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A Novel Axial Flux Brushless Induction Generator with two Mechanical Power Inputs for Wind Energy Generation Applications

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ABSTRACT

A novel brushless axial flux induction generator (BAFIG) with two mechanical inputs for wind energy generation applications is proposed. All parts of the generator topology are described. The BAFIG topology consists of two independent rotors which are rotating in contrast and a fixed stator. This topology leads to elimination of gear box, and excitation system including brushes and slip rings. Moreover, all parts of the AFBIG are modeled and designed using analytical and iterative approaches, respectively. To verify the efficiency of proposed design and validity of the proposed model, simulations with a finite element software package are carried out. The simulations results demonstrate the effectiveness of the proposed topology.
KEYWORDS: Axial flux induction generator, brushless generator, induction generator, wind power.

INTRODUCTION

The energy of surface winds is estimated about 72TW which is five times bigger than global energy demand [1]. This surface winds present a vast layer of energy can be extracted with minimum environmental impacts. The greenhouse effects of coal and oil, initiated in carbon dioxide emission, lead to consideration of wind power as a friendly alternative energy resource. Wind farms consist of arrays of several wind turbines are designed to extract this wind energy. But, recent wind farms have several disadvantages which can be briefly described as follows.

The first problem is high territory occupation of wind farms, which is due to the significant distance between the wind turbines. This distance is due to created wake in output of wind turbines as shown in Fig. 1(a). This helical wake is created by rotation of wind turbine rotor.

The need to high amount of structural materials for wind turbines is another issue in wind farms. The needed materials for construction of towers and blades are significantly high. As the blade and tower lengths increase, the roots cross sectional area them increases with square of length, resulting in higher volume and needed materials.

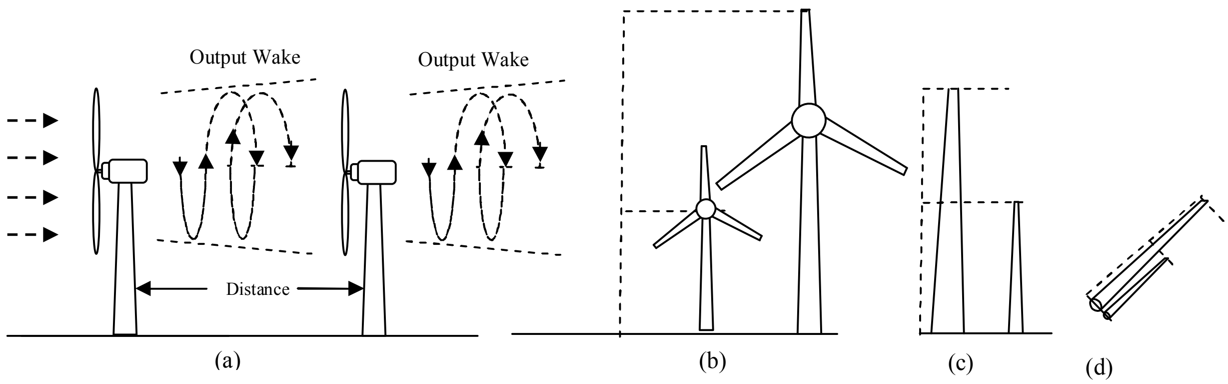

Figure 1. The distance between two turbines on a row is limited to turbinewake. (a) two wind turbines which blade and tower lengths of one of them are two times bigher than another one. (b) incresing trend of wiegh versue lengh of tower. (c) incresing trend of wiegh versue lengh of blade.

For example, the needed material for a blade with length of 2m is 8 times bigger than the needed materials for construction of a blade with length of 1m Fig. 1(d) and Fig. 1(b). Similarly, as the blade length increase, the tower high must be increase, resulting in enhancement of tower weigh with same ratio for the blades Fig. 1(c) and Fig. 1(b). Moreover, excluding the tower, significant weight of wind turbines which are employing induction generators is mainly due to the gear box. Elimination of it can significantly reduce the nacelle weight and turbine cost as well as relevant needed maintenance.

