J Electr Eng Technol.2015; 10(3): 1007-1014
http://dx.doi.org/10.5370/JEET.2015.10.3.1007

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Genetic Algorithm Based Design Optimization of a Six Phase Induction Motor

Z. Fazlipour†, **R. Kianinezhad*** and **M. Razaz***

Abstract – An optimally designed six-phase induction motor (6PIM) is compared with an initial design induction motor having the same ratings. The Genetic Algorithm (GA) method is used for optimization and multi objective function is considered. Comparison of the optimum design with the initial design reveals that better performance can be obtained by a simple optimization method. Also in this paper each design of 6PIM, is simulated by MAXWELL_2D. The obtained simulation results are compared in order to find the most suitable solution for the specified application, considering the influence of each design upon the motor performance. Construction a 6PIM based on the information obtained from GA method has been done. Quality parameters of the designed motors, such as: efficiency, power losses and power factor measured and optimal design has been evaluated. Laboratory tests have proven the correctness of optimal design.

Keywords: Optimization design, Six phase induction motor, Objective function, Genetic algorithm, FEM

1. Introduction

In early 1990s, study on multiphase electric machines accelerated; until the beginning of recent century, it became practical in industries. Multiphase induction motors are predominantly used in electric ship propulsion, traction and generally in high power applications [1-3]. Multiphase induction motors have some advantages over three phase induction motors. Employing multi-phase induction motors would reduce the pulsating torque and would increase the efficiency of the machine. 6PIM reduces 6.7% stator copper losses compared to the same equivalent three-phase [4-5]. Also, multiphase induction motors have less noise pollution compared to three-phase ones [6]. Among several benefits, more phases provide better performance following loss of one or more phases; in addition multiphase motors can start and run even with some phases open circuit [7-10]. The other advantage is the improvement of torque in multiphase motors with concentrated winding [11]. Actually 6PIM is produced based on the reconfiguration of an existing three phase induction motor. The aim of this paper is to introduce a new idea in producing 6PIM. A design package has been developed specifically for a 6PIM. Then GA is used for the optimization process. The procedure is based on the basic electromagnetic equations, GA based optimization and checking the results by FEM. The FEM used in this work is based on the MAXWELL_2D software. The GA optimization method is described in the next section. The third section presents the 6PIM design. In section four, the 2-D Complex Eddy-Current Model will be introduced. Design program, objective functions and constraints are proposed in section five. Simulation and experimental results are presented in sections six and seven respectively. Finally some discussions and conclusions are presented in the last sections.

2. GA optimization method

In the most general sense, GA-based optimization is a stochastic search method that involves the random generation of potential design solutions and then systematically evaluates and refines the solutions until a stopping criterion is met. Genetic algorithm that produces good results in many practical problems is composed of the following three operators [12]: Selection: Selection is a process in which individual strings are selected according to their fitness. The selection probability can be defined by [12]:

$$P_j = F(x_i) / \sum_i F(x_i) \tag{1}$$

Where P_j is the selection probability and $F(xi)$ is the objective function of the string xi. Crossover: This is the most powerful genetic operator. One of commonly used methods for crossover is the single-point crossover. As shown in the following example, a crossover point is selected between the first and the last bits of the chromosome, then binary code of the right of the crossover point of chromosome1 goes to offspring2 and

---

† Corresponding Author: Dept. of Electrical and Electronic Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran. (eng.zahrafazlipour@gmail.com)

* Dept. of Electrical and Electronic Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran. ({reza.kiani, m_razaz}@scu.ac.ir)

Received: July 31, 2014; Accepted: December 27, 2014

chromosome2 passes its code to offspring1. This operation takes place with a defined probability Pc that statistically represents the number of individuals involved in the crossover process.

Chromosome1=0010010|101 offspring1=0010010|100
Chromosome2=0101011|100 offspring2=0101011|101

Mutation: This is a common genetic manipulation operator, and it involves, the random alteration of genes during the process of copying a chromosome from one generation to the next. Raising the ratio of mutations increases the algorithm's freedom to search outside of the current region of parameter space. Mutation changes from a "1" to a "0" or vice versa. It may be illustrated as follows.

