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Genetic Algorithm Based Performance Analysis of 3-phase Self Excited Induction Generator

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***Abstract*— This paper analyzes the steady state performance of an isolated 3-phase self excited induction generator (SEIG) feeding balanced resistive load. The effects of load admittance and excitation capacitance on magnetizing reactance, frequency, terminal voltage, currents have been shown in this paper. The equivalent circuit of SEIG has been analyzed by loop impedance method to develop circuit equation which is non-linear in nature. This can be easily solved by genetic algorithm (GA) optimization technique. The simulated results obtained using genetic algorithm help in understanding the steady state performance of SEIG.**

***Keywords*—equivalent circuit, GA, magnetizing reactance, SEIG and steady state performance.**

<u>*List of Symbols*</u>

R_1 = Stator resistance per phase
R_2 = Rotor resistance per phase
R_L = Load resistance per phase
X_1 = Stator leakage reactance per phase
X_2 = Rotor leakage reactance per phase
X_L = Load reactance per phase
X_m = Magnetizing reactance per phase
X_c = Shunt excitation capacitive reactance per phase
C = Shunt excitation capacitance per phase
a = per unit generated frequency
b = per unit speed
Y_L = Load admittance per phase
Z_L = Load impedance per phase
E_g = Generated air gap voltage per phase
V_L = Load voltage per phase
I_L = Load current per phase
I_S = Stator current per phase
I_R = Rotor current per phase

I. INTRODUCTION

The renewable energy resources play a major role in rural electrification and industrialization programs. Central grid connection is expensive or difficult to provide in remote areas but small-scale autonomous power systems may be developed for supplying the local customers thereby reducing the cost of the distribution lines and increasing the availability of electrical power.

The self-excited induction generator is a strong candidate to harness these renewable energy sources like small hydro and wind energy resources. An SEIG is normally a squirrel cage induction machine excited through an externally connected ac capacitor bank [1]. SEIG becomes one of the important research areas in the field of renewable energy sector and isolated power systems due to the following although the advantages such as brushless construction (squirrel cage rotor), reduced size, absence of dc power supply for excitation, absence of synchronizing equipment, good over-speed capability, reduced maintenance cost, inherent short-circuit protection capability and better transient performance [2-4].

Steady-state analysis of self excited induction generator has importance both from the design and operational points of view and has been studied in different literature [5-13]. In an isolated power system, both the terminal voltage and frequency are not known and have to be calculated for a given speed, capacitance and load impedance.

In case of SEIG the physical system is converted to different models and then the Loop impedance technique used by Murthy [5] and Malik [6] or Nodal admittance technique used by Quazene [7] and Chan [8] is applied to identify the operating point under saturation for the given speed, load and capacitance. Two higher degree non-linear equations as the function of per unit frequency and magnetizing reactance are solved by different conventional methods like Newton-Raphson method [5], iterative method [9], secant method [10], symbolic programming method [8], etc.

In present paper the per phase equivalent circuit of self excited induction generator has been analyzed by loop impedance method and two higher degree non-linear equations are developed. Only one higher degree non-linear equation as the function of per unit frequency and magnetizing reactance is solved by genetic algorithm (GA) optimization technique [14] very easily. The effects of capacitance and load on terminal voltage, frequency, current and other different issues are investigated in steady state analysis.

II. PERFORMANCE ANALYSIS

The following assumptions are made in this study :

i. All the machine parameters except magnetizing reactance are assumed to be constant.
ii. Per unit resistances and leakage reactances of stator and rotor are taken to be equal.
iii. The time harmonics and mmf space harmonics in the induced emf and current waveform are neglected.

