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A Novel Axial Flux Induction-Permanent Magnet Generator with Two Mechanical Power Inputs

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ABSTRACT

A novel Axial Flux Induction-Permanent Magnet Generator with two mechanical power inputs is which is hybrid of induction and permanent magnet generators concepts is proposed. The generator with an axial flux topology and two rotors leads to elimination of gear-box which makes it a low weight and compact generator with a high power-to-weight ratio, which is suitable for upper atmosphere wind energy generation applications. An optimum design for the generator is obtained using analytical and iterative approaches. To evaluate the efficiency of the obtained design, magnetic flux simulations are carried out using a finite element software package. The obtained results from the simulations demonstrated the effectiveness of the proposed generator.
KEYWORDS: Axial flux generator; high altitude wind energy, induction generator, tethered wind turbines.

INTRODUCTION

The high winds with persistent and significant power density present a dense and vast layer of energy over the populated and industrial areas. It has been estimated that the wind power in upper atmosphere layers is about 100 times bigger than global energy demand [1]. Due to greenhouse effects of fossil fuels, high altitude winds can be an attractive alternative energy resource. To extract such enormous resource of energy, some companies namely as: Sky WindPower, Makani Power, Joby Energy present new concepts and technologies [2]. But, high altitude wind energy generation technology has not been developed yet as much as conventional ground mounted wind turbines technology.

From the generator type point of view, several types of generators have been already used for wind energy generation. Since induction generators are not required to rotate in a constant angular speed, they are selected as appropriate generators for wind farms applications among the various types of generators. As an induction generator spins at an angular speed more than the synchronous one, it produces electrical power. Consequently, due to suitable aspects of induction generators, it is necessary to improve them for using in high altitude wind farms for both concentrated and distributed wind energy generation. According to deployment of such systems at high altitudes, the actual trend in high altitude wind energy technology is to achieve generators with low weight, high efficiency, higher power-to-weight ratio, and lower cost.

From the generator type point of view generator compactness, axial flux machines represent a high power density, high efficiency topology with lower total electrical power loss, due to its self cooling structure compared to radial flux machines. Thus, axial flux topology has attracted researcher’s attention widely [3]. But, a majority of proposed axial flux generators are of permanent magnets which are commonly called Axial Flux Permanent Magnet Generator (AFPMG).

Axial flux topology of induction generators which offer some unique aspects that combine both axial flux and induction generator topologies were presented in [4-5]. But, these topologies are not practically used, studied, or developed, and rare literatures are available about them.

From generator weight point of view, a significant weight of wind turbines which employ induction generator belongs to the gear-box. So, its elimination can lead to a significant reduction of the wind turbine generator weight.

A practical approach for reduction of gear-box weigh, or even its elimination, is enhancement of rotating magnetic field angular speed in the generator air-gap using a generator topology with two rotors [6]. These generators have two rotors which are turning in opposite directions on a single axis. When a generator has two rotors, it means it has two inputs for mechanical powers. Also, such topology of radial induction generator was proposed in [7].

Advantages of the topology with two rotors are not restricted only to elimination of gear-box. Since these generators use two turbines which are rotating in contrast, the acting forces on the supporting structure neutralize each other, resulting a near-zero reactive torque. The elimination of gyroscopic effect of generator makes it a suitable generator for high altitude wind turbines [8]. In order to clarify how a generator with this topology can decrease weight of high altitude wind energy conversion systems, consider a conventional high altitude wind turbine proposed by Magenn Inc. [11], as shown in Fig. 1. It is a savonious-style wind turbine which is filled with a lighter than air gas, and is floating at an altitude of 200 meters while it is tethered to a ground station. The electrical power produced by the generators of both sides of the turbine is transmitted via a cable to a ground station. As seen in Fig. 1, this turbine needs a pair of generators and gear boxes.

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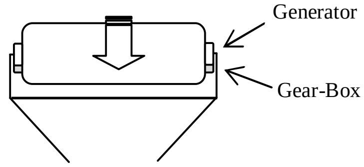

Fig.1 High altitude wind turbine porposed by Magenn Inc.

Obviously, two turbines include four generators and gear-boxes as shown in Fig. 2(a). But, by using two high altitude wind turbine and a generator with two rotors instead of four generators, all the four gear boxes will be eliminated, as well as three out of four generators, resulting a low weight wind turbine system as shown in Fig. 2(b).

