Design and Implementation of Claw Pole Alternator for Aircraft Application

Deepak Arumugam [1], Premalatha Logamani [2], and Santha Karuppiah [1]

[1] Dept. of Electrical & Electronics Engineering
Sri Venkateswara College of Engineering, Chennai, India
adeepakceg@gmail.com, santha@svce.ac.in

[2] School of Electrical Engineering
VIT University, Chennai, India
premaprak@yahoo.com

Abstract **─** Nowadays most of the countries develop special aircraft and utilize them for defense applications. This paper deals with the modeling, simulation, and implementation of the Claw pole synchronous generator. The design specifications of the designed generators are compatible for aircraft applications. The main objective of this work was to estimate and test the performance of the claw pole alternator under high speed operation. The electromagnetic design of the machine was carried out using Finite Element Analysis (FEA) software. The performance of the machine was tested under laboratory environment. The results of experimentation were compared with those of simulation and proved.

Index Terms **─** Claw pole alternator, electromagnetic analysis, finite element method, Light Combat Aircraft.

I. INTRODUCTION

The Indian Aircraft Project is now called the Light Combat Aircraft (LCA) in order to create an identity distinct from the Light Weight Fighter concept. In the early 1980s, India, knowing well that the Mig-21s, Mig-23s, and a variety of other aging Russian fighters composing a vast percentage of their air power would soon grow obsolete, decided to produce a new fighter to replace the MiG-21 "Fishbeds" legacy. The new aircraft would be of indigenous design, and its development would fall under the care of India's own Aeronautics Limited. The aircraft that would spawn from the program was designated the Light Combat Aircraft and it would be one of the world's lightest, yet most capable dedicated multi-role aircraft of all time [1]-[2]. In LCA, 30-60KVA generator provided electrical power supply for all electrical loads. When this power system fails, the backup power supply supports and is called integrated generator system (IGS) providing power supply for emergency loads such as cabin lighting, food preparation, gunshot and cockpit, etc. This IGS consists of 3 electrical generators, namely permanent magnet synchronous generator, brushless synchronous generator (also called main exciter) and synchronous generator (also called main generator) being mounted on single shaft which is driven by aircraft engine gear box. The basic structure of IGS is shown in Fig. 1 [3].The major problem in aircraft to fix in this IGS is the available space in aircraft, which is just 140 mm. Also, aircraft engine rotating speed lies between 7000 rpm and 24000 rpm. So, it does not provide any external cooling arrangements at this dimension for high speed operations. Due to these reasons, much heat is produced in the main generator.

In general, salient pole synchronous generators (SPSG) are used as a main generator in IGS. These SPSGs are normally suitable for low speed applications. For high speed operation SPSG produces much heat in a very short time. Also, it has large rotor diameter and short axial length. Due to their mechanical instability at higher speeds, they are used for generation at low and medium speeds only. On the other hand, the smooth cylindrical (round) rotors are characterized by smaller diameters and larger axial lengths. They are mechanically stable even at high speeds. They are used for generation at high speeds. Also in salient pole generator X_d is higher than X_q, hence more stable (electrically), maximum power transfer is possible at torque angle delta lesser than 90 degree in salient pole; thus electrical advantages are more, but mechanical stability is less at higher speed as said, hence not suitable for modern high speed generators.

These alternators reduce power output due to eddy current losses produced in the machine and these losses are converted into heat [4]. Flux distribution is relatively poor and generated emf is not good compared with non-salient pole type rotor. Salient pole rotors generally need damper windings to prevent rotor oscillations during operation. The finite element analysis based analysis of SPSG for aircraft application was discussed in [5]. This machine produced much heat within short duration when simulation model was developed as a prototype model.

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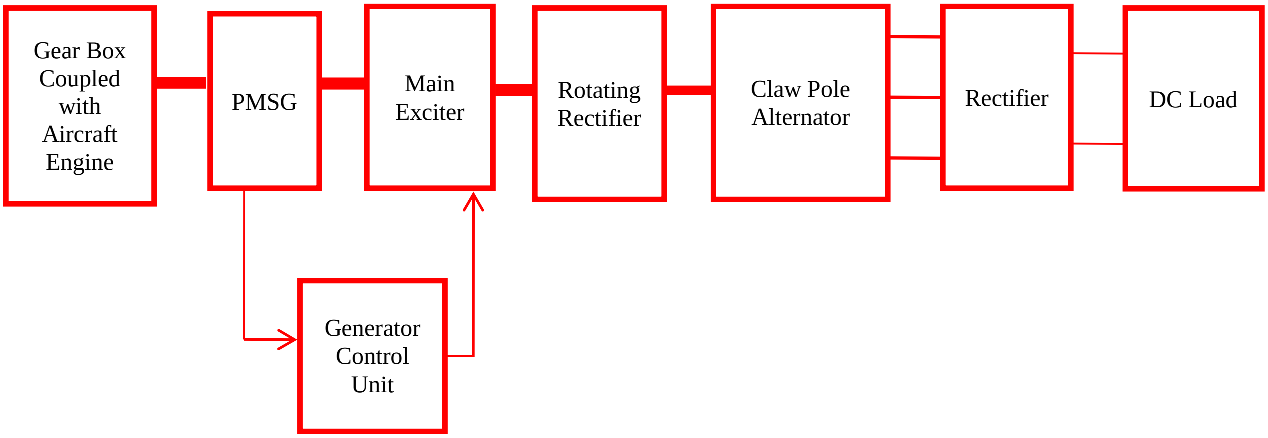


Fig. 1. Basic structure of IGS system.

