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FLOWER POLLINATION ALGORITHM BASED PERFORMANCE ANALYSIS OF SELF-EXCITED INDUCTION GENERATOR

THANDAVAMURTHY ELANGO[1], AJITHAN SENTHILKUMAR[2]

Key words: Flower pollination algorithm, Graph theory, Performance analysis, Self-excited induction generator.

This paper introduces the flower pollination algorithm (FPA) to perform the analysis of an induction generator in a self-excited mode for stand-alone wind energy conversion scheme. Performance analysis is important to forecast their behavior in real working situations of the generator. The analysis is carried out using loop impedance technique and it is solved by the graph theory methodology. FPA has been used to exploit out the equations to find the unknown quantities like magnetizing reactance, frequency and the operation of the self-excited induction generator (SEIG). MATLAB simulated results using proposed algorithm have been compared with experimental results. It is found that the simulated and experimental results confirm the strength of the technique adopted.

1. INTRODUCTION

Every year the electricity demand of the planet is increasing in multifold. The wind energy is one among the fastest growing energy sources in the universe. The SEIGs are much suitable for small and medium type wind energy conversion systems because they are robust, easily usable, inexpensive, and less maintenance cost when compared to the other generators. The performance of SEIG depends on the exact values of frequency F and the magnetizing reactance X_m. These values are mainly depends on the magnetic saturation of the generator. The performance analysis is really important to design as well as working point of perspective. When the generator is plugged into an infinite bus bar, the terminal voltage and frequency are known, then the calculation of the performance of the machine is straightforward. But in case of the self-excited induction generator used as a stand-alone mode, both the terminal voltage and generated frequency are unknown. In order to determine the performance of the machine, the unknowns have to be computed for a given speed, capacitance and load.

The analysis of an induction generator is made by using either the loop impedance method [1–3] or nodal admittance method [4, 5] using per phase steady state equivalent circuit. These methods are required accurate initial guess and it occupies much time to solve the lengthy algebraic equations to determine the coefficients. Many researchers have proposed different techniques and evolutionary methods to solve the nonlinear equations [6–12], artificial n.eural network [13, 14], genetic algorithm [15, 16], particle swarm optimization algorithm [17], direct algorithm [18], artificial bee colony algorithm [19] and flower pollination algorithm [20] and have been used for the performance analysis of SEIG. Due to randomness, evolutionary methods are popular for optimization techniques. This report demonstrates the implementation of the flower pollination algorithm to forecast the performance analysis of a SEIG under all operating conditions.

2. STEADY STATE MODELING OF SEIG

Figure 1 shows the per phase steady state equivalent circuit of SEIG with load, where the parameters F and v are per unit frequency and speed respectively. R_S, R_R and R_L are the resistances of stator, rotor and load respectively. X_S, X_R, X_m X_C and X_L are the reactances of the stator, rotor, magnetizing, capacitive, and load respectively. V_g and V_t are the air gap and terminal voltage. I_S, I_R, and I_L are stator, rotor and load currents respectively. All the machine parameters are taken to be constant except the magnetizing reactance.

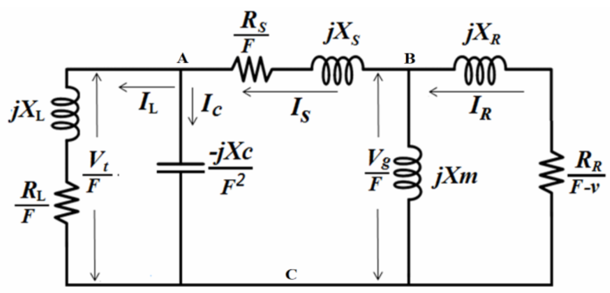

Fig. 1 – Per phase steady state equivalent circuit of SEIG.

