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Genetic Algorithm based Steady-State Analysis of Three-Phase Self-Excited Induction Generators

S. Singaravelu, S. Sasikumar

Abstract—This paper presents a genetic algorithm based steady-state analysis of a three-phase self-excited induction generator (SEIG) for wind energy conversion. A generalized mathematical model based on inspection is developed for a three-phase induction generator for steady-state analysis. The proposed mathematical model is quite general in nature and can be implemented for any type of load such as resistive or reactive load. The proposed model completely avoids the tedious work of segregating real and imaginary components of the complex impedance of the equivalent circuit. Also, any equivalent circuit component can be easily included or eliminated from the model, if required. To carry out the steady-state analysis of SEIG, a genetic algorithm approach is used to find the unknown variables using the proposed model. The parameter sensitivity analysis of the generator is also carried out. The computed performance characteristics of the machine are compared with the experimentally obtained values on a laboratory machine, and a good correlation is observed.

Index Terms - Genetic algorithm, Induction generator, Self-excitation, Steady-state analysis.

I. INTRODUCTION

Utilities in many developing countries are finding it difficult to establish and maintain remote rural area electrification. The cost of delivering power such areas are becoming excessively large due to large investments in transmission lines for locally installed capacities and large transmission line losses. For these reasons, distributed power generation has received attention in recent years for remote and rural area electrification. Thus suitable stand-alone systems using locally available energy sources have become a preferred option. With increased emphasis on eco friendly technologies, the use of renewable sources such as small hydro, wind and biomass is being explored [1], [2]. The self-excited induction generators (SEIG) are used for such applications because of its advantages such as low unit and running cost, free from current collection problems, ruggedness and self protection against large over loads and short circuit faults. Therefore the study of self-excited induction generator has regained importance.

Most of the methods available in literature [3] – [6] on steady-state performance evaluation of SEIG need separation of real and imaginary component of complex impedance. Moreover, the model becomes complicated if any equivalent circuit component is included or excluded. It is also observed that the mathematical model is different for each type of loads and also capacitor configuration at the machine terminals. Subsequently, the coefficients of mathematical model are also bound to change with change in load, and capacitance configuration at the machine terminals. The author made an attempt for the first time to overcome the complication of SEIG model [7], [8] by introducing the concept of graph theory which reduces the lengthy and tedious mathematical derivations of nonlinear equations.

In the present paper, the author has developed a further simplified mathematical model of SEIG in matrix form using nodal admittance method based on inspection. In this model, the nodal admittance matrix can be formed directly from the equivalent circuit of SEIG rather than deriving it from the concept of graph theory. The proposed mathematical model in matrix form completely avoids the work involved in the existing models. Since the model is in matrix form, any equivalent circuit component can be easily included or eliminated from the model. Also the added advantage of this model is the leakage reactance of stator (X_{ls}) and rotor (X_{lr}) can be handled separately if needed, by avoiding the assumption $X_{ls}=X_{lr}$ without any modification in the model. The developed genetic approach uses general mathematical model of SEIG and the same model can be implemented for any type of load and any combinations of unknown variables such as magnetizing reactance (X_M) and frequency (F) or capacitive reactance (X_C) and frequency (F). Having known the magnetizing reactance and frequency, the performance of the machine for the given capacitance is computed at a given value of load and speed. Similarly, knowing the value of capacitive reactance and frequency, the excitation requirement and performance characteristics of the machine are computed for a desired value of terminal voltage under varying load and speed conditions. The computed results of a laboratory machine are compared with the corresponding experimental results and are found to be good agreement with them. Parameter sensitivity on the steady-state performance of SEIG is also investigated. These results may provide guidelines to the design of the machine as induction generator which is used in wind energy conversion.

II. PROPOSED MATHEMATICAL MODEL

The steady-state equivalent circuit of the self-excited induction generator with two nodes is shown in Fig. 1.

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S. Singaravelu, Department of Electrical Engineering, Annamalai University, Chidambaram, India, (e-mail: ganapss@yahoo.com).
S. Sasikumar, Department of Electrical Engineering, Annamalai University, Chidambaram, India, (e-mail: ssasikumar77@yahoo.co.in).