On the other hand, claw pole alternator or Lundell alternators are able to produce large power density compared with the SPSG. It is a simple and highly reliable machine. The popularity of this type of electric machine is mainly due to its high pole pair number which increases the torque density and its robust structure allowing for high speed operation [6]. Generally claw pole alternators are applicable for automobile industry and aircraft [7]. Claw pole alternators have more air gap than the salient pole generators, so they allow more air to flow inside the machine and reduce heating effect when the machine is running at high speed. But it has the characteristics of high saturation, high magnetic leakage between claws, low efficiency and relatively large field time constant [8]-[10]. The 3D modeling and numerical analysis of the alternator with claw poles for electric car applications was discussed in [11]. The performance of the Lundell alternators for high power applications can be improved by reducing their number of turns & diode bridge rectifier replaced with PWM rectifier without modifying the dimensions of the generator [12]. The RMxprt motor design tool greatly simplifies this process and not only it provides the model parameters in seconds but also exports models for either FEA or system level simulation. It allows quick changes in physical design parameters and reduces time consumption for analytical design. The results obtained from RMxprt tools were directly applied to the 3D time stepping transient finite element analysis to directly study transient as well as steady-state performance of a machine [13]. The analytical modeling and testing of a 14V/6000 rpm claw pole alternator was presented in [14].

The above literature, however, does not deal with claw pole alternator pertaining to a specific dimension, speed and power rating. This work proposes the claw pole alternator for aircraft applications with required dimension and high speed operations. The simulation analysis & prototype model of 28V/180A/9000 rpm claw pole alternator are presented. The organization of the paper is as follows: Section II deals with the modeling & model description of the claw pole alternator. The simulation results of the proposed generator are given in Section III. The experimental results are presented in Section IV. The work is concluded in Section V.

II. DESIGN AND MODEL DESCRIPTION OF CLAW POLE ALTERNATOR

A. Basic equations of claw pole alternator and electromagnetic analysis

In claw pole alternator rotor construction differs from ordinary SPSG. It has cylindrical field windings surrounded by forged pole pieces or claw poles. The modeled machine has 4 poles and 24 slots with concentrated stator winding and cylindrical rotor winding. At the steady state the expression for stator current by dqo transformation is:

$$\begin{pmatrix} I_d \\ I_q \\ I_o \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\varphi & \cos(\varphi - \frac{2\pi}{3}) & \cos(\varphi - \frac{4\pi}{3}) \\ -\sin\varphi & -\sin(\varphi - \frac{2\pi}{3}) & -\sin(\varphi - \frac{4\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix}, \quad (1)$$

where

$$I_a = I_p \cos\,(\omega t + \varphi)$$
$$I_b = I_p \cos\,(\omega t + \varphi - \tfrac{2\pi}{3}) \quad (2)$$
$$I_c = I_p \cos\,(\omega t + \varphi - \tfrac{4\pi}{3}).$$

Here, I_p is the peak value of phase current. The stator voltages for d-q axis are:

$$V_d = I_d r_a + \frac{d\psi_d}{dt} - \omega\psi_q, \quad (3)$$

$$V_q = I_q r_a + \frac{d\psi_q}{dt} - \omega\psi_d. \quad (4)$$

The flux linkages for d-q axis are:

$$\psi_d = -I_d L_d + I_f L_{afd}, \quad (5)$$

$$\psi_q = -I_q L_q, \quad (6)$$

d-q axis reactances are:

$$X_d = \frac{\omega_b L_d}{Z_b}, \quad (7)$$

$$X_q = \frac{\psi_q}{I_q}, \quad (8)$$

where r_a is the armature winding resistance, L_q and L_d are d-q axis self inductances and L_{afd} is the mutual inductance between field winding and the direct axis and ω_b & Z_b are the base speed and base impedance.

The electromagnetic equations of the machine are given by:

$$\nabla \times E = \frac{\partial B}{\partial t}, \quad (9)$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}, \quad (10)$$

$$\nabla . B = 0, \quad (11)$$

where E and H are electric and magnetic field intensities, D and B are electric and magnetic flux densities, J is current density and ρ is the amount of charge for unit volume.

The reluctance based magnetic equivalent circuit model of the claw pole alternator is presented in [15] which is shown in Fig. 2.

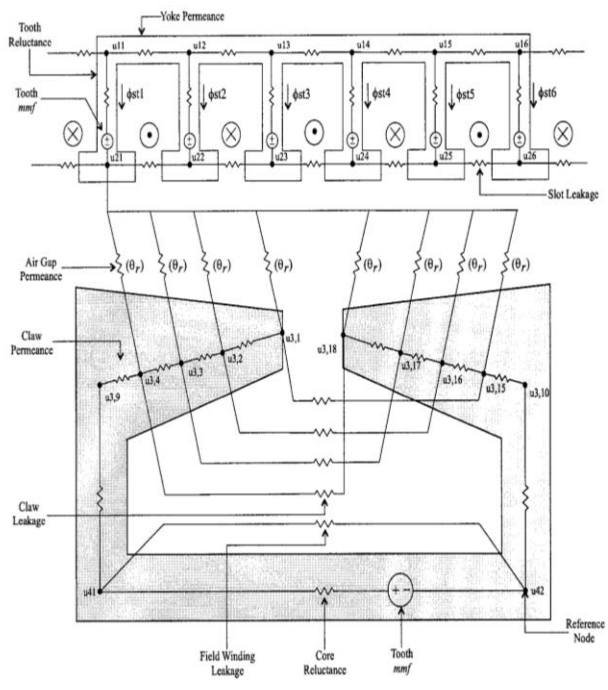


Fig. 2. Magnetic equivalent circuit of claw pole alternator.

