Design and Analysis of a 3 kVA, 28 V Permanent Magnet Brushless Alternator for Light Combat Aircraft

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Abstract--**Permanent magnet (PM) brushless machines have been increasingly used in aircrafts and automobiles due to their light weight, small size, high efficiency, high reliability, variable speed operation and good dynamic performance. The Permanent Magnet Brush less Alternator has a permanent-magnet rotor, and the stator windings are wound such that the induced electromotive force (EMF) is trapezoidal. This paper presents the optimized design of a 3kVA, 28V permanent magnet brushless (PMBL) alternator for light combat aircraft application (LCA). The proposed Alternator has two poles made of NdFeB and 12 stator slots. An analytical algorithm is developed for the design of PMBL alternator. The finite element analysis is carried in MAGNET 2D FEA-package for refining the design and performance evaluation of a three-phase permanent magnet brushless alternator.**

Index Terms--**PM Alternator, Light Combat Aircraft, Electrical Power Generating System (EPGS).**

List of symbol

p	number of poles
n	machine speed;
D_i	inner stator diameter;
γ	angle between two conscecutive slots;
α	short pitching angle;
σ	skewing angle;
B_{sat}	saturation flux density;
B_r	remanent flux density;
B_g	air gap flux density;
B_m	magnet flux density;
μ_{rec}	recoil permeability of the magnet;
C_Φ	flux concentration factor;
τ_p	rotor pole pitch;
τ_s	stator slot pitch;
ω_s	slot width;
t_t	tooth width;
k_{st}	lamination stacking factor;
k_{sf}	slot filling factor;
N_S	number of slots;
A_{slot}	slot area;
α_m	pole pitch coverage co-efficient;

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I. INTRODUCTION

PERMANENT magnet brushless machines (PMBL) present certain advantages over other electrical motors such as dc motors, induction motors, synchronous motors and switched reluctance machines. Due to absence of the field current and field winding, permanent magnet generators exhibit high efficiency in operation, simple and robust structure in construction and high power to weight ratio. The attractiveness of the permanent magnet generators is further enhanced by the availability of high-energy permanent magnet materials like NdFeB. As a result, PMBL machines have been increasingly used in small motor drives for automobiles, aircrafts particularly in high-end vehicle models. Automotive applications require highly competitive costs, low acoustic noise and high efficiency. The stringent requirements and unique operating conditions demand effective methodologies for the design of PMBL machines.

The Permanent-magnet machines allow a great deal of flexibility in their geometry. The permanent magnets of radial-flux machines are radially oriented. Radial-flux permanent-magnet machines can be divided mainly into two types, surface-magnet and buried-magnet machines. The simple way of constructing the rotor with high number of poles is by gluing the permanent magnets on the rotor surface of the machine. The Permanent Magnet Brush less Alternator has a permanent-magnet rotor, and the stator windings are wound such that the induced electromotive force (EMF) is trapezoidal.

Many generators have been proposed in the literature as radial-flux generators. In [5], have designed and constructed two small multi-pole radial-flux permanent-magnet test machines for use as a directly coupled generator in wind turbines. In [6], has investigated how a direct driven wind turbine generator should be designed and how small and efficient such a generator will be. In [7], has described the arrangement of multi-pole radial-flux permanent-magnet synchronous machine. In [8], have designed gearless radial-flux buried and surface mounted permanent magnet wind energy converters. In [9], have presented the design of outer-rotor (the positions of the rotor and stator are exchanged) radial-flux permanent-magnet multi-pole low-speed directly coupled wind power converter for standalone applications. In [10], has proposed a dual rotor, radial-flux, toroidally wound permanent-magnet machines to substantially improve machine torque density and efficiency. In [4], has designed and analyzed a 42V permanent magnet generator for automotive application [4].

