecting charged capacitors was investigated.

Reference [9] presented a performance comparison of an interior mounted permanent magnet synchronous generator (IPMSG) with a synchronous reluctance generator with the same size for a wind application. It was found that using the same geometrical dimensions, a SynRG can convert 74 % of the power that an IPMSG can convert, while it has 80% of the IPMSG weight. Moreover, it is found that the efficiency for the IMPSG is 99 % at rated power compared to 98.7 % for the SynRG.

Reference [10] in their work, investigated the capability of simple salient-pole rotor synchronous reluctance generators at a 5 MW power level. Different salient pole rotor profiles are considered in the finite element design optimization of the generator. It was found that with the simple salient pole rotor, similar torque density and efficiency are obtained as in published equivalent distributed flux barrier rotor reluctance synchronous generators. Also,

Reference [11] presented a performance comparison of a 5MW interior permanent magnet synchronous generator (IPMSG) with a 5 MW PMa-SynRG with the same stator, to be used for a wind energy application. It was found that PMa-SynRG has lower rotor weight as well as 14 % lower magnet weight with the same maximum torque performance. For wind speeds lower than 8.5 m/s the PMa-SynRG has less loss. Moreover, the machine annual energy efficiency for the PMa-SynRG is higher for average wind speeds between 5-10 m/s.

Reference [12] presented a study of permanent magnet assisted synchronous generator for autonomous application using the classical Park's d-q model. It was observed that the generator with permanent magnet had better output performance than the conventional generator when compared. Also [13] carried out steady state performance analysis of permanent magnet synchronous generator with capacitive assistance using d-q model, where capacitor was used to improve power output of the generator and voltage regulation.

The study of electric machines based on the actual geometry of the machine is importance because it gives the actual behaviour of the machine. Widing Function Theory is used to study machines beheviour considering the actual placemen of machine windings. Some studies that adopted the theory of winding function in machine analysis include the use of WFT on induction machines [14], synchronous reluctance motors [15], switched reluctant motors [16] a machine with doubly salient structure [17], and for model of a synchronous reluctance motor including all slot and winding harmonics [18].

Reference [19] derived a symmetrical component for asymmetrical multiphase windings for a motor, where an analytical formulation is presented to relate the harmonic content of winding functions to winding factors. The harmonic leakage factor is accurately formulated from the winding function, and the suggested analysis method was validated with the star of slots and sinusoidal functions of distribution and pitch factors

A five-phase synchronous reluctance motor and permanent magnet synchronous reluctance motor was modelled and simulated in phase variables and the results in phase variables tend to agree with that of the Finite Element Analysis [20-21].

Reference [22] also carried out a performance analysis of a concentrated dual-winding synchronous reluctance machine with capacitive assistance. The machine got its power supply directly on power line. The transient and dynamic performance analysis of a proposed line-start, three-phase concentrated dual-winding synchronous reluctance motor in comparison with the conventional concentrated winding synchronous reluctance motor was made. The modelling of the synchronous reluctance machine was done in direct-phase variables considering only the fundamental magneto-motive force. The machine inductances of both machine models were determined using winding function theory. The derived inductances were used to determine machine performance characteristics such as torque, speed, phase currents etc. The performance characteristics of both motors were monitored using MATLAB/Simulink, and the proposed line-start machine with capacitive assistance was observed to have improved performance characteristics when compared to the conventional machine.

Most study on CW machine considered the machine as motor. There is paucity of literature where the machine was used as generator. This study shall look at the analysis of the synchronous reluctance generator with assistance from permanent magnet for excitation.

To accomplish the goal of the study, the following objectives were addressed.

i. To develop the clock diagram of the CW-IPMSG machine based on the arrangement

ii. To present mathematical models for the inductance of the CW-IPMSG in direct-phase variable using Winding Function Theory

iii. To use the calculated inductance to obtain the phase voltage, phase voltage, load current and electromagnetic torque of the CW-IPMSG at no-load condition using MATLAB/Simulink

iv. To study of the performance of the CW-IPMSG on sudden addition and removal of load using MATLAB/Simulink

v. To study of the effect of variable capacitance on the performance of the CW-IPMSG on using MATLAB/Simulink.

2. MATERIALS AND METHODS

There are several methods used to model or analysis of electric machine in literature. In this section, a list of materials and method adopted is presented.