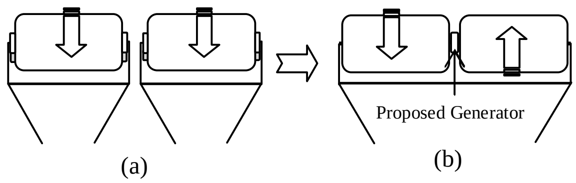

Fig.2 (a) Two independet high altitude wind turbines. (b) low weight high altitude wind turbine system with a generator with two rotors.

In high altitude wind energy generation technology, enhancement of power-to-weight ratio is one of the critical areas which should be focused on to make generators suitable for high altitude wind turbines. Thus, in this paper we proposed a novel axial flux induction generator with two inputs for mechanical powers to address the disadvantages of recent induction generators. The application of this generator in wind energy generation will cause reduction of weight of wind turbine.

The scientific contributions of this paper can be summarized as follows: 1) A novel axial flux induction generator which has two inputs for mechanical powers is proposed. This generator can meet most of the criteria for high altitude wind energy generation application. 2) To reach an optimum design, a procedure is carried out for this type of generators, then, the obtained design is validated.

The rest of this paper has been organized as follows. In section II, a brief description of the generator topology and its construction is presented. In Section III, a procedure for designing of the generator is proposed and followed. In section IV, the input data, and the resulted design are presented. In order to ensure that all points of the generator cores are under saturation, simulations of flux lines and densities are carried out in section V. Finally, in section VI, the conclusion and perspective are presented.

GENERATOR TOPOLOGY

A simplified side view representation of the proposed generator is shown in Fig. 3. As seen, the generator composed of two rotors rotating in opposite directions which are entitled as first and second rotors. A frame is axially supporting the rotors. The excitation system including the brush and slips ring which transfers the generated power in the second rotor to the output terminals.

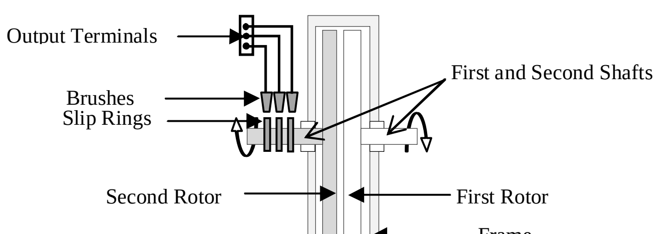

Fig.3 Simplifide side view representain of the proposed generator,

The proposed topology provides a generator with the mentioned desired properties including lower weight and compact structure. This generator has the capability to be driven in its both sides with two independent turbines as two prime movers which are rotating in opposite directions as shown in Fig. 4. The prime mover are the high altitude wind turbines in here.

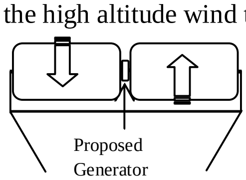

Fig.4 Two savonius-style turbines are driving the proposed generator in both sides

The main parts of the generator are described detail in following.

A. *First rotor*

The first rotor consists of numerous aluminum bars which are positioned in a conductive ring as shown in Fig. 5. The second rotor can be interpreted as a flat type of squirrel cage rotors in the radial flux induction machines.

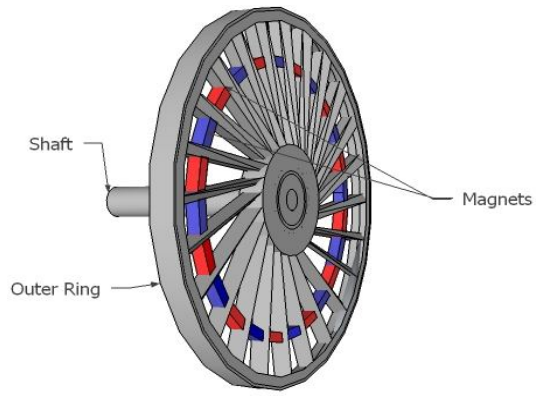

Fig.5 First rotor

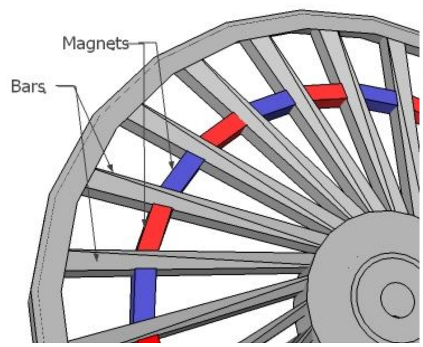

Fig.6 First rotor

The first rotor is supported with the generator frame while is rotated with the prime mover via the first shaft.