A schematic of shunt capacitor self excited induction generator has been shown in the Fig.1

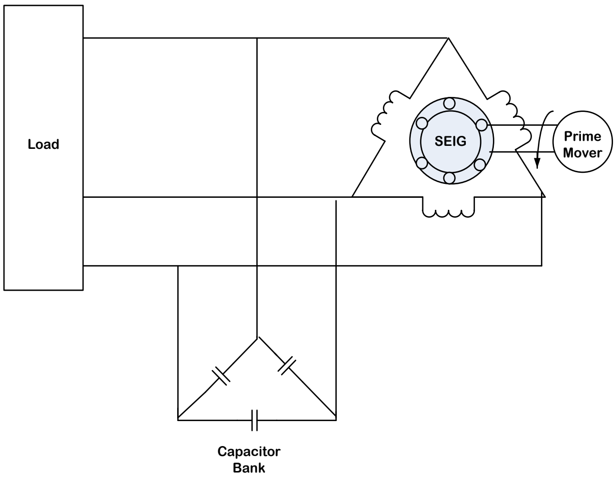

Fig.1. Schematic of SEIG

The per phase steady state equivalent circuit of self excited induction generator with balanced static R-L load is shown in Fig.2.

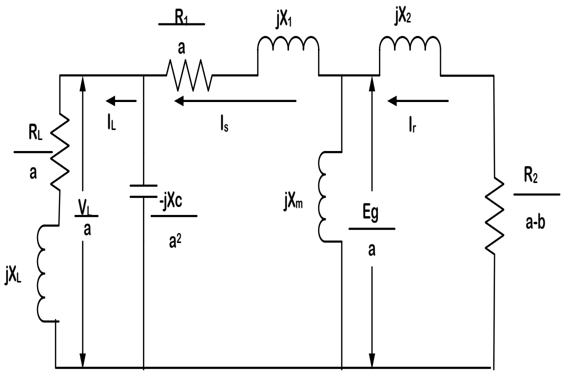

Fig.2. Steady state equivalent circuit of self-excited induction generator with R-L load

Above circuit can be reduced to single loop circuit and by using loop analysis we get the expression as

$$I_{loop} Z_{loop} = 0 \tag{1}$$

Since I_{loop} must be non-zero for energy conversion, equation (1) is only valid for Z_{loop} to be zero.

Where I_{loop} = loop current and
Z_{loop} = loop impedance

$$= \left(\frac{R_2}{a-b}+jX_2\right) \| \left(\frac{-jX_c}{a^2}\right) + \left(\frac{R_1}{a}+jX_1\right) + jX_m \| \left(\frac{R_2}{a-b}+jX_2\right) \tag{2}$$

Z_{loop} to be zero , real and imaginary part of it should be separately zero. From this we get the following two non-linear equations with ‘X_m’ and ‘a’ as two unknown variables.

$$M(X_m, a) =$$

$$-(m_1X_m+m_2)a^3+(m_3X_m+m_4)a^2+(m_5X_m+m_6)-(m_7X_m+m_8)=0 \tag{3}$$

$$N(X_m, a) =$$

$$-(n_1X_m+n_2)a^4+(n_3X_m+n_4)a^3+(n_5X_m+n_6)a^2-(n_7X_m+n_8)a-n_9=0 \tag{4}$$

The values of the coefficients m_1 to m_8 and n_1 to n_9 are given in appendix.

For a given value of machine parameters, shunt capacitance, speed and load, the equations can be solved. To know the value of **‘X_m’** and **‘a’**, only one equation is enough for solution with the help of GA technique very easily. We select the first equation and solve to get the value of ‘Xm’ and **‘a’.**

With E_g/a, X_m, *a*, X_c, *b*, R_L and machine parameters known, calculation of the load voltage V_L , I_L, I_s, I_r, input as well as output active and reactive power is straightforward using the equivalent circuit of Fig. 1. Expressions for the respective variables are given below:

1. $$I_s = \frac{Eg/a}{\left(\frac{R_1}{a}+jX_1\right)+\left(\frac{\left(\left(\frac{-jX_c}{a^2}\right)\left(\frac{R_L}{a}+jX_L\right)\right)}{\left(\frac{R_L}{a}+jX_L\right)+\left(\frac{-jX_c}{a^2}\right)}\right)} \tag{5}$$