110000010 110001010

The genetic algorithm implementation steps are shown as follows [12]:

Step 1: Define parameter and fitness function (initializing)
Step 2: Generate first population randomly
Step 3: Evaluate population by objective function
Step 4: Applying GA operators (selection, crossover, mutation)
Step 5: Evaluate new population
Step 6: Reproduction process, create new generation.
Step 7: Test convergence. If satisfied stop else continue.

The calculated values are checked in order to satisfy the constraints.

3. 6PIM design

The traditional design approach was established nearly half a century ago and is dominated by rules of thumb and empirical curves that reflect the experiences of manufacturers, sometimes passed down from generation to generation as the established "company policy" way of doing it. In the traditional design, designers start by heuristically selecting values of design parameters, and then follow an iterative tuning process trying to achieve design specifications.

3.1The sizing equation

Traditional electric machine design usually starts from the famous sizing equation [14], as follows

$$S = 11K_{w1} \times B_{av} \times ac \times (\frac{D}{1000})^2 \times \frac{L}{1000} \times n \tag{2}$$

Where S is the motor rating in Watt, B_{av} is the specific magnetic loading in Tesla, ac is the specific electrical loading in A/m, D is the stator inner diameter in mm, L is the motor active length in mm, K_{w1} is the winding factor, and n is the rated speed in r. p. s (revolutions per second). Values for B_{av} and ac are selected by the designer at the start of the design process. The magnetic loading B_{av} is limited by the saturation point of the materials used, the hysteresis losses, the eddy current losses, the stray losses, the effectiveness of the cooling strategy, the load profile, and the duty cycle. The specific electric loading ac is limited by the copper loss in the conductors, the effectiveness of the cooling strategy, the temperature limitation of the insulation material, the load profile, and the duty cycle. In the traditional design, the selection of B_{av} and ac is primarily based on the designer's experience [13].

3.2 Selection of the aspect ratio

After B and ac are selected, the D^2L value of the machine is then calculated by (2). For a machine with its pole number denoted by p, an aspect ratio λ is defined as

$$\lambda = \frac{L}{\pi D / P} = \frac{L}{Y} \tag{3}$$

Y is the pole pitch in meters. By choosing a proper value for λ, D and L can be then calculated. Besides B_{av} and ac, λ is another design parameter that designers usually choose at the beginning of the design process. A good choice of λ helps to increase winding induced *EMF* with less coil length. With the same flux density, the induced EMF is proportional to the coil area [13].

3.3 Selection of current density

By selecting values for B_{av}, ac and λ, another important design parameter to select is the stator current density J_s. For a certain rated current I, the current density J_s determines the cross sectional area of the used copper wire A_{wire}, as shown in (4)

$$A_{wire} = \frac{I}{J_s} \tag{4}$$

Higher current density leads to smaller A_{wire} and then greater armature resistance. For the same stator current, the copper loss is increased. This higher copper loss not only leads to lower machine efficiency, but also increases the winding operating temperature because more heat is generated. In the traditional design, the current density is typically selected by rule of thumb or the designer's experience. According to certain empirical rules, the current density is generally selected in the range of 3 to 7 *A/mm2* [13, 14].

3.4 Selection of the flux density

To fully utilize the material, the flux densities in the teeth and cores are usually selected around the knee point of the *B-H* curve. The traditional design rules were mostly developed based on silicon steel with a knee point flux density around 1.5 T [12].