The electrical power generating system (EPGS) for the light combat aircraft consists of one 30 kVA integrated drive generator (IDG) and its generator control unit (GCU). In the absence of the main generator a 3 kVA alternator and its GCU are required to take of the critical loads. There is a requirement to indigenously design, development and testing of a 3 kVA brushless alternator for operating the electrical systems of LCA. The PMBL alternator with control unit is required to produce 28 Vdc, 2.5 kW power. It has to operate efficiently over a high-speed range of 6200 rpm to 12500 rpm and provide 2.5 kW at a constant output voltage of 28 Vdc. When the main generator 30 KVA fails or Transformer Rectifier unit fails, the 3KVA brushless alternator shall operate DC emergency bus for power supply to: Power management relays, System management relays, Radio altimeters, ECS controller, FCS channel, Artificial horizon, Head up display.

The main objective of this work is the design of a minimum volume and good efficient three-phase PMBL alternator supplying 2.5 KW and 28 V to the dc loads. The speed of the alternator varies in the range of 6200 – 12500 rpm. The main requirement is that the PMBL alternator should provide the 2.5 kW power and 28 V in the given speed range. The converter topology of Generator control unit consists of an uncontrolled three-phase bridge rectifier followed by a buck converter shown in fig.1. This paper presents the design algorithm of the three phase PMBL alternator. The Finite element analysis has done using Magnet 2D FEA-package. The iron saturation is validated at no load and full load. The input data and design results are given in the tables I and II.

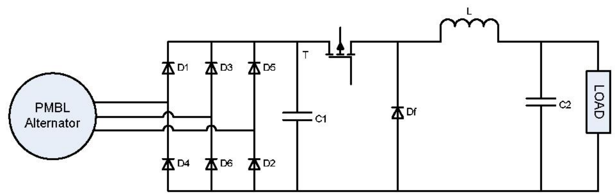


Fig. 1. Un-controlled diode bridge rectifier with buck converter.

II. Alternator Design

A. Topology of alternator

The surface mounted rotor structure is selected for the proposed machine as shown in Fig. 2. The main advantage of this topology is that all of the magnetic flux produced by the magnets links the stator, and therefore, takes part in energy conversion. The type of the winding selected is double layer distributed winding; the air gap is designed such that the output voltage of the machine is trapezoidal wave. The advantage of designing the machine for trapezoidal output voltage wave is the weight and size of the LC filter reduces. The choice of the number of poles depends upon many factors, some of which are as follows: Magnetic material and grade, Mechanical assembly of the rotor and magnets, Speed of rotation, Inertia requirements. The number of poles should be inversely proportional to the maximum speed of rotation. The reason, of course, is to limit the commutation frequency to avoid excessive switching losses in the transistors and iron losses in the stator. For very high speeds two or four pole motors are preferred. Because of very high speed range specified (6200 to 12500 rpm), number of poles selected as 2 for the proposed permanent magnet blush less alternator.

B. Methodology of the design algorithm

The objective of this design is to maximize the efficiency and minimize the volume of the alternator. The design starts with a set of input data that includes apparent power, phase voltage, speed range, stacking factor, and slot filling factor, remanent flux density of Magnet and saturation flux density. Based the practical limitations the number of poles p and the no. of slots/pole/phase m are predefined.

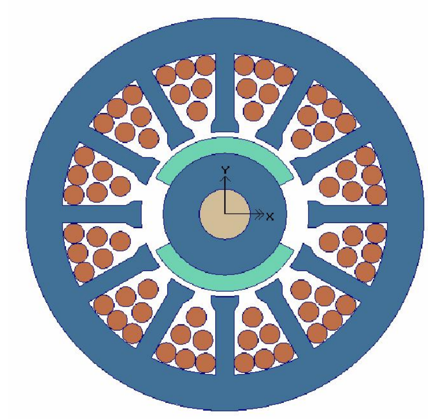


Fig. 2. Structure of the designed machine.