The air gap permeance is:

$$P_{airgap} = \mu_0 \frac{A(\vartheta_r)}{g}, \text{ when claw aligned with stator teeth}$$
$$= 0 \qquad \text{Otherwise}, \quad (12)$$

where $A(\vartheta_r)$ is the area of the overlap.

B. Analytical design of claw pole alternator

The initial dimensions include stator outer diameter and rotor inner diameter; power rating and speed range are given by Combat Vehicles Research & Development. Based on their input, stator design is carried out using design equations available in [16] and a few of them presented below. The design of claw pole rotor is carried out based on [17] and it is verified by using design software RMxprt.

The design can be optimized by using Matlab program with more iteration. The major factors considered for optimized design are efficiency, temperature rise at different load conditions (100%, 125% & 150% of full load) and losses. The optimization can be achieved only at 59th iteration and it is listed in the design table. The general design expressions are given below:

KVA rating of a 3 phase synchronous machine is:

$$\text{KVA} = 11\, K_{w1}\, B_{avg}\, q\, D^2\, L\, n_s * 10^{-3}, \quad (13)$$

where, K_{w1} is winding factor for stator winding, B_{avg} is specific magnetic loading, q is specific electric loading, D is diameter of stator bore and n_s is synchronous speed in rps.

Induced EMF per phase of a synchronous machine is:

$$E_{ph} = 4.44\, K_{w1}\, \Phi_m\, f\, T_{ph} \text{ in Volts}, \quad (14)$$

where, Φ_m is maximum flux passing through the core, f is frequency in Hz and T_{ph} is total number of turns per phase.

Stator Mean Diameter:

(MD) = (Slot Root Dia + Slot Tip Dia)/2. (15)

Pole Mean Diameter:

(PMD) = (Pole Tip Dia + Pole Root Dia)/2. (16)

Self-inductance:

$$L_g = \frac{\mu_0 \Pi L_{stk} r_1 T_p^2}{2 P_p^2 g'}, \quad (17)$$

where g' is the gap coefficient = C_g g and p = number of rotor poles,

$$\text{Peripheral speed} = \pi d n_s \frac{m}{s}, \quad (18)$$

where d = rotor diameter in mm.

The shape of the pole is determined by the pole pitch and it is denoted by τ,

$$\tau = \frac{\pi\, d\, m}{p}. \quad (19)$$

The dimension of claw pole rotor is shown in Fig. 3 which is obtained from simulation tool MagNet 7. In this figure w_b and w_t are the width of the pole at the bottom and the top respectively, r_r is the radius of the rotor and h is the height of the pole. t_t and t_b are the thicknesses of the pole at the top and the bottom respectively.

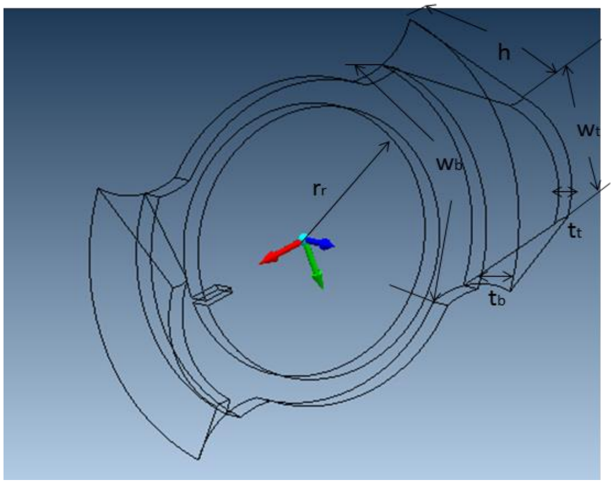


Fig. 3. Dimensions of claw pole.

The design specification of the machine according to the requirement is shown in Table 1.

Table 1: Design parameters

Parameter	Value
Stator diameter in mm	138.5
Core length in mm	23
Rated power in W	5000
Output voltage in V	28
Flux density in Wb/m^2	3.25
Phase current in A	133.3
Field excitation current in A	10
Power factor	0.88
Speed in RPM	9000
Number of slots	24
Number of poles	4
Length of the air gap in mm	0.37

III. FINITE ELEMENT ANALYSIS OF CLAW POLE ALTERNATOR

Finite element analysis is an effective simulation tool for analyzing complicated structure with non-linear elements. Normally electromagnetic analysis of the electrical machines is carried out using finite element software like SPEED, FLUX, MagNet, Motor Solve, etc. These tools act as intermediator between analytical calculation and prototype model for the purpose of reduced cost and improved performance. In this analysis simulation work was carried out using MagNet software which is used to see the visual effect of flux linkage, flux density, and voltage, current and ohmic losses. Generally claw pole alternator has magnetic field effect in the z direction also. So it is not possible to analyze this field in 2D software. Even though 3D analysis takes more time for solving the problems, it is necessary to analyze the electromagnetic effect of claw pole generator in all 3 directions.