2. $$I_r = \frac{\left(\frac{-E_g}{a}\right)}{\left(\frac{R_2}{a-b}\right)+jX_2} \tag{6}$$

$$I_L = I_s\left(\frac{\dfrac{-jX_c}{a^2}}{\left(\dfrac{R_L}{a}+jX_L\right)+\left(\dfrac{-jX_c}{a^2}\right)}\right) \qquad (7)$$

3. $I_c = I_s - I_L$ (8)

4. $Z_L = \dfrac{R_L}{a} + jX_L$ (9)

5. $V_L = aI_LZ_L$; (10)

6. Active power input per phase

$$P_{in} = -a\left|I_r\right|^2\left(\frac{R_2}{a-b}\right)$$

(11)

7. Active power output per phase

$$P_{out} = \left|I_L\right|^2 R_L$$

(12)

8. Reactive power generation by capacitor per phase

$$Q_{gen} = \left|I_c\right|^2\left(\frac{X_c}{a}\right);$$

(13)

III. GENETIC ALGORITHM

The idea of evolutionary computing was developed by I. Rechenberg in 1960 in his work Evolutionary strategies. Genetic algorithms (GA) are computerized search and optimization technique based on the mechanism of natural genetics and the Darwinian theory of evolution i.e "survival of the fittest". Genetic algorithms are good at taking larger, potentially huge, search spaces and navigating them looking for optimal combinations of things and solutions which we might not find in a life time [14].

GA creates strings of binary digits and evaluates each string's strength in terms of fitness value. The stronger strings will last and mate with other stronger strings to produce strong offspring. Finally one becomes best of all.

Objective function for the system under consideration is

Obj.F = ǀ M (X_m ,a) ǀ

It is required to minimize Obj.F near to zero to get the values of ' X_m ' and 'a' for particular condition.

The steps involved for the study of performance of SEIG using GA optimization technique are given below:

Step 1 : Read R_1, R_2, X_1, X_2, X_C, R_L, X_L, b, E_g/a Vs. X_m,
Step 2 : Declare ranges for a and X_m
Step 3 : Select population size (PS), number of chromosomes (Chm), number of generations (Gen) and tolerance (€).
Step 4 : Set Gen = 1
Step 5 : Generate initial population with two sets of chromosomes for respective variables.
Step 6 : Evaluate the objective function M(X_m, a) from equation (3).
Step 7 : If M(X_m, a) ≤ € go to step 10. Else go to next step.
Step 8: If Chm ≤ PS take the variables from the next chromosomes and go to step 6, else go to next step.
Step 9: Generate new set of chromosomes using GA process.
Step 10: Print a and X_m and compute generator performance.
Step 11: Stop

IV. RESULTS AND DISCUSSION

In this paper the simulated results refer to a 3-phase, 2.9 hp, 230 V, 8.2 A, 4-pole, delta-connected squirrel cage induction machine [5] whose per-phase equivalent circuit parameters in per unit are: R_1 =0.062, R2 =0.07, X_1=0.093 and X_2=0.093. The magnetization curve is determined from a synchronous speed test. The approximate equation of the curve is as follows

$$\frac{E_g}{a} = 1.714 - 0.4X_m \qquad \text{(when } X_m \le 2.25\text{)}$$

$$= 0 \qquad \text{(when } 2.25 < X_m\text{)}$$

(14)

For different capacitance values i.e C = 0.61, 0.67 and 0.747 p.u., the values of X_m (magnetizing reactance) and 'a' (generated frequency) obtained from GA technique have been compared with the values obtained from Newton-Raphson (N-R) method under constant mode of operation. These are shown in the tables I, II and III. X_L is taken to be zero. So the load is resistive and power factor is 1.0.

