pp.143:149

Design Optimization for Total Volume Reduction of Permanent Magnet Synchronous Generators

Reza Ilka[1], Yousef Alinejad-Beromi[2], Hossein Asgharpour-Alamdari[3], Hamid Yaghobi[4]

[1,2,3,4] Electrical Engineering Department, Semnan University, Semnan, Iran. Email: ilka@sunlight.semnan.ac.ir
Email: yalinejad@semnan.ac.ir, Email: h.asgharpour@sunlight.semnan.ac.ir, Email: yaghobi@profs.semnan.ac.ir

Abstract

Permanent magnet synchronous generators (PMSGs) are novel generators which can be used in high-performance wind farms. High efficiency and flexibility in producing electricity from variable rotation make them good candidate for wind power applications. Furthermore, because these kinds of generators have no excitation winding, there is no copper loss on rotor; hence, they can operate at high power factor. Besides, performance characteristics of such generators could be further improved by design optimization. This paper presents design optimization of PMSGs used in small wind turbines using novel and efficient optimization algorithm i.e. Artificial Bee Colony (ABC) Algorithm. Then, a well-known optimization algorithm i.e. Genetic Algorithm (GA) is used to show the validity and efficiency of the before-mentioned algorithm. For this purpose, the necessary equations are provided. Objective function of this study is to reduce the total volume of motor. Case study of this study is a 5 kW, 220 V, 50 Hz, 100 rpm generator. Finally, results obtained by optimization are verified with Maxwell software which is based on finite element method (FEM). Comparison shows that the results of optimization approach are in good agreement with that of FEM ones.

Keywords: Permanent Magnet Synchronous Generator (PMSG); Wind Farms; Design Optimization; Artificial Bee Colony (ABC) Algorithm; Genetic Algorithm (GA); Finite Element Method (FEM); Ansoft Maxwell

1. Introduction

Permanent magnet synchronous generators (PMSGs) are developed from conventional synchronous generators. In a conventional synchronous generator, there is multi-phase winding in stator and an excitation winding in rotor, but in PMSGs excitation winding is removed and substituted by permanent magnets. This substitution brings noticeable features to these generators. Above all, efficiency of the generator is improved because of lack of copper loss of excitation winding. Besides, power factor of these generators are high which is a proper characteristic for power system. Drawback of PMSGs is that the materials used for producing permanent magnets are expensive, and they are difficult to work during manufacturing. Additionally, the use of PM excitation requires the use of a full-scale power converter in order to adjust the voltage and frequency of generation to the voltage and the frequency of power system. This is an added expense. However, the benefit is that power can be generated at any speed so as to fit the current conditions. In synchronous generators, frequency of produced voltage is a proportional to the speed of rotor. So, in any wind speed, power is produced.

In [1], the design optimization is performed with a genetic algorithm for optimizing generator system cost. To show the effectiveness of the developed electromagnetic design model, the results of a 500-kW direct-drive PM generator and a 1.5-MW multibrid PM generator with various gear ratios are compared. Ref [2] proposes a new approach to minimize the cogging torque of a stator interior permanent magnet (SIPM) machine. In [3], a 20 kW PMSG is optimized with artificial intelligence approaches. Besides, other surveys presented the design and analysis of PMSGs [4-6].

This paper deals with design optimization of PMSGs used in small wind turbines. In fact, design optimization of PMSGs is not well covered in abovementioned researches. Therefore, this paper tries to perform this task. Aim of this paper is to minimize the total volume of the generator using Artificial Bees Colony (ABC) algorithm. Section II presents a brief description about small wind turbines and PMSGs used in these systems. In section III, design optimization is completely discussed. Design procedure of the case study is then validated via 2D Finite element method by Ansoft Maxwell in section IV. Finally, the paper is concluded in section V.