2.1. Materials

The materials used for the study include typical machine parameters winding presented in Table 1, and MATLAB/Simulink.

2.2. Method

Winding Function Theory was used to accomplish the study's aim. Winding Function involves calculating machine inductances based on actual geometry or placement of the machine coil.

2.1.1. Modeling of the CW-IPMSG

In modeling the CW-IPMSG, it is assumed that

i. the magnetic flux across the air gap is perpendicular. only radial flux is considered

ii. the magnets are seen to be placed adjacent to each other; and the flux density between the adjacent magnets is assumed to be equal to zero. By this, there is no flux linkage between the adjacent magnets.

iii. two coils are series connected and behave like a single phase.

With these assumptions, the magnets can be modeled as coils which are wound in opposite direction with number of turns. So, because of the way they are stacked, the maximum turn is 2. The task here is to use Winding Function Theory to calculate the machine inductance and used the calculated inductance to obtained other relevant quantities like power output, voltage etc. Figure 1 shows the coil clock diagram of the machine based on the winding pattern. The machine is a 4 pole 12 slot machine with double-layer winding. Figure 2 shows an ideal 4 pole machine based on the assumption made

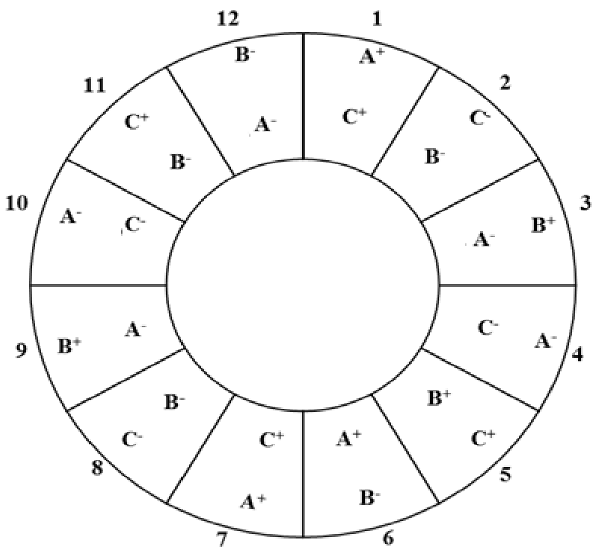

Figure 1 Clock diagram for the machine with double layer

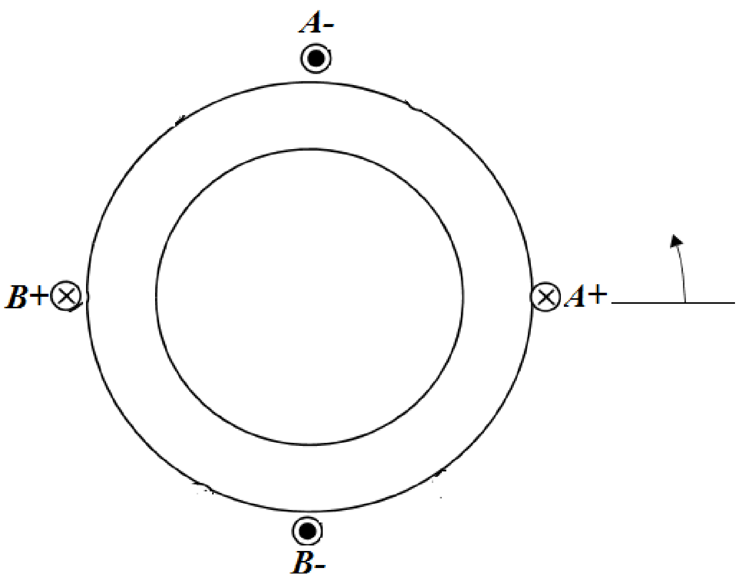

Figure 2 A basic machine

The winding function method is used for calculation of the machine inductances along with the actual machine geometry. Winding function corresponding to the stator windings are defined as a function of stator angle according to their winding layouts in [23]. The procedure used in [24] was adopted to obtain the expression for turn function in (1).

$$\langle n(\varphi_s)\rangle = \left[\frac{1}{2\pi}\int_0^{\pi} n(\varphi_s)\right] = \frac{N_c}{4} \qquad (1)$$

The turn function shows the number of turns as a function of the stator angle.

