Optimal Design of PM Synchronous Generator for Aerial Industries Power Supply Using Cuckoo Algorithm

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ARTICLE INFO	ABSTRACT
	The Generators used in aerial industries should have the characteristics such as high efficiency, power density and reliability, low weight and volume. Among different generators, permanent magnet synchronous generator adequately satisfied these requirements. In this paper, first the dimensions and other quantities of this generator are calculated through an analytical model. Then using Cuckoo Optimization Algorithm (COA), these quantities are optimized to suit for desirable needs of aerospace systems, in order that the total volume of the generator could be minimized and its efficiency could be maximized. The results of this design for the permanent magnet synchronous generator application in aerospace systems have been satisfactory.

1.   Introduction

The use of electric power in the aerial industry has being increase in recent years. As the electrical power supply of aerospace system, generators are needed for the power supply of the various parts i.e. the fuel system with electric motor driven pumps, wing anti-ice electric system, exterior and interior lighting equipment and controller motors in wings of aircraft, rockets and missiles. In wings controlling of aircraft, missiles and aerospace systems, hydraulic actuators are replaced by electrical and electromechanical actuators. Generators used in aerospace systems, are installed at the end of the engine and they provide required electrical energy of its different parts. Figure 1 shows the generator position, inside the aerospace system engine [1-6]. Electrical systems in aircraft are used for the production, regulation, and distribution of electricity throughout the plane. Plane electrical systems work by means of different levels of AC and DC electric voltages. In this typical system 115/200V AC, 400 Hz and 28 volt DC voltages are used. Some different sources of electrical power supply in large aircraft are shown in Figure 2 which includes: 1.The main generator 2.Auxiliary power unit (APU); 3. Ram air turbine (RAT); 4.External power source; For example, the ground power unit (GPU) [6].

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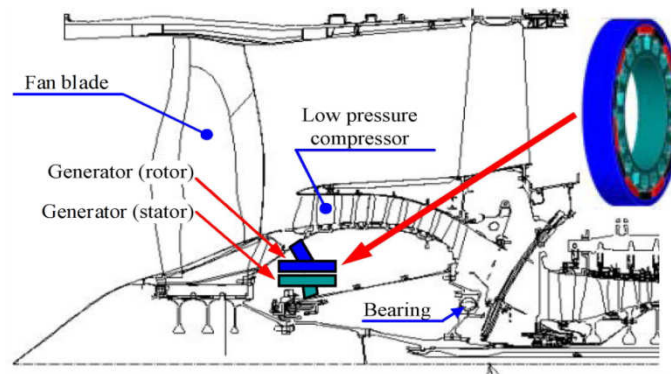E-mail address: amirnikbakhsh@stu.nit.ac.ir

Figure 1. The generator position, inside the aerospace system engine [7].

In normal flights, aircraft use the electricity produced by the generator for its ultimate power supply. When the aircraft is on the ground during maintenance and also when using motor starter, the electrical power generated by APU is used. Since the engine speed of aircraft, varies from full power flight time to idle speed (as is typically 2:1), consequently the resulting frequency varies according to engine speed. So to convert this variable speed to a fixed one, some equipment is needed [6].

The generator used in aerospace system application should have features such as high efficiency and reliability, low maintenance, voltage-current line characteristic and small size [1-7].

By improvement of the magnetic material (better features and Lower prices) as well as advanced power electronics technology, permanent magnet synchronous generator is one of the best choices has the ability to achieve the above purposes. For increasing the performance of a permanent magnet synchronous generator, the design criteria from the perspective of energy consumption in terms of parameters should be optimized. These parameters include efficiency and power density. In addition, because of the lack of space in aerospace systems, the generator volume should also reach to the lowest level through the optimization of the dimensions.

The way used in this paper includes computational analysis and then using cuckoo algorithm for optimization to achieve the above desirable objectives. It should be noted that this research paper due to their simple geometry is limited to non-salient pole Synchronous generators with permanent magnet mounted on surface. Also the single-layer of stator winding and the correct number of the slot for the stator have been regarded.Therefore, optimum design of permanent magnet synchronous generators (PMSGs) has gained great attention in recent years and researching about this subject is a necessity. For example, in [8] from a simple analytic optimization algorithm in the form of a very well-known mathematical method -Lagrange multiplier- with the aim of maximizing apparent transferred power through air gap in PMSG under the limitations tangential pressure has been used. So that optimizing the stator size calculated based on optimum diameter ratio, meeting the required torque has been applied. For multi-objective optimum design of PMSM with a surface permanent magnet mounted on the rotor, a new method for achieving maximum efficiency and power density using the bees algorithm for industrial applications are provided [9]. In

addition to a brief description of the airplane systems, with particular attention to the usefulness of the features of the transient waveform of a short circuit in the electric power system check, after defect failure or crash, the results from the design and the analysis of wound-field synchronous generator (GT40PCh6) of the plane TU-154M, in operating steady state and transient modes, are provided [6].

Figure 2. 1-Main generator, 2- APU, 3-RAT, 4-An external power supply [6].

Also in [7] the electromagnetic design of a reduced-scale multi-phase generator for application in aircraft main gas turbine engine, in order to meet some of the needs of fault tolerance at the aerospace application are discussed and empirical testing to validate six phases PM machine prototype torque are presented. In [10] the optimal design of PMSG with rotor configuration containing Halbach permanent magnets based on operating conditions and requirement analysis, as one of the key components in a hydraulic lift system has been studied. The high speed permanent magnet synchronous machine (HSPMSM) parameters optimization for achieving minimum power loss and maximum efficiency under similar size conditions, have been considered and it has been shown that different values of the stator inner diameter to the outer diameter ratio, can greatly affect the characteristics of the losses, efficiency and power factor. When this ratio increases, the iron loss in the stator, the rotor eddy current loss, windage loss increased and copper loss will decline [11].