3.5 Electrical machine design process

The traditional electrical machine design process is an iterative process and is summarized by the flow chart in Fig. 1. An a priori, assumption of machine efficiency eff_a and power factor pf_a have to be made and the machine rating S in VA is calculated by (5),

$$S = \frac{P_{out}}{eff_a \times pf_a} \tag{5}$$

Where P_{out} is the specified machine rated output power. After the value for S is calculated, values for B_{av}, ac and λ are selected to calculate D and L according to the sizing equation (2). Then, with the given rated voltage and current density, the number of coil turns and wire diameter of stator winding coils are determined for a given winding layout. At the same time, tooth width and core thickness are calculated with the selection of the flux density in the teeth and the core. The machine's outer diameter is then calculated from the slot area needed for the winding and the areas of the teeth and core. Rotor designs are also carried out with certain traditional rules, which can be found in the literature, such as [13]. After one complete trial design is produced, the performance of this trial design is calculated and verified against initially selected design parameters (primarily B_{av}, ac, and J_s) and a priori assumptions of efficiency and power factor. If any of these parameters does not agree with initially assumed values, modifications are made to either design parameters or a priori assumptions and the design process is repeated. This process is repeated as many times as needed until agreement is reached. Even if such agreement is achieved, there are also various performance requirements to meet, such as specified maximum winding temperature, minimum power factor, and maximum weight. For line start induction machines, there are also requirements about starting current and starting torque.

4. 2-D Complex Eddy-Current Model

When eddy-current is considered, the Maxwell equations can be applied to the 2-D domains to give the following equation [15]:

$$\frac{\partial}{\partial x}\left(v\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(v\frac{\partial A}{\partial y}\right) = -J + \sigma\frac{\partial A}{\partial t} \tag{6}$$

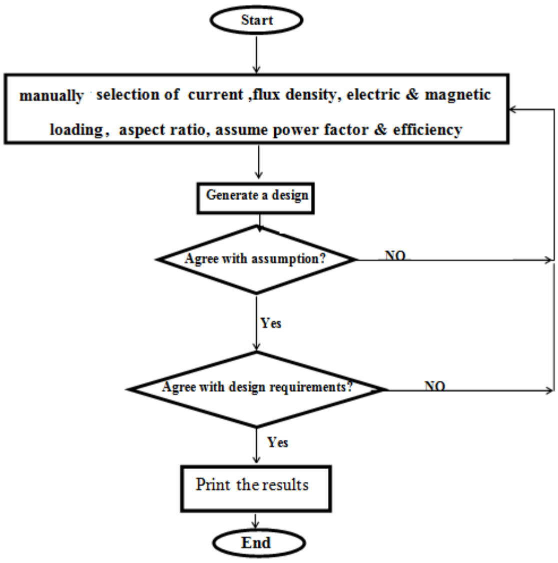


Fig. 1. Illustration of the iterative design process in the traditional machine

σ is the conductivity of material. If the model is linear, the magnetic source and the magnetic field will change sinusoidally with time. Hence J and A are sinusoidal vectors, and $\partial A/\partial t$ can be represented by $j\omega A$. Moreover,

$$W(A) = \iint_{\Omega}\left[\int_0^B HdB - JA + \frac{1}{2}j\omega\sigma A^2\right]d\Omega + \iint_{s_2} H_t A dS = min \tag{7}$$

B is the magnetic flux density and H is the magnetic field strength [15].

5. Design Program, Objective Function and Constraints

Programs written in MATLAB m. file have been tested for the problem under consideration. The program modified the initial values in suitable steps, evaluated the parameters of 6PIM, and retained the values if the constraints are not violated program. However, the design program has been developed, based upon the recommendations of the various references [13, 16, 17]. The design optimization of electric motor requires a particular attention in the choice of the objective function that usually concerns performance features. This problem is represented by the multi objective approach. Then, we have considered the following multi objective formulations [14]:

1. To optimize the stator copper loss

$$P_{SCL} = 6I_{ph}^2 R_s \tag{8}$$

Where I_{ph} is the phase current in Amps and R_S is stator resistance in Ohms.

2. To optimize the rotor copper loss

$$P_{Rcl} = \frac{r_r S_2 I_b{}^2}{a_b}(L_r + \frac{2D_e}{P}) \qquad (9)$$

Where r_r is constant (0.021), S_2 is the number of rotor slots and I_b is rotor bar current in Amps, *De* is mean end ring diameter in mm, *Lr* is length of the core in m and *P* is the number of poles.