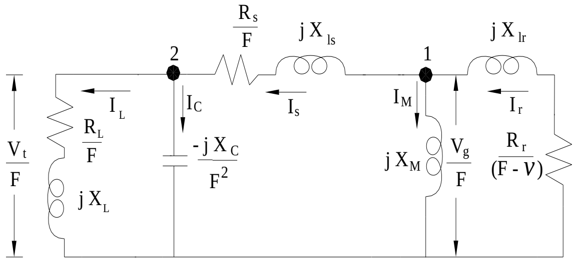


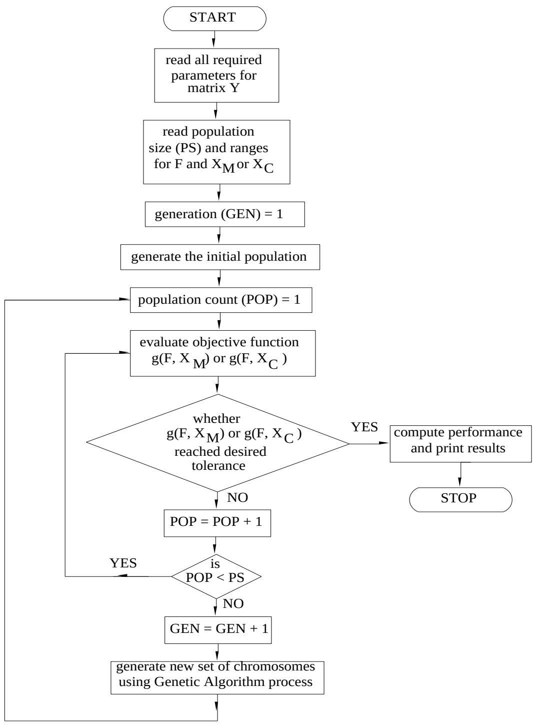
Fig. 1. Steady-state equivalent circuit of self-excited induction generator.

The various elements of equivalent circuit are given below.

$Y_R = 1 / \{R_r / (F - \upsilon) + j X_{lr}\}$; $Y_M = 1 / \{j X_M\}$;

$Y_S = 1 / \{R_s / F + j X_{ls}\}$; $Y_C = 1 / \{- j X_C / F^2\}$;

$Y_L = 1 / \{R_L / F + j X_L\}$;



The matrix equation based on nodal admittance method for the equivalent circuit can be expressed as

$$[Y]\,[V] = [I_S] \qquad (1)$$

Where [V] is the node voltage matrix,

$[I_S]$ is the source current matrix, and

[Y] is the nodal admittance matrix.

The [Y] matrix can be formulated directly from the equivalent circuit (Fig. 1) by inspection [9] as

$$[Y] = \begin{bmatrix} Y_S + Y_M + Y_R & - Y_S \\ - Y_S & Y_S + Y_C + Y_L \end{bmatrix} \qquad (2)$$

where

$Y_{ii} = \sum$ Admittance of the branches connected to i^{th} node

$Y_{ij} = - \sum$ Admittance of the branches connected between i^{th} node and j^{th} node

Since, the equivalent circuit does not contain any current sources, $[I_S] = [0]$ and hence (1) is reduced as

$$[Y]\,[V] = 0 \qquad (3)$$

For successful voltage build up, $[V] \neq 0$ and therefore from (3), [Y] should be a singular matrix i.e., determinant of [Y] = 0. It implies that both the real and the imaginary components of det [Y] should be independently zero. Therefore to obtain required parameter which results det [Y] = 0, genetic algorithm based approach is implemented.