Thus, the actual trend in wind energy generation technology is to achieve compact wind farms with minimum land occupation, and high efficiency and compact wind-turbines generators with minimum weigh and maintenance. To achieve compact generator

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topologies, axial flux configurations of induction generators have been presented in [2-3]. But, these generators need to gear box. It should be noted that, among the various types of the generators, since inductions generators are not required to be rotated in a constant angular speed, they are chosen as a suitable generators for wind farms applications. As an induction generator rotates at an angular speed more than the synchronous speed, it is generating electrical power. Consequently, due to suitable features of induction generators, the researches, in wind energy generation, mostly have been focused on the induction generators to develop them for application in wind farms. Also, several attempts have been carried out to reduce the wind turbine weight. A realistic approach to reduce gear box weight, or even elimination of it, is enhancement of angular speed of rotating magnetic field in the generator air gap [4]. But, these methods are used only for radial flux induction generators [5].

Thus, in this paper, we proposed a novel brushless axial flux induction generator (BAFIG) with two mechanical inputs to alleviate the most drawbacks of recent wind farms and wind turbines. The special topology of the BAFBIG causes to elimination of brushes and slip ring for excitation system. Moreover, the proposed BAFIG does not require gear box to reach speed.

The scientific contributions of this paper can be summarized as follows:

1. A novel axial flux induction generator with two mechanical inputs and without excitation system has been proposed.
2. An electrical model for the BAFIG has been proposed using analytical approaches.
3. To reach an optimum design for the BAFIG, a design procedure is established and followed which can be used for design of other similar generator with two inputs for mechanical power.

The rest of this paper has been organized as follows. In section 2, the topology of proposed BAFIG which can alleviate the drawbacks of recent wind farms and wind turbine is presented. Furthermore, a brief description of the all parts of generator is presented. In section 3, principle of working of the BAFIG is presented. In Section 4, a design procedure for the BAFIG proposed and followed. In section 5, to verify the attained designed and to ensure the generator is under saturation condition, simulations of flux line and magnitude density are carried out. Finally, in section 6, conclusion and perspective are presented.

PROPOSED TOPOLOGY

To address the highlighted problems in pervious section, we proposed a novel generator. Two rotors and a stator are used in construction of this generator. A simplified representation of the BAFIG is shown in Fig. 2(a).The rotors are rotating in opposite directions. As seen, the generator consists of three parts of first rotor, second rotors, stator, and a frame comprising them. It should be noted that the first and second rotors can rotate freely in contrast while the stator is fixed to the frame as seen in Fig. 2(a). Proposed topology provides a generator with capacity of driving with two turbines which are rotating in contrast as shown in Fig. 2(b). We used axial flux topology for the rotors, since axial flux machines feature a high power density, high efficiency and lower total electrical loss power, respect to radial flux machines.

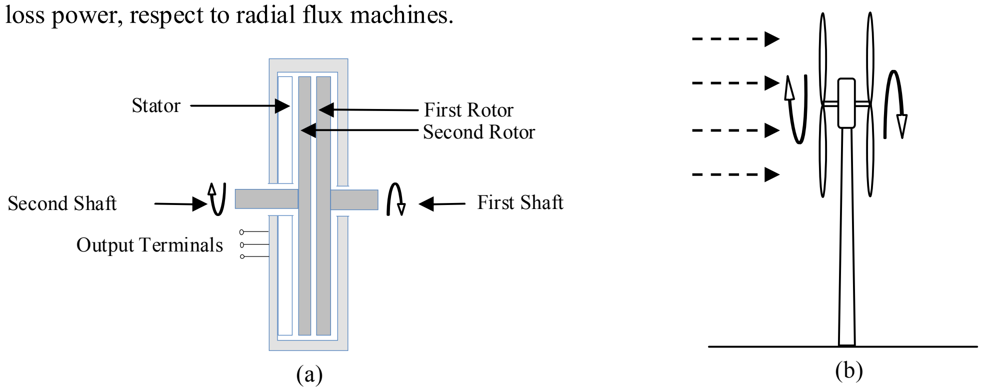

Figure 2. (a) Simplified side view reperetion of the BAFIG. (b) wind-turbine generator system with two rotors using the proposed BAFIG.