3. To optimize the stator iron loss

$$P_{SIL} = W_t \times W_{tk} + W_c \times W_{ck} \qquad (10)$$

Where W_t is weight of the stator teeth, W_c is weight of the stator core, W_{tk} is losses in stator tooth portion W/kg, W_{ck} is losses in stator core W/kg.

4. Full load efficiency

$$\eta = \frac{1000P_O}{1000P_O + P_{SCL} + P_{RCL} + P_{SIL} + P_F} \qquad (11)$$

Where P_O is power in KW, P_{SCL} is stator copper loss in W, P_{RCL} is rotor copper loss in W, P_{SIL} is stator iron losses in W, P_F is friction losses in W. To obtain a desirable performance, the constraints such as, starting current, starting torque, etc. are imposed on the optimization process. As shown in Fig. 2 quantities chosen as the principal motor variables for the optimization consist of the following five parameters: Core length (equal for rotor and stator) (x_1), stator inner diameter (x_2), depth of stator slot (x_3), width of stator teeth (x_4),depth of stator core (x_5). The motor with the nominal ratings, shown in Table 1, is chosen for optimization.

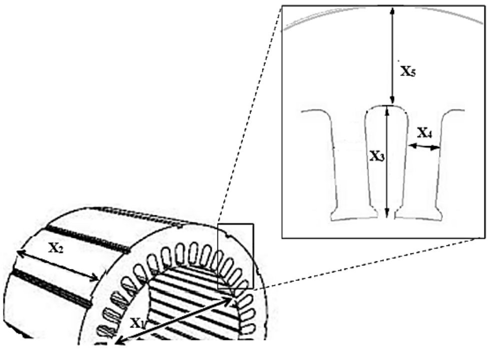


Fig. 2. Optimization variables

Table 1. 6PIM Characteristics

Number of phases	6	Power(w)	260
Rated voltage phase(v)	110	Frequency(Hz)	50
Number of poles	2	Number of stator slot	24
Connection	Y	Number of rotor slot	18

5. Genetic Algorithm Optimization Results

The flow chart of the design optimization procedure is depicted in Fig. 3. Each block consists of number of subroutines. The execution of the program starts with the performance specifications such as the initial motor design variables, the number of generations, population size, crossover rate, and mutation rate. Number of generations, crossover rate and mutation rate can be selected depending on the user. Each design parameter and penalty limit for penalty function can be varied within its domain. Then design parameters of the stator and rotor layout are calculated. The optimization constraints are as follows:

Minimum power factor 0.79, maximum starting current 7.5 (p. u), minimum starting torque 2 (p. u), maximum flux density in stator and rotor core and teeth around 1.5 T, no load power factor between 0.15 and 0.28. Table 3 presents parameters of GA program and Table 4 summarizes the output of the optimized Genetic Algorithm 6PIM design.

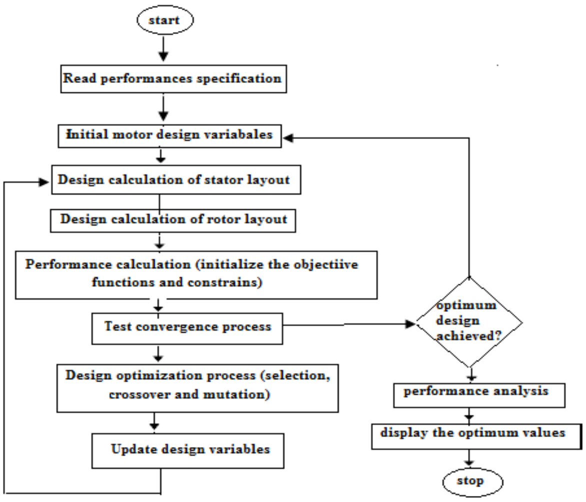


Fig. 3. Flow chart for design optimization process

Table 2. The output summery of the initial design of 6PIM (INI)