From the expression of the air gap power (1), the minimum volume of the machine is obtained by iterating the diameter of the rotor D_r and slot depth d_S between its minimum and maximum limits specified. The minimum volume of the rotor is obtained when the product of the electric and magnetic loading is maximized.

$$P_{gap} = 2k_{sh}k_d k_s \omega_S B_g A\pi R_{or}^2 L_i \tag{1}$$

where k_{sh}, k_d, and k_s and shorting, distribution and skewing factors can be computed from the following equations (2), (3) and (4) respectively.

$$k_{sh} = \frac{\sin\left(\frac{m\gamma}{2}\right)}{m.\sin\left(\frac{\gamma}{2}\right)} \tag{2}$$

$$k_d = \cos\left(\frac{\alpha}{2}\right) \tag{3}$$

$$k_s = \frac{\sin\left(\frac{\alpha}{2}\right)}{\left(\frac{\alpha}{2}\right)} \tag{4}$$

The next task is to determine the pole pitch coverage coefficient of the magnet α_m. According to [3] the α_m is given as (5).

$$\alpha_m = \frac{(n+0.14)}{(N_{spp}N_{ph})} \quad (5)$$

where n is any integer satisfying $\alpha_m<1$.

The areas of the magnet and air gap per pole are found by using (6) and (7).

$$A_m = \frac{(\alpha_m \pi D_{ro} L)}{p} \quad (6)$$

$$A_g = \left[\frac{\alpha_m \pi (D_{ro}+g)}{p} + 2g\right](L+2g) \quad (7)$$

The length of the air gap is usually determined by mechanical constraints. The flux concentration factor and length of the magnet are computed by using (8) and (9).

$$C_{\Phi} = \frac{A_m}{A_g} \quad (8)$$

$$l_m = g.C_{\Phi}.PC \quad (9)$$

The permeance co-efficient represents the slope of the air gap line in the second quadrant of the B-H plane. This is the measure of the capacity of the magnet to withstand demagnetization. According to [1], PC is chosen as 5 in order to minimize the magnet cost.

The values of air gap and magnet flux densities are computed from (10) and (11).

$$B_g = \frac{C_{\Phi}.B_r}{1+\frac{C_{\Phi}k_c g \mu_{rec}(1+p_{r1})}{l_m}} \quad (10)$$

$$B_m = \frac{\left(1+\frac{p_{r1}C_{\Phi}k_c g \mu_{rec}}{l_m}\right)B_r}{1+\frac{C_{\Phi}k_c g \mu_{rec}(1+p_{r1})}{l_m}} \quad (11)$$

According to [2], Carter's factor, k_c can found by using (12).

$$k_c = \left[1-\frac{w_s^2}{5\tau_s(g_c+w_s)}\right]^{-1} \quad (12)$$

The value of the n is iterated between minimum and maximum values and the value of α_m is computed by using (5) such that the satisfied air gap and magnet flux densities are obtained.

The shape of the slots chosen is semi open type. Once the values of α_m and B_g are set, the dimensions of slots are computed according [2]. The dimensions of Stator back iron and rotor back iron are computed by using

$$w_{st} = \frac{\pi D_i \alpha_m B_g}{2k_{st} p B_{sat}} \quad (13)$$

$$w_{rt} = \frac{\pi(D_{or}-2l_m)\alpha_m B_g}{2k_{st} p B_{sat}} \quad (14)$$

where

$$D_i = D_{or} + 2(g+d_s) \quad (15)$$

The outer diameter of the machine OD is

$$OD = D_{or} + 2(g+d_s+w_{st}) \quad (16)$$

The ampere loading, current density, diameter of the conductor and total number of the conductors are computed from (17), (18), (19) and (20) respectively.

$$A = \frac{Z.I_{ph}}{a.\pi.D_{si}} \quad (17)$$

$$J = \frac{I_{ph}.Z}{a.A_{slot}.K_{sf}.N_S} \quad (18)$$

$$d_c = \sqrt{\frac{4A_{slot}.K_{sf}.N_S}{Z.\pi}} \quad (19)$$

$$Z = 2N_{ph}T_{ph} \quad (20)$$

C. Calculation of efficiency

The main Losses in permanent magnet machines include copper losses in the stator windings, iron losses in the stator. Of these, the core losses is the most difficult to compute accurately. The magnet and rotor back iron experience little variation in flux and therefore the iron losses in them can be neglected. According to [4], the iron losses in the stator and copper losses in the stator winding are computed from (21) and (22)

$$P_{iron} = \rho_{iron}.k_{st.}\left(N_S V_t \Gamma_t + V_y.\Gamma_y\right) \quad (21)$$

$$P_{copper} = \frac{\rho_{cu} Z I_{rms}^2 \left(L+\left(\alpha_{oc} p (D_{si}+2.d_S)\right)\right)}{2.a.A_c} \quad (22)$$