2. Permanent Magnet Synchronous Generators

Nowadays, energy production is a major concern and governments make decisions about new ways of producing energy specially electricity. Regarding catastrophic effects of traditional ways of producing electricity on environment, great attentions have paid to renewable energy sources. Among all types of renewable energies, wind energy is an efficient and economic energy resource in comparison to other types of renewable energies such as solar energy and so on. Wind power is a sustainable solution to energy crisis worldwide. Main benefits of wind power turbines are as follows:

- Clean source of energy
- Wind is reachable almost all over the world specially in locations near to sea and blows day and night (compared to solar power which captures energy only day time)
- Long run and utilizing of wind plants due to low maintenance
- Wind energy is a domestic, renewable source of energy that generates no pollution and has little environmental impact. Up to 95 percent of land used for wind farms can also be used for other profitable activities including ranching, farming and forestry.

There can be other benefits related to wind power plants. However, nothing in this universe is completely perfect. There are some drawbacks in using wind power plants which are of minor concern. The most important disadvantage of wind power turbines is noise of their blades (can be bothering in very large turbines). The other one is high investment in wind power projects. This problem is usually solved with well-engineering insight through the years after installation.

There are so many kinds of wind turbines. Small generators require less force to turn than a larger one, but give lower power output. If you fit a large wind turbine rotor with a small generator it will be producing electricity during many hours of the year, but it will capture only a small part of the energy content of the wind at high wind speeds. Large generators are efficient at high wind speeds, but unable to turn at low wind speeds, i.e. if the generator has larger coils, and/or a stronger internal magnet, it will require more force (mechanical) to start in motion [7,8].

From above statement, it is understood that in areas with medium wind speed, wind turbines with small generators are better choice due to their capability of producing electricity with low wind speed. Although their output power is not too high, the ability of turning with low wind speed makes them suitable choice.

Fig. 1 shows general configuration of PMSG wind turbine. At the front, blades absorb wind power. The power in the wind is a function of wind speed and calculated as [7]

$$P_w = \frac{1}{2}\rho A v^3 \qquad (1)$$

Where ρ is the air density (kg/m^3; A is the cross-sectional area through which the wind passes (m^2); and v is wind speed normal to A (m/s). it is obvious that wind power is extremely depended to the wind speed. The absorbed power by the blades is turned into mechanical power and shaft will rotate. Because blades have low rotational speed, there should be a gear to change and adjust the speed of shaft. Gears in wind turbines typically increase the speed which is desirable for generators. Then, PMSG is employed to capture this energy and turn it to electricity. Because of variation of wind speed, the output electricity is no fixed and constant. Full-scale converters are used to fix output electricity.

Fig.2 shows a schematic view of a wind power turbine. As shown in Fig. 2, generator is coupled with shaft of turbine. Fig. 3 and 4 show detailed description schematic 2-D view of a PMSG, respectively.

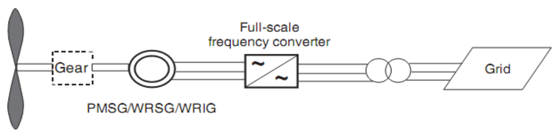

Fig.1. PMSG wind turbine configuration [8]

