Constant Voltage Operation of Self Excited Induction Generator using Optimization Tools

Shelly Vadhera and K. S. Sandhu

Abstract— In this paper MATLAB/ TOOLS such as Genetic Algorithm (GA), Pattern Search (PS) and Quasi-Newton optimization tools have been used to predict the behavior of self excited induction generator (SEIG). GA is used to predict the value of excitation capacitance to maintain the rated terminal voltage for any value of load on the machine terminals. Further analysis is extended to predict the behavior of this generator with voltage fluctuations across the load.

***Keywords*—** Self excited induction generator, Optimization techniques, Induction machine, Renewable Energy, Genetic Algorithm.

***Nomenclature*—**

F, υ	Per unit frequency and speed respectively
I_S, I_R, I_L	Per phase stator, rotor and load current respectively
P_{in}, P_{out}	Per phase input and output power respectively
R_L	Per phase load resistance
R_S, R_R	Per phase stator and rotor resistance respectively
VAR	Per phase volt ampere reactive
V_T, V_g	Terminal and air gap voltage respectively
X_C	Per phase capacitive reactance of the terminal capacitance C
X_M	magnetizing reactance
X_S, X_R	Per phase stator and rotor leakage reactance respectively
(All these quantities are referred to the stator and at base frequency)	

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I. Introduction

PRESENTLY,most of the electricity generated comes from fossil fuels (coal, oil and natural gas). These fossil fuels have finite reserves and certainly will vanish with time. In addition major adverse effect of these fossil fuels is that they produce pollutant gases when they are burned in the process to generate electricity. In contrast, renewable energy resources such as wind, hydro, solar, biomass, geothermal, ocean etc. are believed to be continued and are environmental friendly. Out of these energy resources wind energy seems to be dominating source apart from solar energy. It is a clean and abundant resource that can produce electricity with no pollutant gas emission.

Induction generators are widely used and acceptable machines for wind powered electric generation. Any induction machine may be run as motor or generator, depending upon the operating slip of the machine. Presence of synchronously rotating air gap flux is must for any one of the two operations. As a motor, the rotating air gap flux induces an emf and current in the rotor bars, which is responsible for the production of motor torque and the rotor starts running at a speed less than the speed of rotating field called synchronous speed. This results in to a positive value of operating slip defined by the difference of synchronous and actual operating speed as a fraction of synchronous speed. As generator operation machine is driven by a prime mover mechanically coupled to the rotor to provide the mechanical energy for conversion purpose. Any increase in the speed of the machine beyond synchronous speed causes a reversal in relative direction of rotation between rotor bars and rotating air gap flux. This results in to the reversal of rotor voltage and current in comparison to motor operation .The slip under this operating condition becomes negative. The mechanical energy supplied by the prime mover is transferred across the air gap to the stator, from which it is delivered to the external system as generated power.

An induction generator offers many advantages over the conventional synchronous generators such as reduced unit cost, easy maintenance, rugged and simple construction, brushless rotor (squirrel cage), improved performance due to low transient impedance, natural protection against short circuit, capability to generate the power from variable speed as well as constant speed prime movers and so on [1-5].

The fact that the induction machine has no field windings means that current to magnetize the machine must be supplied by the system to which it is connected. Thus the system must be capable of supplying the lagging KVAR required to establish the air gap flux in induction generator. Depending upon the arrangement to supply the reactive power, two modes of operation are possible for an induction generator. i.e. regeneration and self-excitation. In first mode, the induction generator takes its excitation in terms of lagging magnetizing current from the power source of known voltage and frequency i.e grid, to produce its rotating air gap field for required regeneration. Such generators are known as externally excited generation or grid connected induction generators (GCIG). In this way induction machine draws the reactive power for it's operation from the grid to which it is connected. In second mode the VAR generating unit has to be connected across the terminals of induction machine, which are generally realized in the form of capacitor banks. With suitable capacitors connected across the terminals and with rotor driven in either direction by a prime mover, voltage builds up across the terminals of the machine due to self excitation phenomenon leaving the machine operating under magnetic saturation at some stable point. Such machines are known as self excited induction generators (SEIG).

In this paper an attempt has been made to estimate the excitation capacitance requirement of a self excited induction generator for maintaining rated terminal voltage. Further analysis is extended to predict the behavior of the machine using Genetic Algorithm specifically.