From the steady state equivalent circuit, the parameters can be given as [1–3],

$$Z_R = R_R/(F - v) + jX_R$$
$$Z_M = jX_M$$
$$Z_C = -jX_C/F^2$$
$$Z_S = R_S/F + jX_S$$
$$Z_L = R_L/F + jX_L.$$

In this paper, graph theory has been used for developing equations from loop impedance method [7]. The graph is formed by replacing all the passive elements of the equivalent circuit by lines with dots at the ends as shown in Fig. 2.

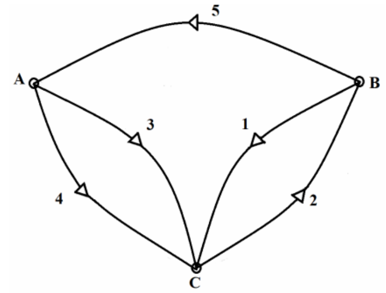

Fig. 2 – Graph of the equivalent circuit.

[1] Anna University, Research Scholar, Department of EEE, Sri Balaji Chockalingam Engg. College, Arni, Tamil Nadu, India, E-mail:telango_arni@yahoo.co.in
[2] SKP Engineering College, Department of EEE, Tiruvannamalai, Tamil Nadu, India

The tree and co-tree are shown in Fig.3.

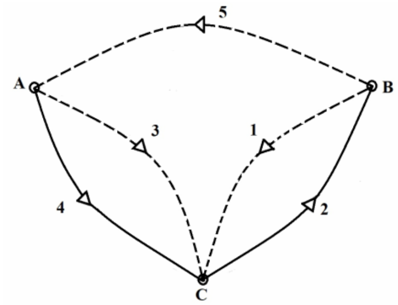

Fig. 3. Tree and co-tree.
Number of tree branches = n–1 = 2
Number of cotree = b–n+1= 3.

By applying the loop method, the balance equation in matrix form is given as,

$$\{[K][Z_b][K]^T\}[I] = [K]\{[V_S] - [Z_b][I_S]\}, \quad (1)$$

where
$[K]$ – tie set matrix,
$[K]^T$ – transposed tie set matrix,
$[Z_b]$ – branch impedance matrix,
$[I]$ – loop current matrix,
$[V_S]$ – voltage matrix.

The tie set matrix of the graph is developed as shown in Table 1.

Table 1

Tie set matrix

Tree branch current	Branches				
	1	2	3	4	5
i_R	1	1	0	0	0
i_S	0	0	1	–1	1
i_L	0	1	0	–1	1

Since there's no electrical source in the equivalent circuit as shown in Fig.1, so the $[V_S] = 0$ and the equation (1) reduced to

$$\{[K][Z_b][K]^T\}[I] = 0 \quad (2)$$

Substitute the branch impedance matrix, tie set matrix and its transpose in the equation (2), after simplification; we get the following matrix,

$$\begin{bmatrix} Z_M + Z_R & 0 & Z_R \\ & Z_C + Z_L & Z_L \\ Z_R & Z_L & Z_R + Z_L + Z_S \end{bmatrix} \begin{bmatrix} i_R \\ i_S \\ i_L \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}.$$

The above equation can also be rewritten as,

$$[Z][I] = [0]. \quad (3)$$

Under steady state, the $I \neq 0$. Therefore, det $[Z]$ must independently zero. This leads to the following non-linear simultaneous equations with X_m and F as the unknown variables.

$$f(X_m, F) = -(c_1 X_m + c_2)F^3 + (c_3 X_m + c_4)F^2 + + (c_5 X_m + c_6)F - (c_7 X_m + c_8) = 0 \quad (4)$$

$$g(X_m, F) = -(d_1 X_m + d_2)F^4 + (d_3 X_m + d_4)F^3 + + (d_5 X_m + d_6)F^2 - (d_7 X_m + d_8)F - d_9 = 0. \quad (5)$$