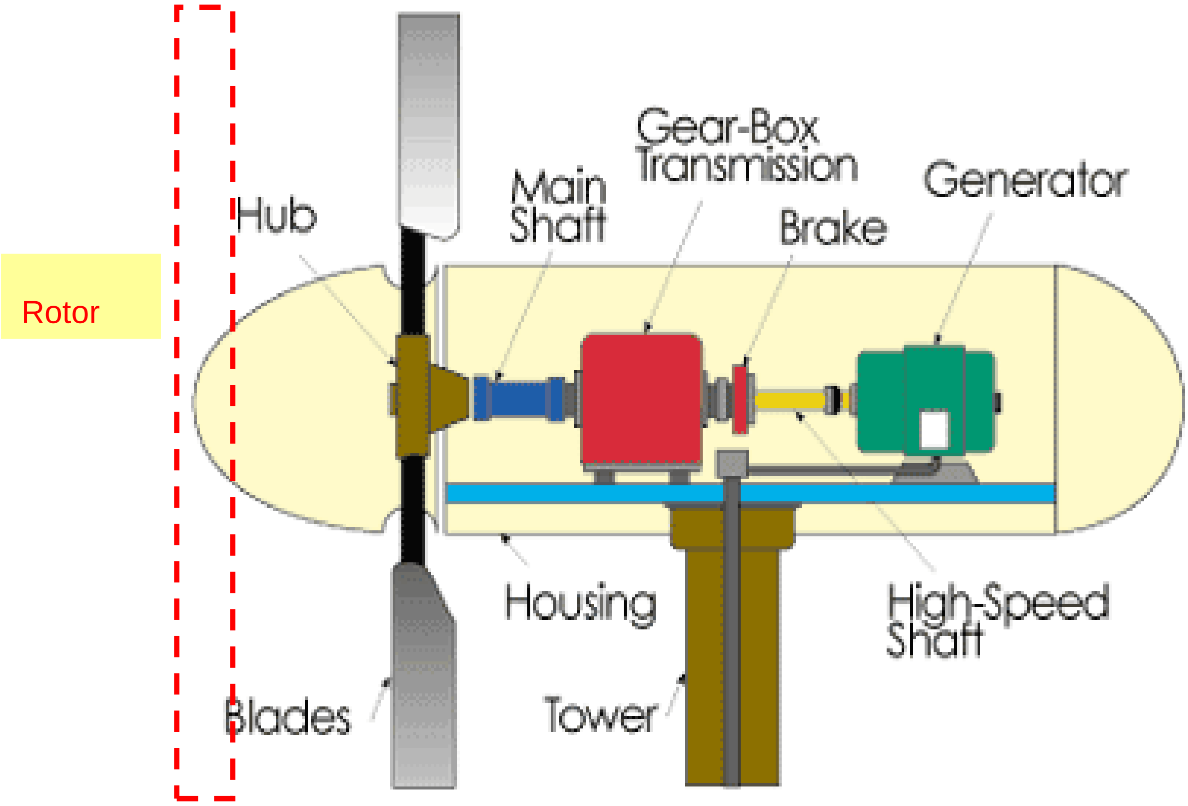

Fig.2. Description of a wind power turbine

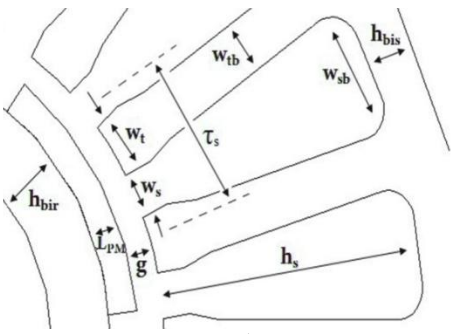

Fig.3. Detailed description of a PMSG

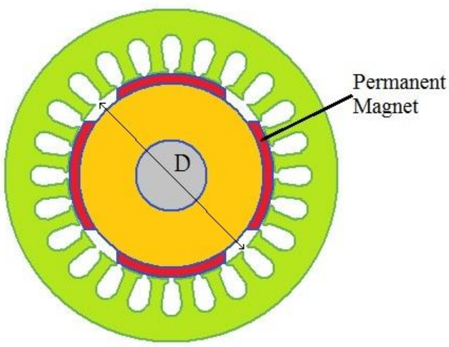

Fig.4. Schematic 2-D view of a PMSG

3. Design Optimization

In this section, firstly, Artificial Bee Colony (ABC) algorithm is discussed. In addition, Genetic Algorithm (GA) is briefly explained. Then, optimization process and selected case study are surveyed. Then optimization results are presented and discussed by these two algorithms. Firstly, ABC algorithm is performed, and then GA validates its results.