II. ANALYSIS OF SEIG

For the purpose of analysis, conventional steady state equivalent circuit of a SEIG with the usual assumptions [6], has been considered and is shown in Fig. 1. The equivalent circuit is normalized to the base frequency by dividing all the parameters by the p.u. frequency.

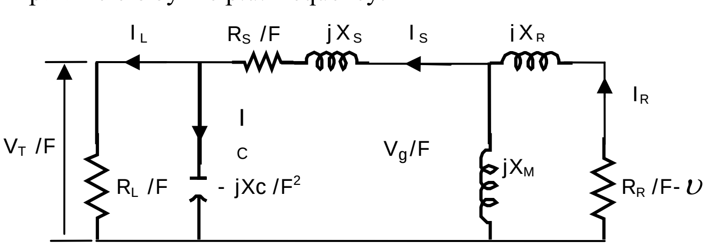

Fig.1 Per-phase equivalent circuit of SEIG

Loop equation in terms of stator current as obtained using Fig.1 is as;

$$Z_S I_S = 0 \quad (1)$$

Where

$$Z_S = Z_1 + Z_2 + Z_3 \quad (2)$$

$$Z_1 = \frac{-jX_C R_L}{\left(R_L F^2 - jX_C F\right)} \quad (3)$$

$$Z_2 = R_S/F + jX_S \quad (4)$$

$$Z_3 = \frac{jX_M\left[R_R + j\left(F - \upsilon\right)X_R\right]}{R_R + j\left(F - \upsilon\right)\left(X_M - X_R\right)} \quad (5)$$

Under steady state operation of SEIG, I_S can not be equal to zero, therefore:

$$Z_S = 0 \quad (6)$$

This equation after separation into real and imaginary parts can be rearranged into two nonlinear equations, which may be solved (using optimization techniques) to estimate the excitation capacitance and generated frequency for the desired terminal voltage.

An objective function for the purpose of optimization may be used as;

$$Z_S = \left(f^2 + g^2\right)^2 \quad (7)$$

Where 'f' and 'g' are defined in Appendix-I

The relation between X_M and Vg/F may be obtained using experimental test data on any machine and is defined as per equation (8).

$$X_M = \frac{\left(K_1 - \frac{V_g}{F}\right)}{K_2} \quad (8)$$

Where,

K_1 and K_2 depend on the design of the machine and

$$V_g = V_T\left(\frac{Z_1 + Z_2}{Z_1}\right) \quad (9)$$

Thus for known value of R_L and V_T, the value of V_g can be determined from equation (9). After estimation of unknown parameter for any operating conditions, the following relations can be used for the computation of the machine performance [7-9].

$$I_S = \frac{\left(V_g/F\right)}{\left(Z_1 + Z_2\right)} \quad (10)$$

$$I_R = \frac{\left(-V_g/F\right)}{\left[R_R/\left(F - \upsilon\right) + jX_R\right]} \quad (11)$$

$$I_L = \frac{-jX_C I_S}{R_L F - jX_C} \quad (12)$$

$$V_T = I_L R_L \quad (13)$$

$$VAR = V_T^2\left(F/X_C\right) \quad (14)$$

$$P_{in} = -\frac{\left|I_R\right|^2 R_R F}{\left(F - \upsilon\right)} \quad (15)$$

$$P_{out} = \left|I_L\right|^2 R_L \tag{16}$$

III. Optimization Techniques

This paper deals with the implementation of many MATLAB based optimization techniques such as Genetic Algorithm (GA), Pattern Search (PS) and Quasi-Newton (QN). These optimization techniques as applied may be discussed in brief as;

A. *Genetic Algorithm*

Genetic Algorithm (GA) is a method for solving optimization problems that are based on natural selection, as the process is derived from biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the GA selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population evolves toward an optimal solution. The GA has several advantages over other optimization methods. It is robust, able to find global minimum and does not require accurate initial estimates [10-11].

The mechanics of the genetic algorithm are elementary, involving nothing more than copying strings, random number generation, and swapping partial strings. A simple genetic algorithm that produces good results in many practical problems is composed of the three operators:

- Reproduction
- Crossover
- Mutation

Reproduction is a process in which individual strings are selected according to their fitness. The fitness is determined by calculating how well each string fits an objective function. Copying strings according to their fitness value implies that strings that fit the objective function well have a higher probability of contributing one or more offspring in the next generation.

