Performance Optimization of Self Excited Induction Generator Using Particle Swarm Technique

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https://doi.org/10.20428/JST.22.2.4

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Abstract:

The performance of self-excited induction generator was thoroughly analyzed regarding the values of the critical excitation capacitance and the frequency of the generated voltage. A robust meta-heuristic optimization technique, Particle Swarm, is applied in this paper for analyzing the performance of self-excited induction generator under different speed/load levels. The Particle Swarm technique is utilized to define the minimum value for excitation capacitor required for providing maximum output power from the generator under different load types/operating conditions. The results from Particle Swarm technique are more accurate and has better performance compared to the conventional methods.

Keywords: Induction generator, Particle Swarm technique, Critical capacitance, Magnetizing Reactance, Newton Raphson.

1. INTRODUCTION:

Induction Generator (IG) is considered the preferred option for harvesting electrical power from non-conventional energy sources, particularly wind. This is attributed to the salient advantages of IG such as: robustness, maintenance free, and absence of separate direct current excitation system [1- 9].

IG could be operated either grid-connected or off-line; for the case of grid-connected, the reactive power requirements for maintaining constant voltage at generator terminals under different load/speed conditions are supplied by the grid. However, for the case of stand-alone operation, which is the case for remote and rural locations, the capacitive excitation is indispensable to regulate the voltage across the machine terminal [5- 14]. For example, for fixed excitation capacitor and speed, the machine terminal voltage decreases/increases with the load increase/reduction. For regulating the terminal voltage, the excitation capacitance has to vary coherently with the load. This is non-economical and complicated solution. However, if the terminal voltage is allowed to vary within a narrow range, attractive, in-expensive and simple approach is to use stepped switching capacitors with the possibility of letting them on/off with the loads.

The principle of self-excitation could also be adopted in other research areas as dynamic braking of three-phase induction motor; therefore, techniques for analyzing the behavior of such machines are of significant practical interest [2, 4]. In general, there are two scenarios for analyzing the steady-state performance of self-excited induction generator (SEIG). The first scenario is to determine terminal voltage, output power, stator and rotor current for given value of capacitance, load and speed, while the second is to determine the required excitation capacitance for desired voltage at given load and speed level [2- 6].

Extensive research effort was draft in the past decades [1- 14] to practical applications and computation of the steady state performance of self excited induction generator using steady state equivalent circuit of the machine. For example, in [5] a mathematical model was developed for obtaining the steady state performance of self induction generator using equivalent circuit. In this approach, the complex impedance is segregated into real and imaginary parts. The resulted nonlinear equations are arranged for unknown variables such as magnetizing reactance (X_m) and frequency (F), while the remaining machine parameters and operating variables are assumed constants. Numerical techniques as Newton Raphson were employed for solving the equations. This approach, however, requires sophisticated computation capabilities in terms of speed and storage.

In [6] an approach for computing steady state performance of the self excited induction generator is proposed; 4^{th} order polynomial is derived from loop equation of equivalent circuit of the machine. The roots of this polynomial are determined to check occurrence of self excitation and to get the corresponding value of magnetizing reactance. The approach proposed in [6] has the advantages of predicting the performance of the machine for given capacitance/load/speed level. However, the load considered in this approach is pure resistive, which has less practical significance.

Another mathematical formulation using steady state equivalent circuit of the machine was proposed in [8] and [17] for computing minimum value of the capacitance required for self excitation and threshold speed below which self excitation could not be established. A third mathematical formula is proposed in [9] for computing the static performance of the induction generator under wide range of operating conditions. In [10], the performance of separate-excited induction generator is proposed to evaluate the range of different parameters as voltage, speed and excitation capacitance, within which self excitation is possible.

Most of the approaches reported in the literature on steady-state performance evaluation of self-excited cage induction generator require splitting the equivalent impedance into real and imaginary components. Moreover, the model becomes rather complicated, if the core losses are included. Accordingly, several assumptions are taken to simplify the analysis. Moreover, different models are used for modeling the machine with different types of loads/excitation capacitor arrangements. Subsequently, the coefficients of the mathematical models vary.

In this paper, a robust optimization technique is employed for analyzing the steady-state performance of self-excited cage induction generator. The proposed technique uses a generic mathematic model for SEIG; this model is used for any load type/excitation capacitor arrangement. In Particle Swarm technique, the complex impedance is formulated as objective function. Two scenarios are considered: In the first scenario, the magnetizing reactance and frequency are selected as independent variable, while in the second,

https://doi.org/10.20428/JST.22.2.4

capacitive reactance and frequency are taken as independent variable. The upper/lower limits of the unknown variables are selected to achieve practically acceptable value. The results from Particle Swarm technique are used for predicting the generator performance under different load/speed levels.

2. CRITICAL EXCITATION CAPACITANCE:

The following analysis is valid for a self-excited IG, squirrel-cage or wound rotor, provided that capacitor bank is allocated in the stator side. The equivalent circuit of self-excited IG, Figure (1), is normalized to base frequency.

