Performance Analysis of Self Excited Induction Generator Using Artificial Bee Colony Algorithm

A. K. Sharma, N. P. Patidar, G. Agnihotri, D. K. Palwalia

***Abstract*—**This paper presents the performance state analysis of Self-Excited Induction Generator (SEIG) using Artificial Bee Colony (ABC) optimization technique. The total admittance of the induction machine is minimized to calculate the frequency and magnetizing reactance corresponding to any rotor speed, load impedance and excitation capacitance. The performance of SEIG is calculated using the optimized parameter found. The results obtained by ABC algorithm are compared with results from numerical method. The results obtained coincide with the numerical method results. This technique proves to be efficient in solving nonlinear constrained optimization problems and analyzing the performance of SEIG.

***Keywords*—**Artificial bee colony, Steady state analysis, Self-excited induction generator, Nonlinear constrained optimization.

I. Introduction

DUE to rapid depletion of fossil fuels, non-conventional sources of energy have made their presence felt increasingly such as wind energy, nuclear energy and solar energy. Induction generators have been used in Wind Energy Conversion Systems (WECS) due to their relative merits such as low maintenance, brushless construction, low cost, no synchronization problems, no requirement of DC supply for excitation. They just require magnetizing current for excitation and external prime-over. When these generators are connected in power systems, then reactive power for magnetization can be obtained by grid itself. But a stand-alone operation generator can be operated in self-excitation mode by connecting a capacitor in parallel with magnetizing reactance. Induction generators can be used in village and remote areas where power supply is not available. Also energy from them is cheaper from the supply coming from grid in such areas. Main drawback of induction generators is no control on terminal voltage and frequency and reactive power consumption.

To estimate the performance of self-excited induction generators, researchers have used steady state model. Murthy et al. [1] has given loop impedance modelling based on conventional single phase equivalent circuit. It separates real and imaginary part, forming two simultaneous equation in terms of magnetizing reactance (X_m) and frequency (F) and then solving for X_m and F. Raina and Malik [2] used the thyristor controlled self-excited induction generator to obtain dc supply. Malik and Haque [3] considered the core losses while carrying out constant voltage constant frequency analysis of SEIG. Quazene et al. [4] suggested admittance-based model using single phase equivalent model to determine generated frequency and magnetic reactance of machine over resistive loading. In this method, two non-linear equations are obtained, real part of equivalent admittance expressed by a higher order polynomial of F and is independent of X_m. Imaginary part of admittance is equation, consisting both X_m and F. Once F is obtained from the real part equation, it is substituted into imaginary part equation to get the value of X_m. Using values of X_m and F steady state performance of the machine can be found using the magnetizing curve of machine. Ammasaigounden et al. used admittance model [5] in which performance equations becomes quadratic, variables being speed and other machine parameters. Alolah and Alkanhal used GA to calculate the capacitance for excitation for a single phase load connected to SEIG [6]. Loop impedance and node admittance method [7] is used to find out generated frequency and magnetic reactance of the machine. Genetic Algorithm (GA) has been used as a global optimization algorithm in [12] for steady state performance of SEIG considering the admittance model. Search space should be narrowed which require prior knowledge of the solution problem solution in order to get accurate results, which is not always possible.

In earlier reported works, it is cumbersome to separate the real and imaginary parts of admittance function. Also, appropriate initial guess [7]-[11] is required. If algorithm is not furnished with correct initial guess, the convergence and true solution it not guaranteed. There is need to calculate the cost function's jacobian matrix [1]. Prior knowledge of solution is needed [12]. The application of Artificial Bee Colony Algorithm (ABC) in this paper eliminates these difficulties.

This paper deals with the performance analysis of SEIG using ABC algorithm based on the intelligent foraging behavior of honey bees by D. Karaboga [14] in 2005. ABC is applied to the SEIG model formulated as numerical optimization problem

II. Analysis of SEIG

The steady state model of SEIG [4] using the per phase equivalent circuit model is shown in Fig 1. The circuit described is used to prepare the expressions for estimation of generated voltage and frequency.

While implementing the model following assumptions have been considered.