In [12] to overcome the problems of PMSG design, an analytical method to obtain both quantitative magnetic flux density in the air gap (Bg) and current density in the conductor (J) using two physical constitution, sum of Ampere-Turns (using Ampere's theorem for magnetic circuit) and the power balance equation has been proposed and optimization is done to achieve maximum efficiency. Also [13] a comprehensive combination of design process consisting the design and simulation of permanent magnet wind generator under the rectified load, and optimization of the design variables using a genetic algorithm to improve generator output voltage waveform is proposed, leading to reduction of the harmonic distortion index by 9%. Advantages, constraints and drawbacks of aircraft electric motors, through a comparison between radial flux permanent magnet machines (RFPM) and axial flux permanent magnet machines (AFPM) for four positions inside main gas turbine engine with limitations, advantages and drawbacks of each of them have been studied in [14]. In [15] the optimal design of high speed axial flux permanent magnet generators (HSAFGs) is provided. The design of this kind of generator varies with typical generator with low speed due to high

speed of the rotor and high frequency of the stator windings current. Also genetic optimization algorithm and particle swarm optimization (PSO) is used for optimizing the efficiency of the machine.

A wound-field synchronous three-phase ac main exciter (ME) 225-KVA as a starter/generator of aircraft with capability to work in both starting and generating has been investigated, and its capability to meet the required output current in both cases, with a minimum amount of input VA rating of the inverter needed to ME drive has been evaluated. Optimization is also done using particle swarm search optimization algorithm [16]. Also in [17] the motor drive technology for safety critical applications used in aerospace systems, with a particular focus on the selection of machines, their drive and topology, is studied and overviewed. It has been considered that in space applications features such as high reliability, availability and power density and on the other hand, reducing weight, complexity, energy consumption, operating costs and environmental effects are required. Various aspects of machine design solutions with high speed and efficiency as a permanent magnet Motor/Generator (M/G) unit used in the flywheel energy storage system is presented in [4], with respect to the temperature change and the armature reaction and that radiation is the only method of heat transfer due to losses in the rotor and special measures have been adopted to reduce rotor losses.

Also [18] presents a method for the design and modeling of a five-phase synchronous generator with high power density for the plane. This method has been presented by expanding the more accurate model of air gap of non-salient pole three-phase synchronous generators for five phases generators. In [1] the design of a high-speed brushless dc motor for aerial applications, in two analytical and software methods are discussed. Increasing engine speed in order to achieve smaller sizes in the aerial systems application will result in rotational losses increase and thus the efficiency reduction. Using steel sheets with less thickness that was made for working at high frequencies and also the reduction of air gap flux density to about half its value in typical engines, has reduced the core losses.

Now this paper is going to describe firstly, the design process of a permanent magnet synchronous generator using in the aerospace industry application. In this step, first, the initial parameters of the studied PMSG for use in the desirable application and also the type of permanent magnet materials and sheets used for stator and rotor core are determined according to the appropriate application of the case study. Second, geometrical dimensions of the generator are calculated including length of the generator, inner and outer diameter of the stator core, stator yoke and tooth height, tooth width and slot dimensions and inner and outer diameter of the rotor through the relationships and equations. Third, the method of the position of the permanent magnets on the rotor is determined; then dimensions of permanent magnets including length, width and thickness of permanent magnets are calculated. Fourth, the generator losses are calculated. Fifth, the efficiency and volume of the generator are obtained. Sixth and the last, the proposed flowchart for the design and computational analysis of PMSG will be provided.

Secondly, multi-objective optimization of PMSG has been studied and the design input variables parameters and their change range are determined. Then the desired objective

functions which are in accordance to appropriate use in the aerial system, are introduced in this paper. In the next part, cuckoo optimization algorithm used in this paper is described. In the end of this stage, the results of the design optimization of PMSG used in this paper, using cuckoo optimization algorithm according to the desired application as well as the diagram of the objective functions has been proposed. Finally, conclusions are the third and last stage of this research paper.

All quantities used in this paper have been introduced in Table 1.

Table 1. Quantities

Quantity	Description
F	Frequency
ε	The ratio of no-load electromotive force (EMF) to the phase voltage
D	Inner diameter of the stator
Dstot	Outer diameter of the stator
Dr	Diameter of the rotor core
g	Length of the air gap
Nph	Number of winding turns per phase
Q	Number of stator slots
hPM	Thickness(height) of permanent magnet
bPM	Width of the permanent magnet (pole shoe width)
LPM	Length of the permanent magnet
Br	Remanence flux density of the permanent magnet material
Hc	The field coercive force of the permanent magnet
A	Linear current density of the armature
Selm	Apparent electromagnetic power crossing the air gap
nsyn	Synchronous speed
Bg	The peak of air gap magnetic flux density
Bg1	The first harmonic of air gap magnetic flux density peak
Bt	Flux density in the tooth
Bys	Flux density in the stator yoke
Pτ	Pole Pitch
kc	Carter coefficient
uτ	Slot Pitch
kw1	First harmonic of stator winding coefficient
C	Output coefficient
Rac	AC resistance of the armature winding
L	Effective length of the generator
Li	Actual length of the generator
PMα	pole Shoe arc (the width of the magnet) to pole Pitch ratio
cosφ	Power factor

Table 1. Continued

Es	Electrical motive force (EMF) that is induced by excitation flux in no-load conditions
Js	Current density in the stator conductors
Sc	Cross-sectional area of each conductor stator
kfill	Copper filling factor in the slot
m	Number of phases
PLoss	The total losses of the generator
PFe	Iron Losses
Phy	Hysteresis loss in the stator yoke
Pey	Eddy current loss in the stator yoke
kh	Empirical hysteresis loss factor
ke	Empirical eddy current loss factor
hρ	Specific hysteresis loss
eρ	Specific Eddy current loss
Volys	Volume of the stator yoke
mys	Iron mass of Stator yoke
Pht	Hysteresis loss in the tooth
Pet	Eddy current loss in the tooth
Volt	Volume of tooth
mt	Iron mass of tooth
PCu	Copper losses
Pρ	Windage and ventilation losses
PStr	Stray loss (additional losses)
krb	Empirical coefficient considering the cooling system
q	The number of slots per pole per phase
p	Number of pole pairs
ZQ	The number of conductors in a slot
η	Efficiency
PMμ	The relative permeability of permanent magnets
0μ	Magnetic permeability of vacuum
bt	Width of the teeth
χ	Effective length of the generator to inner diameter of the stator ratio
St	Cross-sectional area of a teeth
bs1	Minimum width of slot
bs2	Maximum width of slot
htr	Height of trapezoidal part of slot
hz	Slot height (teeth height)
Su	slot Area
hys	Stator yoke height
hyr	Rotor yoke height
Vtotal	The total volume of generator

2. Design Methodology

The Permanent magnet synchronous generator design process includes the following steps:

2.1. Initial parameters and used materials

Electric generators are usually designed for initial conditions including rated voltage, frequency, power, speed and efficiency, power factor and number of phases in accordance with the desirable application.