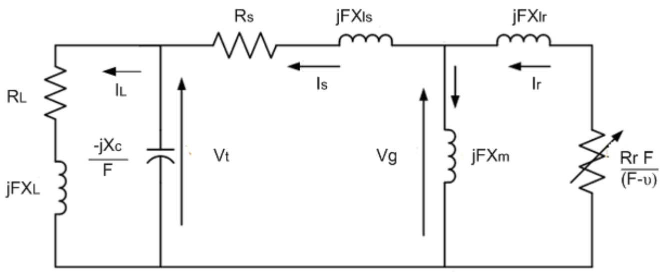

Figure (1): Equivalent circuit of self excited induction generator

where R_s and R_r are per phase stator and rotor resistances. Xl_s and Xlr are per phase leakage reactance of stator and rotor. The X_m is the magnetizing reactance per phase and X_c is the per phase capacitive reactance of the capacitance C connected across the machine terminals at base frequency. R_L is the per phase load resistance. F and υ are per unit(p.u), frequency and speed. I_s, I_r and I_1 are per phase stator, rotor and load currents respectively. The resistance, reactance, current and voltage of the rotor are referred to the stator.

Applying loop-impedance method [3] in the equivalent circuit, figure (1), the following equation results,

$$Z_t I_s = 0 \qquad (1)$$

Zt is given by,

$$Z_t = Z_1 + Z_c Z_L / (Z_c + Z_L) + Z_2 Z_m / (Z_L + Z_m) \qquad (2)$$

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Where:

$Z_1 = R_s + jF X_1$, $Z_c = -j X_c/F$, $Z_2 = Rr F / (F- \upsilon) + jF X_1$,

$Z_L = R_L + j X_L$ and $Z_m = jF X_m$

Under steady-state self excitation, $I_s \# 0$, thus Zt in equation (1) is equal to zero. Equation (1) is used for investigating different load conditions in the following sections.

2.1 No-Load Z_L= infinity

The no-load operation of the SEIG is stimulated by equating load impedance by infinity Z = infinity. Substituting the values of Z_1 ,Z_2 ,Z_m ,Z_L and Z_c into (2) and equating the real and imaginary parts by zero; the value of the critical capacitive reactance is obtained for the no-load condition as,

$$X_{C-CRITICAL} = \left(\frac{R_S}{F} + \frac{R_r}{F-\upsilon}\right)(X_1 + X_m)\frac{F^2(F-\upsilon)}{R_r} \quad (3)$$

and the frequency of the generated voltage is obtained from,

$$(2X_1X_m + X_1^2)F^3 - \upsilon\,(2X_1X_m + X_1^2)F^2 - (X_c(X_m + X_1) + R_sR_r)F + \upsilon X_c(X_m + X_1) = 0 \quad (4)$$

In no-load operation of SEIG, the machine slip is almost zero, and the p,u frequency of the generated voltage is nearly equal to the p.u rotor speed. Thus, substituting $F \approx \upsilon$ and setting $F-\upsilon \approx 0$ in (3), the critical capacitive reactance could be given by,

$$X_{c\ critical} = (X_1 + X_m)\,\upsilon^2 \quad (5)$$

Equation (5) indicates that minimum excitation capacitance is inversely proportional with square of rotor speed, leakage and magnetizing reactances. Thus, the excitation capacitance has to fulfill the machine reactive power requirement for successful operation (5). Equation (5) coincides with conclusions in Section 19.6 in [1].

Equation (4) has three roots; two of these roots are discarded due to their extraordinary values. Thus, third root depicts the frequency. The frequency of the generated voltage was found to be independent of the leakage reactance, and it is speed dependent.

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2.2 Resistive load $Z_L = R_L/F$

The critical capacitance for the resistive load case could be obtained by equating load impedance by $Z_L = R_L/F$; then Substituting the values of Z_s ,Z_r ,Z_L ,Z_m and Z_c into (2) and equating the real and imaginary parts by zero. The value of the critical capacitive reactance for resistive load case is given by:

$$X_{C-CRITICAL} = \frac{R_L\left(\frac{R_S}{F^2}+\frac{R_r}{F(F-\upsilon)}\right)(X_1+X_m)}{\frac{R_rR_L}{F^3(F-\upsilon)}+\frac{R_rR_S}{F^3(F-\upsilon)}-\frac{(2X_1X_m+X_1^2)}{F^2}} \quad (6)$$

and the frequency of the generated voltage is obtained from,

$$R_L(2X_1X_m+X_1^2)F^3-\upsilon R_L(2X_1X_m+X_12)F^2-(X_c(X_m+X_1)(R_L+R_s+R_r)+R_sR_rR_L)F+\upsilon X_c(X_m+X_1)(R_L+R_s)=0 \quad (7)$$

Equation (6) indicates that the critical capacitance is load dependent. Again, it varies with rotor speed and leakage and magnetizing reactances. Similarly to (4), equation (7) has three roots; two of them are ignored, while the third provides the frequency of the generated voltage. The frequency is found to be a function in load resistance and machine speed, which concurs with the slip equation advised in [1].