B. *II. Second rotor*

The second rotor is a single-sided slotted disk which is shown in Fig. 6(a). It is wound as a star-connection winding shown in Fig. 6(b) and Fig. 6(c). It should be stressed that, conventional induction generators do not require brush and slip rings. But, due to rotation of the second rotor, brush and slip rings are needed here. The winding terminals of the second rotor are the output terminals of the generator.

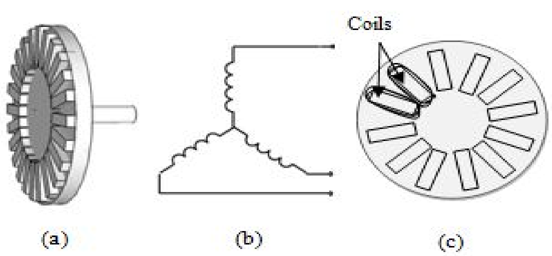

Fig.7 (a) Second Rotor. (b) star-sconnection winding. (c) coils placement on the second rotor.

The second rotor is wound as a star-connection. As the rotors rotate in opposite directions, the first rotor induces electrical voltage in the second rotor winding appears at generator terminals. The second rotor winding is fed by a three- phase capacitor bank. An assembled view of the generator components is represented in Fig. 7. As shown, the frame is supporting both. The simple diagram of power in the generator is shown in Fig. 8. The diagram shows mechanical inputs and losses as well as electrical output and losses in the rotors.

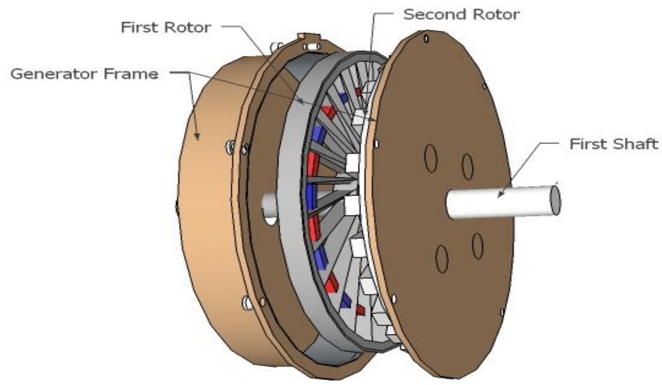

Fig.8 Asembeld representation of the generator

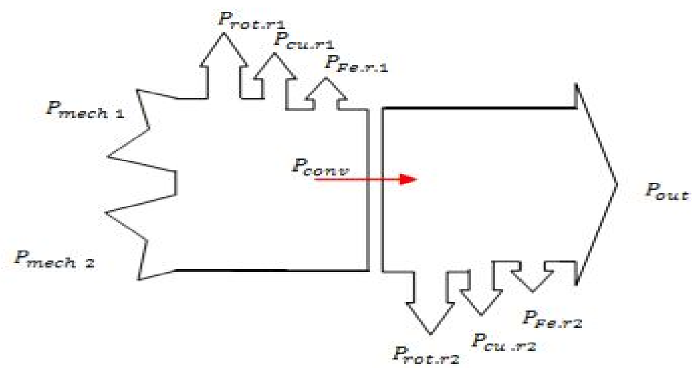

Fig.9 Diagram of power in the generator

DESIGN PROCEDURE

Design side view of the generator is sketched with its geometric dimensions is shown in Fig. 9.