- Iron losses are neglected
- Only magnetizing reactance varies with magnetic saturation

A. K. Sharma is with Rajasthan Technical University, Kota, India (email: aksharma_eck@hotmail.com).

N. P. Patidar and G. Agnihotri are with Maulana Azad National Institute of Technology, Bhopal, India.

D. K. Palwalia is with Rajasthan Technical University, Kota, India.

characteristics of machine, while all other parameters of machine remain same.

- Working slip has no effect on rotor resistance.
- Leakage reactance and rotor reactance are same.
- There is no harmonic components in flux

Applying Kirchhoff's laws to the node consisting magnetizing branch that is node 'a', in Fig. 1 and making the total admittance to be zero as the voltage across the capacitor should not be zero for successful self-excitation.

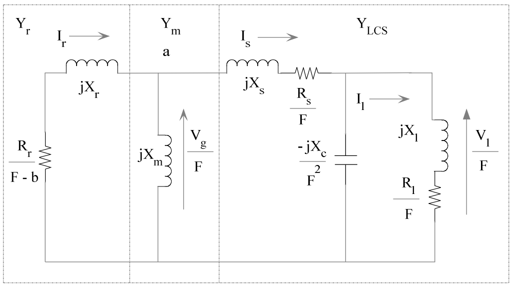

Fig. 1 Per phase equivalent circuit of SEIG

$$\overline{Y} = 0 \tag{1}$$

$$\overline{Y} = \overline{Y_{LCs}} + \overline{Y_m} + \overline{Y_r} \tag{2}$$

$$\overline{Y_m} = -\frac{j}{X_m} \tag{3}$$

$$\overline{Y_r} = \frac{1}{(R_r / F - b) + jX_r} \tag{4}$$

$$\overline{Y_c} = -\frac{jF^2}{X_C} \tag{5}$$

$$\overline{Y_L} = \frac{1}{(R_l / F_\Psi) + jX_l} \tag{6}$$

$$\overline{Y_S} = \frac{1}{(R_S / F) + jX_S} \tag{7}$$

$$\overline{Y_{LCS}} = \frac{\overline{Y_S}.(\overline{Y_C} + \overline{Y_L})}{\overline{Y_S} + \overline{Y_C} + \overline{Y_L}} \tag{8}$$

$$\overline{Y} = \sqrt{Re(\overline{Y}) + Im(\overline{Y})} \tag{9}$$

Differentiating the real part and imaginary part of (1) and equating the real part to zero, a polynomial of frequency of the order of 7 can be obtained [13].

$$P_7F^7 + P_6F^6 + P_5F^5 + P_4F^4 + P_3F^3 + P_2F^2 + P_1F + P_0 = 0 \tag{10}$$

and equating the imaginary part to zero, an expression that corresponds to the magnetizing reactance is obtained.

$$X_m = \frac{\left[(X_1 - X_L)^2 + \left[R_L + \left(R_1 / F\right)\right]^2\right]\left[X_2^2 + \left(R_2 / (F-b)\right)^2\right]}{\left\{(X_1 - X_L)\left[X_2^2 + \left(R_2 / (F-b)\right)^2\right] - X_2\left\{(X_1 - X_L)^2 + \left[R_L + \left(R_1 / F\right)\right]^2\right\}\right\}} \tag{11}$$

where, coefficients P_0 to P_7 are given in [13]. For numerical method equation of seventh order is solved for F and then X_m is calculated from (11).

A. ABC Method

Total admittance $\overline{Y}$ function given in (1) can be observed as a black-box function and is taken as the objective function for optimization with constraints. Benefits of using this black-box function are that, there is no need to separate the real and imaginary parts as well as no requirement of initial guess to start the algorithm.

B. Performance Analysis

From the synchronous speed test magnetizing characteristics curve can be obtained. After X_m and F are computed from (1), Air gap voltage can be found using magnetizing characteristics curve, given in Appendix. After that the performance parameters can be obtained with the help of known machine parameters. These are stator current, terminal voltage and load current.