2.3 Inductive load $Z_L= R_L/F +jX_L$

Inductive load represents the generic case for the SEIG. The load impedance is given by, $Z_L= R_L/F +jX_L$. Substituting the values of Z_1 ,Z_2 ,Z_m ,Z_L and Z_c into (2) and equating the real and imaginary parts by zero; the value of the critical capacitive reactance for inductive load,

$$X_{C-CRITICAL} = \frac{R_L\left(\frac{R_S}{F^2}+\frac{R_r}{F(F-\upsilon)}\right)(X_1+X_m)-(2X_1X_m+X_1^2)X_L+\frac{R_rR_SX_L}{F(F-\upsilon)}}{\frac{R_rR_L}{F^3(F-\upsilon)}+\frac{R_rR_S}{F^3(F-\upsilon)}-\frac{(2X_1X_m+X_1^2)}{F^2}-\frac{X_L(X_1+X_m)}{F^2}} \quad (8)$$

and the frequency of the generated voltage is obtained from,

$$(R_L(2X_1X_m+X_1^2)+X_L(X_1+X_m)(R_s+R_r))F^3\upsilon(R_L(2X_1X_m+X_12)+X_LR_s(X_m+X_1))F^2(X_c(X_m+X_1)(R_s+R_r+R_L)+R_sR_rR_L+X_cX_LR_r)F+\upsilon X_c(X_1+X_m)(R_L+R_s)=0 \quad (9)$$

Equation (8) depicts clearly the relation between the excitation capacitance and load reactive power requirements, which are represented in load inductive reactance XL. Again, the critical capacitive reactance varies with the prime mover speed and leakage and magnetizing reactance. Equation (9) has three roots similarly to (4) and (7), only one of these roots has acceptable value. Accordingly, the frequency of the generated voltage is found to be independent on leakage reactance; however it varies with the load, speed and motor copper losses.

3. PERFORMANCE OPTIMIZATION:

For computation of the performance of the self excited induction generator for a given value of capacitance, load and speed, the mathematical formulation of the problem is as:

$$\text{Minimize } \left| Z_t (F, X_c) \right| \qquad (10)$$

Usually the frequency and capacitive reactance are bounded to reduce the computation time. This approach is used to verify the analytical results in (3)-(9). To fulfill (10), Z_T has to be segregated into real and imaginary parts; accordingly two nonlinear equations are obtained with Xc and F as unknown variables,

$$f(X_c,F) = F^3 a_1 + F^2 a_2 + F(a_3 X_c + a_4) + (a_5 X_c) = 0 \qquad (11)$$

$$g(X_c,F) = F^4 b_1 + F^3 b_2 + F^2 (b_3 X_c + b_4) + F(X_c b_5 + b_6) + (b_7 X_c) = 0 \qquad (12)$$

where the coefficients $a_1 \ldots . a_5$ and $b_1 \ldots . b_7$ are given in appendix A.

4. PARTICLE SWARM OPTIMIZATION (PSO):

The PSO method is a member of wide category of Swarm Intelligence methods for solving the optimization problems. It is a population based search algorithm where each individual is referred to as particle and represents a candidate solution. Each particle in PSO flies through the search space with an adaptable velocity that is dynamically modified according to its own flying experience and also the flying experience of the other particles. In PSO each particles strive to improve themselves by imitating traits from their successful peers. Further, each particle has a memory and hence it is capable of remembering the best position in the search space ever visited by it. The

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position corresponding to the best fitness is known as pbest and the overall best out of all the particles in the population is called gbest [16].

A brief description for PSO is given in the following:

- Step 1: Read Machine data
- Step 2: Assume initial Xm and F
- Step 3: Initialize particle for capacitor and F
- Step 4: Generate velocities for the same
- Step 5: evaluate Xm and F and evaluate the load voltage using the equations. The value of pre specified load voltage already been given.
- Step 6: For one iteration find the fitness in the current location.
- Step 7: calculate the local best and compute the particle's fitness evaluation with the local best. Hence the local best is set to current value and location equal to the current location
- Step 8: calculate the particle's global best and compute best current fitness with global best, if the current value is better than global best, the reset global best to the current best position.
- Step 8: update velocities and position
- Step 9: Repeat steps (5-9) until the best solution is reached until a maximum number of iteration.
- Step 10: Records the global results and Stop