The coefficients c_1–c_9 and d_1–d_9 are presented in appendix. In this work, FPA is employed to solve these equations to find the values of X_m and F. From the magnetization curve, the induced air gap voltage can be obtained. The stator and rotor current can be calculated as

$$I_S = \frac{V_g / F}{Z_S + \left(\frac{Z_C Z_L}{Z_C + Z_L} \right)} \quad (6)$$

$$I_R = -(V_g / F)/Z_R . \quad (7)$$

The voltage across the load can be calculated as

$$V_t = V_g \left(\frac{Z_C Z_L}{Z_C + Z_L} \right) \Big/ \left(\frac{Z_C Z_L}{Z_C + Z_L} \right) + Z_S . \quad (8)$$

The load current is given as,

$$I_L = V_t / Z_L . \quad (9)$$

The input and output powers can be calculated as

$$P_{in} = -|I_R|^2 v R_R / (F - v) \quad (10)$$

$$P_{out} = |I_L|^2 R_L . \quad (11)$$

Using the above equations (7)–(11) the performance characteristics of the induction generator can be calculated with known values of the machine parameters.

3. FLOWER POLLINATION ALGORITHM

The flower pollination algorithm is one of the nature inspired algorithm which does well for multi objective optimization problems. Pollination considered in this algorithm follows biotic pollination and cross pollination process. Pollination can be sorted out as cross pollination and self-pollination. The cross pollination occurs from different flowers, and the self-pollination occurs between different flowers in the same plant. Certain insects and bees can have levy weight behavior, they jump or fly distance obey levy distribution. Some pollinators have established flower constancy. This flower constancy increases the pollination process in certain flower and thus increasing the reproduction.

Flower constancy also provides an assurance of nectar for the pollinators with minimum effort of learning, exploration and development. A set of the N flower population is provided by random solutions. The best solution is found from the initial population using the flower pollen localization algorithm by iteration. The flower which has the best fitness value is taken. The flower which has the minimum localization error is called global flower. Generate a random position if this value is less than the switching probability, then the global pollination procedure is carried out else local flower pollination is considered.

FPA uses the following rules:

1. Biotic and cross pollination is considered for global pollination.
2. Abiotic and self-pollination is considered for local pollination.
3. Reproduction probability depends on flower constancy.
4. Switching probability controls the switching of local and global pollination.

The process of implementing flower pollen localization algorithm constitutes: encoding, fitness function, global pollination, local pollination and stopping criteria. Flower pollen optimization starts with an encoding; it is the process of converting objective function into the fitness function and initializing the control variables. The control variables are converted into flower pollen optimization problem. A set of the *N* flowers population is initialized. Population depends on problem complexity. Initial population is created by generating random values of the location within the solution space. The population size is fixed and does not change till the solution reached.

For the evolution and better convergence fitness function is most important as follows. An appropriate fitness function is vital for the operation, evolution and convergence of the flower localization algorithm. It includes all the objective function and penalty functions, if any. Flower pollen localization algorithm evaluates the fitness function for each flower in the population. The flower which receives the best fitness value is considered as the global flower. A random location sequence is generated, if the value is lesser than the switching probability global pollination is carried out otherwise local pollination is considered.

The local pollination is derived from the abiotic and self-pollination process. The flower constancy is equivalent to the reproduction probability. The local pollination is carried out by the following equation

$$F_i^{n+1} = F_i^n + \in \left(F_j^n - F_k^n \right), \tag{12}$$

where F_i^n – i th pollen at t iterations; $\in$ takes a value of [0, 1]; F_j^n and F_k^n pollen from different flowers from same plant. Global pollination follows the rule of biotic and cross pollination and the reproduction probability depends on flower constancy. The global pollination is carried out by the equation

$$F_i^{n+1} = F_i^n + \gamma L \left(F_g - F_i^n \right), \tag{13}$$

where F_i^n – i th pollen at t iterations; γ – scaling factor that controls the step size; L – step size that corresponds to the strength of pollination, which is, a levy weight based step size; F_g– current best solution at current iteration.