Moreover, the other initial parameters are effective, such as special magnetic loading (B_g) (air gap magnetic flux density), which is limited by saturation and core loss and its amount varies between 0.8 T to 1.05 for non-salient pole synchronous machines [19, 20]. Also the second effective initial parameter is linear current density (*A*) (specific electrical loading) that is dependent on different factors such as rated power, frequency, voltage and speed [21]. Its suitable value for a small PMSG is in the range of 10 KA/m to 25 [22]. Current density in PMSG stator winding also varies between 4 A/mm^2 to 6.5 [9]. In this paper studied rated generator characteristics for use in aerospace systems include rated power 650 watt, speed 12000 rpm, voltage 115 V and Frequency 400 Hz [1]. Figure 3 shows the 2D and 3D layout of radial flux permanent magnet generator (RFPMG).

Considering the high frequency and further loss in Considered application in this paper, less thick steel sheets should be used; so non-oriented electrical steel with code M210-27A and with sheet thickness of 0.27 mm for stator and rotor core (its core loss amount in 0.7T flux density and 400 Hz frequency is equal to 6.93 Watt/Kg) have been selected [1], [23]. In the case of permanent magnetic materials, the most important characteristics include residual flux density B_r, field coercive force H_c , the amount of its energy production and thermal coefficient [9],[21]. Only in a room temperature, NdFeB permanent magnet materials have better magnetic properties than SmCo and demagnetizing curves of NdFeB, especially demagnetizing force are strongly dependent on temperature. Moreover NdFeB is sensitive to corrosion. That is why, SmCo as a permanent magnetic material are being selected for aerospace applications. In this design the magnet SmCo28 with residual flux density of 1.07T and the relative permeability coefficient of 1.04 has been used [1],[3].
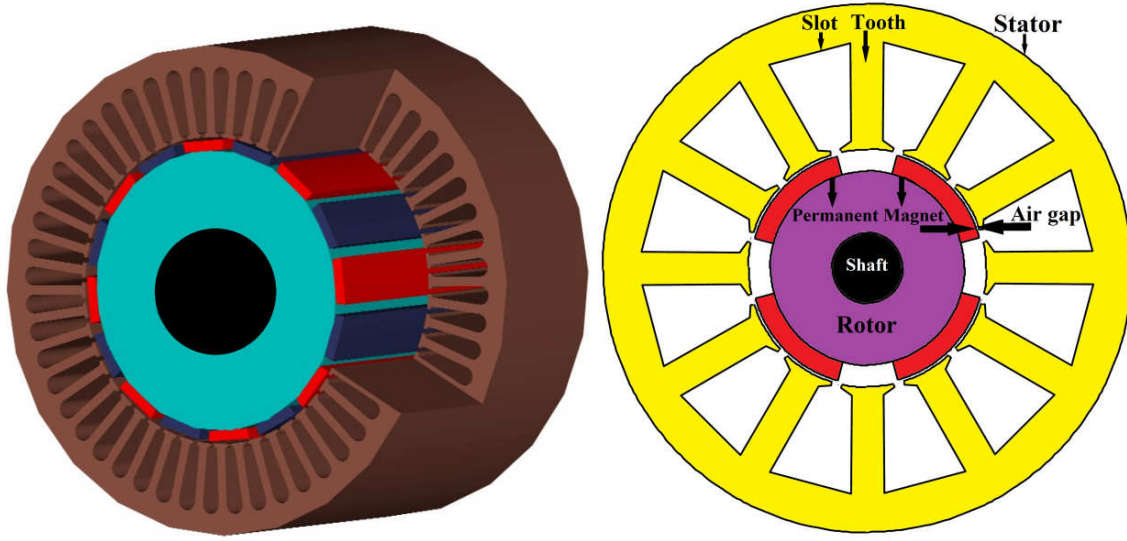
Figure 3. 2D and 3D layout of radial flux permanent magnet generator (RFPMG)

2.2. Geometric dimensions of generator

The most important geometrical dimensions of the generator include length of the generator and its stator outer diameter because these two almost determine the size of the generator. Among the main dimensions of the stator, inner and outer diameter of the stator core, stator yoke and tooth height and width and slot dimensions can be mentioned. Inner and outer diameter of the rotor, are the most important design parameters in the rotor [19]. Figure 4 represent the generator topology in order to show the geometric dimensions. Apparent electromagnetic power crossing the air gap is as follows:

$$S_{elm} = mE_sI_s = \pi\sqrt{2}\phi_f f\, N_{ph}K_{w1}\frac{m\,\pi\,DA}{2m\sqrt{2}\,N_{ph}} = \frac{\pi^2}{2}\left(n_{syn}P\right)K_{w1}\frac{LD^2}{P}A\,B_{g1} = 0.5\pi^2K_{w1}D^2L\,n_{syn}A\,B_{g1} \tag{1}$$

In this equation n_{syn} is the rotor speed according to unit Turn/sec and K_{w1} stands for winding factor which is related to the winding arrangement. Air gap magnetic flux density peak value is approximately equal to the peak value of its first harmonic (B_{g1}) which is following [22]:

$$B_{g1} = \frac{2}{\pi}\int_{-0.5\alpha_{PM}\pi}^{0.5\alpha_{PM}\pi} B_g\,\cos\alpha d\alpha = \frac{4}{\pi}B_g\sin\frac{\alpha_{PM}\pi}{2} \tag{2}$$