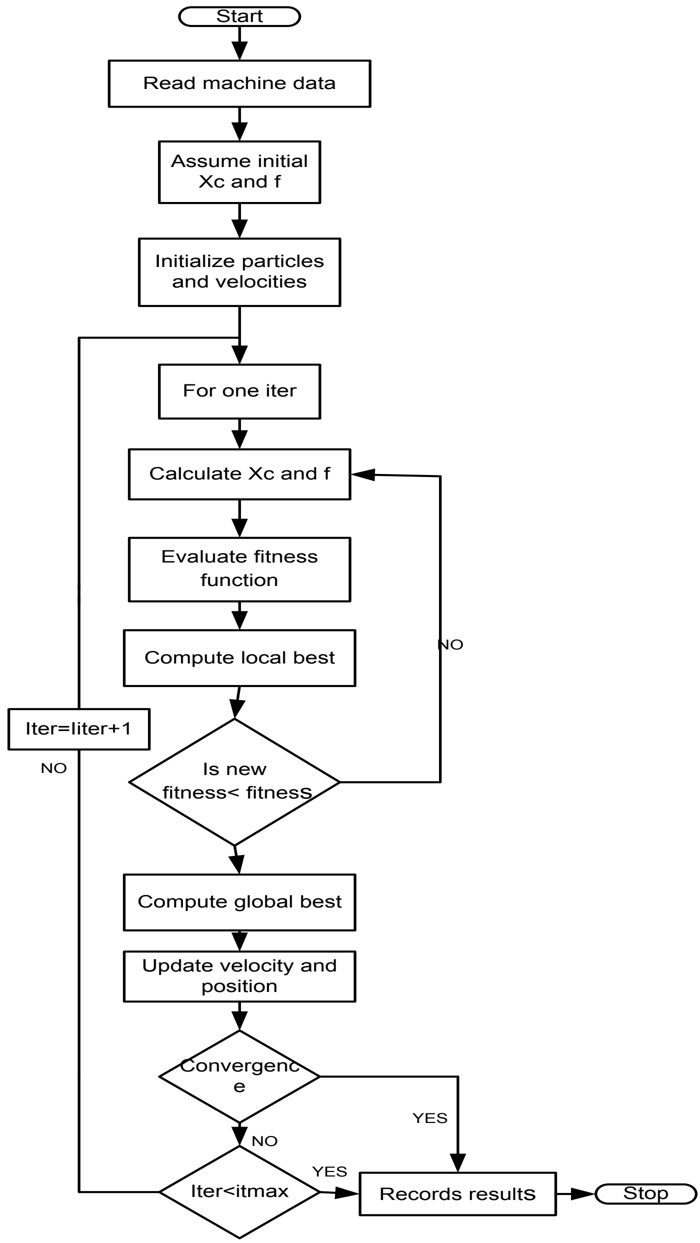

Figure (2): Flow chart of Particle Swarm Algorithm

The number of iteration N in the flowchart is taken around 90, which is considered a good comprise between the accuracy and computation time and faster than method which is used in [9].

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5. CASE STUDY

A delta connected 415V, 3.7kW SEIG is used for validating the derived expressions. The machine parameters are shown in Table 1. The input frequency is kept at base value; while the input voltage is allowed to vary. The input impedance per-phase is calculated for different input voltage, to estimate the value for X_m. The drop in the stator impedance is taken into consideration in calculating air-gap voltage V_g.

Table (1): Parameters of 3.7kW IG

Induction Machine Data	
Resistances	Reactance
R_s =0.053 p.u	$(X_{ls} = X_{lr})$ =0.087 p.u.
R_r = 0.061 p.u	Impedance base=94.5ohm
4 pole	Rated power = 3.7 KW
Voltage line to line = 415 Volts	Frequency = 50Hz
Line current =7.6 Amps	Delta

The saturated magnetizing reactance is approximate by,

$$X_m=3*(1.6275-V_g/F) \qquad (13)$$

To corroborate the derived expressions (3)-(8), a program is written in Matlab M-code for implementing PSO using PSO toolbox fitted in Matlab. The maximum number of iteration is limited to 200, as compromise between accuracy and computation time. The objective function for PSO is obtained from (11) and (12). It is implemented as a Matlab function that accepts the machine and load parameters, and it returns a minimum value of the amplitude of Z_t at a given frequency and capacitive reactance.

6.STEADY-STATE PERFORMANCE OF SELF-EXCITED INDUCTION GENERATOR:

To evaluate the steady-state performance of the IG, the value of magnetizing reactance X_m and the generated voltage has to be determined for given speed, load and excitation capacitance. The magnetizing reactance X_m could possibly be computed under these conditions using PSO, and hence the mathematical formulation of the problem is given by,

$$\text{Minimize} \left| Z_t\,(F,X_m) \right| \qquad (14)$$

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The frequency and magnetizing reactance are bounded. To fulfill (14), Z_t again has to be segregated into real and imaginary parts; accordingly two nonlinear equations are obtained with X_m and F as unknown variables,

$$f(X_m, F)=F^3(c_1X_m+c_2)+F^2(c_3X_m+c_4)+F(c_5X_m+c_6)+(c_7X_m)+c_8 \quad (15)$$

$$g(X_m,F)=F^4(d_1X_m+d_2)+F^3(d_3X_m+d_4)+F^2(d_5X_m+d_6)+F(d_7X_m+d_8)+d_9 \quad (16)$$

where the coefficients c_1-c_8 and d_1-d_9 are given in the Appendix A .