3.1. Artificial Bee Colony (ABC) Algorithm

Artificial Bee Colony (ABC) algorithm is a swarm-based algorithm. ABC, proposed by Karaboga in 2005, is inspired from the foraging behavior of bee colony. Main applications of the algorithm are solving continuous optimization problems and optimizing multi-variable and multi-modal numerical functions. Using fewer control parameters than other algorithms, ABC has better performance.

A colony of honey bees start foraging by sending scout bees to perform a random search for promising food sources. The colony has the ability to explore long distances (about 14 km) in multiple directions which assures exploiting a large number of patches [9]-[10]. As the foraging process advances, a number of bees in colony are always assigned as scout bees [10]. If the food gathered from a patch meets a criterion threshold, the scout bee can deposit it in the hive and advertises the relative patch in the waggle dance [9]. The waggle dance is an important means for communication in the colony and provides it with all the necessary information of the outside [9]-[12]. The bees in the hive to choose among different patches according to the information gained from waggle dances about their relative qualities. Thus more bees visit the more promising patches [11]-[12], this helps an efficient foraging process. Recruiting more bees to a promising patch continues until the patch fitness is decided to fall below the criterion threshold.

ABC algorithm is initialized by finding random population from the search space with (2) i.e. the initial population phase:

$$x_{mi} = x_i^{min} + rand.(x_i^{max} - x_i^{min}) \quad (2)$$

where x_{mi} is a solution vector for optimization problem, m=1,…,SN and i=1,…,n. SN denotes number of initial population and each x_i is a n-dimensional vector. Then, the fitness of each solution is calculated.

Next step is the employed bees phase in which a new solution is produced in the neighborhood of x_i for each solution.

$$v_{mi} = x_{im} + \varphi_{mi}(x_{mi} - x_{ki}) \quad (3)$$

$$k = int(rand.SN)+1 \quad (4)$$

In (3), φ_{mi} is a monotonic distribution of a real random number between [-1, 1]. x_{ki} denotes ith dimension of kth solution of population that k is chosen randomly among {1,…,SN}. The new solution is replaced with the previous only if it has a better fitness.

In the onlooker bee phase each onlooker bee chooses a solution based on its probability amount calculated with (5), by using a selection method (e.g. Roulette Wheel). Then, the onlooker bee finds a new solution in the neighborhood of the chosen solution. It is replaced, if it is better than the previous one. The number of onlooker bees is equal to SN.

$$\vec{P}_m = fit_m(\vec{x}_m) \Big/ \sum_{m=1}^{SN} fit_m(\vec{x}_m) \quad (5)$$

Where $fit_m(X_m)$ is the fitness of x_m.

If the number of cycles that a solution cannot be improved is greater than a predetermined value (limit), the solution is discarded and a new one is produced randomly. These phases are repeated until a stopping criterion is satisfied. The flowchart of the proposed method has been shown in Fig. 5.