And the friction and windage losses have taken according to [4]. The output power and the efficiency of the alternator can be found from (25) and (26).

$$P_{out} = S.pf \quad (25)$$

$$\eta\% = \frac{P_{out}\times 100}{P_{gap}+P_{copper}+P_{iron}+P_f+P_w} \quad (26)$$

D. Armature Reaction

The proposed design considered the effect of the armature reaction. Current flowing in the stator tends to distort the magnetic field set up by the permanent magnet. The flux density due to armature reaction, according to [1], is found by using.

$$B_a = \frac{(T_{ph} I_{ph} \mu_o \mu_{rec})}{2(l_m+\mu_{rec} g)} \quad (27)$$

In permanent magnet machines where the magnets are of surface type, the effect of armature reaction is weak. Because the low recoil permeability of the magnets and their long relative length make the stator field as increased air gap. As long as the stator teeth and shoes are not highly saturated due to the permanent magnets acting alone, armature reaction is not a problem. The greatest concern with respect to armature reaction normally occurs under faulty conditions, where machine currents exceeds their normal range, the armature reaction field can become large enough to demagnetize the rotor magnets[3].

E. Input Data and design Results

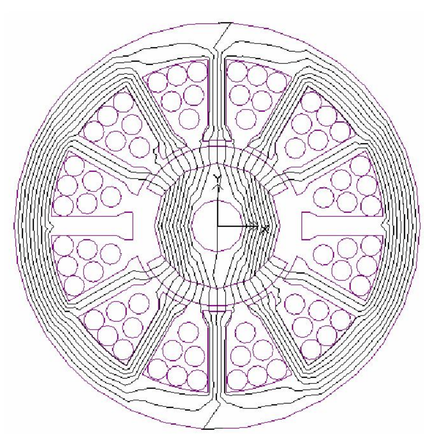
The input data and design results are given in the Tables I and II.

TABLE I
DESIGN INPUT DATA

Apparent Power, S	3 kVA
phase voltage, V_{rms}	25 V
phase current,, I_{rms}	40 A
power factor, pf	0.85
Speed, n	6200 rpm
B_{sat} (cobalt iron alloy)	2.2 T
Remnant flux density B_r	1.17 T
stacking factor, k_{sk}	0.94
slot filling factor, k_{sf}	0.6
short pitching,	1 slot

III. RESULTS OF FINITE ELEMENT ANALYSIS

The magnets are NdFeB with a remanent flux density B_r of about 1.17T, coercivity H_c of about –700kA/m and maximum energy product $(BH)_{max}$ of about 370kJ/m^3 at room temperature. The cobalt iron alloy is chosen as the stator and rotor core material with a saturation flux density B_{sat} of about 2.2T. The finite element analysis has been carried out by using Magnet 2D FEA-package. The iron saturation is verified for alternator for both no load and full load. The distribution of flux lines in the machine for no-load condition at two different rotor positions are shown in Fig.2. The distribution of the magnitude of the flux density for both no-load and full load conditions is shown in Fig.3 and 4. The maximum values of air gap flux densities at no load and full load are of about 0.55T and 0.68T respectively. The maximum values of iron flux densities at no load and full load are of about 1.45T and 1.96T respectively, while the saturation value of cobalt iron had been set at 2.2T. The value of the flux density was verified in various points of the teeth, stator yoke, and rotor core of the machine shown in Table III. The results obtained shows that the iron sections of the machine are not saturated.