According to [24], the inductances will be calculated for the case in which the two coils, A and B, are treated as distinct coils, and ones which are connected in series. Equation (2) gives the expression for the first series. While equation (3) gives the expression for the second series

$$N_A(\varphi_s) = \frac{3N_c}{4} \quad (2)$$

$$N_B(\varphi_s) = \frac{-N_c}{4} \quad (3)$$

The magnetizing-inductance of phase A is calculated by integrating the turn function with respect to the stator angular position from the reference period zero degree as the machine rotates to 360 degrees for complete revolution. as found in (4)

$$L_A = \frac{\mu_o r_s l_s}{g_{eff}} \int_0^{2\pi} {N_A}^2(\varphi_s) n_A \, d\varphi_s \quad (4)$$

Solving gives (6)

$$L_A = \frac{1}{8}\frac{\pi N^2 \mu_o r_s l_s}{g_{eff}} * g_o \quad (5)$$

Similarly, the magnetizing-inductance of B is calculated as

$$L_B = \frac{\mu_o r_s l_s}{c} \int_0^{2\pi} {N_B}^2(\varphi_s) n_B d\varphi_s \quad (6)$$

Again, Solving gives (8)

$$L_B = \frac{3}{8}\frac{\pi N^2 \mu_o r_s l_s}{g_{eff}} * g_o \quad (7)$$

where

μ_0 is the relative permeability of free space

r_s is the stator radius

l_s is the stator length

N_c is the number of turns of coil

g_{eff} is the effective air-gap

g_o is the amplitude of the first order harmonic

From (5) and (7), the magnetizing-inductance is proportional to the square of the number of turns per tooth, stator length and stator radius, and inversely proportional to the effective air gap length. It is also clear that total inductance does not depend on the number of stator slot. Therefore, air-gap inductance does not depend on the number of slots. Furthermore, the inductance does not depend on the number of poles. So, air-gap inductance is not a function of a combination of number of poles per slot.

To achieve a sinusoidal field, each of the stator windings of machine is shifted in space relative to the others by 2π/3. In the stator reference frame, the self-inductances of the stator for phase B and C describing the electrical circuit of a three-phase synchronous machine using conventional notations are given as (8) through (11), if leakage inductance is accounted for [25].

$$L_{aa} = L_{ls} + L_A - L_B \cos 2\,\theta_r \quad (8)$$

$$L_{bb} = L_{ls} + \frac{1}{2}L_A - L_B \cos 2\left(\theta_r - \frac{\pi}{3}\right) \quad (9)$$

$$L_{cc} = L_{ls} + \frac{1}{2}L_A - L_B \cos 2\left(\theta_r + \frac{\pi}{3}\right) \quad (11)$$

The mutual inductances are in (12) through (17)

$$L_{ab} = -\frac{1}{2}L_A - L_B \cos 2\left(\theta_r - \frac{\pi}{3}\right) \quad (12)$$

$$L_{ac} = L_{ls} + L_A - L_B \cos 2\left(\theta_r - \frac{2\pi}{3}\right) \quad (13)$$

$$L_{ba} = -\frac{1}{2}L_B - L_A \cos 2\left(\theta_r + \frac{\pi}{3}\right) \quad (14)$$

$$L_{bc} = -\frac{1}{2}L_B - L_A \cos 2\left(\theta_r + \frac{\pi}{3}\right) \quad (15)$$

$$L_{ca} = -\frac{1}{2}L_A - L_B \cos 2\,(\theta_r + \pi) \quad (16)$$

$$L_{cb} = \frac{1}{2}L_A - L_B \cos 2\left(\theta_r - \frac{2\pi}{3}\right) \quad (17)$$

The stator total inductances can be given in matrix form in equation (18) for phase A, B and C

$$L_S = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \quad (18)$$

Also, considering stator phase displacement angle, the phase A, B and C flux linkage is expressed as in equations (19) (20) (21)

$$\lambda_{as} = L_{aa}i_a + L_{ab}i_b + L_{ac}i_c + \lambda_m(\sin\theta_r) \quad (19)$$

$$\lambda_{bs} = L_{bb}i_a + L_{ba}i_b + L_{bc}i_c + \lambda_m \sin\left(\theta_r - \frac{2}{3}\pi\right) \quad (20)$$

$$\lambda_{cs} = L_{cc}i_a + L_{cb}i_b + L_{cc}i_c + \lambda_m \sin\left(\theta_r + \frac{2}{3}\pi\right) \quad (21)$$

where

λ_m is the permanent magnet constant flux.