FPA improves localization problems solution iteration by iteration and the iteration has to be stopped with either the problem is converged or iteration reached its maximum value. Stopping of iteration is important to provide solution for time complexity. Moreover the algorithm code has taken lesser time while execution. In this research work maximum numbers of iterations are considered as stopping criteria. The stopping criterion should be selected in such a way to get the optimal location information value with required accuracy for the localization problem. The flow chart explains the fundamental steps of FPA shown in Fig. 4.

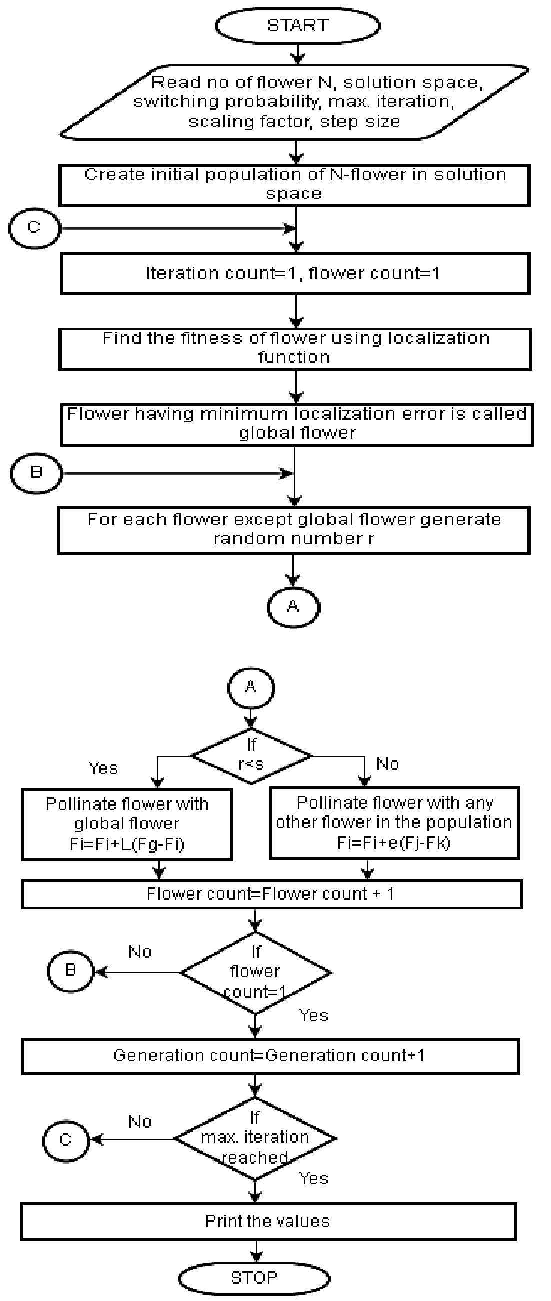

Fig. 4 – Flowchart of FPA.

4. PERFORMANCE ANALYSIS OF SEIG USING FPA

The flower pollination algorithm is becoming a popular method for optimization, because it has many advantages over other optimization methods. It is robust, lesser computing time to find global minimum, does not require accurate initial estimates and detailed derivations of analytical equations. The two unknowns X_m and F are determined by optimizing (minimizing) the objective function. The equation (4) is considered as objective function of the system. A flower has a set of control variables; in this approach two control variables X_m and F are considered. Hence a flower has two values corresponds to X_m and F. A population has set of flowers; in this research work 20 such flowers are considered. The objective is to minimize the total impedance by optimizing these control variables. But these control variables X_m and F

have minimum and maximum limits which form the lower and upper boundary of these control variables.

Two types of pollination, such as local and global pollination may take place for each flower in the population of 20 flowers. In global pollination, levy flight movement is considered and it is mimicked using levy flight constant L. For each loading (R_L), a flower population is initialized. The objective function for the individual flower in the population is calculated. The flower having the minimum objective value is considered as global flower. This global flower and levy flight, constant is used for the global pollination. The pollination of the flower is decided by generating a random number for the flower if this number is less than the switching probability, then the global pollination process is carried out otherwise local pollination is considered for the flower. After pollination again the flower has 2 control variables X_m and F. The pollination process is repeated till the maximum number of iterations is reached. After the maximum number of iterations is executed, the global flower gives the best value of X_m and F, which gives the minimum value of total impedance.