TABLE I
Comparison of values of X_m and 'a' obtained from GA and N-R method for C = 0.61 p.u.

b = 1.0 p.u., power factor (p.f) = 1.0					
		N-R method		GA method	
Sl. No	R_L (p.u)	X_m (p.u)	a (p.u)	X_m(p.u)	a(p.u)
1	100	1.5598	0.9974	1.5581	0.9975
2	50	1.5648	0.9967	1.5635	0.9968
3	20	1.5806	0.9943	1.5731	0.9941
4	5	1.6764	0.9832	1.6760	0.9831
5	3	1.7888	0.9737	1.7269	0.9736
6	1.8	2.0521	0.9587	1.9677	0.9586
7	1.5	2.2331	0.9516	2.2274	0.9516

TABLE II
Comparison of values of X_m and 'a' obtained from GA and N-R method for C = 0.67 p.u.

b = 1.0 p.u., power factor (p.f) = 1.0					
		N-R method		GA method	
Sl. No	R_L (p.u)	X_m (p.u)	a (p.u)	X_m(p.u)	a(p.u)
1	100	1.4135	0.997	1.4105	0.997
2	50	1.4181	0.9962	1.4129	0.9963
3	20	1.4326	0.9937	1.4295	0.9937
4	5	1.5189	0.9827	1.5087	0.9829
5	3	1.6184	0.9731	1.6024	0.9732
6	1.5	2.0008	0.9509	1.9845	0.9511
7	1.3	2.1758	0.9445	2.1279	0.9444

TABLE III
Comparison of values of X_m and 'a' obtained from GA and N-R method for C = 0.747 p.u.

b = 1.0 p.u., power factor (p.f) = 1.0					
		N-R method		GA method	
Sl. No	R_L (p.u)	X_m (p.u)	a (p.u)	X_m(p.u)	a(p.u)
1	100	1.2605	0.9964	1.2611	0.9964
2	50	1.2646	0.9957	1.2627	0.9958
3	20	1.2777	0.9933	1.2739	0.9929
4	5	1.3545	0.9819	1.3457	0.9818
5	1.5	1.7645	0.95	1.7644	0.9527
6	1.3	1.9085	0.9435	1.8975	0.9435
7	1.1	2.1573	0.9351	2.1129	0.9350

The above tables show that the values of 'X_m' and 'a' are higher for lower values of excitation capacitance at particular load. GA technique and N-R method are giving almost the same results.

Other observations are given below:

1. *Variation of stator current with load admittances for different excitation capacitances.*

In Fig. 3 the variation of stator current (I_S) w.r.t load admittance (Y_L) at different capacitances (C) with b = 1.0 p.u and power factor (p.f) = 1.0 has been shown. The nature of curve shows that no-load I_S is very high and its value depends on C. If C is high, no-load Is is high. When Y_L increases, stator current also increases gradually and reaches its peak value for a fixed value of C. If Y_L increases further stator current decreases. If the capacitance increases, I_S increases for fixed value of load admittance.

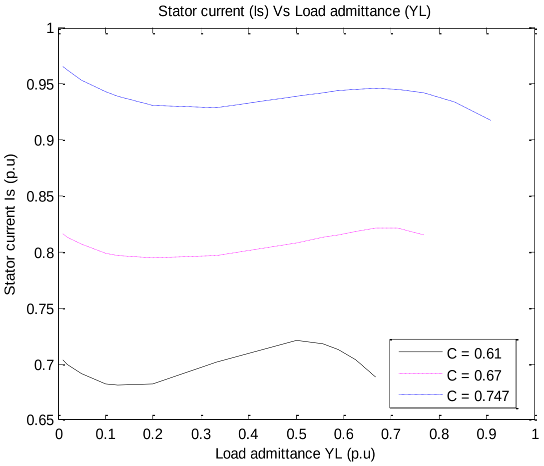

Fig.3. Variation of stator current with load admittance at u.p.f.