Using Kickoff's voltage law, the generator voltage equation is given as (22).

$$E = I_S R_S + \frac{d}{dt}(L_S I_S) + V_c \quad (22)$$

Rearranging (23) gives (24)

$$\frac{dI_S}{dt} = \left[E - I_S\left(R_S + \omega_r * \frac{dL_S(\theta_r)}{d\theta_r}\right)\right] * L_S(\theta_r)^{-1} - V_c \quad (23)$$

where

V_c is the capacitor voltage

I_S is the stator three phase current given in matrix form as:

$$I_S = [I_a\ I_b\ I_c] \quad (24)$$

R_S is the stator three-phase resistance, given in matrix form as (24).

$$R_S = diag\begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \quad (25)$$

where $R_a = R_b = R_c$

$\boldsymbol{E}$ is given as $= [\boldsymbol{E_a};\quad \boldsymbol{E_b};\quad \boldsymbol{E_c};]$ (26)

where

$$E_a = \lambda m * \cos wt \quad (27)$$

$$E_b = \lambda m * \cos\left(wt - \frac{2\pi}{3}\right) \quad (28)$$

$$E_c = \lambda m * \cos\left(wt - \frac{4\pi}{3}\right) \quad (29)$$

For the sake of making the capacitor voltage as a system state variable for simulation, the integral equation for the capacitor voltage is given as (30).

$$V_{ca} = \frac{1}{C}\int I_s dt \quad (30)$$

where C is the capacitance of the capacitor.

The load equation is given in as [26] as:

$$L_{aL} = \frac{R_{aL}}{\omega_r}\sqrt{\left(\frac{1}{\cos\theta}\right)^2 - 1} \quad (31)$$

where

R_{aL} is the per phase resistive load

Consequently, the output power is given as (32).

$$P_{out} = 3EI_a \cos \Phi \quad (32)$$

where

Φ is the load power factor.

The electromagnetic torque can be derived in (33) using co-energy method.

$$T_e = \frac{1}{2}[I_S]^2 \frac{d|L_S(\theta_r)|}{d\theta_r} + \lambda_m \quad (33)$$

3. Results and Discussion

The performances of the CW-IPMSG at no-load condition, load perturbs and capacitance variation are shown in Figures 3 to 13. The results were obtained using equations (5), (7) through (21), (23) through (25), (27) through (33) with the relevant parameters shown in Table 1. Excitation capacitor of 90 µF was used while the permanent magnet flux used was 0.8 at 0.8 power factor.

3.1. Dynamic Performance of CW-IPMG at No-Load Condition

Figure 3 through 7 shows the phase voltage, stator phase current, capacitor phase current per phase load current and electromagnetic torque of the CW-IPMSG at no-load condition. The CW-IPMSG exhibited the quality of producing voltage of about 230 V. This closely match the value given in the machine nameplate. The corresponding phase current is shown in Figure 4. The phase current for the CW-IPMSG is about 7 A while the capacitor current is about 7.5 A as illustrated in Figure 5. In Figure 6, the load current is about 0.0015 A. The electromagnetic torque is illustrated in Figure 7. At initial start, the value of the torque rose to about 5.6 Nm. The generator continues to run, it started gaining stability. That was from 0.2 seconds through 0.4 seconds when it stopped running.