III. APPLICATION OF GENETIC ALGORITHM FOR STEADY-STATE ANALYSIS OF SEIG

Application of genetic algorithm [10] to obtain det[*Y*] = 0, which provides solution for unknown quantities, is illustrated in Fig. 2. The objective function whose value is to be minimized is given by (4).

$$g\,(F, X_M \text{ or } X_C) = \text{abs}\{\text{real}(\det[Y])\} + \text{abs}\{\text{imag}(\det[Y])\} \qquad (4)$$

In many optimization problems to obtain initial estimates suitably, certain trials may be required. However, in the present problem of the SEIG, it is easy to give the range for the unknown variables F and X_M or X_C because in well-designed self-excited induction generators, it is known that the slip $\{(F - \upsilon)/F\}$ is small and operation of the machine is only in the saturated region of the magnetization characteristics. So, the ranges for F can be given as 0.8 to 0.999 times the value of υ and for X_M as 25% to 100% of critical magnetizing reactance X_{MO}. Similarly for X_C, the same range 25% to 100% of C_{MAX} can be used, where C_{MAX} is the maximum capacitance required under any conditions. Thus, starting from such initial estimates, the final value of F and X_M or X_C is obtained through GA. The air gap voltage V_g can be determined from the magnetization characteristics corresponding to X_M, as described in Section IV. Once the air gap voltage V_g is calculated, the equivalent circuit can be completely solved to determine the steady-state performance of SEIG.

IV. EXPERIMENTAL SET UP AND MACHINE PARAMETERS

The rating of the machine under study is 4-pole, 50 Hz delta connected stator winding rated 5 HP, 230V, 12.5A and the practical setup is shown in Fig. 3. Theoretical computations are carried out in per unit, using the following particulars of the machine:

Fig. 3. Self-excited Induction Generator driven by D.C. Shunt Motor (Left) and capacitor bank (Right).

V_{base} = rated phase voltage = 230 V
I_{base} = rated phase current = $12.5/\sqrt{3}$ = 7.217 A
Z_{base} = V_{base} / I_{base} = 31.87 ohms
Base power $P_{base} = V_{base} * I_{base}$ = 1.66 kW
Base speed N_{base} = 1500 rpm
Base frequency f_{base} = 50 Hz

The measured machine parameters are:

R_S = 0.0678 p.u, R_r = 0.0769 p.u
$X_{ls}=X_{lr}$=0.1204 p.u (at rated current)

To determine the magnetizing reactance at different air gap voltage V_g, the machine was driven at synchronous speed by the dc motor, and the input impedance per phase was measured at different input voltages. As we need the variation of X_M with the air gap flux, proportional to V_g/F, it is necessary to calculate the air gap voltage by subtracting the voltage drop in the stator leakage impedance from the input voltage and X_M at each voltage is obtained by subtracting the stator leakage impedance from the measured input impedance. Fig. 4 shows the experimental results relating V_g/F with X_M. Because we need to know the values of V_g for a particular X_M, X_M has been taken as the independent variable. The variation of V_g/F with X_M will be nonlinear due to magnetic saturation. To simplify the analysis, the variation under the saturated region can be made linear as shown in Fig. 4. The function may be expressed as (5) and this relation can be incorporated in the computer program.

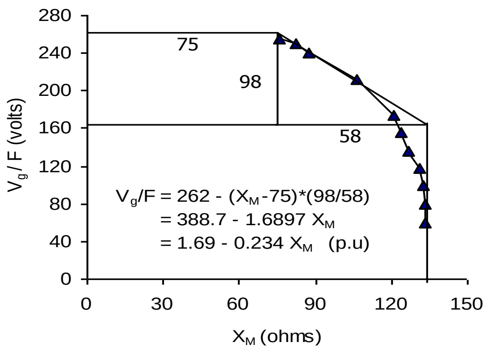


Fig. 4. Variation of air gap voltage with magnetizing reactance.

$$V_g/F = 1.69 - 0.234\ X_M \qquad (5)$$

V. RESULTS AND DISCUSSION

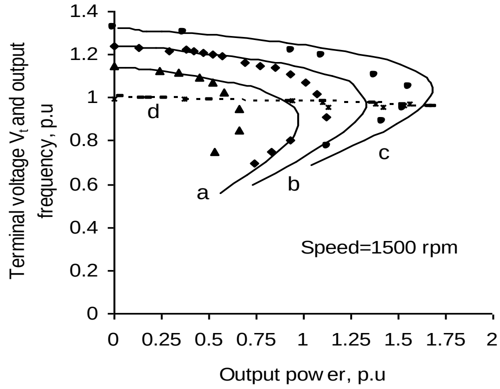
Generally the steady-state performance of the self-excited cage induction generator is to be computed for two operating conditions. In one case, the performance of the machine (load characteristics) could be computed in terms of terminal voltage, output power, stator and rotor current etc., for given value of capacitance, load and speed (X_M & F are unknown). In another case, the capacitance requirements could be computed of the machine for a desired value of terminal voltage with a given value of load and speed (X_C & F are unknown).