Magnet software version 7 is used for performing magnetic analysis of the machine. Boundary used in this problem is closed boundary, so problem formulation is based on vector potential with magneto dynamic computations. Also number of nodes is 57317, number of edges is 178965, and number of faces is 121727. The FEM based 3D design of claw pole generator is shown in Fig. 4. In the preprocessor step the generator was designed based on analytical design values. After the design completion, machine stator and rotor core were filled with cold rolled steel and windings were filled with copper material. The stator-rotor structure is shown separately in Fig. 5. The mesh generated claw pole generator is shown in Fig. 6. In this problem the size of the meshes is 2 mm for entire generator includes stator and rotor. Also, the shape of mesh is triangular, because it will give accurate result when compared with other mesh shapes. If the size of mesh is reduced below 2 mm, overlap will occur between meshes and it will not be possible to get output properly. The calculation time of the generator can be increased by increasing the number of steps fixed in the software. The number of steps fixed to solve this problem is 10.

In the processing step, the machine goes through 10 steps and it takes 32 hours 12 minutes for solving the problem. In post processor, the flux linkage, magnetic flux density, voltage and current plots are obtained. In Fig. 7, the magnetic flux density plot and direction of magnetic flux density are shown. From the figure it is observed that the maximum value of flux density is 3.28 Wb/m^2.

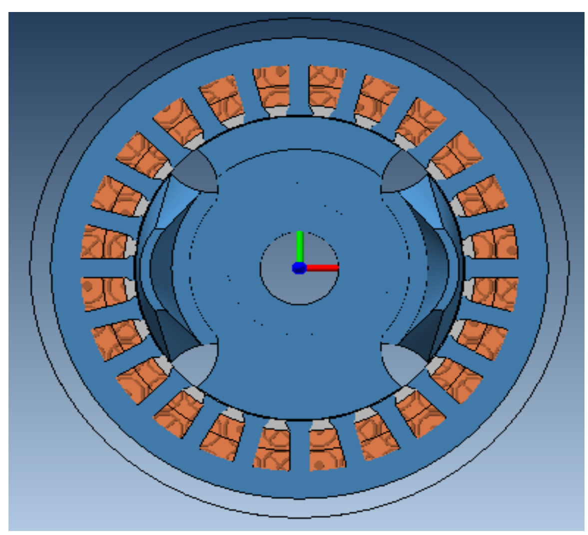
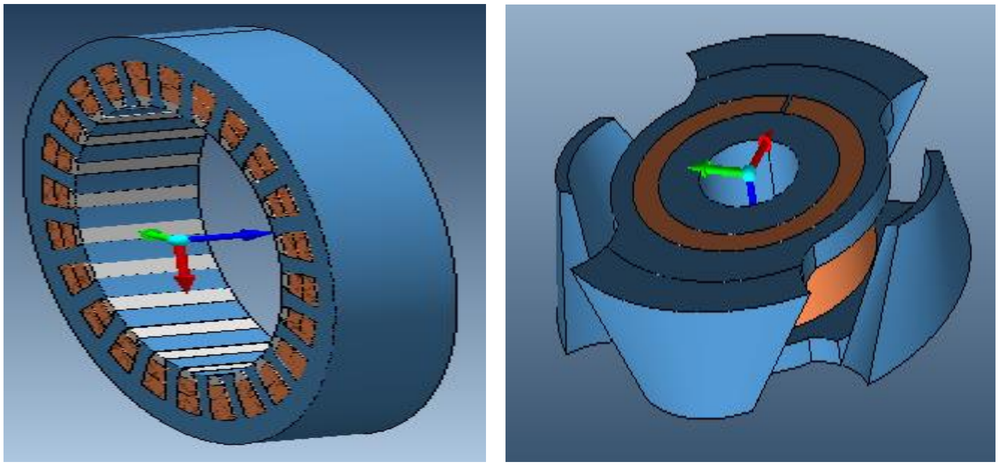
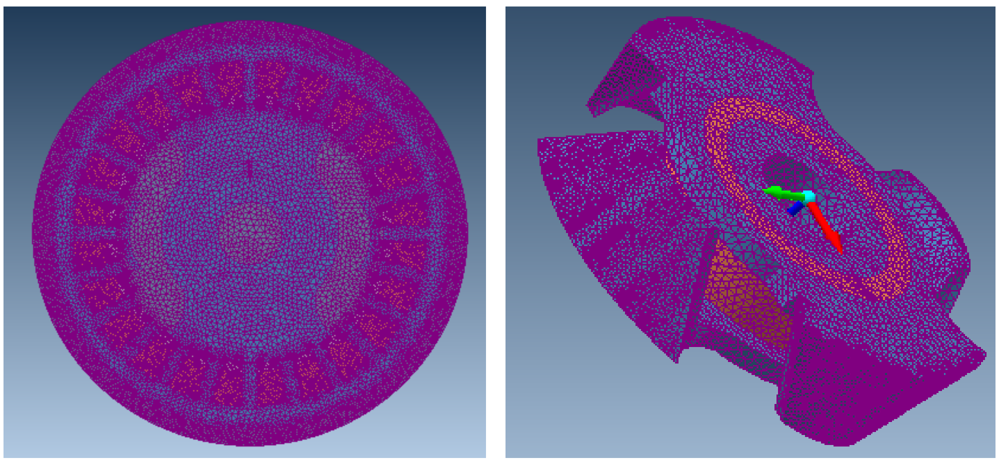


Fig. 4. 3D model of claw pole alternator.