2. *Variation of rotor current with load admittances for different excitation capacitances (quantities are in p.u).*

Fig. 4 shows variation of rotor current (I_r) w.r.t load admittance (Y_L) at different capacitance (C) with b = 1.0 p.u and power factor (p.f) = 1.0. At no load condition small amount of I_r flows in the rotor. As the load admittance increases, I_r increases to some peak value for fixed value of C. If the value of C is increased, both the value of rotor current and range of operation are increased.

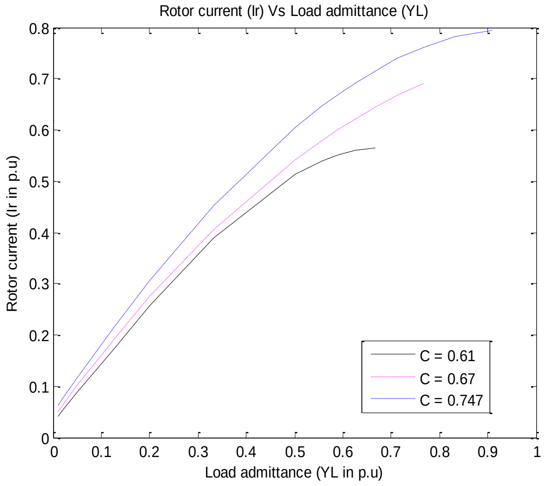

Fig.4. Variation of rotor current with load at u.p.f.

3. *Variation of load current with load admittances for different excitation capacitances (quantities are in p.u).*

Fig. 5 shows the effect of excitation capacitance on load current (I_L) with unity power factor and speed (b) = 1.0. It is calculated at C = 0.61, 0.67 and 0.747 p.u. Load current increases to peak value and then decreases with the increment in load admittance (Y_L) for fixed value of C. The range of operation is increased with increment in C.

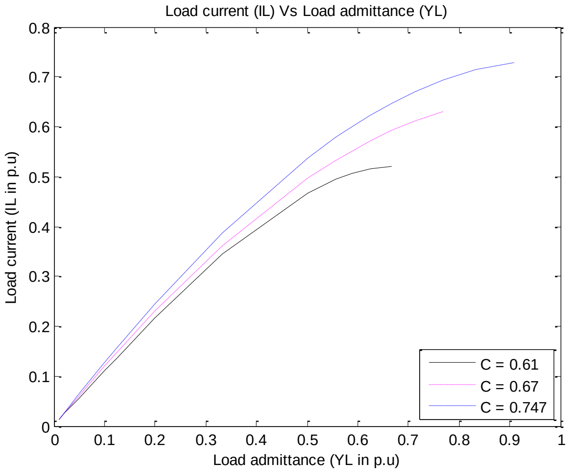

Fig.5. Variation of load current with load at u.p.f.

4. *Variation of load voltage with load admittances for different values of excitation capacitances (quantities are in p.u).*

Effect of excitation capacitance (C) on per phase load voltage (V_L) has been shown in Fig. 6. with b = 1.0 p.u and p.f = 1.0. No-load voltage is higher for higher value of capacitance. V_L drops as the Y_L increases. If the capacitance increases V_L increases and range of operation also increases. Voltage regulation is better for higher values of C.

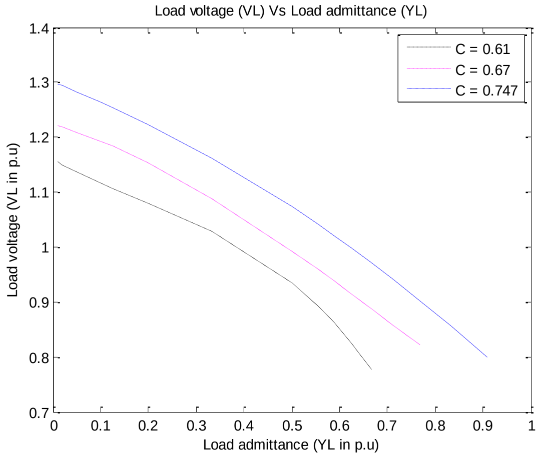

Fig.6. Variation of load voltage with load admittance at u.p.f.