Primary amount of B_g in the ferrite permanent magnet material can also be estimated by $B_g{\approx}(0.4.........0.7)B_r$ [22]. α_{PM} is also equal to the ratio of the width of permanent magnet (b_{PM}) to the pole pitch (τ_P). This α_{PM} varies in the range between 0.6 to 0.9. In the generators having P pairs of poles, pole pitch (τ_P) equals to:

$$\tau_P = \frac{\pi D}{2P} \tag{3}$$

Relations (4) and (5) indicate the generator output power and factor:

$$P_{out} = mV_{ph}I_s\cos\phi = \frac{1}{\epsilon}S_{elm}\cos\varphi \tag{4}$$

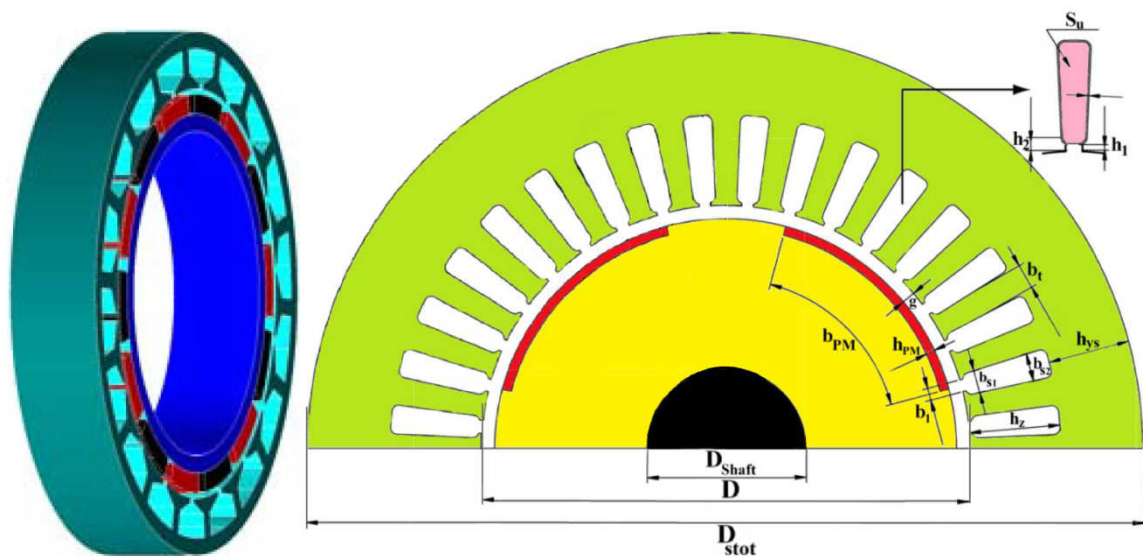$$C = \frac{\epsilon\,P_{out}}{D^2L\,n_{syn}} = 0.5\,\pi^2 K_{w1}AB_{g1}\cos\varphi \tag{5}$$

Figure 4. Generator topology representing geometric dimensions [14].

In generators $\varepsilon = E_s/V_{ph} = 1.05.........1.45$, which E_s is the electrical motive force (EMF) that is induced by excitation flux in no-load conditions and V_{ph} is the stator phase voltage. According to the relations (1), (4), (5) and considering $\chi = L/D$, D internal diameter of the stator can be achieved based on equation (6).

$$D = \sqrt[3]{\frac{\epsilon\, P_{out}}{C\, \chi\, n_{syn}}} \tag{6}$$

Which the value of χ for synchronous generators is equal to [19], [20]:

$$\chi \approx \frac{\pi}{4p}\sqrt{p} \qquad p > 1 \tag{7}$$

$$\chi = 1 ..... 3 \qquad p = 1 \tag{8}$$

Finally the effective length of the generator is $L = \chi \times D$. The effective length should also be multiplied by laminated iron filling coefficient (K_{st}). Typically K_{st} varies between 0.9 to 0.97 .

$$L_i = L \times k_{st} \tag{9}$$

In the above equation, L_i is the actual length of the generator. Also air gap length of the generator (g) can be estimated by relations (10):

$$g = \gamma\, \tau_P \left(\frac{A}{B_g}\right) \tag{10}$$

In equation (10), γ is a coefficient that its valuefor different types of generators is in the table in [20]. Based on experience, for small PMSG, the air gap length (g) is recommended between 0.3 mm to 1 [22]. Also in this design, semi-closed slots are considered for the generator because they provide more suitable strength, and lower slot coefficient, than open slots.

To calculate the dimensions of slot and stator teeth, in the first step, the maximum magnetic flux density for the teeth and yoke should be chosen. The maximum amount of tooth flux density B_t, 0.96 T and for the stator yoke B_{ys} and rotor yoke flux density B_{yr}, 0.71 T has been chosen [20]. Flux density in the teeth is equal to [19], [23]:

$$B_t = B_g \frac{L\tau_u}{S_t} \tag{11}$$

$$\tau_u = \frac{\pi D}{Q} \tag{12}$$

In this equation t_u is the slot pitch. As a result, the cross-sectional of tooth (S_t) and tooth width (b_t) are [19], [20]:

$$S_t = B_g \frac{L\tau_u}{B_t} \tag{13}$$

$$b_t = \frac{S_t}{L_i} \tag{14}$$

Figure 5 shows the slot type in the studied design. Considering Z_Q as the number of conductors in a slot and N_{ph} as the number of coil turns in per phase, slot area (S_u) will be as equation in (15) [19], [20]:

$$S_u = \frac{Z_Q S_c}{k_{fill}} \tag{15}$$

$$Z_Q = \frac{2\,m}{Q} N_{ph} \tag{16}$$

$$N_{ph} = \frac{A\pi D}{2\sqrt{2}I_s m} \tag{17}$$

K_{fill} is the slot space filling factor by copper conductor that depends on voltage level, the type of material and winding type. For low voltage generators, K_{fill} typical value is between 0.5 to 0.6 and for high voltage generators it is between 0.3 to 0.45. Also in equation (15), the cross-section area of each conductor will be:

$$S_c = \frac{I_s}{J_s} \tag{18}$$

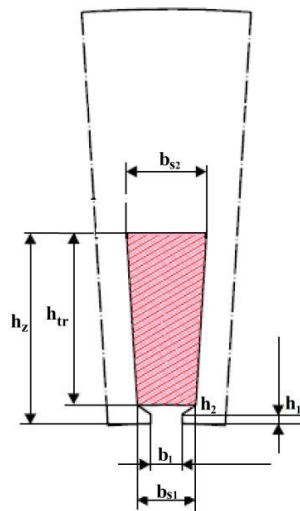In the above equation, J_s is the current density in a conductor and I_s is the stator phase current.