The generator parts are described in detail in following:

A. First rotor

The first rotor consists of aluminum bars which are positioned in a conductive ring as shown in Fig. 3(a). Indeed, the rotor is flat type of squirrel cage rotors in radial induction machines. Not only the bars can be skewed in $x - z$ plan to avoid torque pulsation, but also the bars are skewed in $y - z$ plan to operate as a cooler fan. The first rotor is being supporting with a frame while is being rotating with a prime mover via its shaft.

B. Second rotor

The second rotor is a double sided disk, which both of its sides have been slotted as shown in Fig. 3(b). Each side has equal slot numbers which are separately wound as three phase star-connection. The star-connection windings of each side are connected together as a parallel connection as shown in Fig. 3(c). The second rotor is located between the first rotor and the stator while is being rotating by means of another independent prime mover via its shaft.

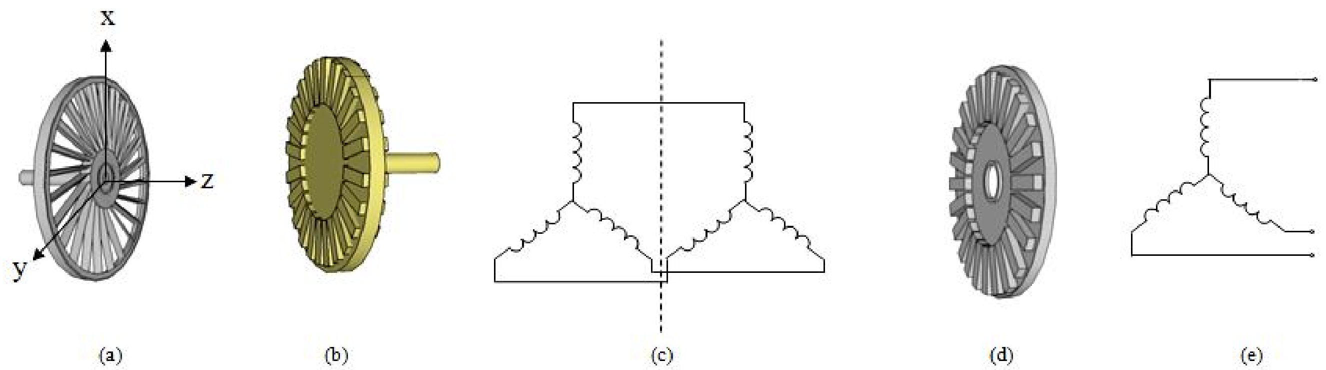

Figure 3. (a) The constructed rotor as fan style structure for self cooling purpose. (b) The second rotor is a doubes sided sloted disk. (c) righ and left sides of the second rotor wounded as three phase star-connection (d) The stator single sided disk which is sloted. (e) A three phase star-connection winding will be wounded on the stator.

C. Stator

Induction generators do not require brushes and slips rings as excitation system. But, in generators with two rotors, due to rotation of both of them, brush and rings will be required. To achieve a brushless excitation system, we used a stator. The stator is wound as star-connection, and is fixed to the generator frame. The stator winding terminals are the output terminals of the BAFIG. The second rotor induces electrical voltage at the stator winding appears in the terminals. The stator will be fed using a three phase capacitor bank which provides reactive power for the BAFIG.

All the generator parts including first rotor, second rotor, and stator are shown in Fig. 4(a). As seen the generator has two shafts and two inputs for mechanical powers. A frame comprises the rotors and the stator which is shown in Fig. 4(b).

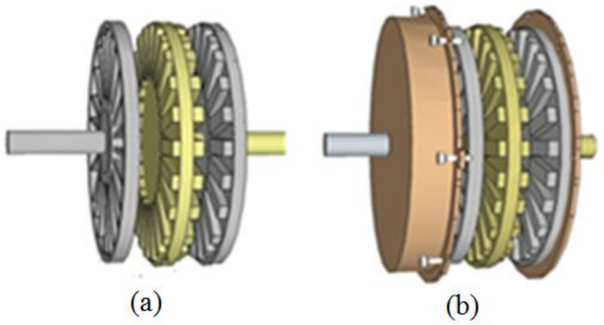

Figure 4. (a) Assembly representation of the first rotor, second rotors, and the stator. (b) repersenation of the frame comparising the rotors and the stator

The advantages of employment BAFIG in wind turbines are summarized in following. As discussed in previous section, the significant distance between single-rotor wind turbines in a wind farm is mainly due to the output weak of turbines. But the output wake of the double rotor wind turbine is very low, as ideally is shown in Fig.5 (b). Lower turbine wake make it possible to decrease the wind turbine in wind farms allow to construction of compact wind farm.