To determine the minimum X_m for the given condition, a program coding PSO is written in Matlab environment. After determining the value of magnetizing reactance X_m and frequency F for given capacitance, speed, and load, the generated voltage V_g could be obtained from Figure (4). Then, the load voltage, current and power could be obtained using the equivalent circuit by,

$$I_s = V_g/ \{F (Z_l+Z_{LC})\} \quad (17)$$

$$I_1 = I_s.Z_C/ (Z_L+Z_C) \quad (18)$$

$$V_t=I_l.Z_L \quad (19)$$

$$I_r = I_s.Z_m/ (Z_2 +Z_m) \quad (20)$$

$$VAR = m\, Vt^2\, F/Xc \quad (21)$$

$$P_{in} = m1_r^{\,2}.R_r.F/ (F- \upsilon) \quad (22)$$

$$P_o = mV_t.1_1 \quad (23)$$

where the number of phases m for the machine under concern is 3.

7. ALGORITHM AND FLOW CHART OF NEWTON RAPHSON METHOD:

The computational procedure of Newton Raphson method for solution of Xm or Xc and F, and performance parameters of SEIG is as follows:

- Read machine data such as R_1, X_1, R_2, X_2, X_c R_l, X_l etc.
- Assume initial values of X_{m0} or X_{c0} and F_0.
- Calculate $\Delta fn1 = - fn1$ and $\Delta fn2 = - fn2$ and

$$\begin{bmatrix}\Delta fn1\\ \Delta fn2\end{bmatrix}=\begin{bmatrix}H\ N\\ M\ L\end{bmatrix}\begin{bmatrix}\Delta Xm\\ \Delta F\end{bmatrix} \quad \text{where:}$$

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$fn_1 = f(X_c, F) = F^3 a_1 + F^2 a_2 + F(a_3 X_c + a_4) + (a_5 X_c)$ or

$F(X_m, F) = F^3 (c_1 X_m + c_2) + F^2 (c_3 X_m + c_4) + F(c_5 X_m + c_6 + (c_7 X_m) + c_8$

$fn_2 = g(X_c, F) = F^4 b_1 + F^3 b_2 + F^2 (b_3 X_c + b_4) + F(X_c b_5 + b_6) + (b_7 X_c)$ or

$G(X_m, F) = F4(d_1 X_m + d_2) + F^3 (d_3 X_m + d_4) + F^2 (d_5 X_m + d_6 + F(d_7 X_m + d_8) + d_9$

$a_1, a_2, \ldots\ldots$ are constants.

- Compute the derivative of function with respect to 'F' and 'X_m' or 'X_c'.
- Compute the elements for jacobian matrix $\begin{bmatrix} H\,N \\ M\,L \end{bmatrix}$, where H, M, N, L are the jacobian elements as:

$$H = \frac{dfn1}{dXm} \text{ or } \frac{dfn1}{dXc}, \quad N = \frac{dfn1}{dF}$$
$$M = \frac{dfn2}{dXm} \text{ or } \frac{dfn2}{dXc}, \quad L = \frac{dfn2}{dF}$$

- Compute the deviations in results ΔX_m or ΔX_c & ΔF by
- Calculate the modified values of Xm or Xc and F as $X_c = X_{c0} + \Delta X_c$ or $X_m = X_{m0} + \Delta X_m$ and $F = F_0 + \Delta F$.
- Start the next iteration cycle with these modified results and continue until scheduled error is within a specified tolerance limit and get the value of X_c or X_m and F.
- Calculate the performance parameters of machine using equations (17) – (23).

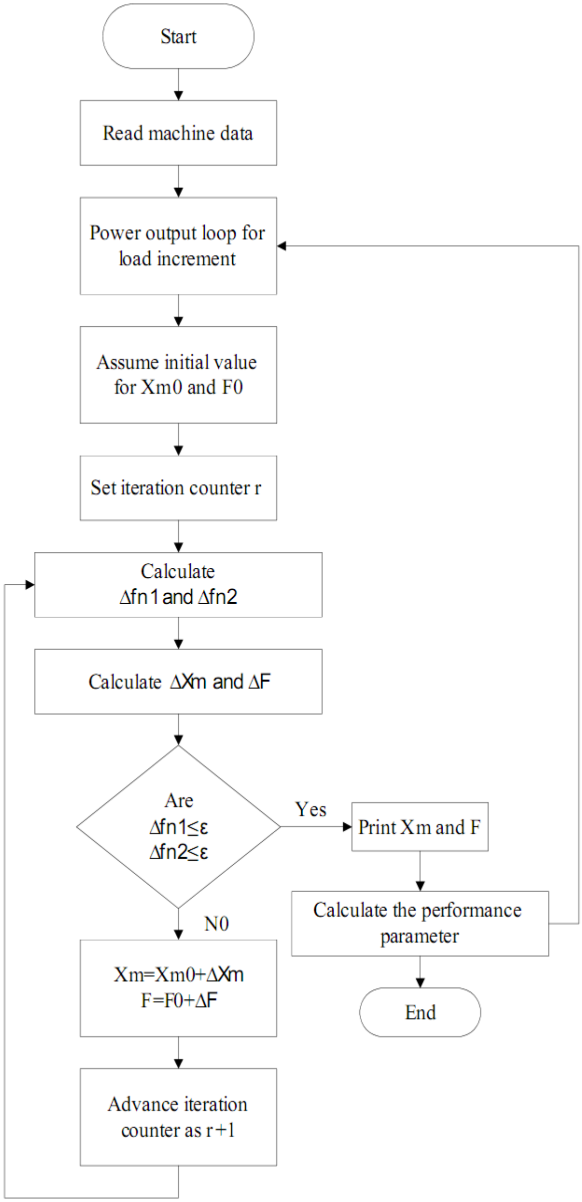

Figure (3): Flow chart of Newton Raphson method

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8. RESULTS AND DISCUSSIONS:

The Particle Swarm has found that self-excitation is not achievable at all operating speeds/excitation capacitors, and if the excitation capacitor is reduced than a certain value for speed, the generator will not build up irrespective to load type. Analytical expression for the minimum excitation capacitance was introduced in [13], however it was only for the case of no-load.