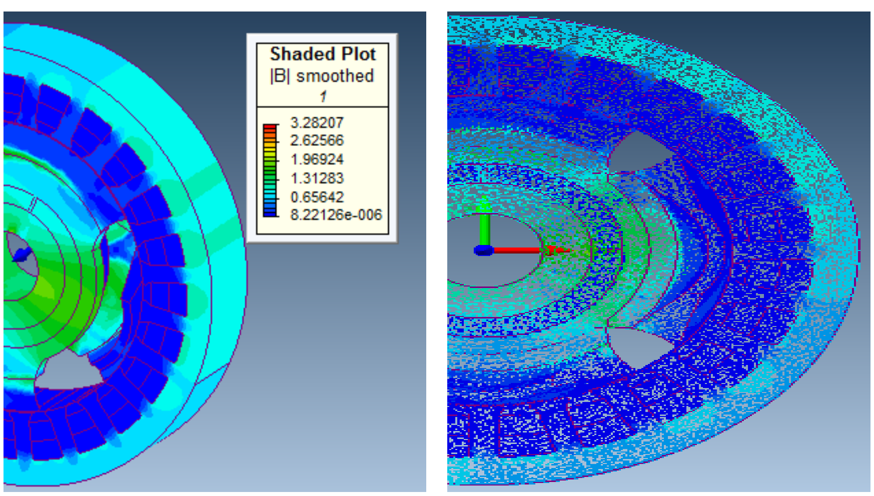
(a) Stator model (b) Rotor model

Fig. 5. Stator-rotor structure (3D view).



(a) Stator mesh (b) Rotor mesh

Fig. 6. Stator and rotor mesh generation.



(a) Flux density distribution (b) Flux density arrow plot

Fig. 7. Flux density plot.

The required output from the claw pole generator is DC. So, the stator coils are connected to resistance load at a value of 0.155 Ω through a diode bridge rectifier circuit and this is shown in Fig. 8. The output AC voltage & current at armature windings, DC current & voltage at load are obtained from the machines which are shown in Fig. 9 and Fig. 10 respectively.

From Fig. 9 and Fig. 10 it is seen that both the voltage and the current waveforms are slightly oscillating on their peak values and approximately the value of the output voltage is 28V and the output current is 180A. From the simulation results it is seen that the values obtained from the simulation analysis are the same as the analytical values.

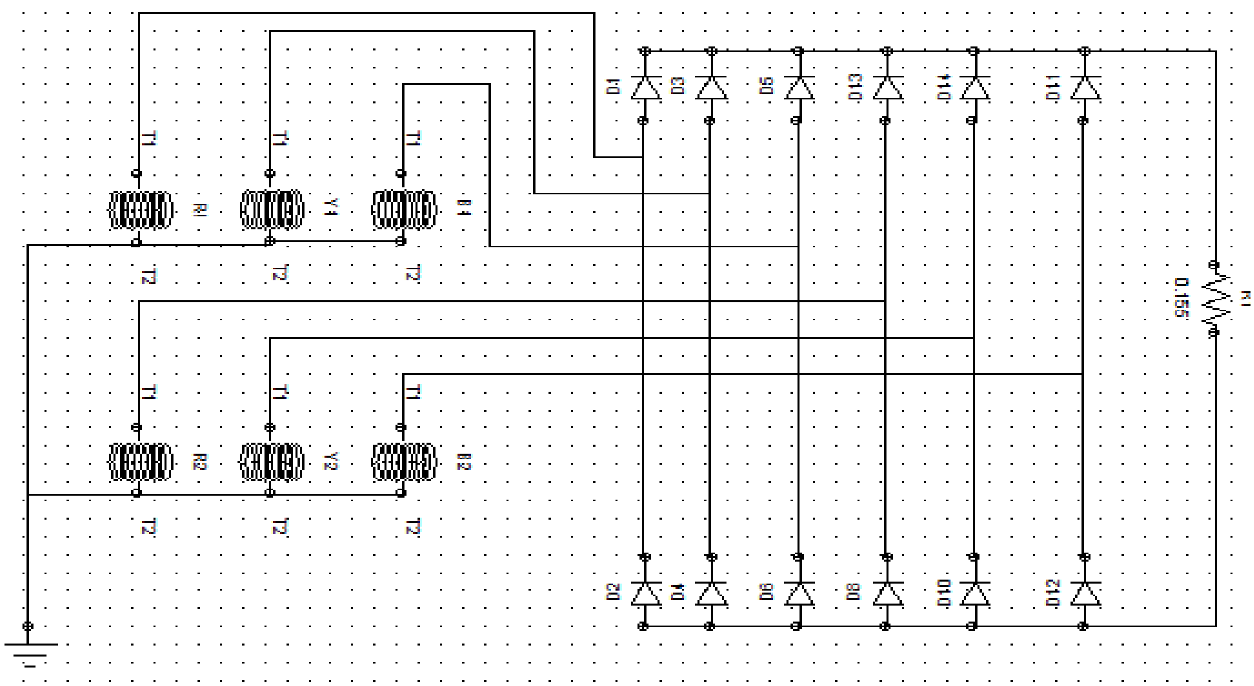
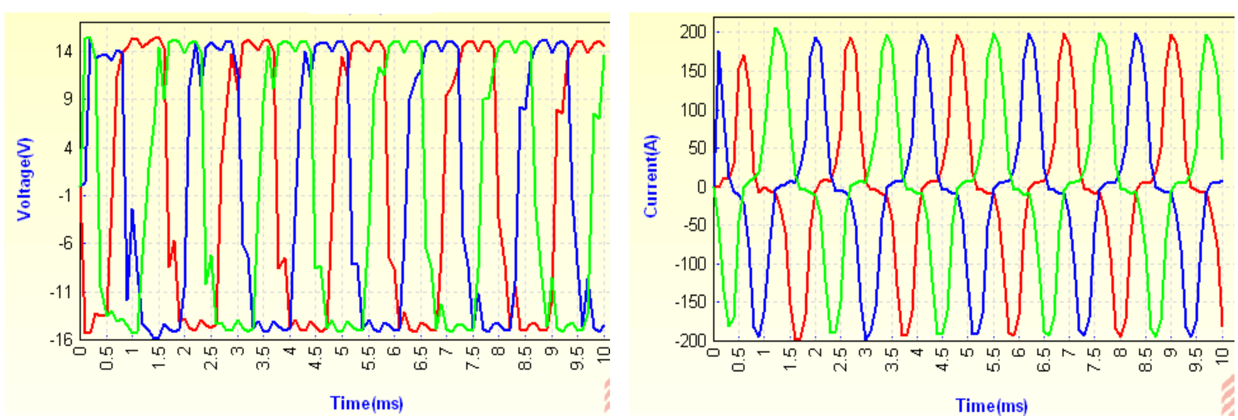