Figure 5. slot type in the studied design

Now slot area is obtained from geometric relations as following:

$$S_u = \frac{1}{2}(b_{s1} + b_{s2})h_{tr} \tag{19}$$

h_{tr} is the height of the trapezoid part of the slot also b_{s1} and b_{s2} are the minimum and maximum width of the slot respectively. Also b_{s1} and b_{s2} will be [19]:

$$b_{s1} + b_t = \frac{\pi(D + 2(h_1 + h_2))}{Q} \tag{20}$$

$$b_{s2} + b_t = \frac{\pi(D + 2h_{tr})}{Q} \tag{21}$$

Now, by solving equations (19), (20) and (21), two unknown parameters b_{s2} and h_{tr}, could be obtained. A slot opening of b_1 is also as much as four times the radius of a conductor and the height h_1 and h_2 are both considered 1 mm. As a result, the slot height (h_z) in equation (22) is estimated as bellow:

$$h_z = h_1 + h_2 + h_{tr} \tag{22}$$

Tooth height is also equal to the slot height. Also the height of stator yoke (h_{ys}) and the outer diameter of the stator (D_{stot}) are obtained as follows:

$$\phi_{ys} = B_g b_{PM} L \tag{23}$$

$$h_{ys} = \frac{\phi_{ys}}{2 L B_{ys}} \tag{24}$$

$$D_{stot} = D + 2(h_z + h_{ys}) \tag{25}$$

2.3. Permanent magnets

After selecting permanent magnet materials, first it must be determined how and where to mount permanent magnet on the rotor. The arrangements of PM rotors are divided into four categories: The surface mounted PM rotor, inset-type PM rotor, buried PM motors and interior-type PM motors [24]. In this design the structure of surface mounted PM rotor is selected since its construction is much easier to use. Then, the main dimensions of surface permanent magnets including permanent magnet thickness (h_{PM}), width (b_{PM}) and length (L_{PM}) must be determined. Typically the width of the magnet (b_{PM}) is 0.8 to 0.85 times of the pole pitch [25]. Magnet length will be equal to the effective length of the generator. Also the magnet thickness should be small enough in order to use fewer amounts of permanent magnet materials because the cost of providing these materials is very high. On the other hand, magnets should be thick enough to generate the required air gap magnetic flux density [19]. By calculating Carter coefficient, (K_c) with respect to the slot form, the equation of the permanent magnets thickness (h_{PM}) will be as bellow [22], [26].

$$B_g = B_r \frac{1}{1 + \mu_{PM}.(\frac{g.k_c + \frac{h_{PM}}{\mu_{PM}}}{h_{PM}})} \Rightarrow h_{PM} = \frac{g.k_c.\mu_{PM}}{(\frac{B_r}{B_g} - 2)} \tag{26}$$

$$k_c = \frac{\tau_u}{\tau_u - \gamma g} \tag{27}$$

$$\gamma = \frac{4}{\pi}\left[\frac{b_1}{2g} arctan\left(\frac{b_1}{2g}\right) - ln\sqrt{1 + (\frac{b_1}{2g})^2}\right] \tag{28}$$

2.4. Losses

Losses in electrical generators could be classified according to various bases. In studied application in this paper, the above-mention losses can be divided into four parts: the iron losses (P_{Fe}), which includes hysteresis and eddy current losses in the stator yoke and tooth; copper losses (P_{Cu}); windage-ventilation losses ($P\rho$) and stray (additional) losses (P_{str}) [24]. Iron losses in the stator yoke consist of two parts: hysteresis losses (P_{hy}) and eddy current losses (P_{ey}), which these losses are proportional to frequency and the magnetic flux density [24], [27], [28]:

$$P_y = [k_{hy}\rho_h + k_{ey}\rho_e][m_{ys}\frac{f}{50}(\frac{B_y}{1.5})^2] \tag{29}$$

$$m_{ys} = \rho_{Fe}.Vol_{ys} \tag{30}$$

$$Vol_{ys} = \pi L_i \left[(\frac{D_{stot}}{2})^2 - (\frac{D+2h_z}{2})^2 \right] \tag{31}$$

In the above equation f is the frequency, B_y is the magnetic flux density in the stator yoke and k_{hy} and k_{ey} are hysteresis empirical loss factor and eddy current empirical loss factor related to the type and thickness of sheet applied to the stator core respectively and ρ_h and ρ_e represent the specific hysteresis losses (Watt/Kg) and specific eddy current losses (Watt/Kg) respectively and ρ_{Fe} is special weight of the sheets. In this paper , due to high frequency in the studied applications, for used stator and rotor core sheets (non-oriented electrical steel with code M210-27A) ρ_h and ρ_e values are high values of 6.93 and 2.05[1]; In this application high values of these coefficients, will result in losses increase and efficiency reduction of PMSG; while in other applications, because of low frequency, these coefficients, and hence losses of these generators, will have lower values and more efficiency.

Also Vol_{ys} and m_{ys} represent volume and mass of the stator yoke iron, respectively. Iron losses in the teeth will also be calculated by the above equation, considering the fact that Vol_t will be as the following:

$$Vol_t = \left(\frac{D_{stot} - D}{2} - h_{ys} \right) b_t L_i Q \tag{32}$$

Since the high-order harmonics in the stator current and the space harmonics in winding distribution are generally small, rotor eddy current losses in permanent magnet generator is typically negligible [24],[29]. Copper losses (P_{Cu}) and windage-ventilation losses (P_ρ) could also be found in the following relations [9], [19], [20], [22] and [24]:

$$P_{Cu} = mR_{ac}I_s^2 \tag{33}$$

$$P_\rho = k_{rb}D_r \left(L + 0.6\tau_p \right)(2\pi n_{syn}\frac{D_r}{2})^2 \tag{34}$$

$$D_r = D - 2g - 2h_{PM} \tag{35}$$

In the above equation D_r is the rotor core diameter and k_{rb} is an empirical coefficient depending on the cooling system type and the size of generator can be determined, according to table [20]. The additional and stray losses are typically considered as a small percentage of the output power [19]:

$$P_{Str} = 0.0075P_{out} \tag{36}$$

2.5. Efficiency and total volume of the generator

At the end of the design process, the efficiency (η) and the total volume of the designed generator (V_{total}) will be calculated as the following:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{Fe} + P_{Cu} + P_{\rho} + P_{Str}} \tag{37}$$