The following two steady-state analysis of SEIG and parameter sensitivity analysis is presented using the generalized mathematical model and genetic algorithm based approach as discussed in Sections II and III respectively.

- Load characteristics. (X_M & F are unknown)
- Capacitance requirements. (X_C & F are unknown)
- Parameter sensitivity analysis.

A. Load Characteristics

To obtain the load characteristics, magnetizing reactance X_M and frequency F are selected as unknown variables. Solve for det [Y] and find the unknown variables X_M and F using proposed model and the genetic algorithm discussed in sections II and III respectively.



(a) Terminal voltage for Xc=3.066 p.u with experimental points
(b) Terminal voltage for Xc=2.628 p.u with experimental points
(c) Terminal voltage for Xc=2.299 p.u with experimental points
(d) Output frequency F for Xc=2.299 p.u with experimental points

Fig. 5. Load characteristics for unity power factor loads.

The load characteristics of the induction generator, indicating the variation of terminal voltage and frequency with output power is shown in Fig. 5. The terminal voltage for three different values of fixed X_C at constant speed υ =1.0 p.u is shown in Fig. 5. It is observed that the terminal voltage drops with increase in load. The agreement between predicated and measured terminal voltage is best for highest value of C (lower value of X_C). At lower value of C (higher value of X_C), measured maximum output power is considerably lower than the predicted results. However, the general pattern of the measured load characteristics is as predicted. Fig. 5 also indicates the variation of output frequency with load for X_C =2.299 p.u. Frequency drops to about 4% from no load to a load of about 1.7p.u. A close agreement between calculated and measured values can be seen.

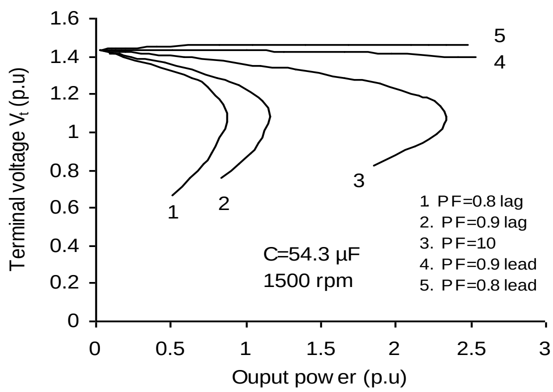
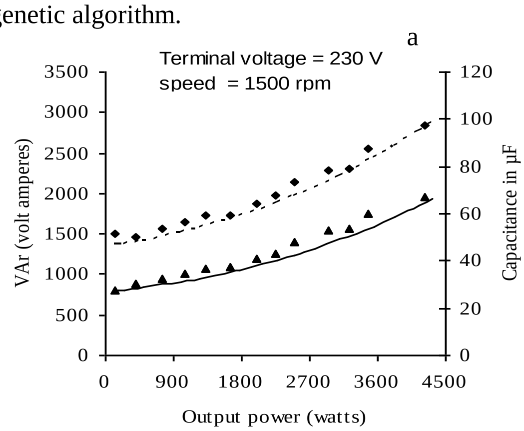


Fig. 6. Calculated Load characteristics for different power factor loads.

Fig. 6 shows the load characteristics of the induction generator with output power for different power factors for fixed capacitance of 54.3 µF at constant speed of 1500 rpm. From the Fig. 6, it is observed that the terminal voltage drops with load is more pronounced with lagging power factor load than unity and leading power factor loads.

B. Capacitance Requirements

Here the selected unknown variables are capacitive reactance X_C and frequency F. To obtain the excitation requirement to maintain the required terminal voltage under varying load conditions, det [Y] is solved and the unknown variables X_C and F are found out using the proposed model and genetic algorithm.