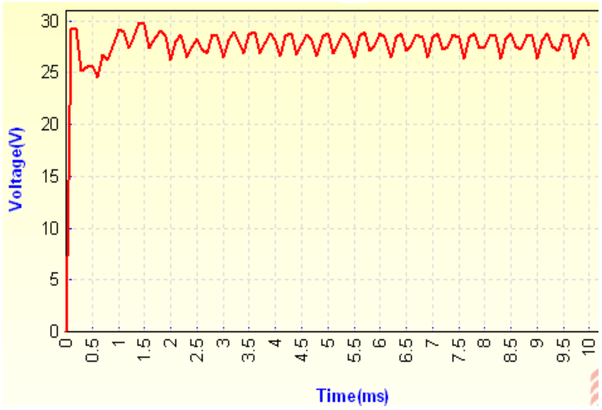
Fig. 8. Stator coil connected to external load.



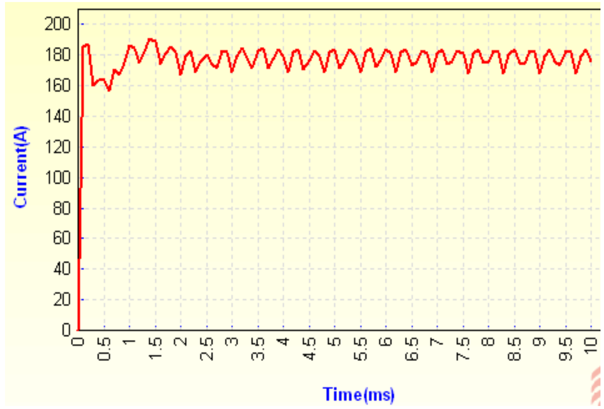
(a) Generated voltage at the armature

(b) Armature current

Fig. 9. Voltage and current at the armature.



(a) Voltage across load



(b) Current flowing through the load

Fig. 10. Voltage and current at load.

IV. HARDWARE IMPLEMENTATION

The structural block of the experimental set-up is shown in Fig. 11. In this figure generator control unit is the combination of rectifier and CUK converter to provide constant DC current to the field windings of the claw pole alternator. Diode bridge rectifier circuit is connected inside the claw pole alternator.

The prototype model of the 5KW claw pole alternator was fabricated and tested in the laboratory. The snapshot of the alternator is shown in Fig. 12. It consists of 5KW claw pole alternator coupled with induction motor acting as prime mover, gear box, generator control unit and load bank. The performance of the generator was tested under the speed of 2000 rpm to 10,000 rpm with 10A field excitation current. Under no-load condition generator terminal voltage varies linearly with respect to the speed, while the GCU is operated under manual control. On the other hand, terminal voltage varies inversely with respect to the load and current varies linearly with respect to the load and this is shown in Fig. 13. Similarly the terminal voltage of the generator under closed loop control of the GCU is shown in Fig. 14. It is observed that the peak values of terminal voltage & current are approximately 27.5V and 179.3A respectively. The analytical results were compared with those of simulation and experiment in Table 2.

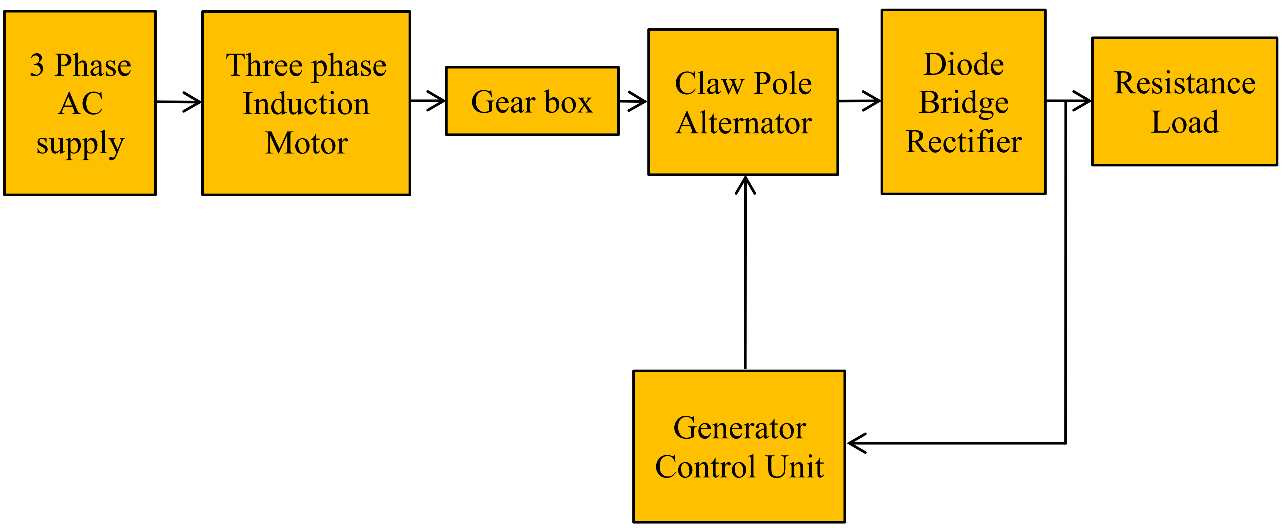


Fig. 11. Experimental set-up of the proposed alternator.