Quantity	INI
Power factor	0.99
Efficiency	0.6823
Total losses (W)	121.0658
No load power factor	0.1731
Start torque (p. u)	2.0287
Start current (p. u)	3.7948
Stator resistance (Ω)	19.93
Equivalent resistance (Ω)	34.7880
Equivalent reactance (Ω)	26.0631
Magnetization reactance (Ω)	212.8436
Stator stack length (m)	0.0816
Stator inner diameter (m)	0.0520
Rotor inner diameter (m)	0.0201
width of stator teeth (m)	0.0019
depth of stator slot (m)	0.0108
Stator slot width (m)	0.0077
depth of stator core (m)	0.0082

Table 3. Parameter of GA Program

Population	500	Crossover Rate	0.5
Generation	100	Mutation rate	0.015

Table 4. The output summery of the initial design of 6PIM

Quantity	GA
Power factor	0.99
Efficiency	0.73408
Total losses (W)	94.186
No load power factor	0.2057
Start torque (p. u)	4.5898
Start current (p. u)	5.7853
Stator Resistance (Ω)	5.69
Equivalent resistance (Ω)	20.3318
Equivalent reactance (Ω)	20.2971
Magnetization reactance (Ω)	251.6265
Stator stack length (m)	0.11114
Stator inner diameter (m)	0.065569
Rotor inner diameter (m)	0.022
width of stator teeth (m)	0.0036137
depth of stator slot (m)	0.012784
Stator slot width (m)	0.0083161
depth of stator core (m)	0.017784

Some discrepancies appear between the initial design and optimum design results are shown in Table 2 and Table 4. As shown in Tables 2 and 4, starting torque of the GA based design is 4.5898 (p. u), that greater than initial design and therefore, it exhibits a better performance for greater loads. Also as it can be seen in Tables 2 and 4 starting current of the GA based design is 5.7853(p. u), that higher than initial design due to the lower equivalent resistances of the motor and so, the temperature rise in the motor will be lower at the rated load.

Figs. 4, 5 show the flux density distribution for the motor. According to results that shown in Tables 2 and 4, optimized 6PIM has higher stator stack length and stator inner diameter than initial 6PIM so has greater flux in each pole. Table 5 shows the calculated and the finite element amount of flux densities in initial and optimized 6PIM are in relatively good agreement considering the required simplifications in the analytical design algorithms. The ratio of stator inner diameter to width of the stator tooth in GA based design is lower than initial design, so maximum flux density in optimized design is lower than flux density in initial design. As be seen maximum flux density in stator teeth is 1.004 T and mean flux density in stator core is 0.81312 T for GA based design and FEA result shows that these flux density specifications are achieved correctly. According to Figs. 4, 5and results shown in Table 5, flux densities in stator core and teeth of initial design and GA based optimization design are around 1.5 T, so both of these motors are working in knee point correctly.

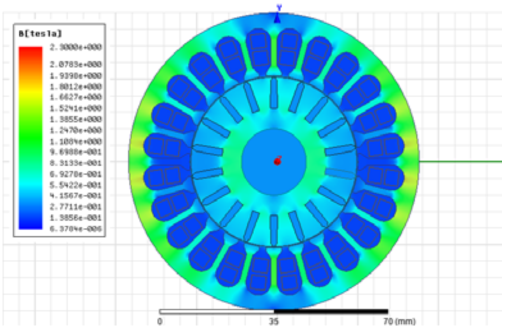


Fig. 4. Flux and flux density distribution (Initial design)

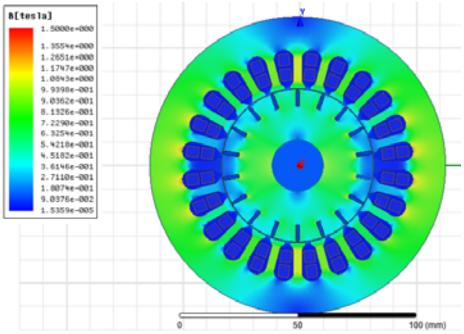


Fig. 5. Flux density distribution (GA design)