(a) Capacitance: theoretical with experimental points, and

(b) VAr: theoretical with experimental points

Fig. 7. Variation of Capacitance and VAr for constant terminal voltage at rated speed for unity power factor loads.

The variation of reactive power in terms of reactive VAr and capacitance with output power for constant terminal voltage at rated speed is shown in Fig. 7. It is observed that the value of capacitance and VAr increases with output power in order to maintain constant terminal voltage. It may also be seen that for an increase in output power of the machine at rated speed, the reactive VAr has to vary continuously for regulating the machine terminal voltage. Such data can provide suitable guidelines for the design of voltage regulating system to keep the terminal voltage constant by varying effective capacitive reactance continuously.

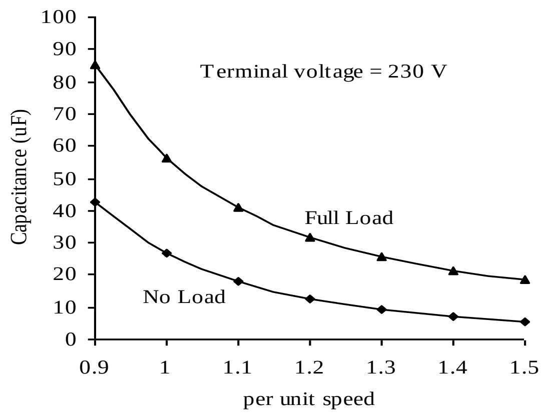


Fig. 8. Calculated capacitance Vs. per unit speed characteristics at constant terminal voltage for unity power factor loads.

For the variable speed prime mover, the effect of speed on the excitation requirements by the machine is also analyzed. Fig. 8 shows the variation of speed with capacitance value to maintain constant rated terminal voltage under no load and loaded condition of the machine. It may be noted that the speed increases, the capacitance requirements are reduced at full load and no load. It is also observed that the machine requires higher value of capacitance at full load compared to no load condition of the generator.

C. Parameter Sensitivity Analysis

The validity and usefulness of the proposed model (described in section II) is tested by applying the model to investigate the parameter sensitivity on steady-state performance of three-phase SEIG. In this section, families of load characteristics are presented by varying one machine parameter at a time and keeping the other parameters constant. These results may provide guidelines to the design of the machine and for identifying the sensitive parameters.

Fig. 9 shows the load characteristics for different values of stator resistance equal to KR_S, where R_S is the actual stator resistance of the machine. Results are provided for K = 0.7, 1.0 and 1.3. Increased stator resistance causes more drooping characteristics and decreases the maximum output power. Thus, it is desirable to choose a minimum possible value of R_S, even though its effect is not very appreciable.

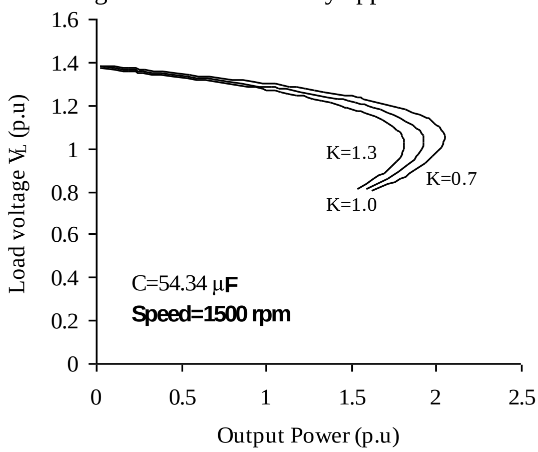


Fig. 9. Effect of stator resistance.

Fig. 10 shows the family of load characteristics for different values of leakage reactance ($X_{ls} = X_{lr} = X_l$) equal to KX_l, where X_l is the actual leakage reactance of the machine. Results are provided for K = 0.7, 1.0 and 1.3.

For a given capacitance and speed there is one value of output power for which V_L is independent of X_l. Leakage reactance is also not a very sensitive parameter.