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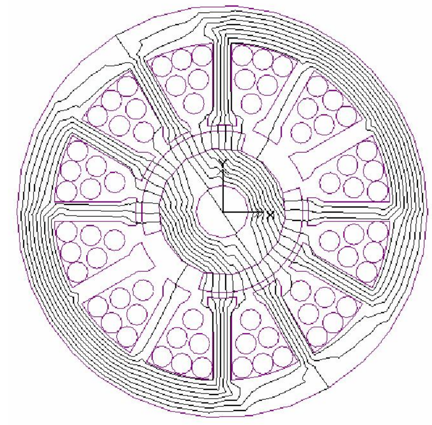


(b)

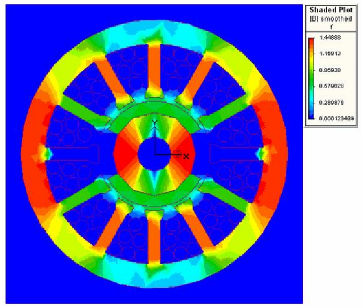
Fig. 3. Flux distribution at no-load (open-circuit condition) at two different positions of the rotor.

TABLE II
DESIGN RESULTS

Number of poles, p	2
number of slots per pole per phase, q	2
Rotor outer diameter D_r	35.3 mm
Motor diameter, OD	110 mm
Length of the stator core, L	103 mm
Air gap flux density, B_g	0.7113 T
Magnet flux density, B_m	0.828 T
Current density, J	4.224 A/mm^2
Ampere loading, A	44376.5 A/m
Stator yoke thickness, w_{st}	8.18mm
Number of coils per phase	4
Number of turns per coil	8
Number of parallel paths	2
Pole coverage coefficient, α_m	0.69
Slot depth, d_s	17.88mm
Tooth width at the slot opening	6.15mm
Slot width at the slot opening	3.76mm
Tooth width just below the stator yoke	4.09mm
Slot width at just below the stator yoke	15.19mm
Air gap power, P_{gap}	2730.19W
Copper losses, P_{copper}	83.86W
Core losses, P_{iron}	40.15 W
Output power, P_{out}	2550W
Efficiency, η	93.41%

TABLE III
MAGNITUDE OF THE FLUX DENSITY AT DIFFERENT POINTS OF THE MACHINE

B (Tesla)	No load	Full load
Teeth	1.448	1.954
Rotor core	1.432	1.903
Stator Yoke	1.415	1.932



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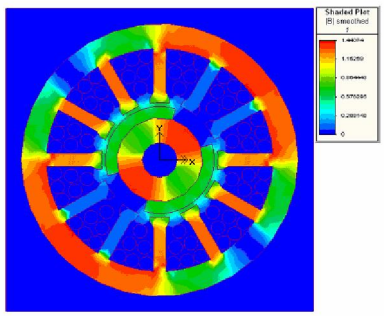

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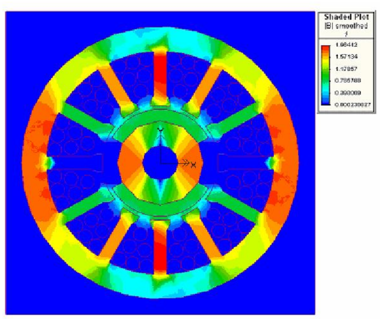
Fig. 3. Magnitude of flux density at no load at two different positions of rotor.



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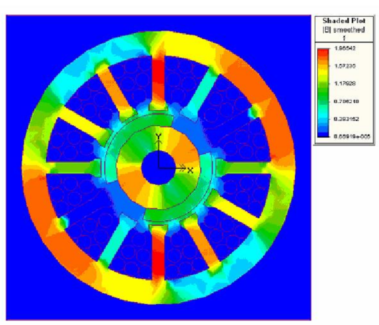

(b)

Fig. 4. Magnitude of flux density at full load at two different positions of rotor.

IV. CONCLUSION

A methodology of design algorithm of a PMBL alternator for light combat aircraft is presented. The design input data and design results are given. In the proposed design the effect of the armature reaction is considered. The magnitude of the armature reaction flux density in the air gap is of about 0.0619T. The design results of the Permanent Magnet Brushless alternator are verified using MAGNET2D, FEA-package. The distribution of flux lines and the magnitude of the flux density in the machine are verified at no load and full load conditions. The value of the flux density was verified in various points of the teeth, stator yoke, and rotor core of the machine. The results obtained shows that the iron sections of the machine are not saturated.

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