$$V_{total} = \frac{\pi D_{stot}{}^2}{4} L \tag{38}$$

2.6. The proposed flowchart of design and computational analysis of PMSG

The proposed flowchart of design and computational analysis of PMSG is shown in figure 6. In this flowchart, in the first stage after determining the initial parameters according to the desirable demands of the generator client and its application type, then in the second stage, stator linear current density and the air gap magnetic flux density according to the experimental ranges, power, size, voltage and other characteristics of the application type should to be determined.
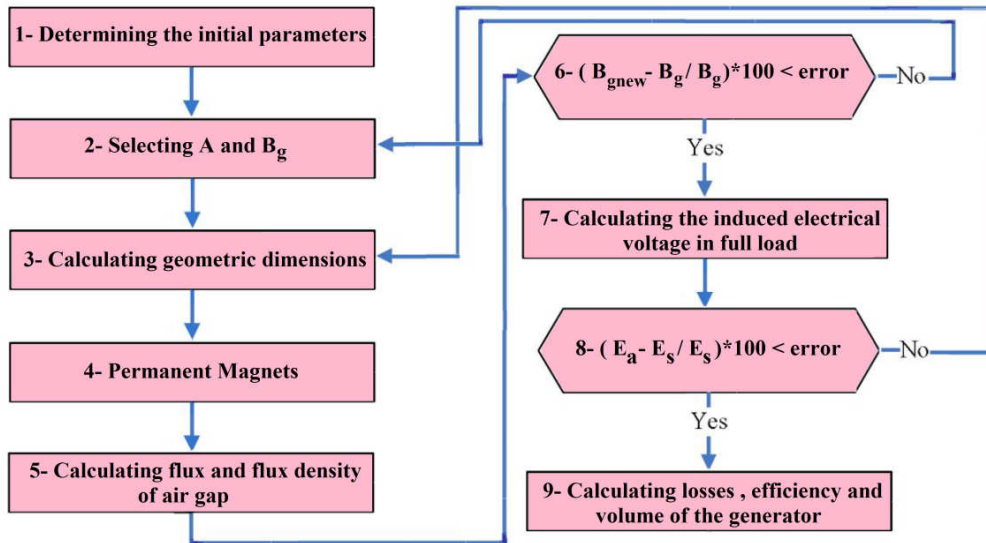

Figure 6. The proposed flowchart of design and computational analysis of PMSG

Then the generator geometric dimensions including effective and actual length of the generator, internal and external diameter of the stator, height of the yoke and teeth, teeth width, slot and rotor dimensions and the air gap length will be calculated. Selecting the type of permanent magnet materials, place of installation and calculating the dimensions including the width and thickness of the permanent magnets will be done in the fourth stage.

In the fifth stage, the air gap flux and magnetic flux density could be obtained too. If this amount of magnetic flux density in the air gap (B_{gnew}) is equal to the amount of its primary assumption of the second stage (B_g), the design stages will be continued; But if the new value is not equal to the initial assumed value, through a repetitive process, the air gap magnetic flux density should be corrected in a way that the difference between these two values reach

to less than one percent. Then in the seventh stage, the induced electrical voltage in full load (E_a) is calculated. Steps 3 to 8 will repeat until the voltage (E_a) comparison to the no-load induced voltage (E_s), does not change more than one percent.

In the next steps losses, efficiency and the size of the generator will be calculated. Now, according to the desired purposes in intended application and the relationship between output quantities and input parameters, through this model and the analytical method and full search in the range of input parameters, the optimal solution related to all the design parameters could be found.

3. Optimization

Optimization of PMSG is a multi-objective optimization problem with multiple variables and constraints. The optimization process will be in three stages: In the first stage optimization variables which are the same as the generator modifiable input parameters are defined. Secondly, the objective functions and constraints are formulated. In this paper objective functions include efficiency, volume and a combination of efficiency and volume. In the third phase, an optimization algorithm is used for finding the generator's optimal geometric dimensions and other quantities of it [9].

3.1. Optimization purposes

In this optimization, finding the maximum of the objective function F_1 related to the efficiency (η) according to equation (37) (Since through this optimization method, we will find the minimum of the objective functions, in order to find the maximum of efficiency, we should optimized function ($1/F_1$) to achieve the value of maximum efficiency), and finding the minimum of the objective function F_2 related to the total volume of the generator (V_{total}) according to equation (38) also finding the optimal objective function F_3 related to the simultaneous optimization of efficiency and total volume of the generator according to equation (39), are considered.

$$F_3 = \alpha_1 F_1 + \alpha_2 F_2 \tag{39}$$

Which in equation (39) α_1 and α_2 are set so that, through optimization, efficiency reach to its maximum value and volume to its minimum value. The variation ranges of eight generator adjustable design parameters are listed in Table 2.

Table 2: Variation range of the generator design input parameters

ϵ	χ	αPM	A(A/m)	B(T)	Q	P	g(mm)
[1.05; 1.45]	[0.14;0.6]	[0.6; 0.9]	[10000 ; 22000]	[0.62;0.83]	[12;36]	[2;6]	[0.5;1.5]

3.2. Cuckoo Optimization Algorithm (COA)

In this paper, the optimization of PMSG has been performed by Cuckoo Optimization Algorithm (COA). This algorithm is about a new evolutionary algorithm. This optimization algorithm has loaned the life style of a bird family which is called cuckoo. Because of the special characteristics of these birds' life style and the way they lay their eggs and their

breeding, cuckoo optimization algorithm has concentrated based on it. COA begins with a primary population, as it is the case in other revolutionary methods. The cuckoo population, in different societies, consists of two types including mature cuckoos and eggs [30].

Endeavor for survival among cuckoos is the best of cuckoo optimization algorithm. This is the case of a competition to live after the death of the others in a society. During this survival competition some cuckoos or their eggs will die. The cuckoo societies which have survived migrate to a better environment. There, they start reproduction and laying eggs [30].