The computing procedure is as follows:

1. Initialize all parameters of flower pollination algorithm such number of flowers, switching probability, step size, λ, maximum number of iterations and read machine data such as: R_S, R_R, X_S, X_R, speed and capacitance.
2. Create an initial population of flower which has X_m and F, and these values should be within its minimum and maximum range.
3. To find the objective function, the equation (1) is considered as total impedance. The flower's value of X_m and F is used to compute c_1 to c_8 and d_1 to d_9 and these values are used to compute total impedance value.
4. The flower having minimum objective value is considered as global flower and used for global pollination.
5. The equations (7)–(11) is used to determine the performance characteristics, such as stator current, terminal voltage, input and output power of the machine, for different values of R_L, the process is repeated to obtain their corresponding best value of X_m and F.

5. RESULTS AND DISCUSSION

A 3-phase, 0.75 kW, 415 V, 1.8 A, 50 Hz, star-connected squirrel cage induction machine coupled with 5 HP DC machine is used for testing purposes. The SEIG parameters in per-unit is given as, $R_S = 0.149$, $R_R = 0.063$, $X_S = 0.196$, $X_R = 0.127$, $X_C = 1.0$ and $\nu = 1.0$. The third-order polynomial equation of X_m was obtained from the synchronous impedance test results. The experiments are conducted to confirm the hardiness of an execution of FPA for analysis of SEIG and also the results are compared with simulation results.

Figure 5 shows the simulation and experimental results for typical load characteristics of terminal voltage with output power for fixed excitation capacitance, unity power factor and a constant wind speed. The voltage decreases as the output power increases in corresponding to a reduction of load impedance from infinity, this shows a stable area, and it continues until the maximum power level reached. A further decrease of load impedance decreases both the terminal voltage and output power; this presents an unstable region of a SEIG. It is evident that the terminal voltage decreases with the load. Thus, the additional excitation capacitor is needed to keep the terminal voltage constant. The no-load generated voltage of simulated and experimental values is about the same. It is observed that the experimental results are marginally lower than a simulation result.

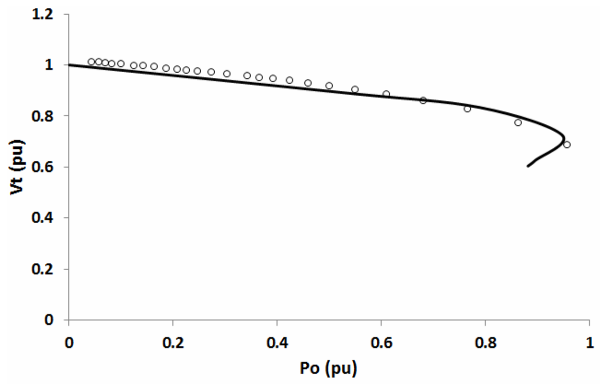

Fig. 5 – Variations of terminal voltage to output power '–' experimental result, 'o' simulation result.

Figure 6 shows the terminal voltage decreases with the increase in the load. It illustrates that the experimental values are very close to the corresponding simulation results.

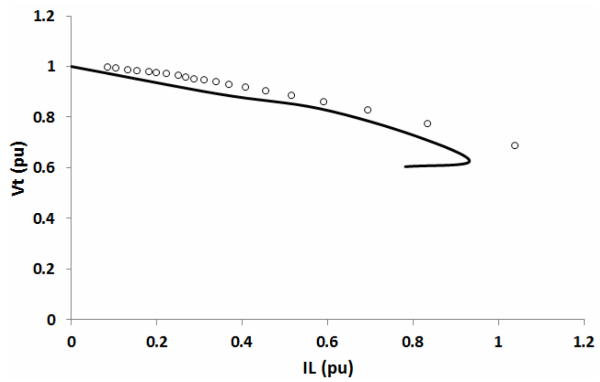

Fig. 6 – Variations of terminal voltage to load current '–' experimental result, 'o' simulation result.