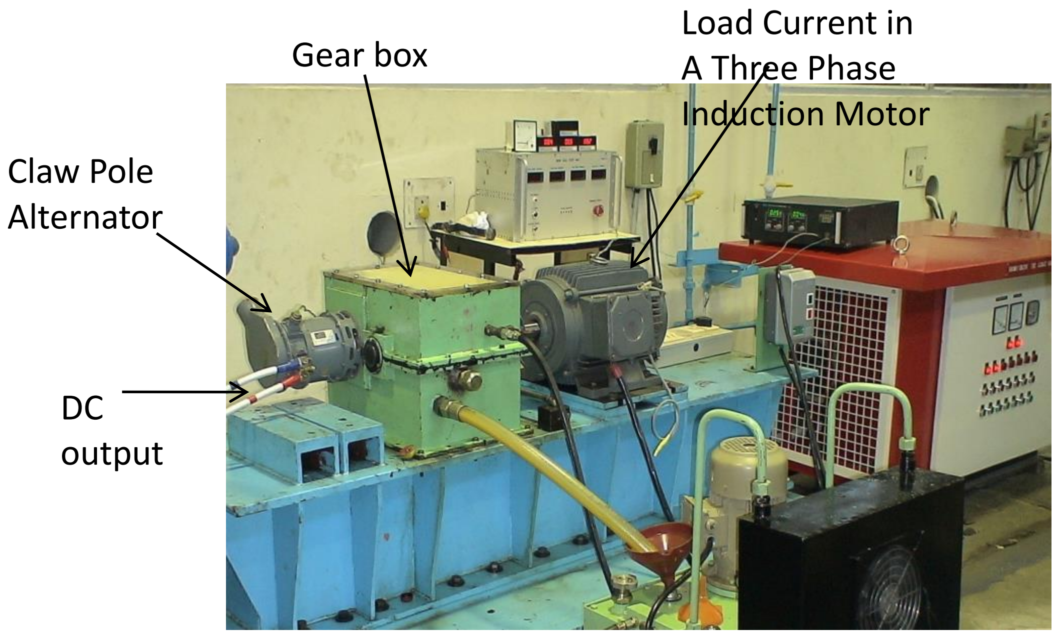


Fig. 12. Prototype model of the 5KW claw pole alternator.

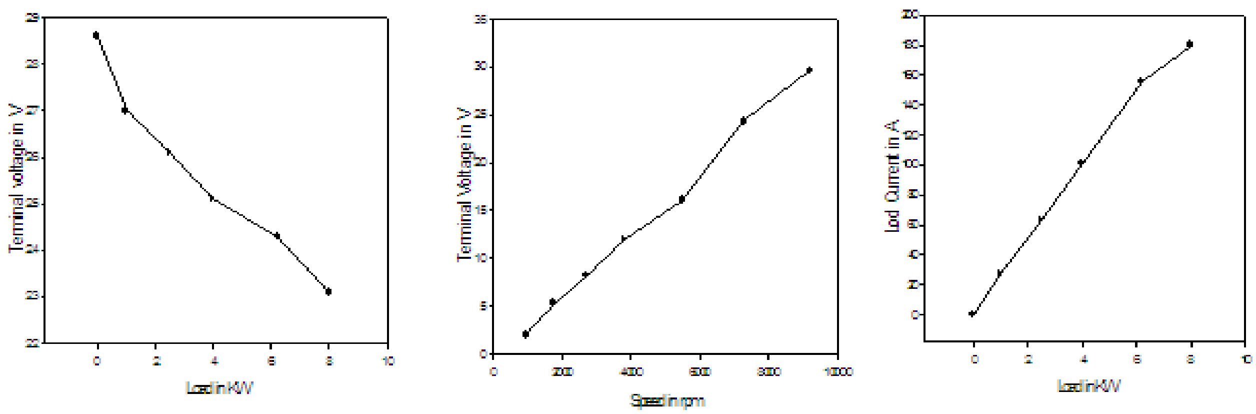


Fig. 13. Open loop characteristics with & without load condition.

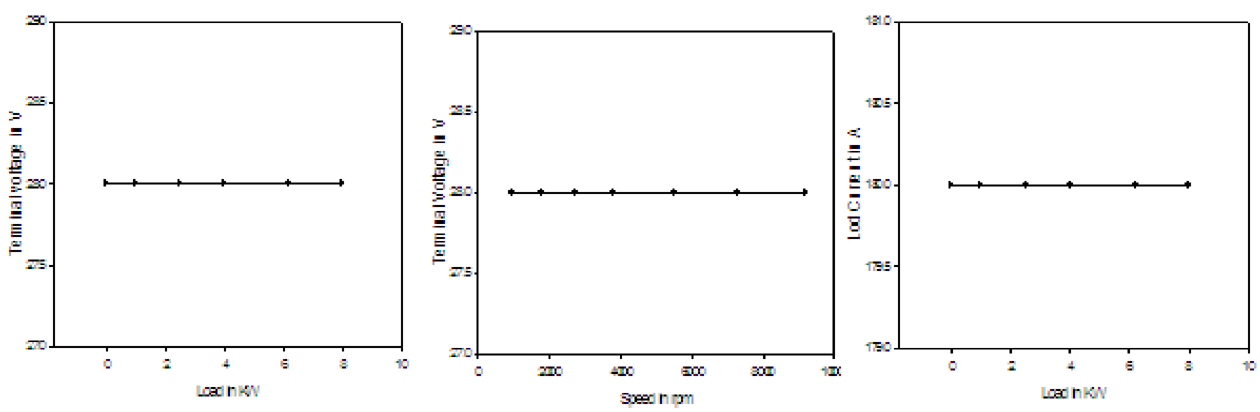


Fig. 14. Closed loop characteristics with & without load condition.