In other words, mother cuckoos never build their own nests and lay eggs in some other birds nest. These eggs grow and become mother cuckoos, if they are not recognized and killed by host birds. Therefore, groups (societies) of cuckoos immigrate to find the best environment for reproduction. Figure 7 shows the immigration of a sample cuckoo toward goal habitat.
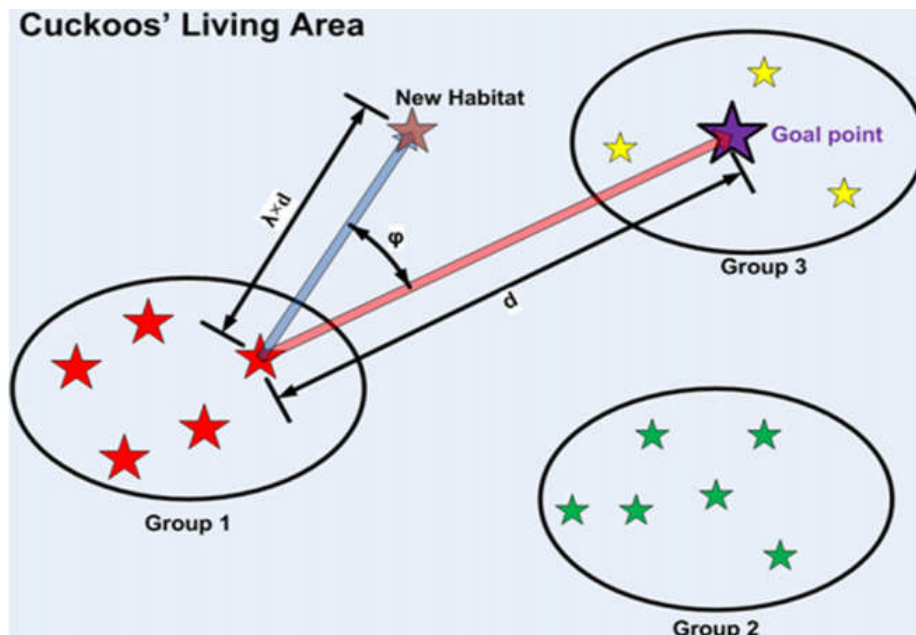

Figure 7. Immigration of a sample cuckoo toward goal habitat [30].

The effort to survive among cuckoos ends when there is only one cuckoo society which all has the same profit values [30]. Also the flowchart of COA is illustrated in Fig 8.
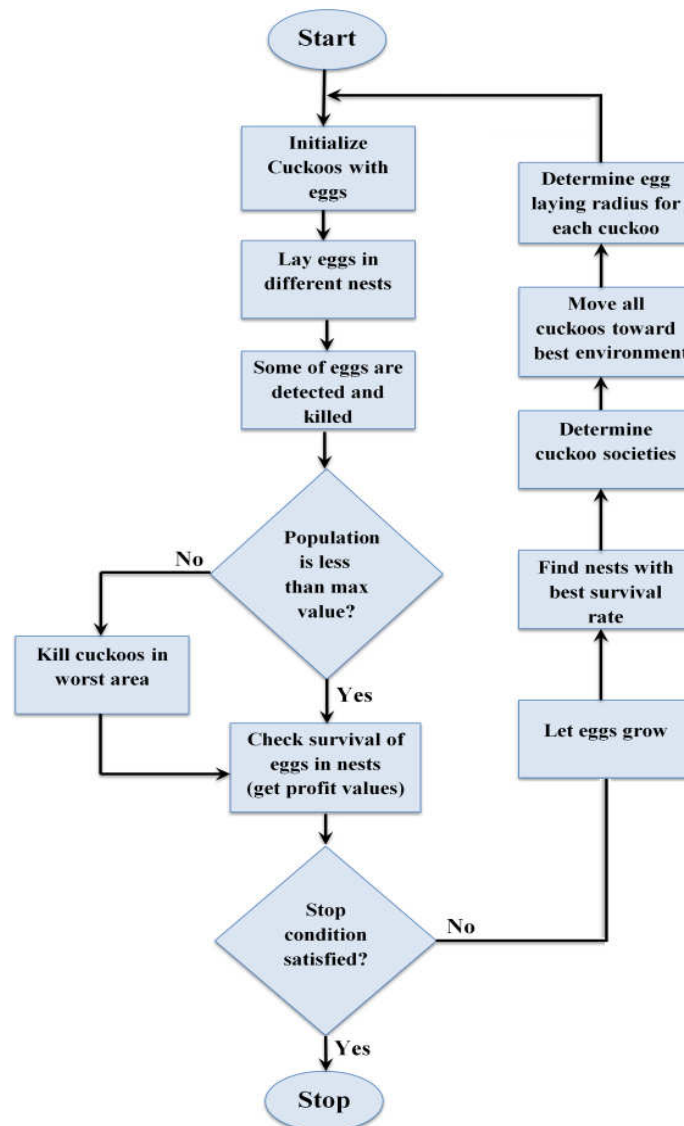
Fig 8. Flowchart of cuckoo optimization algorithm [30].

The values of cuckoo optimization algorithm parameters are adjusted to achieve the desired goal in this paper, as shown in the Table 3.

Table 3. The adjusted values for cuckoo optimization algorithm parameters

MaxIteration	Radius Coeff	No.ofCuckoos	knnClusterNo.	MaxNo.fCuckoos	motionCoeff	cuckooPopVariance	Npar
100	1	12000	5	50	2	1e-10	8

3.3. Results of Optimization

In this section, the results of PMSG optimized parameters, using cuckoo optimization algorithm and MATLAB software and Figure objective functions ($1/F_1$), F_2 and F_3 are presented, in Table 4 and Figures 9, 10 and 11 respectively.