Table 5. Electromagnetic parameters of initial (INI) and GA optimized design (GA) of 6PIM

Quality	INI	GA
Flux density in stator core	1.3935 T	0.81312 T
Flux density in rotor core	1.6 T	0.93211 T
Maximum flux density in stator teeth	1.5035 T	1.0004 T
Maximum flux density in rotor teeth	0.7597 T	0.56167 T

6. Experimental Results

As design aspects of Genetic Algorithm optimization are closer to the standard electric motor forms, construction of the 6PIM based on information obtained from this optimized design has been done. Fig. 6 shows manufacturing process of 6PIM. Tests results of constructed motor are presented in Table 5 and Table 6. As can be seen, the only major difference is the equivalent reactance, which may be due to differences in the dimensions considered in the design of the rotor to be used but it will not have much

Table 6. No load, locked rotor and DC test results of constructed 6PIM

No load current (A)	0.42	Stator DC resistance (Ω)	6.37
No load power	52	Equivalent resistance (Ω)	13.366
Locked rotor voltage (V)	21.4	Equivalent reactance (Ω)	29.058
Locked rotor power (W)	36	Magnetization reactance(Ω)	242.72

Table 7. Results of 6PIM test under load condition

Rated output power(w)	238.62	Slip (%)	2.3
Total losses(w)	88	Efficiency	0.7305
Power factor	0.9986		

impact on the efficiency and motor losses. It makes improvement in motor performance, because the increase in impedance value causes a reduction in the start current and the short circuit power factor and all of these reasons cause improvement in motor performance. To verify 6PIM under load condition, a 300 W, 220 V, 1.8 Amp, DC generator coupled with the made 6PIM. Fig. 7 shows 6PIM under load condition. Results of 6PIM test under load are represented in Table 7.

Two most important characteristics that we were interested in are torque-speed and current-speed curves (which is) represented in Fig. 8. Fig. 9 shows variations of performance characteristics with phase voltage at nominal load. In order to compare the simulation results and experimental results from optimized constructed 6PIM, each performance characteristic of initial, GA based optimization and constructed 6PIM is given in one figure. Reduction of s corresponds to the reduction of the rotor current (Pm constant) and input current. It can reduce the major Ohmic loss of the motor, and efficiency will be higher. With comparison of results shown in Figs. 9 (a, b) and Table 2, 4, slip at rated voltage in optimized and constructed 6PIM is smaller than initial design so GA based design improved efficiency around 5% at rated voltage. Slight differences between numerical and experimental results in start torque and start current because of probable error in stator resistance measure and so differences in equivalent resistance and equivalent reactance are acceptable.