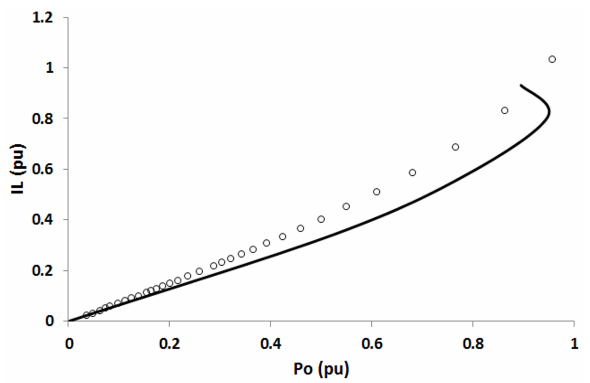

Fig. 7 – Variations of load current to output power. '–' experimental result, 'o' simulation result.

It is observed that from Fig. 7. The load current increases linearly with output power. The maximum generated power is around 670 W without exceeding the rated current of the machine. Figure 8 shows the capacitive current decreases with the load. Consequently, it takes an additional excitation capacitor for reactive power support.

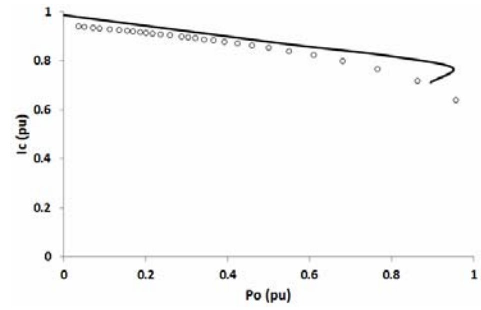

Fig 8 – Variations of capacitive current to output power '–' experimental result, 'o' simulation result.

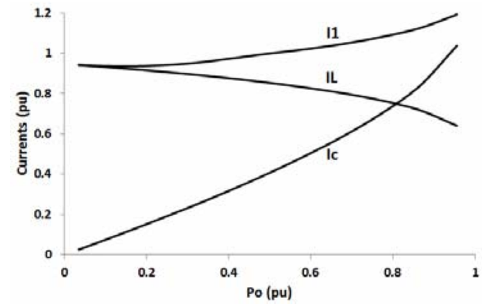

Fig 9 – Variations of current to output power – simulation results.

Figure 9 shows simulation results of variation in I_1, I_C and I_L against P_o and it shows that, in the normal operating region, I_L increases with P_o, because of the decrease of terminal voltage. I_1 is the phasor sum of I_C and I_L, it is unresponsive to P_o. The reduction of IC is moderately compensated by I_L, this is the reason for I_1 is almost remain constant.

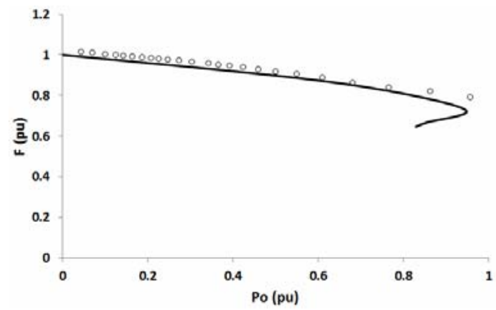

Fig 10 – Variations of frequency with output power '–' experimental result, 'o' simulation result.

From Fig. 10, it is noticeable that the frequency decreases with the increase in the load. The experimental results are very close to the simulation result.

The convergence curve for the FPA is shown in Fig. 11.

Figure 12 depicts the photograph of the experimental setup. Table 3 shows the values of X_m and F obtained for different values of capacitance and load from FPA method.