Table 4. Optimization Results

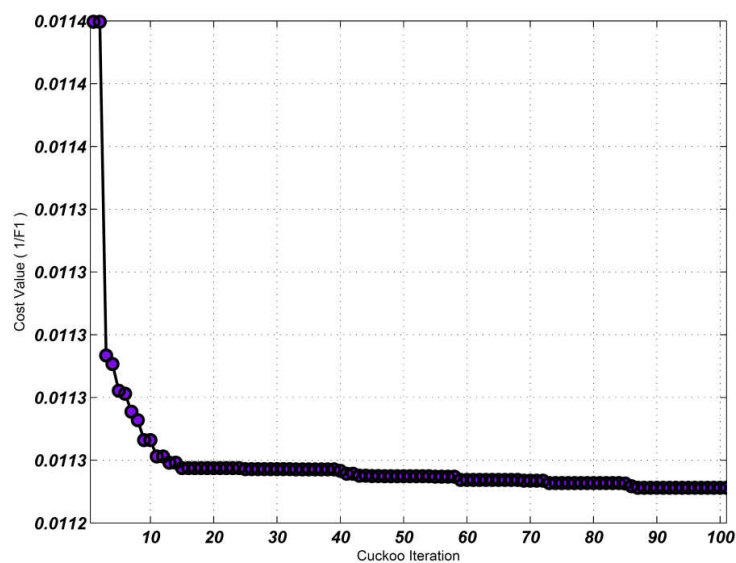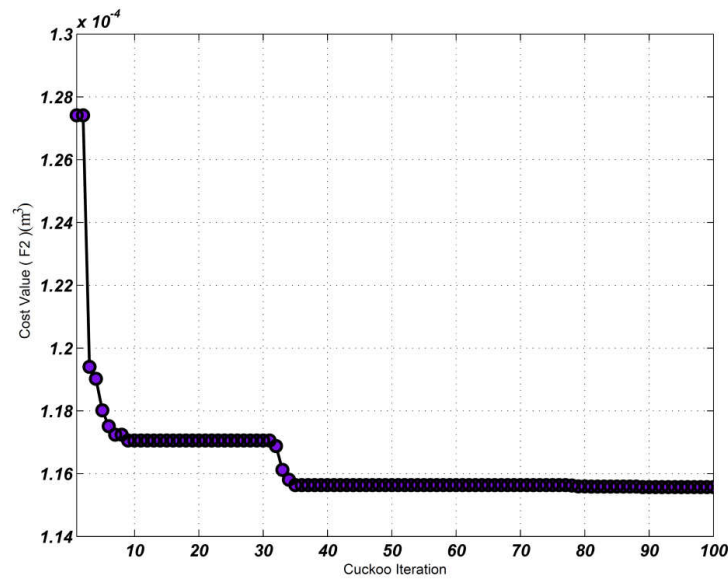| The objective of optimization \ Quantity of generator	Optimization of efficiency	Optimization of Volume	Optimization Combination of efficiency and volume
Dstot (mm)	90.1	124	113.6
D (mm)	43.8	63.7	56.5
L (mm)	19.8	9.6	11.6
hz (mm)	12.8	14.4	13.9
bs2 (mm)	3.5	4.4	4.1
bs1 (mm)	1.6	2.2	2
bt (mm)	2.5	3.7	3.3
Dr (mm)	33.1	54.6	47.1
hPM (mm)	4.2	3.5	3.7
hys (mm)	10.3	15.8	14.7
hyr (mm)	10.3	15.8	14.7
Nph	144	216	186
Zq	24	36	31
PLoss(Watt)	81	92.28	85.75
Ea (volt)	73.2	77.07	75.19
Es (volt)	73.32	77.42	75.38
η (%)	89	87.57	88.35
Vtotal (cm3)	126.25	115.71	117.18
Cost ($)	134.86	133.3	133.67
A (A/m)	21951.19	21998.14	21996.66
Bg (T)	0.62	0.62	0.62
2P	4	4	4
Q	36	36	36
g(mm)	1.16	1	1.1
αPM	0.667	0.7	0.74
χ	0.452	0.151	0.21
ϵ	1.11	1.17	1.14

Figure 9. objective function (1/ F1)
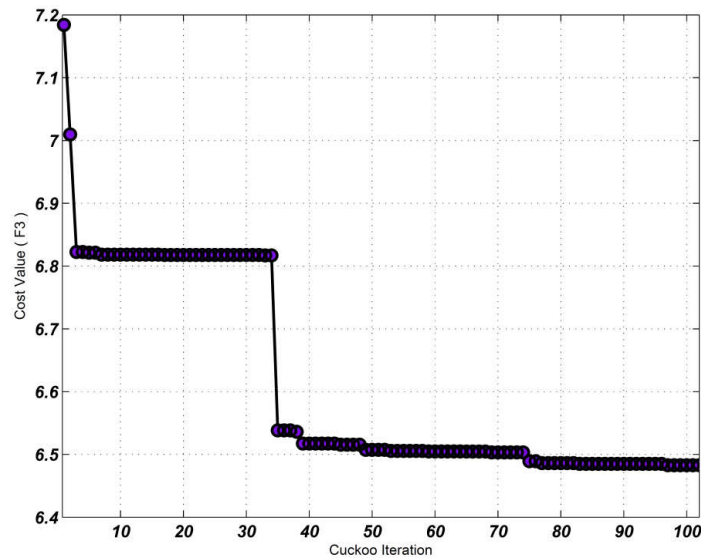
Figure 10. objective function F2

Figure 11. objective function F3

4. Conclusions

Permanent magnet synchronous generators because of the favorable features, such as high efficiency, low repair and maintenance and low weight and size, satisfy requirements in the aerospace industry and are one of the best options to be used in this application. In this paper investigation has been concentrated on the performance increase of the generator in aerospace systems.

In other words, by using an analytical-computational design method and then optimization by using cuckoo optimization algorithm (COA), it has been tried to take the losses and volume to minimum and efficiency to maximum by optimizing the dimensions and other variable quantities of the generator. The obtained quantity from analytical techniques and optimization using COA, with a small percentage of differences, are equal. Also more efficiency and less volume of this type of generator comparing to other types of generators for use in aerospace systems are completely approved. In the future, another objective function can be defined

such as the power density and the cost of the generator production and by other optimization methods such as bees, ants, particle swarm, imperialist and genetic optimization algorithm, optimizing can be used for these purposes.

The PMSG design optimization studied in this paper leads to a 2.78% increase in efficiency in a mode that the objective function is a mere maximization of the efficiency than that of reference [1] and efficiency has increased by 89%. Also by optimization just for minimizing the total volume of the generator, the volume has decreased by 115.71 cm^3. Whereas in simultaneous optimization of efficiency and total volume of the generator, maximum efficiency has reduced by 0.65% and minimum volume has increased by as much as 1.47 cm^3, in comparison to the time when these two quantities have been optimized individually.

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