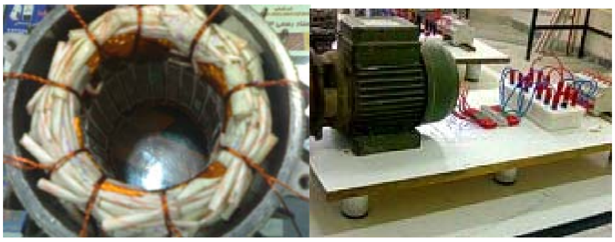


Fig. 6. 6PIM manufacturing process

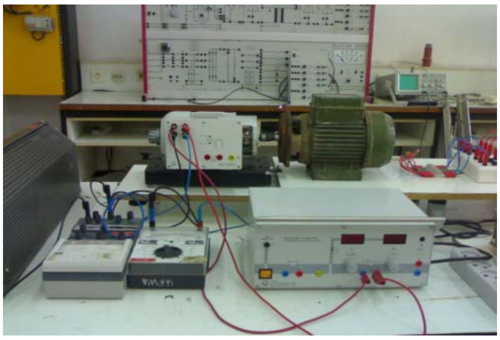
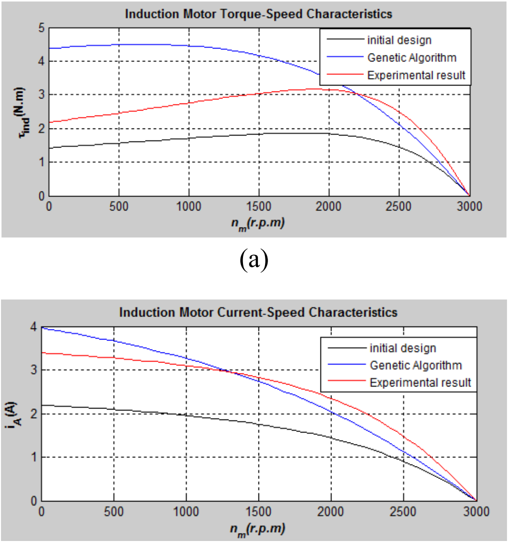


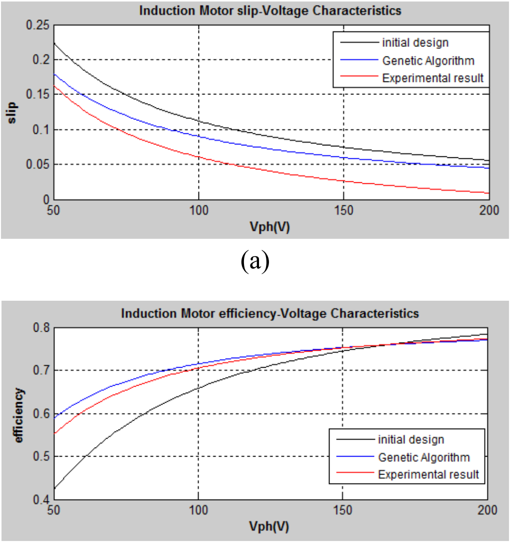
Fig. 7. Constructed 6PIM coupled with DC generator



(a)

(b)

Fig. 8. (a) Torque-speed and (b) current-speed characteristics



(a)

(b)

Fig. 9. (a) Variation of slip with phase voltage at nominal load and (b) Variation of efficiency with phase voltage at nominal load and

6. Conclusion

As can be seen obtained output power from constructed optimal motor is 238.625w which is very close to the predicted value from optimum design and the error is negligible. So accuracy of optimal design of GA has been proven by experimental results. This paper introduced a new approach in designing 6PIM. A 0.26Kw motor has been designed and constructed. According to studies, the following results are obtained:

- Comparison of the final optimum design with the initial design indicates that the gain of the proposed performance is even better than expected. In this instance, a higher starting torques and finally a greater efficiency (with respect to the corresponding constraints) for an optimum design of 6PIM can be noted. The Genetic Algorithm optimum design improves efficiency around 5%.

- Variations of performance characteristics (in %) of the optimum designs with phase voltage is rather low compared to the initial design.
- The calculated and the finite element flux densities in the motor are in relatively good agreement considering the required simplifications in the analytical design algorithms.
- Construction a 6PIM based on information obtained from GA method has been done. Quality parameters of the designed motors, such as: efficiency, power loss and power factor, measured and optimal design has been evaluated. Laboratory tests have proven the correctness of optimal design.

References

[1] G.K. Singh, “Multi-phase induction machine drive research – a survey”, *Electric Power Systems Research*, Vol. 61, No. 2, 2002, pp. 139-147.

[2] C. Hodge, S. Williamson, A.C. Smith, “Direct drive marine propulsion motors”, *ICEM Proc. Int. Conf. on Electrical Machines*, Belgium, 2002.

[3] E. Levi, “Multiphase electric machines for variable-speed applications”, *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 5, 2008, pp. 1893-1909.

[4] J.M. Apsley, S. Williamson, A.C. Smith, M. Barnes, “Induction motor performance as a function of phase number”, *IEE Proc.-Electric Power Applications*, Vol. 153, No. 6, 2006.

[5] S. Williamson, A.C. Smith, “Pulsating torque and losses in multiphase induction machines”, *IEEE Transactions on Industry Applications*, Vol. 39, No. 4, 2003, pp. 986-993.