Stator Current is expressed as

$$\overline{I_s} = \frac{V_g}{F}.\left(\overline{Y_m} + \overline{Y_r}\right) \tag{12}$$

Terminal voltage is given by

$$\overline{V_l} = \frac{\overline{I_S}.F}{(\overline{Y_L} + \overline{Y_C})} \tag{13}$$

Load Current is given by

$$\overline{I_L} = \frac{\overline{V_L}}{F}.\overline{Y_L} \tag{14}$$

Real Output Power

$$P = 3.R_L.\left|\overline{I_L}\right|^2 \tag{15}$$

For different values of excitation capacitor, rotor speed and load impedance the steady state performance of the machine can be derived by equations mentioned above.

III. Artificial Bee Colony Algorithm

D. Karaboga proposed an Artificial Bee Colony algorithm (ABC) based on the foraging behavior of honey bees for optimization problems [14], [15]. In the ABC algorithm, the artificial population of bees consists of three types of bees: employed bees, onlooker bees and scouts. Half of the population is employed bees and rest is onlooker bees. Each employed bees represents a food source or in other words, number of food sources and number of employed bees is same. An employed bee turns into a scout if its food source is discarded or abandoned by the other bees of hive.

The position of any employed bee corresponds to a possible solution for the optimization problem. The fitness or the nectar amount of any food solution represents the quality of that solution. In the beginning of the algorithm a randomly generated population is distributed across the search space, which consists of N_f food solutions. Here, N_f denotes the number of employed bees or onlooker bees as both is equal. Each solution x_i is a D dimensional vector, D being the total number of parameter to be optimized or the number of variables of the objective function. Next this population is subjected to repetitive iterations *iter=1,2,…max_iter* of search mechanism carried out by employed bees, onlooker bees and scout bee. An employed bee makes alterations in the positions of food sources in her memory depending upon the local information and checks the nectar amount (fitness) of the new position (new solution). If the nectar amount of new food source rules out the older one then, the bee memorizes the new solution and forgets the old one. When all the employed bees have searched out all the food sources, they share the information of food sources (position and nectar amount) with the other members of the hive through a specific way of dance called “waggle dance”. Here onlooker bees evaluate the nectar amount of all food sources gained from employed bees and select a food source on the basis of probability related to its nectar amount. Just like the employed bees, they also produce some modifications in the selected food source and check the nectar amount of new food source. If the nectar amount of the new source is better, then they memorize the new source else retain the old source in their memory.

An onlooker bee selects the food source on the basis of probability value associated with the individual food source calculate p_i, calculated as follows:

$$p_i = \frac{fit_i}{\sum_{n=1}^{N} fit_n} \tag{16}$$

here, fit_i is the fitness value of solution I which is proportional to the nectar amount of food source in position i, N_f being the number of food sources.

In ABC algorithm, there are three steps in each iteration: dispersion of employed bees to different food sources and evaluation of their nectar amount; sharing of the food sources and their selection by onlooker bees in order to make some modifications in them for better nectar amount; determination of scout bee and sending it to find a random food source from the whole search space.

For producing the new food source from the old one, artificial bees use the following expression:

$$x_{ij}^{new} = x_{ij}^{old} + \phi_{ij}(x_{ij}^{old} - x_{kj}^{old}) \tag{17}$$

here, k and j are randomly chosen indexes and k € $\{1,2,\ldots N_f\}$, j € $\{1.2\ldots.D\}$. In order to get a new solution k should be different from i. ϕ_{ij} is an arbit number in range of [-1, 1]. Its function is to control the modification of new source and represents the comparison of two food sources by bee. As the difference between x_{ij} and x_{kj} increases, the disturbance of the position of x_{ij} decreases. Hence, the solution progresses towards the optimum solution.

If a food source is not updated for a certain number of trials, it is abandoned by the bees and it is replaced by a new random food source by scouts. The value of predetermined number of trials is an important control parameter in ABC and is called “*limit*” for abandonment. For a scout bee to obtain a new food source following expression is used.

$$x_i^j = x_{min}^j + rand[0,1](x_{max}^j - x_{min}^j) \tag{18}$$

IV. ABC Algorithm to Analyze the SEIG Performance

For analyzing the SEIG performance the absolute value of the admittance is taken to be zero as described in (9). This can be treated as multivariable nonlinear constrained optimization problem.