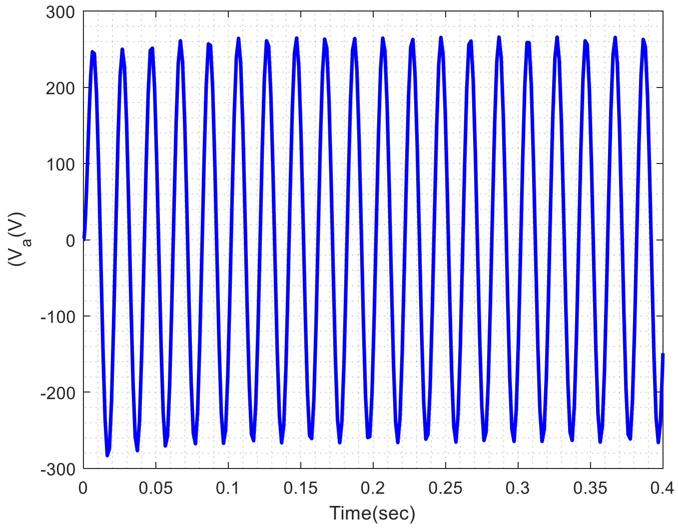

Figure 3: Per phase voltage of the CW-IPMSG on no-load condition

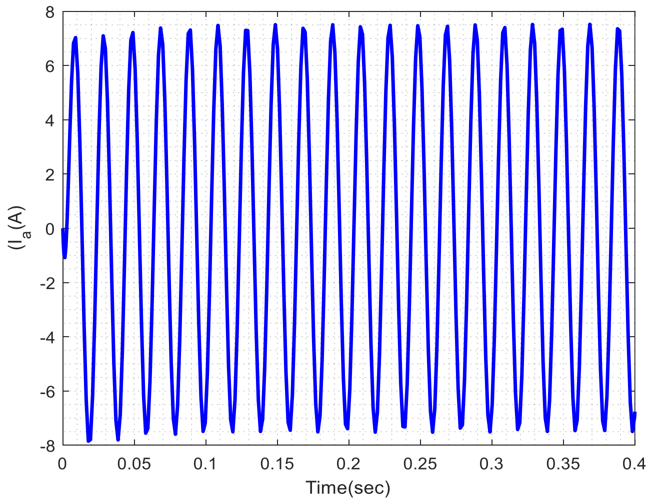

Figure 4: Per phase current of the CW-IPMSG at no-load condition

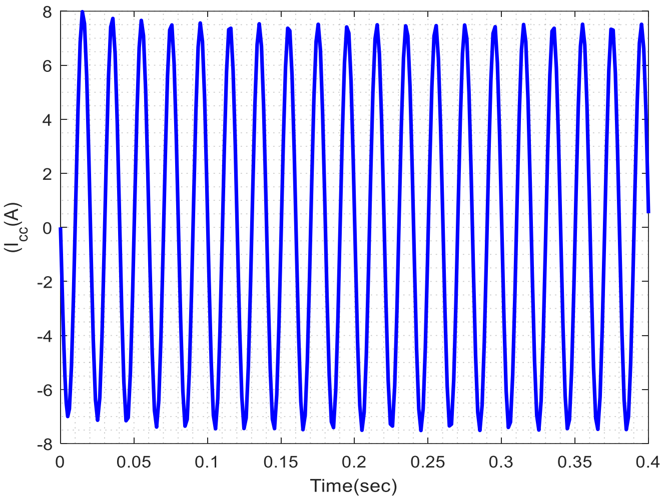

Figure 5: Per phase capacitor current of the CW-IPMSG at no-load condition

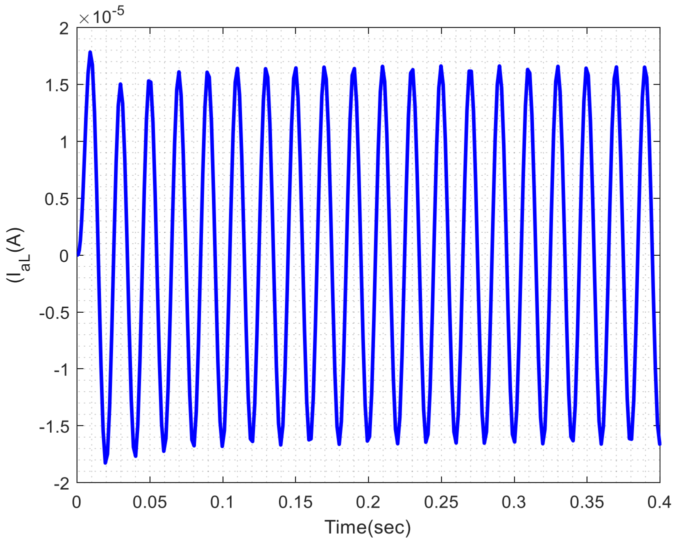

Figure 6: Per phase load current of the CW-IPMSG at no-load condition

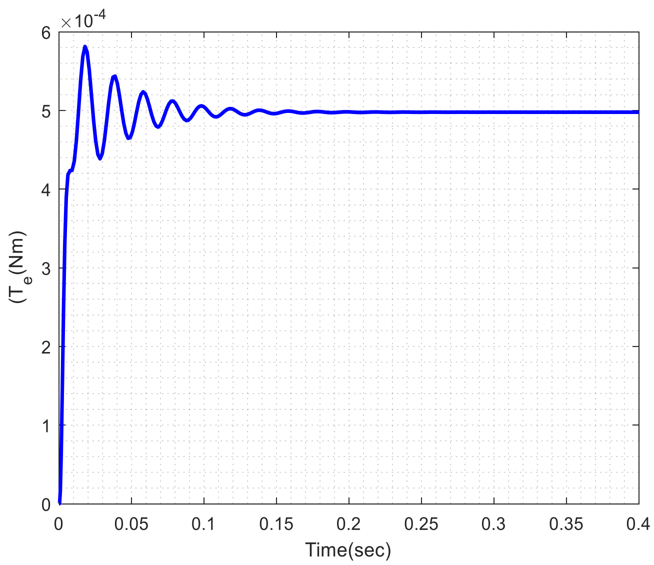

Figure 7: Electromagnetic torque of the CW-IPMSG at no-load condition

3.2. Performance of the CW-IPMG on Sudden Addition and Removal of Load