[6] J. M. Apsley, S. Williamson, A. C. Smith, M. Barnes “Induction motor performance as a function of phase number”, *Proc. IET*, vol. 153, no. 6, 2006, pp. 898 - 904.

[7] H.A. Toliyat, “Analysis and simulation of five-phase variable-speed induction motor drives under asymmetrical connections”, *IEEE Transactions on Power Electronics*, Vol. 13, No. 4, 1998, pp. 748 - 756.

[8] Jen-Ren Fu, T.A. Lipo, “Disturbance-free operation of a multiphase current-regulated motor drive with an opened phase”, *IEEE Transactions on Industry Applications*, Vol. 30, No. 5, 1994, pp. 1267-1274.

[9] A. C. Smith, S. Williamson, C. G. Hodge, “High torque dense naval propulsion motors”, *IEMDC Proc. IEEE International Electric Machines and Drives Conf*, Vol. 3, 2003, pp. 1421-1427.

[10] R. Kianinezhad, B. Nahidmobarakeh, L. Baghli, F. Betin, and G. A. Capolino, Modeling and control of six-phase symmetrical induction machines under fault condition due to open phases, *IEEE Trans. Ind. Electron*, vol. 55, no. 5, May 2008, pp. 1966-1977.

[11] R.O.C. Lyra, T.A. Lipo, “Torque density improvement in a six-phase induction motor with third harmonic current injection”, *IEEE Transactions on Industry Applications*, Vol. 38, No. 5, 2002, pp. 1351-1360.

[12] D.E. Goldberg, *Genetic Algorithms in Search, Optimisation, and Machine Learning*, Addison Wesley, NewYork, 1989.

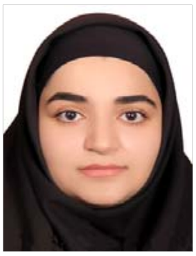
[13] V. N. Mittle, *Design of Electrical Machine*, 1996s, pp. 321-404.

[14] M. G. Say, *Performance and design of AC machines: Pitman*, London, ISBN: 273 40199 8, 1970.

[15] Chrari. M.V.K., “Finite element solution of eddy-current problem in magnetic structure”, *The transactions of Institute of Electrical and Electronics Engineers on Power Apparatus and Systems* 93, 62_72, 1974.

[16] Ramamoorty M, *Computer aided design of electrical equipment*, Chichester, UK. Wiley, 1988.

[17] S. S. Sivaraju, N. Devarajan, “Novel Design of Three Phase Induction Motor Enhancing Efficiency, Maximizing Power Factor and Minimizing Losses”, *European Journal of Scientific Research*, Volume 58 Issue, 2011.



Zahra Fazlipour She was born in Ahvaz, Iran, in 1989. She received B.S degree in electrical engineering from Shahrekord University at Shahrekord, in Iran in 2012 and the M.Sc. degree in electrical power engineering from Shahid Chamran University of Ahvaz, Iran, in 2014. Her research interests are power electronic and electrical machine design.

Reza Kianinezhad He was born in Ahvaz, Iran, in 1963. He received the B.Sc. degree in electrical engineering from Shahid Chamran University of Ahvaz, in 1988, the M.Sc. degree in electrical power engineering from Tarbiyat Modares University, Tehran, Iran, in 1995, and the Ph.D. degree from the University of Picardie Jules-Verne, Amiens, France, in 2006. Currently, he is with the Department of Electrical Engineering at Shahid Chamran University, Ahvaz, Iran. His research interest is modeling and control of multiphase induction machines.

Morteza Razaz He was born in Dezful, Iran, in 1948. He received BS and MS degrees in Electrical Engineering and Applied Mathematics from Texas University, USA, in 1977 and 1979, respectively, and a PhD degree from Sharob University, UK, in 1993. Currently, he is with the Department of Electrical Engineering at Shahid Chamran University, Ahvaz, Iran. His research interests include power electronics, protection relay, and electric machinery.