The variation of the generated voltage with excitation capacitance at rated speed for no-load case is shown in Figure (4).

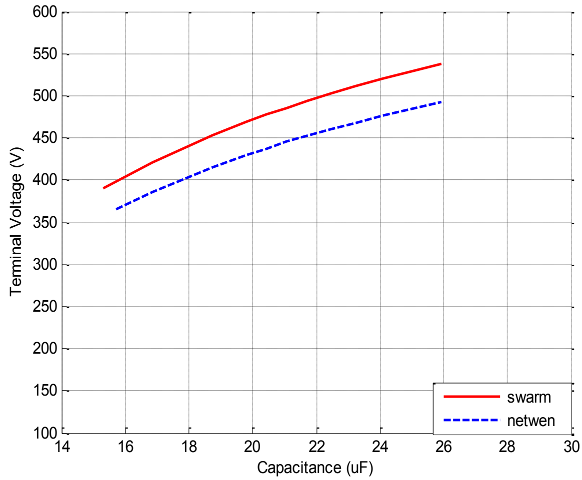

Figure (4): Terminal voltage versus capacitance at no load and rated speed

Figure (4) shows that for 3.7kW, Particle Swarm gives minimum capacitance 15 μF whereas the Newten Raphson gives 15.7 μF value for the excitation capacitor at rated speed, below which the machine will not build up. Moreover, the Figure shows that there is upper limit for the excitation capacitor above which the machine reverts into saturation. In the saturation the increase in the excitation capacitor will not produce significant increase in output power/generated voltage, which could not overwhelm the increase in capacitor size, cost and losses.

The variation of the minimum critical capacitance with the speed for different load conditions was shown in Figure (5).

The critical capacitance is a speed dependent, Figure (5); the capacitance drops nearly by 40% for 25% increase in the speed. The critical capacitance for no-load shown in Figure (5) is similar to that obtained from analytical expression derived in [14] for no-load. As mentioned before these expressions given in [14] are restricted to no-load conditions, while here as shown in Figure (5), the minimum capacitances are obtained for different load types.

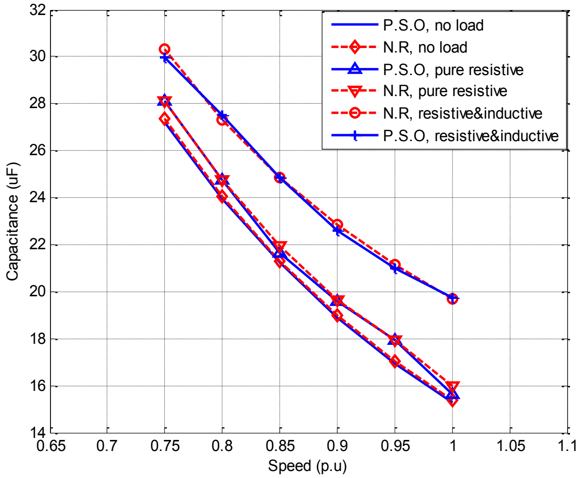

Figure (5): Critical capacitance with speed for no-load resistive and inductive load at particle swarm and Newton raphson

Figure (5) shows that the critical capacitance for inductive load is significantly high. As, for the inductive load case as mentioned before, the excitation capacitor has to satisfy the reactive power requirements for the load and the generator. Accordingly, for capacitive load it is predicted that minimum capacitance will be lower than that corresponding for no-load case.

For a given speed, the performance of self-excited IG is dependent on the excitation capacitance. This is shown clearly in Figure (6), where the terminal voltage of the generator is illustrated against output power for different load types/capacitor values.

The terminal voltage/output power of IG increases/decreases with increase/ decrease in the excitation capacitor, Figure (6), provided that saturation is not reached. The saturation was included in the above analysis through the upper limit of the excitation reactance, X_{cu}.

Figure (6) shows that the voltage regulation for the inductive load is inferior to that of the resistive load; this may be attributed to the function of the excitation capacitor in case of inductive load in fulfilling the reactive power requirements load and the generator.