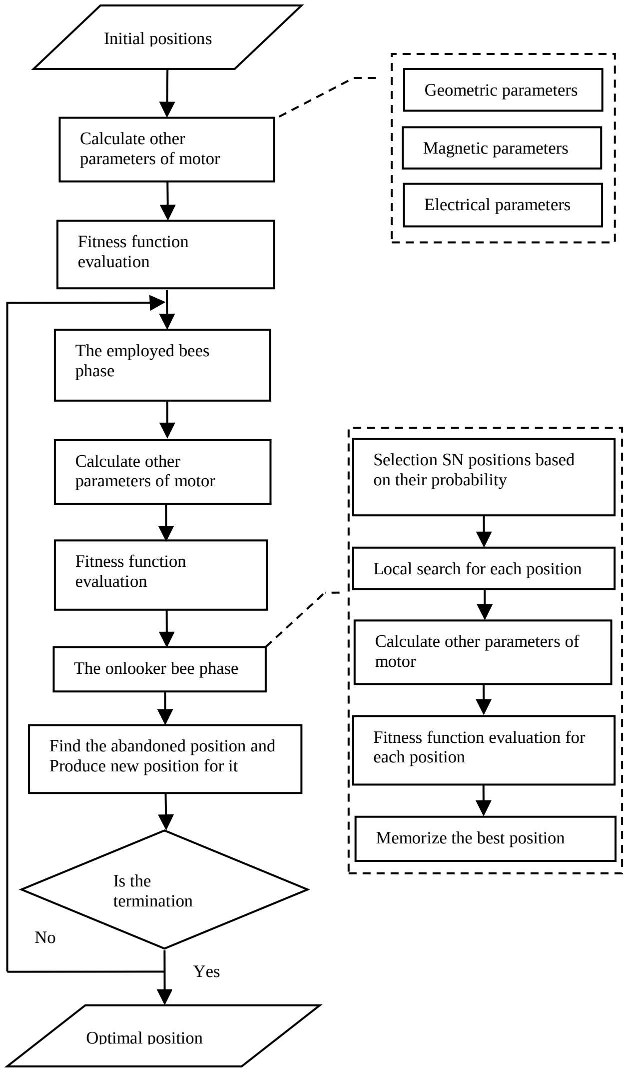

Fig.5. Flowchart of the proposed method

3.2. Genetic Algorithm

GA is a programming method that mimics biological evolution as a problem solving strategy based on Darwinian's principle of evolution and survival of fittest to optimize a population of candidate solutions towards fitness. GA uses an evolution and natural selection that uses a data structure like chromosomes and evolve the chromosomes, using selection, crossover, and mutation operators. The process of GA begins with a random population of chromosomes, which represent all possible solution of a problem that are assumed as candidate solutions. The size of the population is depended to the size and the nature of the problem. The locations of each chromosome are encoded as characters or numbers and could be referred to as genes. Then according to the desired solution an evaluation function is used to calculate the goodness of each chromosome known as “Fitness Function”. Two basic operators, crossover and mutation, are used to simulate the natural reproduction and mutation of species during evaluation. The main aim of crossover is to search the parameter space and it is the most important operator in GA. The crossover operator takes two strings from the old population and exchanges the next segment of their structures to form the offspring. The function of mutation is used to prevent the loss of the information. Mutation can keep the population more diverse so that it alters a string locally to create a better string. Once the new proportion is completed, the program will continue to generate new population. The iteration can be stopped while no further significant change of the solution occurs or when the specified number of iteration is reached. The Selection of chromosomes for survival and combination is biased towards the fittest chromosomes. A GA generally has four components. A population of individuals represents a possible solution. A fitness function which is an evaluation function by which we can tell if an individual is a good solution or not. A selection function decides how to pick good individuals from the current population for creating the next generation. Genetic operators such as crossover and mutation which explore new regions of search space while keeping some of the current information at the same time [13].

3.3. Optimization Process

According to the Fig.s 3 and 4, Total volume of generator can be expressed as follows:

$$Vol_{tot} = (\pi L[(\frac{D}{2}) + 2(h_s + h_{bis})]^2) \quad (6)$$

Where D is inner diameter of stator, L is axial length of motor, h_s is slot depth and h_{bis} is stator back-iron. These parameters and dimensions are shown in Fig.s 3 and 4. Equation (6) is the objective function of this study. The aim of optimization is to minimize it i.e.

$$f\ (x) = \min[Vol_{tot}] \quad (7)$$

3.4. Case Study

In this section a case study is presented. This case study is chosen for a small wind turbine. The aim of designing this generator is to capture low winds energy with a low investment. In fact, the chosen specification is applied to the design process in section III.