Minimize $\bar{Y}$ ***subjected to:*** $0 \le F \le b$ ***and*** $0 \le X_m \le X_o$

To implement ABC on SEIG, control parameters are taken as per unit speed, per unit load (resistive) and excitation capacitance. ABC is initialized with taking objective function as $\bar{Y}$ and inputs are control parameters mentioned above. A population size set by user starts finding solutions in the search space. The number of employed bees N_f is taken to be 20 that is also equal to number of onlooker bees. The value of limit, criteria to declare a solution abandoned is taken to be 100. Total number of iterations N is taken to be 500.

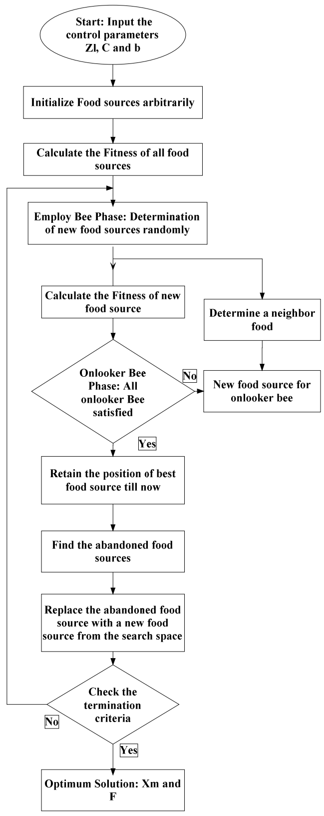

Fig. 2 Flowchart of ABC

V. RESULTS

The method as described in section II is used to compute the performance characteristics of 3-phase induction machine whose parameters are given in [7]. There are three parameters which define the working of the SEIG. These are rotor speed, excitation capacitance and load impedance. The output voltage, frequency and generated power also depend on them.

Case 1: Rotor speed is kept constant at 1 p.u. and magnetizing reactance and frequency are observed for different values of load impedance and capacitances. Fig. 3 shows the variation of the magnetizing reactance X_m with increasing load impedance. Fig. 4 depicts frequency variation on increasing impedance at different capacitances. In Fig. 3 at lower impedances magnetizing reactance goes beyond the unsaturated value X_o, which indicates failure to get self-excitation. Also in Fig. 4, there is not much difference in the frequency, with different capacitances. The different capacitances are chosen to be 20 µF, 30 µF and 40 µF. In Fig. 9 the variation of output voltage with respect to the power delivered. It can be seen from the graph that, increasing the value of capacitance increases the maximum power that can be delivered.

Case 2: Here, for a particular value of excitation capacitance, the variation is noted in magnetizing reactance and frequency with increasing load, for different rotor speeds. Fig. 5 shows different curve lines of X_m for different rotor speeds. The excitation capacitance here is taken to be 30µF. With increasing rotor speed, magnetizing reactance decreases. In Fig. 6, the plot describes the curves of frequency for different rotor speeds. Increasing the rotor speed also decreases the frequency of the machine. Different rotor speed is chosen to be 0.9 p.u., 1 p.u. and 1.1 p.u.

Case 3: In this case rotor speed is kept constant to 1 p.u. and variation in magnetizing reactance and frequency is seen for different loads. Curves are plotted for different loads that are 1 p.u., 3 p.u. and 1.5 p.u. at 0.8 p.f.. Fig. 7 shows the magnetizing reactance varying with increasing capacitance. From the curve, it can be seen that for certain range of capacitances the value of magnetizing reactance lies under the unsaturated magnetizing reactance value, hence the self-exciting region. Beyond this range, the machine fails to get self-excited. Also, increasing the load increases the X_m. In Fig. 8, it can be seen that, there in not much difference in the frequency with respect to the load.