Performance of the of the CW-IPMSG on sudden addition and removal of load was also studied in Figure 8 through Figure 10. The generator operated with load from zero seconds to 0.7 second when load was suddenly removed and the added again at 2 seconds. As seen in Figure 8, there was voltage flicker observed as the load was added. There was also some level of oscillation on the electromagnetic torque, from 0.5 second to 1 second when the load was added and removed in Figure 9. Figure 10 shows the same effect for the load current. The load current was 0.4 A when the generator operated on load. When load was removed, the load current is about zero

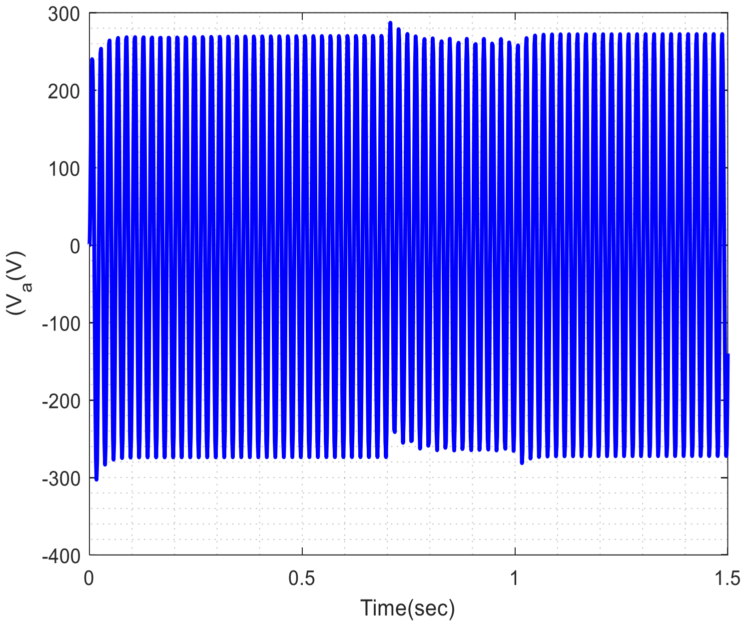

Figure 8: Phase voltage of the CW-IPMSG on sudden removal and addition of load condition