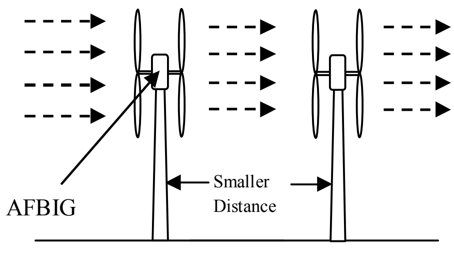

Figure 5. Smaller distance between the turbines using the BAFIG

Also, radial induction generators which are being used in wind farm need to gear box to enhance the angular speed of turbine. But, this generator does not need to gear box. Since the rotors are rotating in contrast, increasing angular speed of the rotating magnetic field in the generator air gap.

It is worthwhile mentioning that, since the BAFIG uses two turbines which are rotating in contrast, the acting forces on the generator supporting structure cancel each others, resulting in a near zero reacting torque on the tower. Thus, the mechanical stress on the tower decrease and a tower with smaller cross sectional will be required. Also, elimination of this stresses, which typically is being called gyroscopic effect, will make the BAFIG a suitable generator for moored or tethered turbines [8].

PRINCIPLE OF WORKING

By connecting the output terminals of the generator to a capacitor bank or the grid, the electrical current will flow to the stator winding. A conceptual representation of the BAFIG is shown in Fig. 6.The stator winding creates variable magnetic field in the second air gap which induces variable voltage in the secondary winding of second rotor (right side winding). The induced voltage in the secondary winding feeds the primary winding of second rotor (left side winding). Thus, it provides a magnetic field in the first air gap which causes to flow of current in first rotor bars and ring.

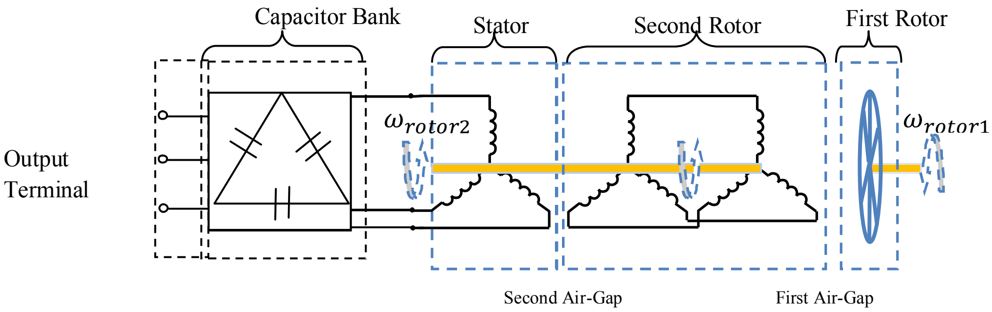

Figure 6. Conceptual repersenation of the BAFIG

The resulted magnetic field of the first rotor induces voltage in the primary winding of second rotor. This voltage supplies the secondary winding of second rotor. The resulted magnetic field in the second air gap wills induces voltage in the stator winding which will appearing in the output terminals.

Since the rotors are rotating in opposite directions, for simplicity in analytical analyses, we can assume rotor stationary while the first rotor is rotating with relative speed the rotors. Thus, the relative speed between the generators is:

$$N_{Syn} = N_{rotor1} + N_{rotor2} \tag{1}$$

Thus, while the relative speed of the generator is more than of rotating field speed, the generator can generate power.

$$N_{syn} > \frac{120f}{p_{r2}} \tag{2}$$

Thus, in this speed, the slip will be:

$$s = \frac{N_s - N_m}{N_s} \tag{3}$$

A simple diagram of powers in the BAFIG is shown in Fig. 7. As seen in, there are two air gaps in the BAFIG. In the first air gap conversion of mechanical to electrical energy is occurring while in the second air gap, produced power in the second rotor is transferring to the stator.