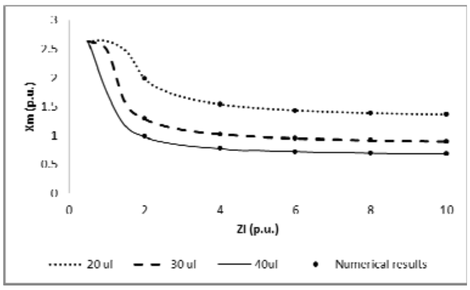

Fig. 3 Xmvs Z_L for different capacitance

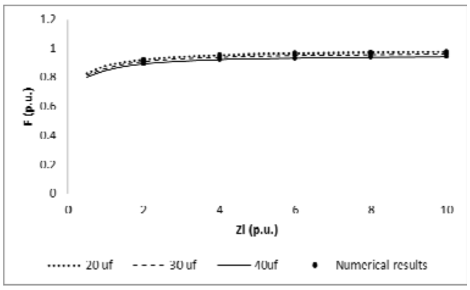

Fig. 4 F vs Z_L for different capacitance

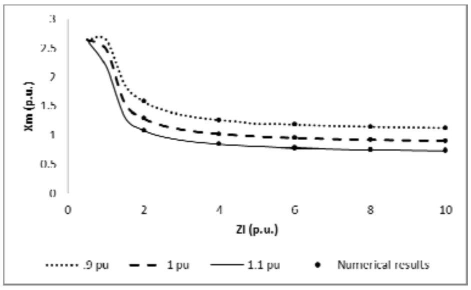

Fig. 5 $X_m$vs Z_L for different b

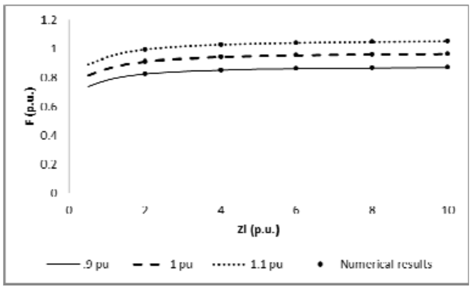

Fig. 6 F vs Z_L for different b

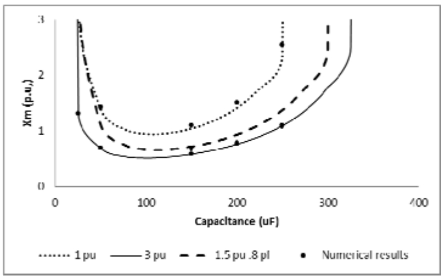

Fig. 7 $X_m$vs capacitance for different Z_L

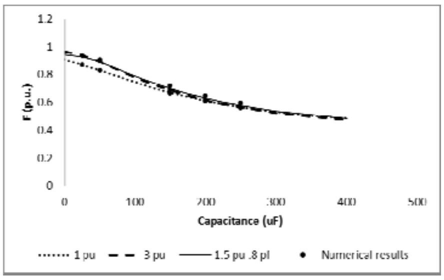

Fig. 8 F vs capacitance for different Z_L

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:8, No:6, 2014

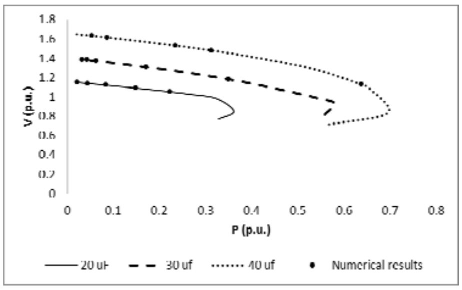

Fig. 9 V vs P for different capacitance

VI. Validation of Results

The results obtained from the ABC algorithm are compared with those from the numerical method as explained in Section II. Numerical methods are much complex and tedious to solve. On other hand ABC algorithm, no need to separate out the real and imaginary parts, so it is much easier to solve using them with same accuracy as of numerical methods. The dotted point in all the graphs depicts the numerical solutions and coincides with the ABC solutions in most cases. There competiveness of ABC can be seen from Tables I and II. In Table I the error in magnetizing reactance is shown and in Table II error in frequency is shown. It is observed that the error is of the order of e^{-4}. In Table III comparison in terminal voltage calculation is shown.