Table 2: Comparison of analytical, simulation, and hardware results

Parameter	Theoretical Design Value	Simulation Result	Hardware Result
DC output voltage	28V	27V	27.5V
DC output current	180A	178A	179.3A
Flux destiny	3.25 Wb/m^2	3.28 Wb/m^2	3.2 Wb/m^2

V. CONCLUSION

Integrated generator system provides continuous power supply to the aircraft during war and emergency conditions. Synchronous generator is the one main generator in this IGS. The performance of the non-salient pole alternator is better than that of the salient pole alternator for high speed applications due to large air-gap, less eddy current loss, and high efficiency. In this paper the electromagnetic analysis of the 5KW/28V claw pole alternator at a speed of 9000 rpm was presented using finite element analysis software. The prototype model of the 5KW claw pole alternator was tested in the laboratory and it was observed that the output voltage and the current obtained from the simulation tool were equal to the laboratory results. This generator has the advantages of more air gap space, less temperature rise, less eddy current loss, better ventilation compared with the salient pole generator. Significant results for the proposed system pertaining to the aircraft application were presented. The thermal analysis of the claw pole generator and the overall performance of the integrated generator system will be studied in future.

REFERENCES

[1] https://en.wikipedia.org/wiki/HAL_Tejas

[2] http://www.tejas.gov.in/

[3] D. Arumugam and P. Logamani, "Performance evaluation of brushless exciter for aircraft applications," *Australian Journal of Basic and Applied Sciences*, vol. 8, no. 18, pp. 151-158, 2015.

[4] H. B. Chen and M. T. York, "Alternator having claw-pole rotor," *US6989622 B1*, 24 Jan 2006.

[5] D. Arumugam and P. Logamani, "Coupled magnetic field and thermal analysis of synchronous generator," *Australian Journal of Basic and Applied Sciences*, vol. 8, no. 2, pp. 124-131, 2014.

[6] G.-H. Lee, G.-S. Choi, and W. Choi, "Design considerations for low voltage claw pole type integrated starter generator (IGS) systems," *Journal of Power Electronics*, vol. 11, no. 4, pp. 527-532, 2011.

[7] L. Tutelea, D. Ursu, I. Boldea, and S. Agarlita, "IPM claw-pole alternator system for more vehicle braking energy recuperation," *Journal of Electrical Engineering*, pp. 1-10, 2013.

[8] H. Bai, S. D. Pekarek, J. Tichenor, W. Eversman, D. J. Buening, G. R. Holbrook, M. L. Hull, R. J. Krefta, and S. J. Shields, "Analytical derivation of a coupled-circuit model of a claw-pole alternator with concentrated stator windings," *IEEE Transactions On Energy Conversion*, vol. 17, no. 1, pp. 32-38, 2002.

[9] A. G. Kladas, M. P. Papadopoulos, and J. A. Tegopoulos, "Design considerations for claw pole alternators for wind power applications," *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 17, no. 1, pp. 151-154, 1998.

[10] S. Felicia, K. B. Agoston, M. C. Steluta, and T. Raluca, "Stator geometry influence on the machine magnetic field distribution for claw-pole generator," *International Conference on Clean Electrical Power (ICCEP)*, 2011.

[11] C. Barz, C. Oprea, and F. Dragan, "Numerical modeling of claw-poles alternator," *Carpathian Journal of Electronic and Computer Engineering*, vol. 5, pp. 9-12, 2012.

[12] R. Ivankovic, J. Cros, M. T. Kakhki, C. A. Martins, and P. Viarouge, *Power Electronic Solutions to Improve the Performance of Lundell Automotive Alternators, New Advances in Vehicular Technology and Automotive Engineering*, ch. 6, In Tech Press, Croatia, pp. 169-190, 2012.

[13] B. Knorr, D. Devarajan, D. Lin, P. Zhou, and S. Stanton, "Application of multi-level multi-domain modeling to a claw-pole slternator," *Society of Automotive Engineers*, pp. 1-7, 2004.

[14] S. C. Tang, T. A. Keim, and D. J. Perreault, "Thermal modeling of Lundell alternators," *IEEE Transactions On Energy Conversion*, vol. 20, no. 1, pp. 25-36, 2005.

[15] J. M. Williams, "Modeling and Analysis of Electrical Machines with Asymmetrical Rotor Poles using Reluctance based Magnetic Equivalent Circuit," *University of Missouri Rolla*, USA, 2004.

[16] A. K. Sawhney, *Course in Electrical Machine Design*, Dhanpat Rai & Sons Publications, Sixth edition, 2006.

[17] R. Arumugam and M. Azhagr Raj, "Performance Analysis of Claw-Pole Alternator by Three Dimensional Finite Element Analysis," *Anna University*, India, 2009.