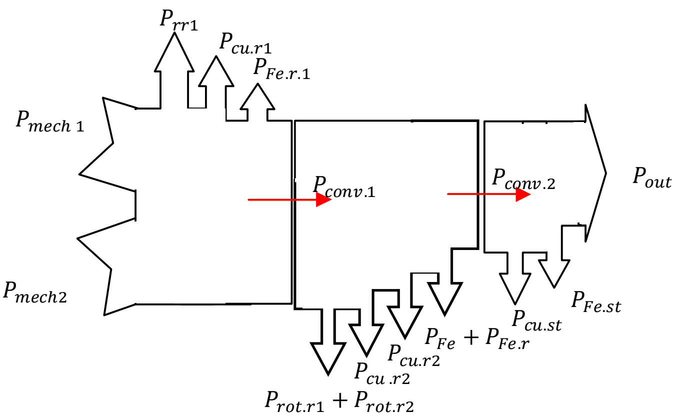

Figure 7. Diagram of powers in the BAFIG

DESIGN PROCEDURE

A simple design of generator is sketched with its geometric dimensions shown in Fig.8.

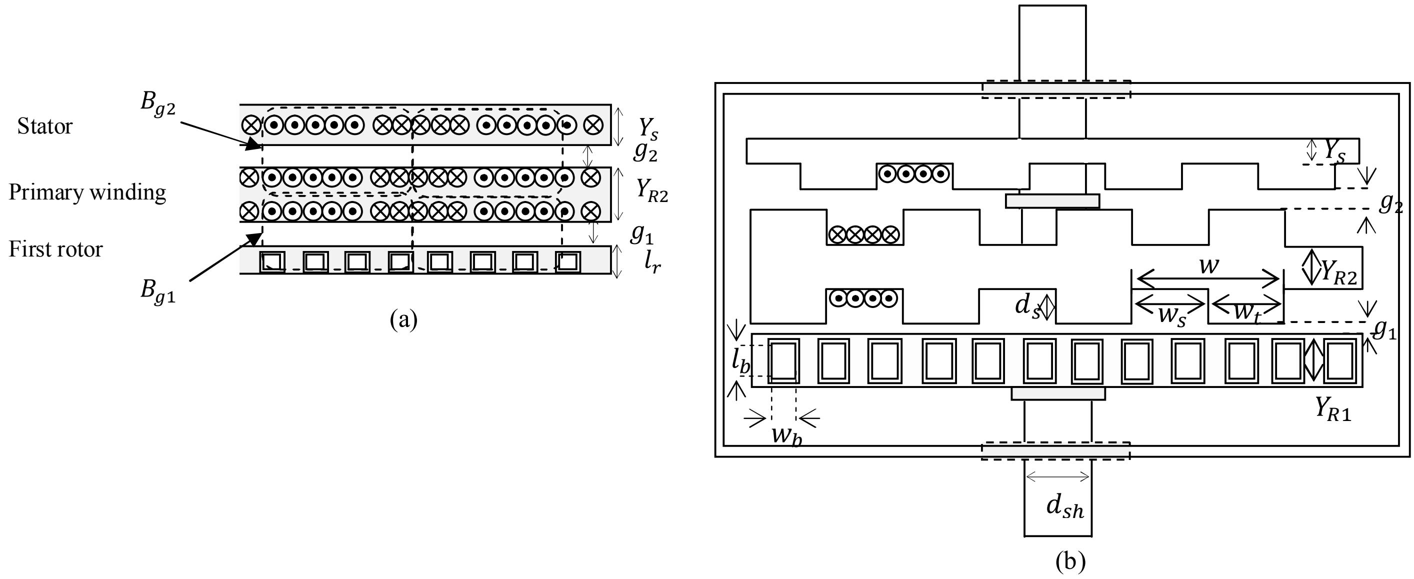

Figure 8. (a) Side view reperqtion flux pathes and winding of the BAFIG (b) Sketched design of BAFIG with dimentions

