Development of an Axial-Flux Permanent Magnet (AFPM) Technology based Power Source for Military Engineering Applications

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Abstract- This paper discusses the indigenous development of an onboard compact, lightweight and highly efficient Axial Flux Permanent Magnet (AFPM) technology based power source. This power source comprises of an Axial Flux Alternator which is mounted on flywheel of variable speed engine along with power conditioning unit. The prototype version has been successfully developed and realized by the author team @ R&DE (Engrs), Pune. This development has immense potential for various military engineering applications where space is always at premium. The uniqueness of this power source is that it can be easily configured and capable of being accommodated in confined spaces on different mobile platforms. In this paper the basic principles as well as design, construction, hardware development and performance related aspects of the power source along with its experimental results are presented.

Key Words- **Axial-field alternator, twin stator, rotor compact generators, and permanent-magnet (PM) machines.**

I. INTRODUCTION

A reliable and high quality electric power supply system is indispensable for the successful battle field operations. There is an ever increasing demand for the specialized ground power units suitable for modern, sophisticated equipments such as computers, communication systems, missile ground support systems like launchers, radars for defence applications etc.

The futuristic requirement of power sources expected for the defence applications would be characterized by high power to weight and power to volume ratios, high fuel efficiency and low noise level high. It is also required that power source should maintain high reliability and least susceptibility to the electromagnetic interference (EMI) effects under all environmental and electrical loading conditions. For a machine to deliver high power from a small space, it must have:

(a) High electric and magnetic loadings.
(b) Intensive cooling to remove the loss from the small space

The AFPM technology based alternator uses high-performance Neodymium-Iron-Boron magnets on the rotor disc so that a high magnetic loading is achieved. Its disc rotors act naturally as fans and so good cooling of the stator winding is ensured even with a high electric loading. It is possible to generate the required EMF using a small number of winding turns and so resistances and inductances are low. Thus, AFPM alternator is inherently light weight and compact. In addition, its mechanical configuration makes it well suited for integration with the engine to form a compact unit. The machine is very short and so can be mounted directly on the engine flywheel.

The development of advanced Axial flux PM (AFPM) machines has enhanced the tactical Power requirement of defence forces for various types of load system. Existing electrical machines used in defence sector are based on conventional methods like either AC excited or brushed which works on radial flux technology.

II. TOPOLOGIES AND GEOMETRIES

From construction point of view, AFPM machines are basically different combinations of various features which can be classified as:

2.1 Stator-rotor arrangement:

- Multi-disk structure.
- Single-sided structure
- Double-sided structure.
  - a) Internal stator
  - b) Internal rotor.

2.2 The technique to integrate the permanent magnets to the rotor:

- Surface-mounted
- Internal or buried

2.3 Existence of armature slots

- Slotted
- Toroidally-wound slotless

The effort has been taken towards the slotted stators and surface-mounted permanent magnets. The geometries of AFPM machine is twin stator single rotor type. The rotor is sandwiched between two stators to give more strength. Neodymium Iron Boron (NdFeB) permanent magnets are used for this machine and are placed on the rotor disc by using adhesive. The surface mounted permanent magnets are preferred mainly due to constructional convenience. The slotted stators are advantageous in terms of robustness.

III. BASIC PRINCIPLE

The Axial-flux machines are different from conventional electrical machines in terms of the direction of the flux which runs parallel with the mechanical shaft of the machine. The current flowing through each stator coil interacts with the flux created by the magnets on the rotor, producing a force tangential to the rotor circumference.