5. *Variation of load voltage with power output for different excitation capacitances (quantities are in p.u).*

Effect of excitation capacitance (C) on per phase load voltage (V_L) has been shown in Fig. 7 with b = 1.0 p.u and p.f = 1.0. No-load voltage is higher for higher value of capacitance. If the load is increased, the terminal voltage drops. If the capacitance increases V_L increases and range of operation also increases. Voltage regulation is better if we increase the value of C.

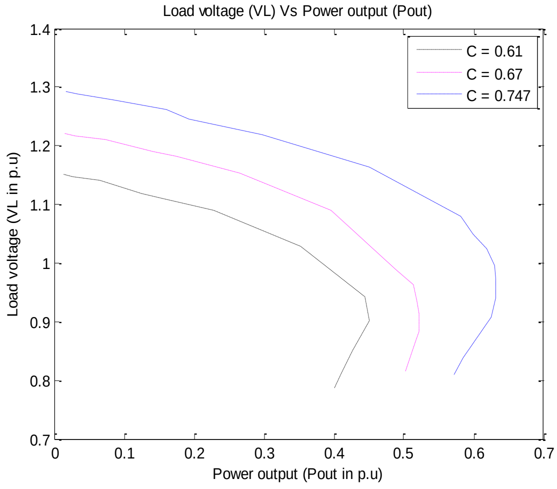

Fig.7. Variation of load voltage with load at u.p.f.

6. *Variation of active power input per phase of SEIG with load admittance for different excitation capacitances.*

Fig. 8 shows the variation of active power (P_{in}) with load admittance (Y_L) at three different values of C (0.61 , 0.67 and 0.747 p.u.) with b = 1.0 and p.f = 1.0.

Under no load condition, P_{in} is positive that indicates the losses in the system. Initially P_{in} increases gradually and then decreases as Y_L increases for constant value of C. If C is increased, P_{in} is increased. High value of C maximizes P_{in} and range of operation. Load admittance at which the P_{in} is maximum increases when C is high.

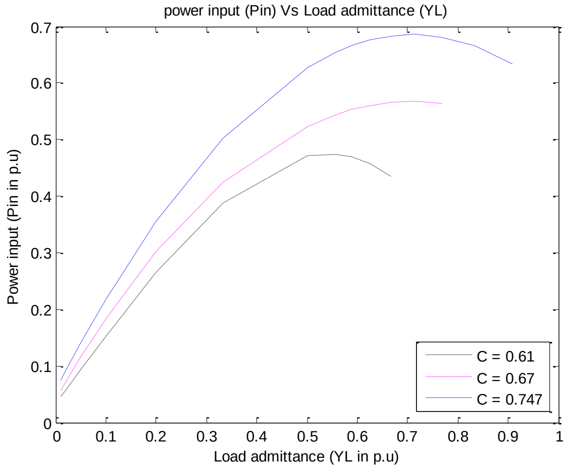

Fig.8. Variation of active power input with load admittance at u.p.f.

7. *Variation of efficiency of SEIG with load admittances for different excitation capacitances under constant speed mode of operation.*

Fig. 9 shows the efficiency of SEIG at different capacitance (C = 0.61, 0.67and 0.747 p.u) w.r.t load admittance (Y_L). When the capacitance value is smaller the efficiency reaches its maximum value very rapidly and remains almost constant rest of the operating period.

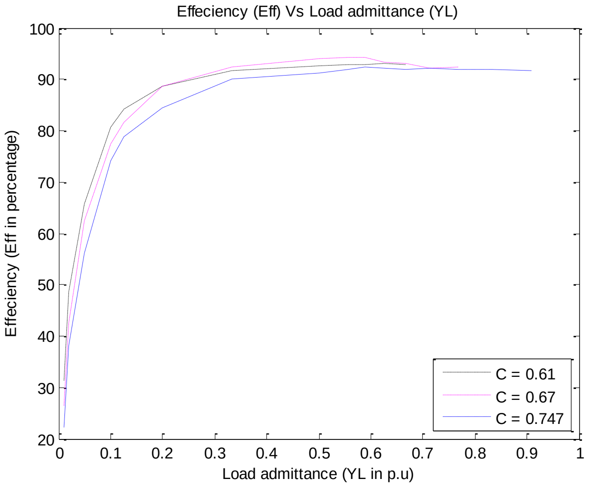

Fig.9 Variation of efficiency with load admittance at u.p.f.