l_b	Axial thickens of bars
w_b	Width of bars
l_r	Axial thickens of ring
g_1	First air gap length
g_2	Second air gap length
Y_{r2}	Axial length of first rotor yoke
Y_{r1}	Axial length of second rotor yoke
Y_s	Axial length stator yoke
w_s,w_t	Slot and teeth width
d_s	Slot depth
d_{sh}, d_{sh}	Shaft diameter and length
p	Numbers of pole pair number
q	Number of slot per pole
R_i, R_o	Inner and outer diameters of rotors
m	Number of phases
d_c	Conductor diameter
N_{cs}	Number of conductor per slot
N_{ph}	Number of series turn per phase per pole

D. Material Selection and User Defined Data

The first initial data to start the design are the bars, iron, and conductor material data as well as the air gap length. The air gap length is mainly limited and selected with mechanical constraint. The bars are made of aluminum alloy. The chosen Iron is of type -1008.

The user defined parameters for starting the design procedure are the numbers of pole pairs p and the number of slot per pole per phase q.

E. Winding Configuration and Factors

The configuration of the windings of the generator is shown in Fig.8. A, B, and C are indicating the phases and direction of current denoted as signs of "$+$" and "$-$", respectively.

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

Figure 9. Phase arranmgemnt of winding

Following [6], the winding factor is

$$k_w = k_d k_{sp} k_{sp} \tag{4}$$

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

$$k_d = \frac{\sin\left(\frac{p\theta_s}{2}\right)}{p\sin\left(\frac{\theta_s}{2}\right)} \tag{5}$$

$$k_{sp} = \sin\frac{\theta_s}{2} \tag{6}$$

$$k_{sp} = \frac{\sin\frac{\gamma}{2}}{\frac{\gamma}{2}}. \tag{7}$$

F. Determination of Teeth and Slot Width

Determination of widths of slot and teeth is mainly referred to the air gap flux density and the generator ampere loading. As the flux density in the air gap increases, the width of tooth should be increased to avoid saturation in the teeth. A wider tooth cause to a smaller slot width consequently, a lower space for conductor results in a lower output power respect to the expected rated power for the design. This triad off between the rated power, air gap flux density, the teeth, slot width, and the slot depth causes to a complex optimization problem. Therefore, we benefit a simple relation between dimension of teeth and slot which is presented in [9] to attain minimize volume to rated power ratio.

$$w_t = (1 - w_s)w \tag{8}$$

Where, $0.5w < w_t < 0.6w$

Furthermore, for simplification of calculations, the slot and teeth width are considered equal. Thus, the width of slot and teeth will be

$$w_t = w_s = \frac{\pi R_i}{k_{st}N_s}.\frac{B_g}{B_{sat}}. \tag{9}$$

G. Determination of Maximum Flux Density in the Air Gap

To avoid the saturation of the machine core, the calculation of maximum magnetic field density in the air gap is crucial. As the second rotor is being fed with a three phase capacitor bank or gird, a rotating magnetic field with relative speed of rotors and amplitude of B_g appears in the first air gap can be express as

$$B_{g1} = B_{m1}\cos\left(p\theta - \omega t\right). \tag{10}$$

$$B_{g2} = B_{m2}\cos\left(p\theta - \omega t\right) \tag{11}$$

Where B_{m1} and B_{m2} are:

$$B_{gm1} = \frac{D_s l_c \mu_0 \mathcal{F}1}{l_{ge}} \tag{12}$$

$$B_{gm2} = \frac{D_s l_c \mu_0 \mathcal{F}2}{l_{ge}} \tag{13}$$

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

$$\mathcal{F}1 = \frac{4}{\pi}\frac{k_{w1}N_{ph}}{2p}\sqrt{2}I_{M1} \tag{14}$$

$$\mathcal{F}2 = \frac{4}{\pi}\frac{k_{w1}N_{ph}}{2p}\sqrt{2}I_{M2} \tag{15}$$

H. Determination the Dimension of Second Rotor Yoke

To avoid the second rotor yoke saturation, minimum yoke of first and second are rotor as well as stator length should be at least