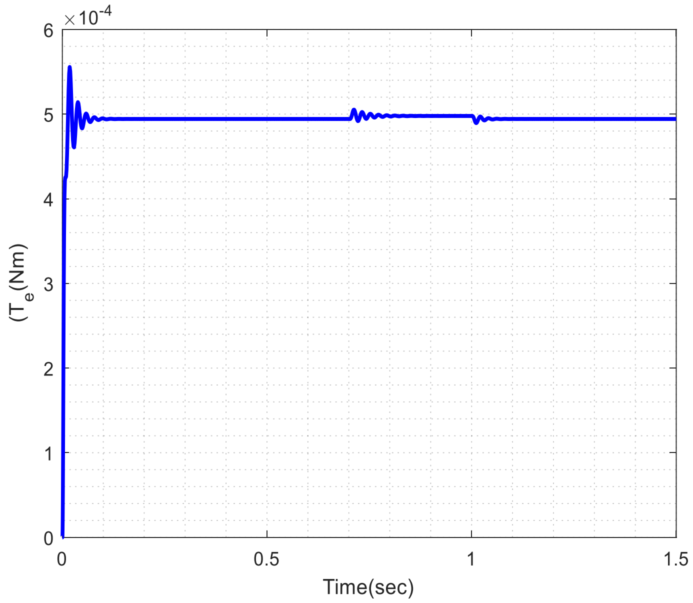

Figure 9: Electromagnetic torque of the CW-IPMSG on sudden removal and addition of load condition

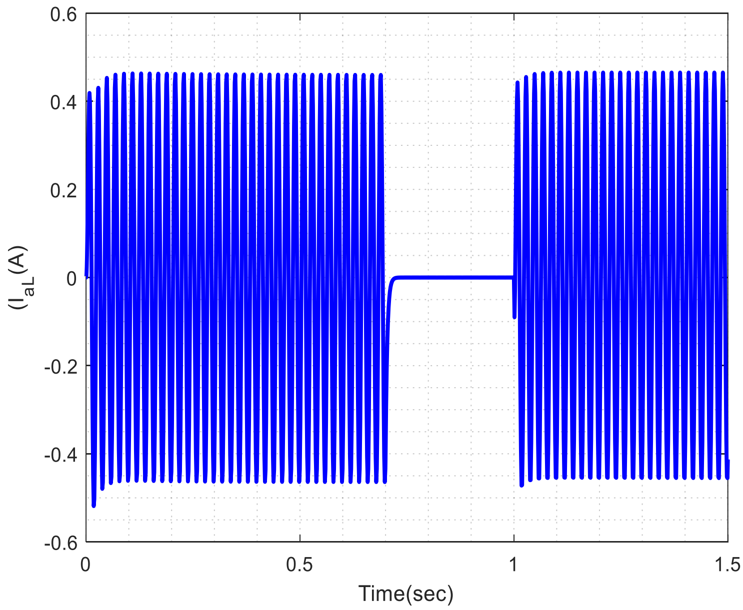

Figure 10: Load current of the CW-IPMSG on sudden removal and addition of load condition

3.3. Performance of the CW-IPMG on Varriable Capacitance

Since the generator is equipped with a balanced three phase capacitor, which can be varied, the analysis extended to the effect of change in excitation capacitor. The capacitance is made to change from 32 µF to 52 µF and then to 92 µF. The corresponding time of change is from 0 to 0.5 second and then 1.0 second. The change in the capacitance and the corresponding voltage build-up, load current and the electromagnetic torque is illustrated in Figure 11 through Figure 13. The behavior of the generator with respect to the performance parameters indicates that increase in capacitor capacitance yields more voltage and electromagnetic torque and this can also be applicable to other parameters or quantities. The simulation was done at resistive-