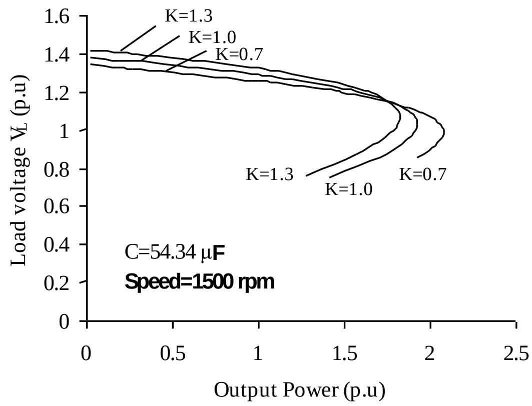


Fig. 10. Effect of leakage reactance.

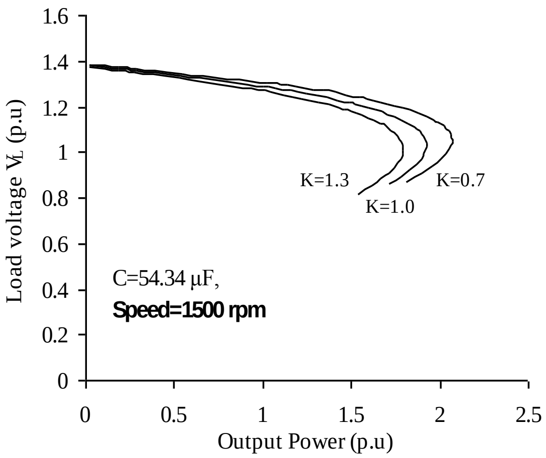


Fig. 11. Effect of rotor resistance.

Fig. 11 shows the family of load characteristics for different values of rotor resistance equal to KR_r, where R_r is the actual rotor resistance of the machine. Results are provided for K = 0.7, 1.0 and 1.3. Increase in R_r decreases V_L and the maximum output power. Therefore, in designing the generator, minimum possible R_r can be chosen, a criterion that cannot always be used in motor design owing to starting requirements.

It is apparent that the magnetization characteristics indicated by the variation of X_M with air gap flux, has an important bearing on the load characteristic. Both the saturated and unsaturated magnetizing reactance can be changed by appropriate alteration in design. The variation of saturated X_M can be approximately represented by a linearized equation similar to (6). The constant K_1 and K_2 are varied one at a time with a factor K = 0.9, 1.0 and 1.1.

$$V_g = (K_1 * K) - (K_2 * K) * X_M \quad (6)$$

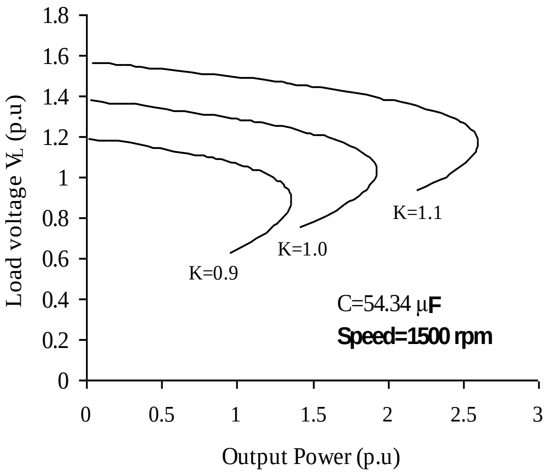


Fig. 12. Effect of magnetizing reactance, $K_1 = K * K_1$ (nominal).

Fig. 12 shows the family of characteristics for different values of K_1 equal to $K * K_1$, Results are provided for K = 0.9, 1.0 and 1.1. From Fig. 12, it is observed that the increase in K_1 and consequent X_M causes increased load voltage and maximum power output. These variations are quite pronounced. Voltage almost doubles for output power of 1p.u, if K is changed from 0.9 to 1.1.