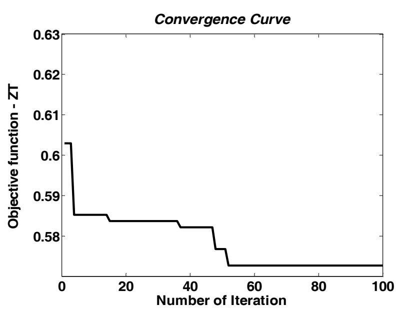

Fig. 11 – Flower pollination algorithm convergence curve.

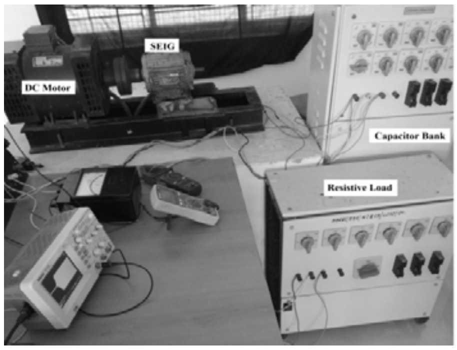

Fig 12 – Experimental setup.

Table 2

Parameters of flower pollination algorithm

Parameters	Values
No. of flowers	20
Maximum iteration	100
Step size	6
Switch probability (p)	0.5
Constant (λ)	1.5
Scaling factor	0.6
Step size (gamma)	0.01

Table 3

Values of *Xm* and *F* obtained from FPA method

S.No.	Load	V = 1.0 p.u., p.f = 1.0			
		C = 0.8025 pu		*C* = 1 pu	
		X_m	F	X_m	F
1	100	1.2577	0.9944	0.9257	0.9919
2	10	1.3591	0.9709	1.1591	0.9733
3	50	1.4611	0.9668	1.3611	0.9627
4	2	1.6368	0.9587	1.5368	0.9465
5	1.46	1.9194	0.9469	1.8294	0.9259

6. CONCLUSION

In this paper, the graph theory based mathematical model from loop impedance method is used for analysis of SEIG. Flower pollination algorithm was implemented to obtain the optimized values of magnetizing reactance, frequency and the performance analysis of SEIG. This algorithm has a better convergence speed. The simulation results are compared with experimental results and it is found that the simulation results are in accord with experimental results.

APPENDIX

$$c_1 = R_L(X_R + X_S) + X_L(R_S + R_R);$$
$$c_2 = (X_S X_R R_L) + X_L(R_R X_S + R_S X_R);$$
$$c_3 = v(c_1 - R_R X_L);$$
$$c_4 = vX_R(X_L R_S + R_L X_S);$$
$$c_5 = X_C(R_S + R_R + R_L);$$
$$c_6 = X_C\{R_R(X_S + X_L) + X_R(R_S + R_L)\} + (R_S R_R R_L);$$
$$c_7 = vX_C(R_S + R_L);$$

$c_8 = X_R c_7$;
$d_1 = X_L(X_S + X_R)$;
$d_2 = X_L X_S X_R$;
$d_3 = v d_1$;
$d_4 = v d_2$;
$d_5 = X_C(X_S + X_R + X_L) + R_L(R_S + R_R)$;
$d_6 = X_C X_R(X_S + X_L) + R_L(R_S X_R + R_R X_S) + R_S R_R X_L$
$d_7 = v(d_5 - R_R R_L)$
$d_8 = v(d_6 - R_R(X_S R_L + R_S X_L))$; $d_9 = R_R X_C(R_S + R_L)$.