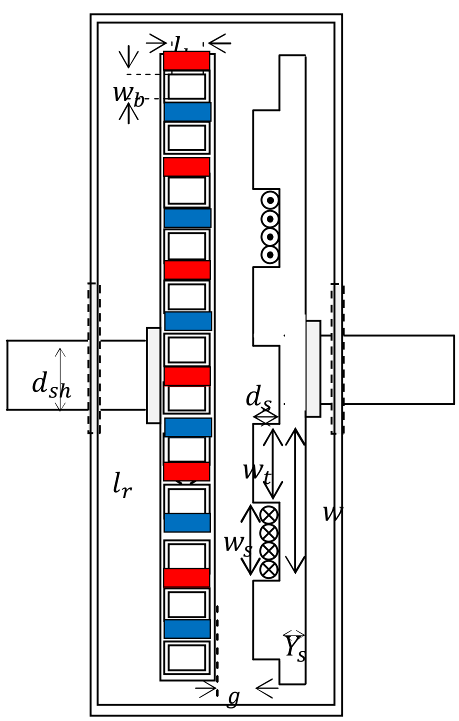

Fig.10 Side view represation of the generator with its geometric dimensions.

C. Material Selection and user defined data

The fist initial data to start the design are the bars, iron, and conductor material data, as well as the air-gap length which is mainly affected by mechanical constraints. The bars are made of aluminum alloy. The Iron is chosen as of type -1008. The user defined design parameters are the number of pole pairs, p, and the number of slot per pole per phase, q.

D. Winding Configuration and Factors

The configuration of the windings of the generator is shown in Fig. 10. A, B, and C indicate the phases and direction of current denoted as signs of "+" and "−" respectively.

A	$-C$	$-A$	C	$-B$	A	B	$-A$	$-B$

Fig.11 Phase arragmenet

The winding factor is

$$k_w = k_d k_{sp} k_{sp} \quad (1)$$

Where, the k_d, k_{sp} , and $k_{sp}$are the distributions, skewing, and short pith angle factors, respectively which are:

$$k_d = \frac{\sin\left(\frac{p\theta_s}{2}\right)}{p\sin\left(\frac{\theta_s}{2}\right)} \quad (2)$$

$$k_{sp} = \sin\frac{\theta_s}{2} \quad (3)$$

$$k_{sp} = \frac{\sin\frac{\gamma}{2}}{\frac{\gamma}{2}}. \quad (4)$$

E. Determination of Teeth and Slot Width

Determination of slot and teeth width is mainly refers to the air-gap flux density, and the generator ampere loading. As the flux density in the air-gap increases, the width of teeth should be increased to prevent teeth saturation. A wider tooth leads to a smaller slot width; and a lower space for conductor results in a lower output power, compared to the expected power for the generator. This relationship among the rated power, air-gap flux density, teeth, slot width, and slot depth results in a complex optimization issue. Thus, a simple relation between dimensions of teeth and slot width presented in [9] was used to achieve minimum volume of rated power.

$$w_t = (1 - w_s)w \quad (5)$$

Where, w_t is in the range of $0.5w < w_t < 0.6w$.

For simplicity, we consider slot and teeth width to be equal. Thus, the width of slot and teeth will be:

$$w_t = w_s = \frac{\pi R_i}{k_{st} N_s} . \frac{B_g}{B_{sat}}. \quad (6)$$

F. Determination of Maximum Flux Density in the Air-Gap

To avoid saturation of the parts of the machine cores, the calculation of maximum magnetic field density in the air-gap is crucial.

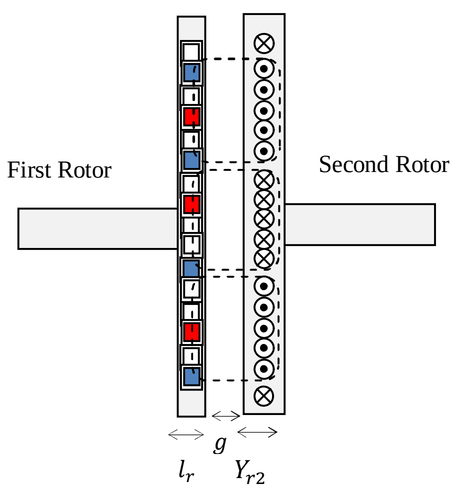

Fig.12 Represention of the fluxes path in the generator yokes

As the second rotor is fed by a three-phase capacitor bank, or a gird, a rotating magnetic field with relative speed of rotors and amplitude of B_g appears in the air-gap, which can be expressed as:

$$B_g = B_{g1}\cos(p\theta - \omega t). \quad (7)$$

Where, B_{g1} is:

$$B_{g1} = \frac{D_s l_c \mu_0 \mathcal{F}}{l_{ge}} \quad (8)$$

Where, $\mathcal{F}$ is the fundamental MMF driving the air-gap flux which can be obtained by product of RMS magnetization current, I_M, and the effective number of series turn per phase:

$$\mathcal{F} = \frac{4}{\pi}\frac{k_{w1}N_{ph}}{2p}\sqrt{2}I_M. \quad (9)$$

G. Determination of the Dimensions of Second Rotor Yoke

To prevent saturation of the second rotor yoke, thickness of yoke should be at least:

$$Y_{r2} = \frac{\pi R_i}{4k_{st}p}.\frac{B_g}{B_{sat}}. \quad (10)$$

H. Determination of the Conductor Diameter and Series Turns per Phase

As the number of series turn per phase, N_{ph}, is found, the conductor diameter can be calculated as:

$$d_c = 2\sqrt{\frac{k_{sf}A_{slot}}{\pi N_{cs}}} \quad (11)$$

Where, A_{slot} is the cross sectional area of the slots:

$$A_{slot} = d_{1s}w_s. \quad (12)$$

Thus, the number of conductor per slot can be obtained:

$$N_{cs} = \frac{N_{ph}}{pq}. \quad (13)$$

I. Determination of Machine Diameter

The diameter of a machine relates closely to the number of the series turn per phase, N_{ph}, There is a reveres relationship between the machine diameter and number of turn per coils; as the series turns per phase increase, the machine diameter decreases. Thus, to achieve a specific diameter, N_{ph} should be iterated while the diameter converges to the desired diameter, which results the minimum volume. According to [10], the power balance is:

$$P_{gap} = P_{out} + P_{Core} + P_{Copper} \quad (14)$$

Based on [10], the air-gap power in axial flux machine can be written as:

$$P_{cov} = \pi^2 k_w {}^{f}/_{2p}\left(A.B_{g1}\right)(R_o + R_i)^2(R_o - R_i)sin\beta \quad (15)$$

Where, β is the power angle of the generator.

$$P_{Copper} = \frac{N_{ph}(2(R_o - R_i) + (r_{co} + r_{ci})\frac{\pi}{2})}{\sigma_{cu}A_{cu}K_p}I^2. \quad (16)$$

The expression for core loss density, P_{core}, including hysteresis and eddy current losses is given by Steinmetz equation [10]:

$$P_{core} = P_h + P_e = c_h B^{n(B)} f + c_e B^2 f^2 \quad (17)$$

Where, the coefficients of c_h, c_e, and n are determined with construction data. The ampere loading, A, is:

$$A = \frac{6N\sqrt{2}IN_{ph}}{(R_o + R_i)\pi}\,. \quad (18)$$

Since the generator with the desired diameters presents numerous possible designs, the maximum power-to-torque ratio, $\mathcal{E}$, was used as a constraint to obtain a compact generator suitable for high altitude wind energy generation:

$$\mathcal{E} = \frac{T}{V_{Gen}} \quad (19)$$

Where, T and V_{Gen} are the generator torque and volume, respectively, and can be written as:

$$T = \frac{\pi}{2}k_w B_{g1} A(R_o + R_i)^2(R_o - R_i)sin\beta \quad (20)$$

$$V_{Gen} = \pi(R_o - R_i)^2(Y_{r2} + g + l_r). \quad (20)$$

Flowchart of design procedure is shown in Fig.10.

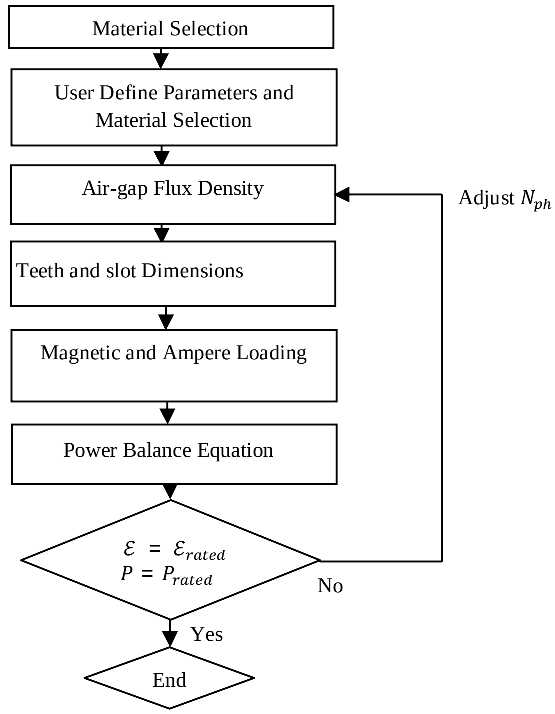

Fig.13 Fowchart of design procedure

J. Input Data and Design Results

The input data and obtained design from the iterative algorithm procedure are given in Tables I and II.