inductive load of 500 Ω-300 mH and permanent magnet flux of 0.8

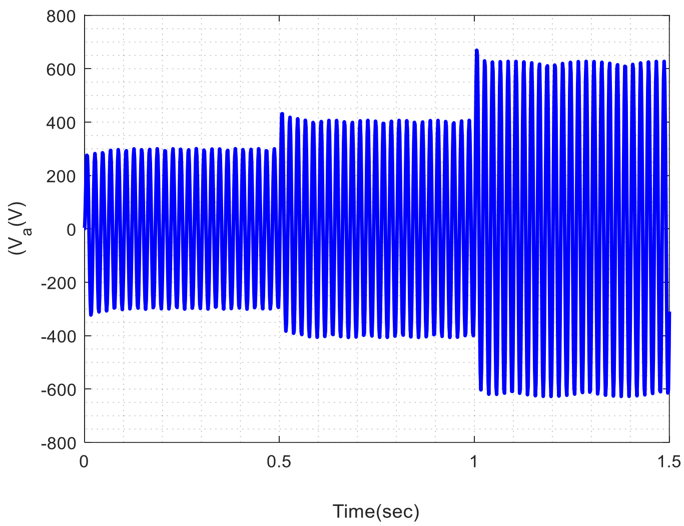

Figure 11: Voltage of the CW-IPMSG on variable capacitance

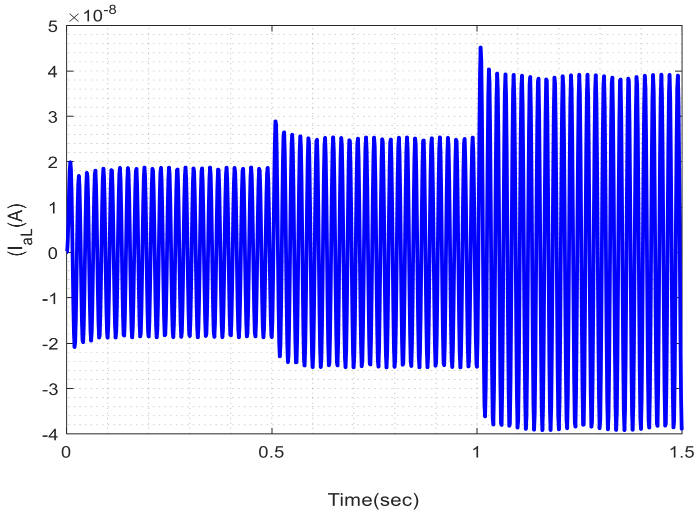

Figure 12: Load current of the CW-IPMSG on variable capacitance

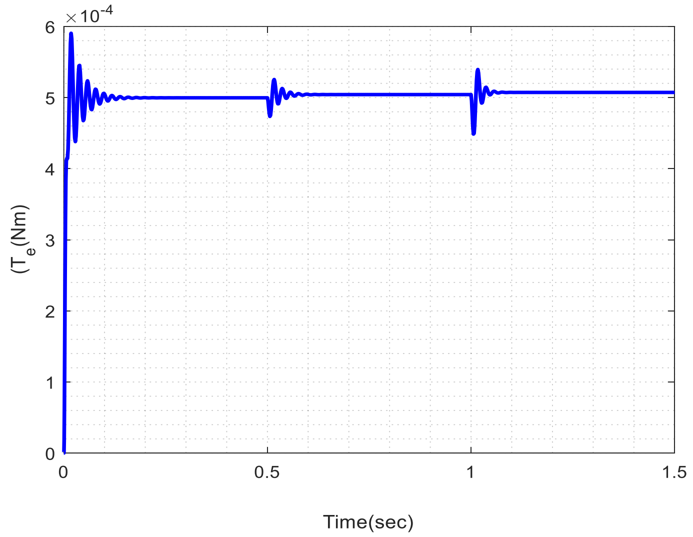

Figure 13: Electromagnetic torque of the CW-IPMSG on variable capacitance

Table 1: Studied Machine Parameters

S/N	Parameters	Value
1	Rated voltage	220 V
2	Rated power	110 kW
3	Rotor speed	2400 rpm
4	Number of turns per coil	115
5	Amplitude of the 1st order harmonics	5.8
6	Stator Stack length	800 mm
7	Frequency	50Hz
8	Resistance	0.03 Ω
9	Effective airgap	1.2 mm
10	Stator radius	82.4 mm

CONCLUSION

Dynamic and transient performance analysis of concentrated winding permanent magnet synchronous generator with capacitor assistance has been studied. The coil winding diagram of the studied permanent magnet synchronous generator with concentrated winding was developed. The inductance of the machines was also calculated based on Winding Function Theory. It was seen that inductance is proportional to the square of the number of turns per tooth, stator length and stator radius, and inversely proportional to the effective air gap length. It is also clear that total inductance does not depend on the number of stator slot. The calculated inductance was used to obtain the voltage, electromagnetic torque etc of the generator at no-load condition, sudden addition and removal of load, and capacitor variation using MATLAB/Simulink tool. At no-load condition, it was observed that CW-IPMSG maintain the desired performance where the output voltage is 230 V and electromagnetic torque is 5 Nm. When load was suddenly added to the generator, there were oscillations at the time when the load was added, and another oscillation was observed when load was removed. Increase in value of capacitor also increase the output performance of the generator at particular load and permanent magnet flux. This study was performed for a 4 pole 12 slot concentrated winding of permanent magnet synchronous generator.

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