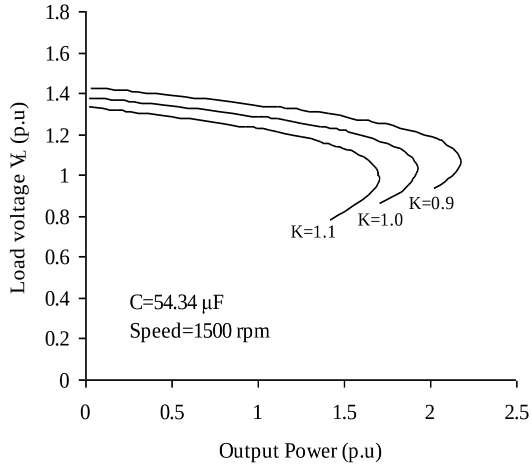


Fig. 13. Effect of magnetizing reactance, $K_2 = K * K_2$ (nominal).

Fig. 13 shows the family of characteristics for different values of K_2 equal to $K * K_2$, Results are provided for K = 0.9, 1.0 and 1.1, K_2 seems to be a less sensitive parameter than K_1. The increase in K_2 and consequent X_M causes decreased load voltage and maximum power output.

It is clear from the above graphs that, using increased X_M, the connected capacitance can be decreased for the same V_L. For the same air gap flux, X_M can be varied by changing the frame, number of turns, etc. A designer has to compare the economy of choosing a larger frame or a higher valued capacitor for the desired output voltage.

VI. CONCLUSION

This paper presented a generalized mathematical model and a genetic algorithm based computation of steady-state performance of SEIG for different operating conditions. The proposed model avoids extensive efforts in separating real and imaginary components of the complex impedance of the equivalent circuit. Also the model is generalized wherein an element of the equivalent circuit can be included or eliminated from the model easily. The results are projected keeping X_M and F as unknowns to determine the performance of SEIG under specified X_C and speed. Also X_C and F are considered as unknown variables, to calculate the capacitance requirements to maintain terminal voltage constant under varying load and speed conditions. For the above two operating modes mentioned, the same proposed mathematical model can be used. This indicates that the proposed model is so flexible to choose the necessary unknown variables. Also, the parameter sensitivity analysis which is useful in designing the generator is presented. The computed results obtained by proposed method have been verified with experimental results and found to be good agreement with them.

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REFERENCES

1. M. Abdulla, V.C. Yung, M. Anyi, A. Kothman, K.B. Abdul Hamid, and J. Tarawe, "Review and comparison study of hybrid diesel/solar/hydro/fuel cell energy schemes for rural ICT Telecenter," *Energy*, Vol. 35, pp. 639-646, 2010.
2. R.C. Bansal, "Three-phase self-excited induction generators: An overview," *IEEE Trans. Energy Conversion*, Vol. 20, pp. 292-299, 2005.
3. M.I. Mosaad, "Control of self excited induction generator using ANN based SVC," *International Journal of Computer Applications*, Vol. 23, pp. 22-25, 2011.
4. S.P. Singh, K. Sanjay, Jain, and Sharma, "Voltage regulation optimization of compensated self-excited induction generator with dynamic load," *IEEE Trans. on Energy Conversion*, Vol. 19, pp. 724-732, 2004.
5. Tarek Ahmed, and Mutsuo Nakaoka, "Static VAr compensator based terminal voltage control for stand-alone ac and dc outputted self excited induction generator," *IEE Proc.* pp. 40-45, 2004.
6. T.F. Chan, and L.L Lai, "A novel excitation scheme for a stand-alone three-phase induction generator supplying single phase loads," *IEEE Trans. on Energy Conversion*, Vol. 19, pp.136-142, 2004.
7. S. Singaravelu, and S. Velusami, "Capacitive VAr requirements for wind driven self-excited induction generators," *Energy Conversion and Management*, Vol. 48, pp.1367-1382, 2007.
8. S. Velusami, and S. Singaravelu, "Steady state modeling and fuzzy logic based analysis of wind driven single-phase induction generators," *Renewable Energy*, Vol. 32, pp. 2386-2406, 2007.
9. M.E. Van Valkenburg, *Network Analysis*, Third Edition, Prentice Hall of India Pvt. Ltd., New Delhi, 1994.
10. D.E. Goldberg, Genetic algorithm in search, optimisation, and machine learning, Pearson Education, New Delhi, 2001.