SIMULATIONS

The obtained design in previous section should be validated to check its saturation status. The flux lines and magnitude flux density in the machine can be computed and observed with a finite-element analysis package. The obtained simulations for flux line and flux magnitude distribution in a no-load condition are shown in Fig. 13 and Fig. 14, respectively.

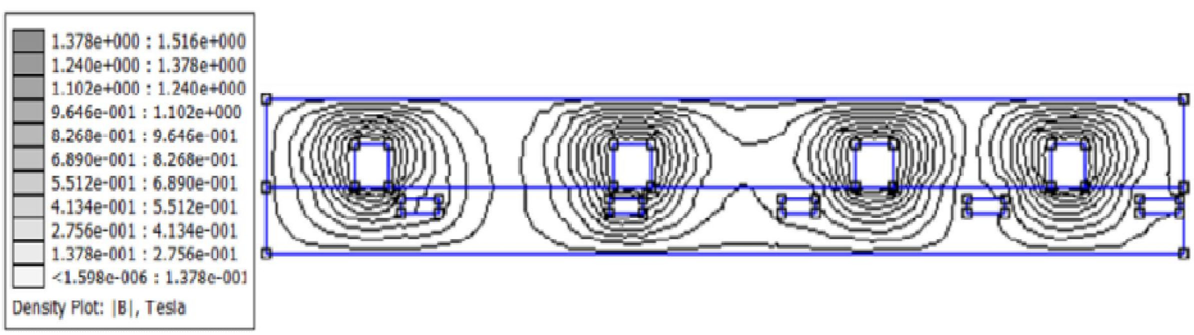

Fig.14 Flux line distribution in no load condition

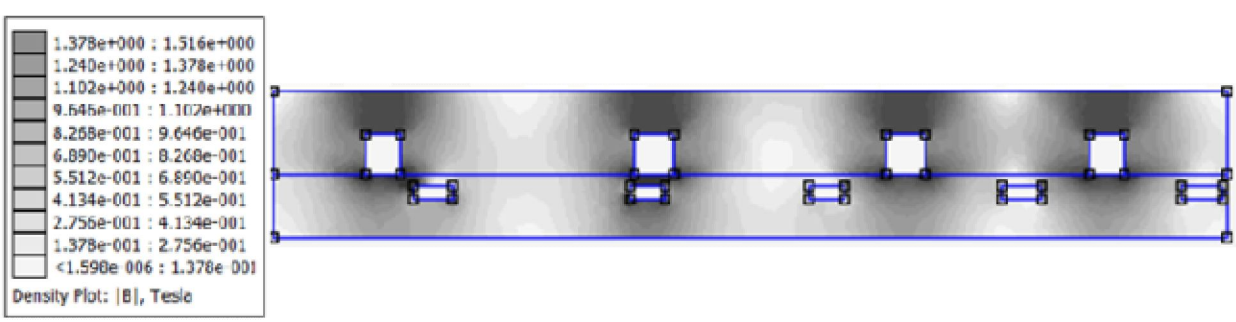

Fig.15 Flux density distribution in no load condition

By checking the values of flux magnetic densities in the machine cores, it can be observed that the maximum value of flux density is 1.5 T, while the saturation flux is 1.7 T. The, maximum flux density in yokes and teeth are given in Table III.

TABLE III
THE AMPLITUDES OF FLUX IN GENERATOR PARTS

B (Tesla)	No-Load	Full-load
Core	1.41	1.45
Yoke	1.36	1.42
Teeth	1.48	1.5

CONCLUSION

This paper presented the construction and design procedure of a novel type of generator. The design begins with selection of initial data to reach primary geometry in order to avoid saturation in all parts of the generator cores. It continues to iterate the machine parameters to achieve maximum power-to-weight ratio and the desired rated power. To observe the flux line and flux magnitude densities in the obtained design, a finite element analysis software package was utilized. The simulation results demonstrated that any area was not saturated.

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