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REFERENCES

1. S.S. Murthy, O.P. Malik, A.K. Tandon, *Analysis of self-excited induction generators*, IEE Proc., Pt-C **129**, *6*, pp. 260–265 (1982).
2. S.P. Singh, B. Singh, M.P. Jain, *Performance characteristics and optimal utilization of a cage machine as capacitor excited induction generator*, IEEE Trans., EC **5**, *4*, pp. 679–685 (1990).
3. A.K. Al Jabri, A.I. Alolah, *Limits on the performance of the three phase self-excited induction generators*, IEEE Trans., EC **5,** *2*, pp. 350–356 (1990).
4. L. Ouazene, G. McPherson, *Analysis of the isolated induction generator*, IEEE Trans., PAS **102**, *8*, pp. 2793–2798 (1983).
5. T.F. Chan, *Analysis of self-excited induction generators using an iterative method*, IEEE Trans., EC **10**, *3*, pp. 502–507 (1995).
6. G.K.Singh, A. Senthil Kumar, R.P. Saini, *Steady-state modeling and analysis of six-phase self-excited induction generator for renewable energy generation,* Electric Power Components and Systems, **38**, *2*, pp. 137–151 (2009).
7. Sambaran Ray, S.N. Mahato, N.K. Roy, *Performance analysis of isolated 3-phase self-excited induction generator using graph theory and PSO technique*, TENCON 2014–2014 IEEE Region 10 Conference; IEEE, 2014.
8. T.F. Chan, *Self-Excited Induction Generators Driven by Regulated and Unregulated Turbines*, IEEE Trans. Energy Conversion, **11**, *2*, pp. 338–342 (1996).
9. L. Alolh, M.A. Alkanhal, *Optimization-Based Steady State Analysis of Three Phase Self-Excited Induction Generator'*, IEEE Trans. Energy Conversion, **15**, *1*, pp. 61–65 (2000).
10. K.A. Nigim, M.M. Salama, M. Kazerani, *Solving Polynomial Algebraic Equations of the Stand Alone Induction Generator*, International Journal of Electrical Engineering Education, **40**, *1*, pp. 45–54 (2003).
11. K. Gurung, P. Freere, *Matlab Symbolic Computation for The Steady State Modelling of Symmetrically Loaded-Self Excited Induction Generator*, Kathmandu University Journal of Science, Engineering and Technology, **I**, *III* (2007).
12. M.H. Haque, *A Novel Method of Evaluating 15] D. Joshi, K.S. Sandhu, M.K. Soni, Performance analysis of three-phase self-excited induction generator using genetic algorithm*, Electr. Power Syst. Res., **34**, pp. 461–470 (2006).
13. D. Joshi, K.S. Sandhu, M.K. Soni, *Performance Analysis of Self- Excited Induction Generator Using Artificial Neural Network*, Iranian Journal of Electrical and Computer Engineering, **5**, *1*, pp. 57–62 (2006).
14. Raja Singh Khela, R.K. Bansal, K.S. Sandhu, A.K. Goel, *Cascaded ANN for Evaluation of Frequency and Air-gap Voltage of Self-Excited Induction Generator*, World Academy of Science, Engineering and Technology, **27**, pp. 301–307 (2007).
15. D. Joshi, K.S. Sandhu, M.K. Soni, *Performance analysis of three-phase self-excited induction generator using genetic algorithm*, Electr. Power Syst. Res., **34**, pp. 461–470 (2006).
16. J. 16. Radosavljevic, D. Klimenta, M. Jevtic, A genetic algorithm-based approach for a general steady-state analysis of three-phase self-excited induction generator, Rev. Roum. Sci. Techn. – Electrotechn. et Energ., **57**, pp. 10–19 (2012).
17. H.E.A. Ibrahim, M.M. Metwaly, M.F. Serag, *Analysis of Self Excited Induction Generator using Particle Swarm Optimization*, World Academy of Science, Engineering and Technology, **57**, pp. 236–240 (2011).
18. Kheldoun, Aissa, Larbi Refoufi, Djalal Eddine Khodja. *Analysis of the self-excited induction generator steady state performance using a new efficient algorithm.* Electric Power Systems Research, **86**, pp. 61–67 (2012).
19. A. Sharma, *Performance analysis of self-excited induction generator using Artificial Bee Colony algorithm*, World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, **8**, *6*, pp. 980–985 (2014).
20. Yang, Xin-She, Mehmet Karamanoglu, Xingshi He, *Flower pollination algorithm: a novel approach for multi objective optimization,* Engineering Optimization, **46**, *9*, pp. 1222–1237 (2014).