The considered design is a 5 kW, 220 V, 100 rpm, 50 Hz generator. There are 60 poles onto the surface of the rotor (surface-mounted permanent magnets). This specification of a PMSG is well suited for small wind turbines for capturing low winds energy. Generator’s main parameters are presented in Table 1. Other parameters of the generator are presented in table 2.

Table.1
Generator’s main parameters

Parameter	Value
Power (kW)	5
Rated voltage (V)	220
Rated speed (r/min)	100
Frequency (Hz)	50

Table.2
Other parameters of the generator

Variable	Value
B_{av} (T)	0.7
ac (A/m)	60000
B_{ys}, B_{yr} (T)	1.5
B_t (T)	1.5
B_r (T)	1.2
S	72
K_{fill}	0.7
J_s	4
η (%)	90
PF	0.9

3.5. Optimization Results

Objective functions for this study is defined as Equation (6) which has to be minimized according to equation (7). Four variables are chosen as design variables i.e. D (inner diameter of stator), L (axial length of motor), h_s (slot depth) and h_{bis} (stator back-iron). These variables together with their maximum and minimum ranges are listed in Table 3.

Table.3
Minimum and maximum ranges of design variables

Variable	Min	max
D (mm)	50	90
L (mm)	60	100
h_{bis} (mm)	5	15
h_s (mm)	10	25

Fig.6 shows total volume of motor versus iteration. Optimum value for total volume of generator is 3.0159e+005 which is converged after 6.5969 Seconds. Optimal design variables are listed in Table 4. Fig. 7 shows total volume of motor versus iteration for GA optimization which is done for further validation of ABC algorithm .Optimum value for total volume of generator by GA is 3.0159e+005 (as ABC algorithm) which is converged after 6.1721 Seconds.

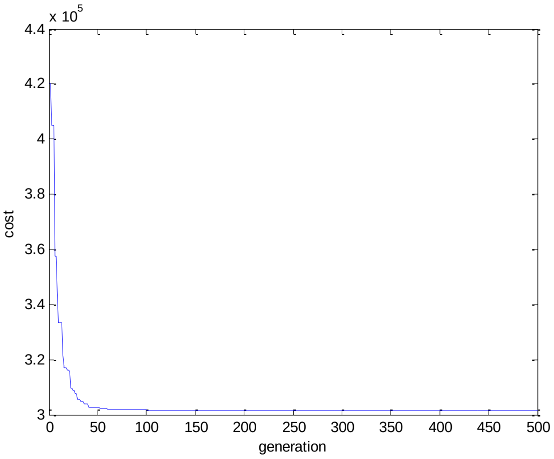

Fig.6. Total Volume of motor versus iteration (ABC Algorithm)

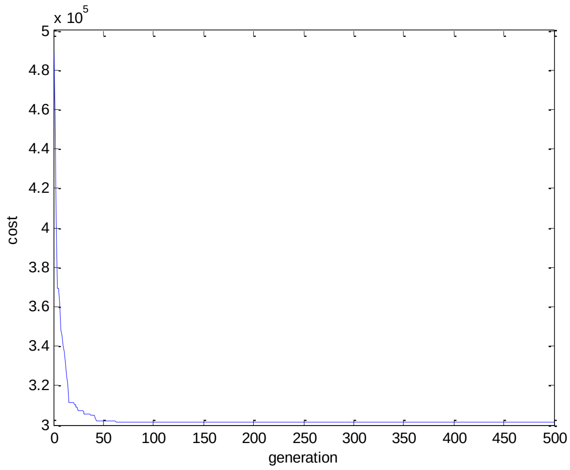

Fig.7. Total Volume of motor versus iteration (Genetic Algorithm)

Table.4
Optimal values of design variables for minimizing Total Volume

Variable	Min
D (mm)	55.2
L (mm)	74.5
hbis (mm)	9.8
hs (mm)	14.6

4. Finite Element Method Validation

In this section, we investigate the accuracy of the analytical method using computer simulation. This paper uses Maxwell 2-D software in Magnet-Static mode for FEM analysis. Parameters and dimensions of the generator are implemented in this software. Surface-mounted pole is composed of Nd-Fe-B with residual flux density of 1.2 T.