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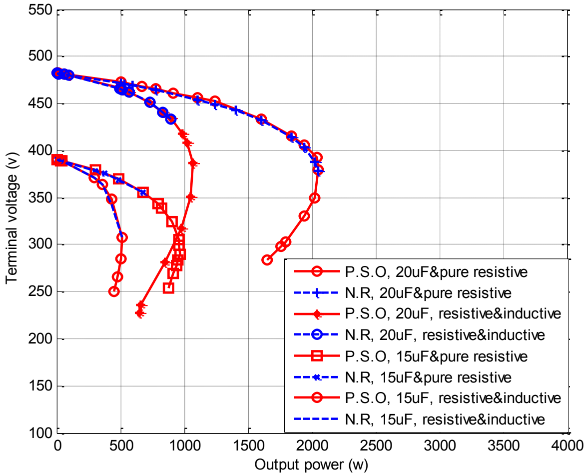

Figure (6): Terminal voltage versus output power at rated speed v for particle swarm and Newton Raphson for different capacitance and load

The dependency of the output power on the excitation capacitance is exploited in figure (7), where the output powers are plotted versus the capacitance for constant terminal voltage/speed.

For constant terminal voltage/speed, the capacitance has to increase for an increase in the output power. The excitation capacitance in figures (4) and (5) is limited to 28μf. This is to avoid the operation in saturation.

The variation of magnetizing reactance X_m, with load at rated voltage and speed for two levels of excitation capacitance is shown in figure (8).

Figure (8) shows the magnetizing reactance (X_m) for resistive load is nearly constant. Also it shows that for inductive load there are two values at one load level. The above value point at unstable condition

It is observed from figure 6, that the characteristic of self-excited induction generator is nearly similar to that of separate-excited DC generator

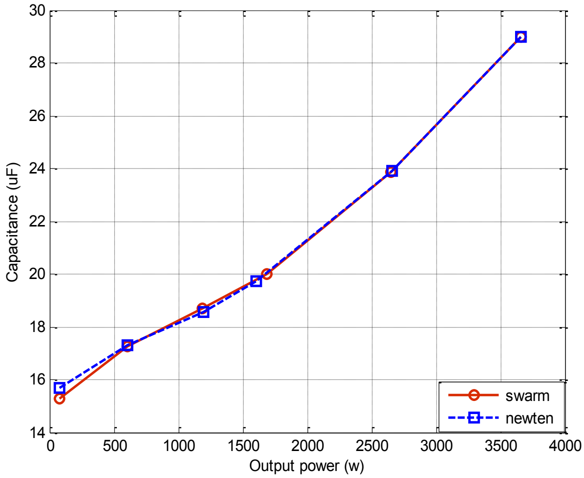

Figure (7): Excitation capacitance with output power at rated terminal voltage and rated speed

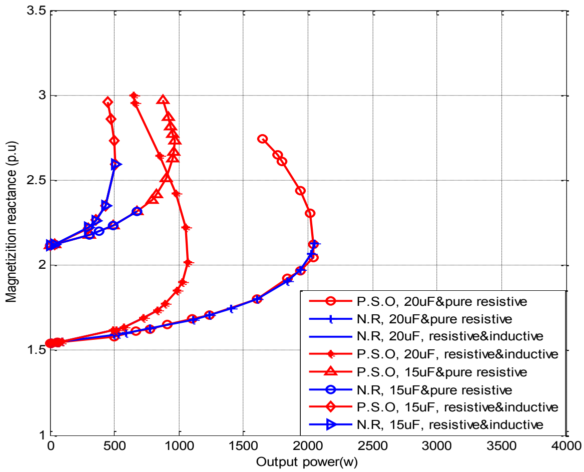

Figure (8): Magnetization reactance versus output power at rated speed for particle swarm and Newton Raphson for different capacitance and load

The iteration number (200) Newton Raphson failed to give us normal results when the load increasing to 3.5pu and X_c is 2.1991 p.u. But PSO success to obtain normal results. These responses are shown in figure (9), and figure (10).

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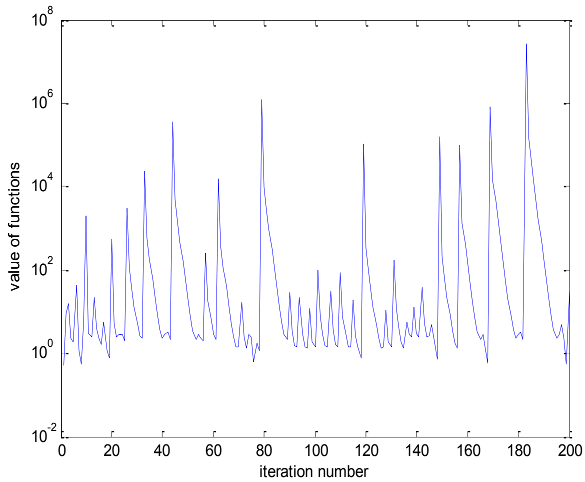

Figure (9): Value of function versus iteration number (4000) for Newton Raphson at impedance load=3.5 p.u & X_c=2.1991 p.u