8. *Variation of reactive power generation per phase by the capacitor with power output per phase.*

The effect of excitation capacitance (C) on reactive power generation (Q_{gen}) per phase by capacitor is plotted in Fig. 10. At fixed speed (b) = 1.0 p.u and unity p.f Q_{gen} decreases as load (P_{out}) increases for fixed value of ‘C’ . If ‘C’ is increased reactive power generation is increased radically for fixed value of load.

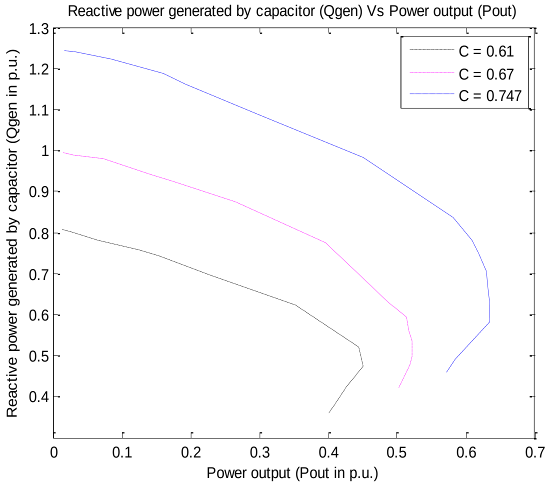

Fig.10. Variation of reactive power generation by capacitor with u.p.f load.

V. CONCLUSION

A general analysis using genetic algorithm (GA) optimization technique has been applied to predict the steady-state behavior of isolated self-excited induction generators feeding static resistive load. It calculates the values of saturated magnetizing reactance and the output frequency for the given capacitance, speed and load. The steady-state equivalent circuit can then be used to compute the performance. The results show that the terminal voltage and stator current increase significantly with increase in capacitance value. This analytical technique is very efficient requiring very little computational time, to an accuracy of 10^{-08}.

VI. APPENDIX

$$m_1 = R_L\left(X_2 + X_1\right) + X_L\left(R_1 + R_2\right);$$

$$m_2 = X_1X_2R_L + X_L\left(R_2X_1 + R_1X_2\right);$$

$$m_3 = b\left(m_1 - R_2X_L\right);$$

$$m_4 = bX_2\left(X_LR_1 + R_LX_1\right);$$

$$m_5 = X_C\left(R_1 + R_2 + R_L\right);$$

$$m_6 = X_C\left\{R_2\left(X_1 + X_L\right) + X_2\left(R_1 + R_L\right)\right\} + R_1R_2R_L;$$

$$m_7 = bX_C\left(R_1 + R_L\right);$$

$$m_8 = X_2m_7;$$

$$n_1 = X_L\left(X_1 + X_2\right);$$

$$n_2 = X_LX_1X_2;$$

$$n_3 = bn_1;$$

$$n_4 = bn_2;$$

$$n_5 = X_C\left(X_L + X_1 + X_2\right) + R_L\left(R_1 + R_2\right);$$

$$n_6 = X_CX_2\left(X_1 + X_L\right) + R_L\left(R_2X_1 + R_1X_2\right) + R_1R_2X_L;$$

$$n_7 = b\left(n_5 - R_LR_2\right);$$

$$n_8 = b\left\{n_6 - R_2\left(X_1R_L + R_1X_L\right)\right\};$$

$$n_9 = R_2X_C\left(R_1 + R_L\right);$$

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