$$Y_{r2} = \frac{\pi R_i}{4k_{st}p}.\frac{B_g}{B_{sat}} \tag{16}$$

$$Y_{r2} = \frac{\pi R_i}{4k_{st}p}.\frac{B_g}{B_{sat}}. \tag{17}$$

$$Y_s = \frac{\pi R_i}{4k_{st}p}.\frac{B_g}{B_{sat}} \tag{18}$$

I. Determination of the Conductor Diameters and Series Turns per Phase

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

$$d_c = 2\sqrt{\frac{k_{sf}A_{slot}}{\pi N_{cs}}} \tag{19}$$

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

$$A_{slot} = d_{1s}w_s \tag{20}$$

And the conductor per slot is obtained

$$N_{cs} = \frac{N_{ph}}{pq} \tag{21}$$

J. Determination of Machine Diameter

The diameter of machine is relates closely to the number of the series turn per phase N_{ph}. There is a reverse relation between the machine diameter and number of turn per coils. As the series turn turns per phase increase, the machine diameter decrease. Thus to determine of a specific diameter, N_{ph} should be iterated. For determination of desired machine diameter the number of series turn per phase should be iterated while the diameter converges to the desired diameter results the minimum volume. According to the power balance is [7]

$$P_{gap} = P_{out} + P_{Core} + P_{Copper} \tag{22}$$

According [7], the air gap power is axial flux machine can be written as

$$P_{cov} = \pi^2 k_w \, {}^{f}/_{2p} (A.B_{g1})(R_o + R_i)^2 (R_o - R_i) sin\beta \tag{23}$$

Where, β is the power angle

$$P_{Copper} = \frac{N_{ph}(2(R_o - R_i) + (r_{co} + r_{ci})\frac{\pi}{2})}{\sigma_{cu} A_{cu} K_p} I^2 \tag{24}$$

The expression for core loss density P_{core} including hysteresis and eddy current loss (in W /kg) is given by Steinmetz equation [7]

$$P_{core} = P_h + P_e = c_h B^{n(B)} f + c_e B^2 f^2 \tag{25}$$

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

$$A = \frac{6N\sqrt{2} I N_{ph}}{(R_o + R_i)\pi}. \tag{26}$$

The designs with the desired diameters propose several achievable designs, we use greatest power to torque ratio as a restriction which results in a compact generator.

$$\mathcal{E} = \frac{T}{V_{Gen}} \tag{27}$$

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

$$T = \frac{\pi}{2} k_w B_{g1} A (R_o + R_i)^2 (R_o - R_i) sin\beta \tag{28}$$

$$V_{Gen} = \pi (R_o - R_i)^2 (Y_{r2} + g + l_r) \tag{29}$$

Flowchart of design procedure is shown in Fig.10.

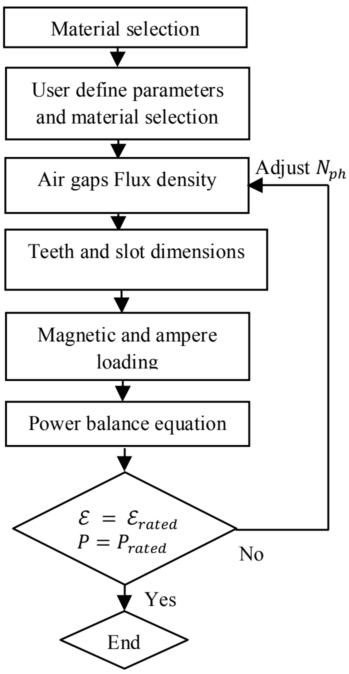

Figure 10. Design procedur flowchart

TABLE I
DESIGN INPUT DATA

Quantity	Value
Apparent power, S	50kVA
No-load phase voltage (rms)	220V
Phase current (rms)	40
Number of phase, m	3
Power factor, pf	0.72
Rated relative speed, $N_{r1} + N_{r2}$	12000 rpm
Iron	Type of 1008,
B_{sat}	1.7 T
Pole pairs numbers, p	4
Number of slot/ pole/phase	3
Outer dimeter, D_o	210 mm
Air-gap axial length	0.6 mm
Axial thikness of bar, l_b	21 mm
Width of bar, w_b	101mm
Axial thikness of ring, l_r	9mm