Running the software gives preferred output quantities. In this analysis, total number of mesh elements is 5437. Fig. 8 shows generated mesh of the machine. Fig. 9 shows flux lines in the generator. Flux density distribution is shown in Fig. 10. As shown in this Fig., maximum flux density occurs in the corners of the tooth as field variations are very fast in these regions. Phase and line voltage of generator is shown in Fig. 11 and flux density in the air-gap is also shown in Fig. 12. It is obvious that, these values are compatible to the ones considered in the analytical design optimization.

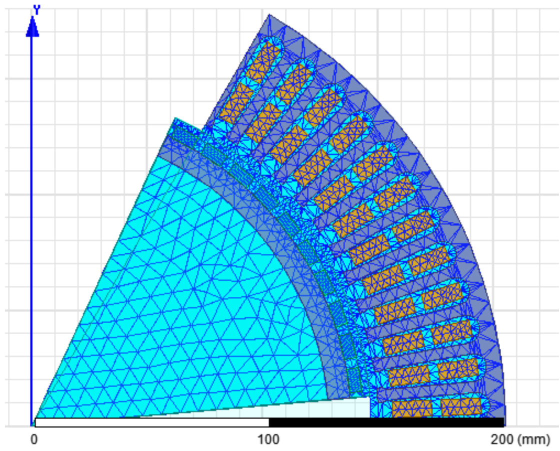

Fig.8. Generated mesh of the software

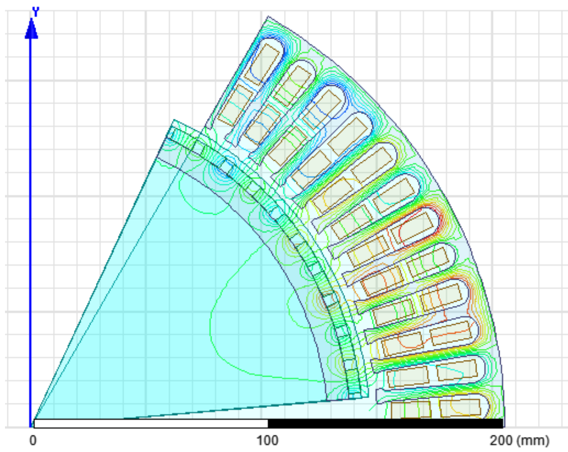

Fig.9. Flux lines diagram

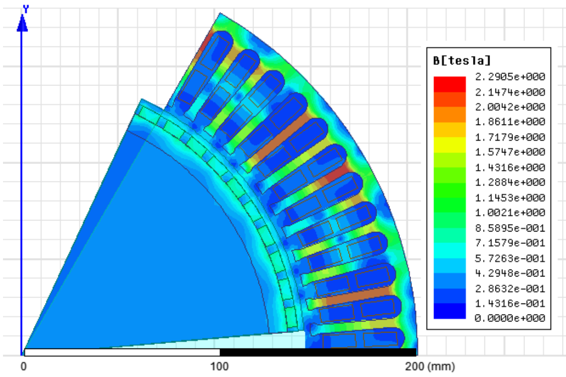

Fig.10. Flux density distribution

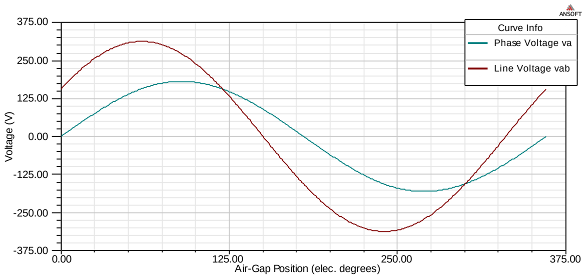

Fig.11. Phase and line Voltage of generator

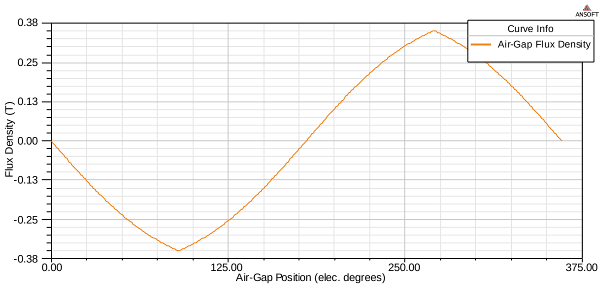

Fig.12. Flux density of generator in air-gap

5. Conclusion

Design optimization of permanent magnet synchronous generators (PMSGs) is presented. This paper presents design optimization of PMSGs used in small wind turbines using novel and efficient optimization algorithm i.e. Artificial Bee Colony (ABC) Algorithm. Then, a well-known optimization algorithm i.e. Genetic Algorithm (GA) is used to show the validity and efficiency of the before-mentioned algorithm. For this purpose, the necessary equations are provided. Objective function of this study is to reduce the total volume of motor. Case study of this study is a 5 kW, 220 V, 50 Hz, 100 rpm generator. Finally, results obtained by optimization are verified with Maxwell software which is based on finite element method (FEM). Comparison shows that the results of optimization approach are in good agreement with that of FEM ones.

References

[1] H. Li, Z. Chen, H. Polinder, Optimization of Multibrid Permanent-Magnet Wind Generator Systems, IEEE transactions on energy conversion, vol.24, no. 1, pp. 82 – 92, mar. 2009.