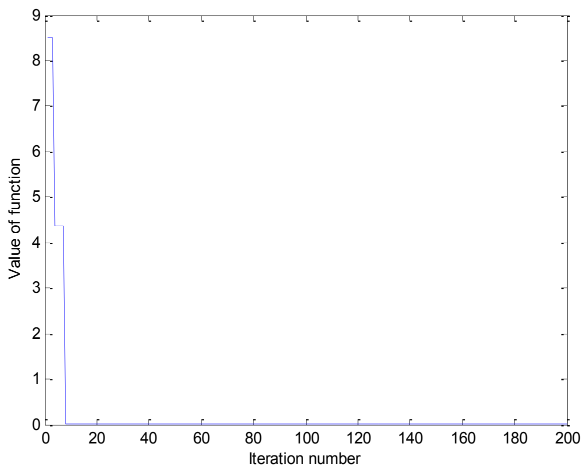

Figure (10): Value of function versus iteration number (4000) for particle swarm .at impedance load=3.5 p.u & X_c =2.1991p.u

9. CONCLUSION:

The following conclusions can be drawn:

1. For isolated generation in remote areas a variable capacitance is required to build up the voltage in an SEIG.
2. For efficient conversion of wind energy into electrical energy the induction generator needs to operate smoothly, giving sustained generated voltage at the stator terminals without any transients.
3. Calculation of the capacitance value of the capacitor bank is critical for the desired operation of the induction generator. Thus the value of excitation capacitance required has been calculated.
4. A Capacitor bank are essential for stand-alone operation of IG for supplying the machine with reactive power requirements
5. Analytical expressions were derived for minimum capacitance and generated frequency for different load types. These formulas show explicitly the parameters that affected the critical capacitance and the generated frequency. The minimum capacitor varies nearly inversely with the square of the rotor speed. The generated frequency drops with the load increase, while excitation capacitance increases.
6. Particle Swarm predicts with relatively small computation requirements, the minimum capacitor 15μF, required for self-excitation under different load/speed conditions whereas the Newten Raphson gives 15.7 μF.
7. Particle Swarm technique give us more accurate for few iteration.
8. PSO analysis improves slightly the performance of SEIG than NR, it affects its loading capability and as well as its voltage regulation.
9. The results from Particle Swarm technique are more accurate and has better performance compared to the conventional methods.
10. The fineness of results can be further improved by using Particle Swarm technique.
11. For a speed, there is critical capacitance below which the self-excitation is not possible.
12. The terminal voltage of IG increases/decreases with increase/reduction in the output capacitance
13. For constant terminal voltage and speed, the excitation capacitance has to vary with the load.

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11. APPENDIX:

The coefficients of equation (11)

$a_1 = -((2X_m+X_1)\, X_1\, R_L + X_L\, (X_1+X_m)\, (R_r+R_s))$

$a_2 = (2X_m+X_1)\, X_1\, R_L\, \upsilon + R_s\, X_L\, (X_1+X_m)\, \upsilon$

$a_3 = (R_L + R_s + R_r)\, (X_m+X_1) + (X_L\, R_L)$, $a_4 = R_s\, R_L\, R_r$

$a_5 = -(R_s+R_L)\, (X_m+X_1)\, \upsilon$

The coefficients of equation (12)

$b_1 = -X_1\, X_L\, (X1 + 2X_m)$, $b_2 = -B_1\, \upsilon$

$b_3 = (X_m+X_1)\, (X_L+X_1) + (X_1 X_m)$

$b_4 = R_s\, X_L\, R_r + R_L\, (X_m+X_1)\, (R_s+R_r)$

$b_5 = -((X_m+X_1)\, (X_L+X_1) + X_1\, X_m)\, \upsilon$

$b_6 = -R_s\, R_L\, (X_m+X_1)\, \upsilon$, $b_7 = -R_r\, (R_s+R_L)$

The coefficients of equation (15)

$c_1 = -X_L\, (R_s+R_r) - (2X_1)\, R_L$, $c_2 = -X_L X_1\, (R_s+R_r) - (X_1^{\,2})\, R_L$

$c_3 = (2X_1 R_L\, \upsilon + R_s X_L\, \upsilon)$, $c_4 = X_1 (R_s X_L\, \upsilon + X_1 R_L\, \upsilon)$

$c_5 = X_c (R_L+R_s+R_r)$, $c_6 = X_L X_c R_r + R_s R_L R_r + X_1 X_c\, (R_L+R_s+R_r)$

$c_7 = -X_c\, (R_L+R_s)\, \upsilon$, $c_8 = -X_1 X_c\, (R_L+R_s)\, \upsilon$;

https://doi.org/10.20428/JST.22.2.4

The coefficients of equation (16)

$d_1=-2X_1X_L$, $d_2=-X_L(X_1^2)$, $d_3=2X_1X_L\,\upsilon$

$d_4=(X_1^2)\,X_L\,\upsilon$, $d_5=(R_sR_L+2X_1X_c+X_LX_c+R_rR_L)$

$d_6=X_L\,(R_sR_r+X_cX_1)+(X_1R_L)\,(R_r+R_s)+(X_1^2)\,X_c$

$d_7=\upsilon\,((-2X_1X_c)-(R_sR_L)-(X_cX_L))$

$d_8=X_1\,\upsilon\,(-R_sR_L-X_1X_c-X_cX_L)$, $d_9=-X_cR_r\,(R_s+R_L)$