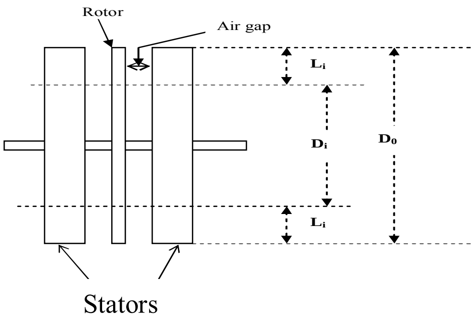

Fig.1 Simplified representation of an AFPM machine

The r.m.s. phase emf equation is

$$E_{ph} = \frac{1}{\sqrt{2}} \hat{B}_{g1}\omega_m k_{w1} N_{ph} D_{av} L_i$$

Electromagnetic power of the machine for 3-phase system is

$$S = 3hE_{ph}I = \pi\frac{h}{4}\hat{B}_{g1}\omega_m k_{w1} K_1 D_{av}^2 L_i$$

Airgap flux density is given as

$$B_{go} = \frac{B_r}{1 + \frac{2g\mu_r}{L_m}}$$

Stator Yoke

$$L_y = \frac{\tau_p B_{g0}}{2B_{\max}}$$

$$PolePitch = \tau_p = \frac{D_{av}\pi}{2p}$$

where,

$$Dav = \frac{D_0 + Di}{2}$$

L_i = $r_o - r_i$. (Effective stator core length)

N_{ph} = Number of series turns per phase

$\hat{B}_{g1}$ = Amplitude of the fundamental component of air gap flux density

h = No. of stator faces

k_{w1} = Fundamental winding factor

K_1 = Electric loading ($10,000 < K_1 < 40,000$)

L_M = Magnet Length

Based on above equations, analytical design of stator, rotor, stator yoke and rotor permanent magnet of AFPM alternator has been done.

Design data are given below:

i	Outer Diameter(D_O)	409.6 mm
ii	Inner Diameter(D_i)	237.5 mm
iii	Magnet axial length (H_M)	4 mm
iv	Magnet Length (L_M)	86.05mm
v	Magnet/Pole Width (ω_M)	45.74 mm
vi	Magnet Volume (V)	15.743×10^{-6} m^3
vii	Weight of PM	118 gm.
viii	Bmax.	1.5T
ix	Bg0	0.7 T
x	Stator Yoke length	14.23mm
xi	Each Stator axial length (Ly)	60 mm

IV. REALIZATION OF AFPM GENERATOR

The Prototype AFPM generator (40kVA) has been designed developed and manufactured to demonstrate the axial flux technology. The basic layout is as shown below:

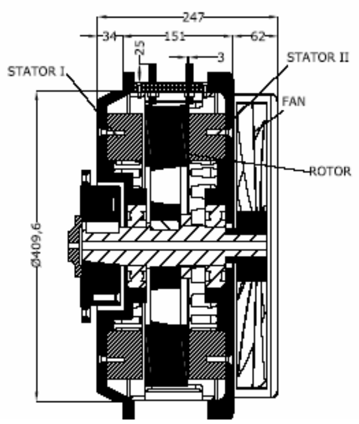

Fig. 2 Basic Layout of AFPM alternator

The Alternator is driven by IC engine and it is mounted on the flywheel of engine. Due to the flywheel-machine arrangement, the outside diameter is constrained. The inside-to-outside diameter ratio is (0.58) and the air gap flux density levels are kept constant in space between rotor and stator. The number of stator slots and the winding configuration of the stators are chosen in such a way to reduce the higher order space harmonic components of the windings. Magnet skewing is also done to eliminate the cogging torque. Adequate cooling system is provided by using cooling fan. Due to presence of high energy Neodymium Iron Boron (NdFeB) permanent magnets, the overall efficiency of the machine is increased as the ohmic losses in the field winding are no more present. When machine is getting loaded from no load to full rated load the transient recovery is fast and system get stabilized quickly. It provides a continuous quality electric power to the different loads. The GA drawing and pictorial view of an AFPM alternator is shown below:

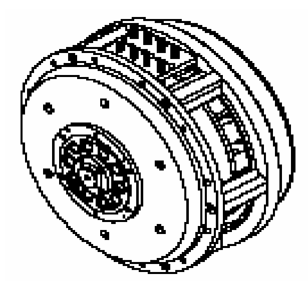

Fig. 3 GA Drawing of AFPM alternator

Fig.4 Pictorial View of AFPM alternator

V. DIMENSIONAL DETAILS:

Overall Dimensions	
Total Length	205±5
Diameter	Ø409.6
Shaft Length	56.5±2
Weight of the alternator	<85 Kg
Cooling Arrangement	Forced cooled
Power output Termination	Bolted terminations with proper isolation

VI. CONSTRUCTIONAL DETAILS

The constructional details of AFPM machine is as given below:

6.1 Stator Assembly

Since torque is produced as a result of the interaction between the magnetic field of the permanent magnets on the rotor and the current in the stator conductors, it is obvious that by increasing the number of stators, the torque of the machine will be increased proportionally. Two stator faces are chosen for this machine. The stator body is fabricated using cold rolled non oriented steel. The thickness of steel sheet used for making stamping (laminations) is of around 0.5 mm and core length is about 60 mm. The stator has 18 slot and 18 coils are placed in it. The cross section area of conductor used for winding is 7 square mm and each coil have 10 turns. The fill factor considered is 0.4 and coil span is 1-2. The GA drawing and internal stator views are shown below:

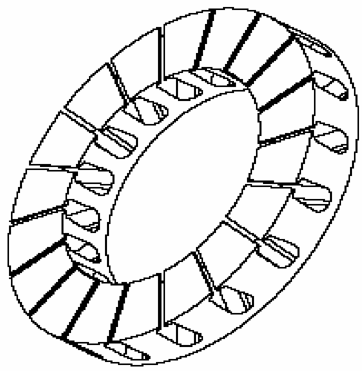

Fig. 5 Stator GA Drawing

Fig. 6 Internal view of Stator

6.2 Rotor Assembly

The flux in the machine is mainly established by the magnets because the torque production is directly proportional to the flux. The shape and size of magnets decide the flux density available in air gap. Air gap flux density 0.9 wb/m^2 is considered for this machine. The rotor is fabricated using soft low carbon steel stampings. There are total 32 slots on rotor core. 16 slots are on one side and 16 slots on other side. Soft iron core is used for conducting flux in between two magnets. High temperature adhesive is used for placing the magnets in slots.

Neodymium Iron Boron (NdFeB) permanent magnets are used for this machine and are fixed in slots made on rotor core (stampings) by using adhesive. The rotor core is placed in between two plates to give more strength. The whole structure is finally mounted on alternator shaft. The rotor body is then placed between two stator plates. The GA drawing and internal rotor views are shown below:

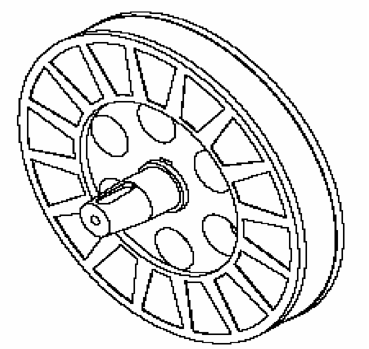

Fig. 7 Rotor GA Drawing

Fig.8 Internal view of Rotor

VII. SYSTEM INTEGRATION

Stator body is housed in a back iron (yoke) and this assembly is mounted on a shaft. Rotor is also positioned on the same shaft in between two stators. The complete assembly in a single package called as AFPM alternator is integrated with induction motor with variable speed drive for system evaluation under simulated load conditions.

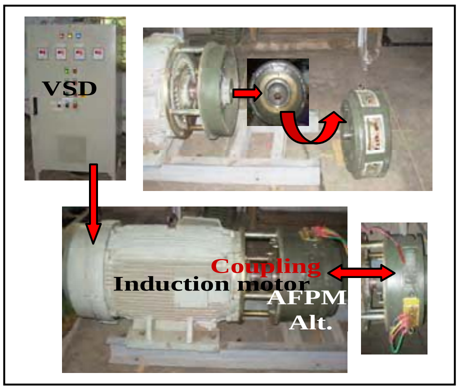

Fig.9 Simulation test set up

After on bench testing of alternator, it was integrated with flywheel of variable speed prime mover (IC engine) in acoustic container with suitable anti vibration mountings on a base frame to make it as a dedicated compact power source. Integrated view of mobile power source is as shown below:

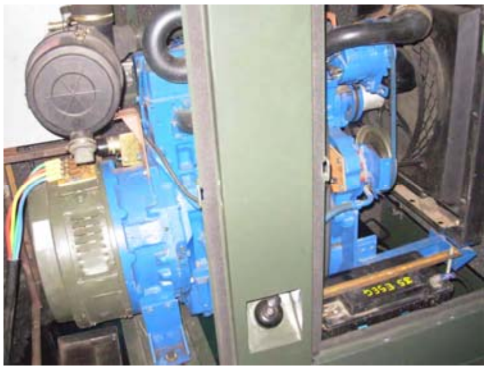

Fig.10 Integrated view of Compact Mobile Power Source

7.1 Performance Evaluation and Testing:

After integration of AFPM Alternator, it was tested under simulated conditions to study the characteristic and behavior of alternator in terms of electrical performance parameters such as transient voltage dip, rise and its recovery from no load to full load and vise versa. Temp rise during endurance (continuous run of 7 to 8 hrs) of the machine was also noted at air intake and hot air outlet point and it was less than 65°C. This integrated machine inside an acoustic container has been tested at various speeds from 800 to 2300 rpm and corresponding alternator output voltage is also increased from 148 to 401V.

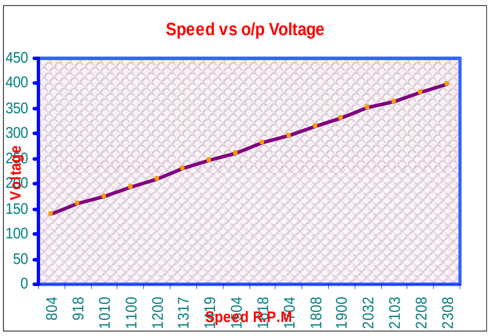

Fig. 11 Speed v/s output voltage curve

This machine has undergone rigorous testing for resistive and inductive load (0.8 power factor) for verification of actual load conditions and found efficiency of 94%, which shows excellent and satisfactory performance results of the machine. The waveform given below shows the smooth sinusoidal voltage output.

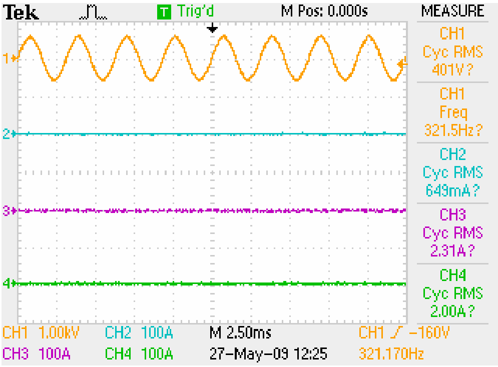

Fig.12 Voltage and current waveform at no load

Voltage and current waveforms of AFPM alternator are captured with waveform measuring instrument (oscilloscope) for no load and full load and it shows the output quality of the system.

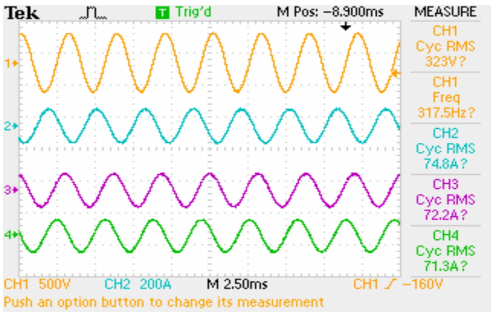

Fig.13 Voltage and current waveform at full load

VIII. Conclusion

Since, the Axial Flux Permanent Magnet Technology Based machine has been designed, developed and tested successfully and due to its unique features like very compactness, high torque to weight ratio, reliable, efficient and quality power output, this machine is considered as a futuristic power source for weapon system and military engineering applications.

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References

[1.] Gieras, Jacek F., Wang, Rong-Jie & Kamper, Maarten J.,"Axial Flux Permenet Magnet Brushless Machines", 2nd edition , Springer Publications.

[2.] Vito, P. V.T. & Vito, E. Peters, Belgium; "Design of a New Axial Flux Permanent Magnet Generator for hybrid electrical vehicles", IEEE Transactions, 2003.

[3.] Caricchi, Federico, Mezzetti, Fabio & Santini, Ezio; "Multistage Axial-Flux PM Machine for Wheel Direct Drive", IEEE Transactions, 1996.

[4.] E. Spooner, B.J. Chalmers, 1992, "TORUS, a slotless, toroidal-stator, permanent-magnet generator", IEE Proc. B, 139, November 1992, 497-506.

[5.] Cirani, Maddalena, Thelin, Peter & Sadarangani, Chandur;" Design Procedure for an AFPM Machine for Field-Weakening Applications", IEEE Transactions, 2000.