TABLE II
DESIGN RESULTS

Quantity	Value
Inner diamterer of rotor	110 mm
Machine axial length	80 mm
Slot depth, d_s	6 mm
Tooth width, w_t	12 mm
Slot width, w_s	11 mm
Axial length of second rotor yoke, Y_{r2}	2.5 mm
Number of series coil per phase, N_{ph}	17
Number of conductor per slote, N_{cs}	4
Conductors	AWG 17
Air gap peak flux density, B_g	0.825 T
Output power, P_{out}	46450 W
Ampere loading, A	20312 A/mm^2
Active power per generator mass	15 kWT $/m^3$

K. Input Data and Design Results

The input data to start the design procedure and the attained design from the iterative approaches are given in Tables I and II.

SIMULATIONS

The attained design in previous section must be validated to see whether each point of machine core is saturated or not. The flux lines and flux densities in the machine can be computed and seen with 2-D Maxwell Software package. The simulations for flux line and flux magnitude distribution in no-load and full load condition are shown in Fig.12 and Fig.13 respectively.

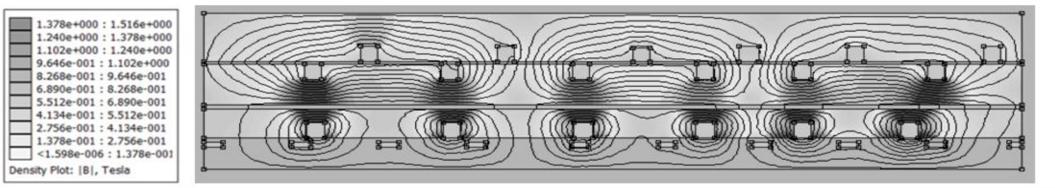

Figure 11. Flux line distribution in no load condition

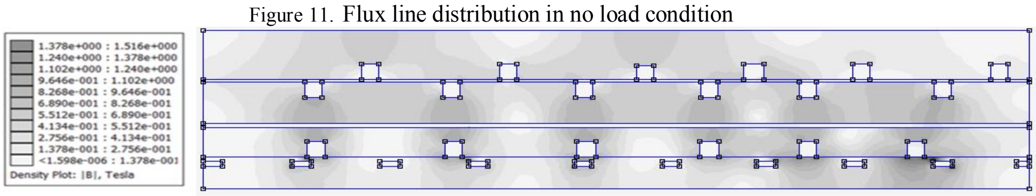

Figure 12. Flux magnitude density distribution in no load condition

Also, the flux magnitude simulation in full-load codition is obtaine shown in Fig.13

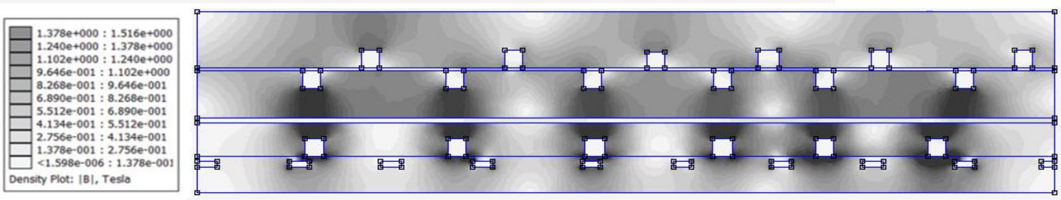

Figure 13. Flux magnitude density distribution in full-load condition

By inspection the values of flux magnitude densities in the machine cores points, it can be founded that the maximum value of flux density is 1.4 T, while the saturation of the used iron is occurs in 1.7 T.

CONCLUSION

This paper presents the construction and design procedure of a novel type of brushless induction generator with two mechanical inputs and which can alleviate the most drawbacks of recent wind farms and wind turbines. The design started with selection of initial and user defined data to reach a primary geometry which grantee the cores are under saturation condition. Then, the parameters are iterated to achieve maximum power to weight ratio and efficiency. The flux lines and flux magnitude densities in the achieved design were observed using a finite element analysis with software package .The results demonstrated the effectiveness of the proposed topology and obtained design.

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