TABLE I
COMPARISON OF XM OBTAINED FROM ABC AND NUMERICAL METHOD

	Magnetizing Reactance Xm						Error		
Load	*20 µF (Numerical method)*	*20 µF (ABC)*	*30 µf (Numerical method)*	*30 µf (ABC)*	*40µf (Numerical method)*	*40µf (ABC)*	*Error in 20 µF*	*Error in 30 µF*	*Error in 40 µF*
2	1.99437	1.98848	1.29354	1.28841	0.98041	0.97548	5.89E-03	5.12E-03	4.93E-03
4	1.54391	1.54297	1.01917	1.01824	0.77584	0.77488	9.38E-04	9.20E-04	9.50E-04
6	1.43873	1.43837	0.94954	0.94916	0.72169	0.72130	3.66E-04	3.70E-04	3.90E-04
8	1.39219	1.39199	0.91779	0.91758	0.69664	0.69642	1.94E-04	2.00E-04	2.10E-04
10	1.36599	1.36587	0.89962	0.89950	0.68219	0.68206	1.20E-04	1.20E-04	1.30E-04

TABLE II
COMPARISON OF F OBTAINED FROM ABC AND NUMERICAL METHOD

	Frequency F						Error		
Load	*20 µF (Numerical method)*	*20 µF (ABC)*	*30 µf (Numerical method)*	*30 µf (ABC)*	*40µf (Numerical method)*	*40µf (ABC)*	*Error in 20 µF*	*Error in 30 µF*	*Error in 40 µF*
2	0.92406	0.92463	0.91041	0.91126	0.89369	0.89481	5.69E-04	8.50E-04	1.76E-02
4	0.95483	0.95500	0.94130	0.94155	0.92361	0.92395	1.69E-04	2.50E-04	1.79E-02
6	0.96616	0.96624	0.95274	0.95287	0.93470	0.93486	8.06E-05	1.20E-04	1.82E-02
8	0.97205	0.97210	0.95872	0.95880	0.94050	0.94059	4.61E-05	7.18E-05	1.83E-02
10	0.97567	0.97570	0.96240	0.96244	0.94406	0.94412	3.06E-05	4.68E-05	1.84E-02

TABLE III
COMPARISON OF TERMINAL VOLTAGE

	Voltage						Error		
Load	*20 µF (Numerical method)*	*20 µF (ABC)*	*30 µf (Numerical method)*	*30 µf (ABC)*	*40µf (Numerical method)*	*40µf (ABC)*	*Error in 20 µF*	*Error in 30 µF*	*Error in 40 µF*
2	0.8504	0.8499	1.0187	1.0165	1.1295	1.1289	5.0E-04	2.2E-03	-6.0E-04
4	1.0282	1.0277	1.1814	1.1813	1.36	1.3603	5.0E-04	1.0E-04	3.0E-04
6	1.0694	1.0693	1.2495	1.2495	1.4511	1.4514	1.0E-04	0.0E+00	3.0E-04
8	1.0904	1.0904	1.2861	1.2861	1.4993	1.4995	0.0E+00	0.0E+00	2.0E-04
10	1.1033	1.1033	1.3088	1.3089	1.5292	1.5293	0.0E+00	-1.0E-04	1.0E-04

VII. Conclusion

In this paper, the performance of self-excited induction generator is investigated using artificial bee colony algorithm. The nodal admittance of the machine acquired from the per phase equivalent circuit of self-excited induction generator is minimized. This method produced results with more accuracy without segregating the real and imaginary nonlinear equations of the admittance function. Also, no prior knowledge about the solution is required in this method. The simulated results of ABC algorithm are compared with the results obtained by numerical techniques involving solution of higher degree polynomial. Promising agreement is found between the two results, hence assuring the effectiveness and ease of implementation of the proposed method.