[2] J. Zhang, M. Cheng, Z. Chen, Optimal design of stator interior permanent magnet machine with minimized cogging torque for wind power application, energy conversion and management vol. 49, no. 8, pp. 2100–2105, Aug. 2008.

[3] S. Kiartzis, A. Kladas, Deterministic and artificial intelligence approaches in optimizing permanent magnet generators for wind power applications, journal of materials processing technology, vol. 108, no. 2, pp. 232–236, Jan. 2001.

[4] H. Li, Z. Chen, Design optimization and site matching of direct-drive permanent magnet wind power generator systems, renewable energy, vol. 34, no. 4, , pp. 1175–1184, Apr. 2009.

[5] M. Pinilla, S. Martinez, Optimal design of permanent-magnet direct-drive generator for wind energy considering the cost uncertainty in raw materials, Renewable Energy, vol. 41, pp. 267–276, May. 2012.

[6] T. Gundogdu, G. komurgoz, Technological and economical analysis of salient pole and permanent magnet synchronous machines designed for wind turbines, journal of magnetism and magnetic materials, vol. 324, no. 17, pp. 2679–2686, Aug. 2012.

[7] G.M. Masters, Renewable and Efficient Electric Power Systems, John Wiley & Sons, 1st edition ,Aug. 11.

[8] T. Ackermann, Wind Power in Power Systems, John Wiley & Sons, Second edition, May. 2012.

[9] K. Von Frisch, Bees: Their Vision, Chemical Senses and Language. (Revised edn) Cornell University Press, N.Y.,Ithaca, 1976.

[10] K. Von Frisch, Bees: Their Vision, Chemical Senses and Language. (Revised edn) Cornell University Press, N.Y.,Ithaca, 1976.

[11] E. Bonabeau, M. Dorigo, and G. Theraulaz, Swarm Intelligence: from Natural to Artificial Systems. Oxford University Press, New York, 1999.

[12] S. Camazine, J. Deneubourg, NR. Franks, J. Sneyd, G. Theraula and E. Bonabeau, Self-Organization in Biological Systems. Princeton: Princeton University Press, 2003.

[13] A. P. Engelbrecht, Computational Intelligence: An Introduction, John Wiley & Sons, 2007.