Appendix

The Rating of the Induction Machine and Its Parameters [7]:

Rated Power: 0.75 KW
Base voltage: 220 V
Base current: 2.31 A
Base impedance: 95.238 *Ω*
Rated frequency: 60 Hz
Rated speed: 1800 rpm

R_s=0.111 pu
R_r=0.132 pu
X_s=X_s=0.157 pu
X_o=2.64 Ω

The Magnetizing Curve is a Polynomial of Degree Three and Is Written Below:

$$V_g / F = 2.594 - 2.92318 X_m + 1.8711 X_m^2 - 0.418359 X_m^3$$

NOTATIONS

F	per unit frequency
I_s	stator current per phase, A
I_r	rotor current per phase, referred to stator, A
I_l	load current per phase, A
N	rated speed, rpm
R_l	load resistance per phase
R_s	stator resistance per phase
R_r	rotor resistance per phase, referred to stator
b	per unit speed
V_g	air-gap voltage per phase at rated f,V
V_l	terminal voltage per phase, V
X_s	stator reactance per phase
X_r	rotor reactance per phase, referred to stator,
X_C	capacitive reactance due to ‘C’ at rated f,
X_m	magnetizing reactance per phase at rated f,
X_0	unsaturated value of magnetizing reactance
Y	total admittance
Y_s&Y_r	stator and rotor admittance
Y_L	load admittance
Y_m	magnetizing admittance
Y_C	capacitive admittance

REFERENCES

[1] S. S. Murthy, O. P. Malik and A. K. Tandon, “Analysis of self-excited induction generators”, IEE Proc., Generation, Transmission and Distribution, Vol. 129, No. 6, pp. 260-265, 1982.
[2] G. Raina and O. P. Malik., “Wind energy conversion using a self-excited induction generator”, IEEE Transactions on Power Apparatus and Systems, Vol.102, No. 12, pp. 3933–3936, 1983.
[3] N. H. Malik and S. E. Haque, “Steady state analysis and performance of an isolated self-excited induction generator”, IEEE Trans. on Energy Conversion, Vol. EC-l, No. 3, pp. 134-139, 1986.
[4] L. Quazene and G. McPherson, “Analysis of the isolated induction generator”, IEEE Trans. on Power Apparatus and Systems, Vol. 102, No. 8, pp. 2793-2798, 1983.
[5] N. Ammasaigounden, M. Subbiah and M. R. Krishnamurthy, “Wind-driven self-excited pole-changing induction generators”, IEE Proc. B Electric Power Applications, Vol. 133, pp. 315-321, 1986.
[6] A. I. Alolah and M. A. Alkanhal, “Excitation requirements of three phase self-excited induction generator under single phase loading with minimum unbalance”, IEEE Winter Meeting of Power Engineering Society, Vol. 1, pp. 257-259, 2000.
[7] L. A. Alolah, and M. A. Alkanhal, “Optimization-based steady state analysis of three phase self-excited induction generator”, IEEE Trans. on Energy Conversion, Vol. 15, No. 1, pp. 61-65, 2000.
[8] M. H. Haque, A novel method of evaluating performance characteristics of a self-excited induction generator, IEEE Trans. EC, Vol. 24, No.2, pp. 358–365, 2009.
[9] M. H. Haque, “Comparison of steady state characteristics of shunt, short-shunt and long-shunt induction generators, Electr. Power Syst. Res. Vol.79, pp. 1446–1453, 2009.
[10] K. A. Nigim, M. M. A. Salama and M. Kazerani, “Identifying machine parameters influencing the operation of the self-excited induction generator, Electr. Power Syst. Res. Vol. 69, pp.123–128, 2004.
[11] T. F. Chan and L. L. Lai, “Capacitance requirements of a three-phase induction generator self-excited with a single capacitance and supplying a single-phase load”, IEEE Trans. EC, Vol.17, No.1, pp. 90–94, 2002.
[12] D. Joshi, K. S. Sandhu and R. C. Bansal, "Steady-state analysis of self-excited induction generators using genetic algorithm approach under different operating modes", International Journal of Sustainable Energy, 2011
[13] M. H. Salama and P. G. Holmes, “Transient and steady-state load performance of a stand-alone self-excited induction generator”, IEE Proc. Electric Power Applications, Vol. 143, No. 1, pp. 50-58, 1996.
[14] D. Karaboga, “An Idea Based On Honey Bee Swarm For Numerical Optimization”, Technical Report-TR06, Erciyes University, Engineering Faculty, Computer Engineering Department, 2005.
[15] D. Karaboga and B. Akay, “A comparative study of Artificial Bee Colony algorithm”, Applied Mathematics and Computation, No. 214, pp. 108–132, 2009.