Crossover is a two-step process that involves mating and swapping of partial strings. Each time the crossover operator takes action: two randomly selected strings from the mating pool are mated. Then, in the case of simple crossover, a position along one string is selected at random, and all binary digits following the position are swapped with the second string. The result is two entirely new strings that move on to the next generation

Mutation follows crossover and protects against the loss of useful genetic information (1's and 0's). The operator works by randomly selecting one string and one bit location and changing that string's bit from a 1 to a 0 or vice versa. The probability for mutation to occur is usually very small, roughly one mutation per 1000 bit transfers.

The three genetic operators, reproduction, crossover and mutation provide an effective search technique using natural selection and random number generation. Advanced operators, such as dominance, inversion, and segregation exist, but are generally not too effective for the solution of many problems. Even in some cases, the advanced operators can degrade the performance of the genetic algorithm.

The flowchart describing the GA optimization technique implemented in this paper is shown in Fig. 2.

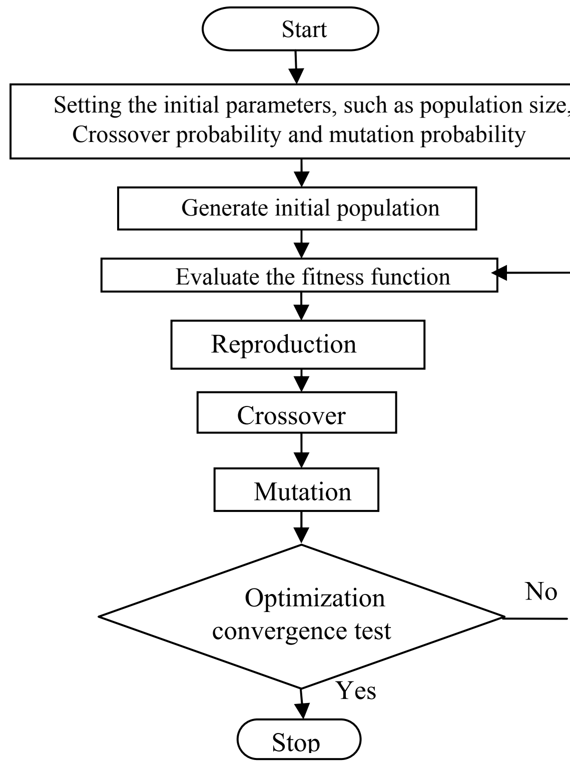

Fig.2 Flow chart of genetic algorithm

B. *Pattern Search*

Direct search is a method for solving optimization problems that does not require any information about the gradient of the objective function. As opposed to more traditional optimization methods that use information about the gradient or higher derivative to search for an optimal point, a direct search algorithm searches a set of points around the current point, looking for one where the value of the objective function is lower than the value at the current point. Direct search can be used to solve problems for which the objective function is not differential, or even continuous.

Pattern Search is a subclass of direct search algorithms, which involve the direct comparison of objective function values and do not require the use of explicit or approximate derivatives.

This is a technique where there is a collection of vectors that the algorithm uses to determine the points to search at each iteration. At each step, the pattern search algorithm searches a set of points, called a mesh, for a point that improves the objective function. The algorithm forms the mesh by:

1. Multiplying the pattern vectors by a scalar, called the mesh size.

2. Adding the resulting vectors to the current point i.e. the point with the best objective function value found at the previous step.

At every step, the algorithm polls the points in the current mesh by computing their objective function values. When option complete poll has the default setting off, the algorithm stops polling the mesh points as soon as it finds a point whose objective function value is less than that of the current point. If this occurs, the poll is called successful and the point it finds becomes the current point at the next iteration. The algorithm only computes the mesh points and their objective function values up to the point at which it stops the poll. If the algorithm fails to find a point that improves the objective function, the poll is called unsuccessful and the current point stays the same at the next iteration. Whereas if the poll is set to on, the algorithm computes the objective function values at all mesh points. The algorithm then compares the mesh point with the smallest objective function value to the current point. If that mesh point has a smaller value than the current point, the poll is successful.

The flowchart describing the PS optimization technique implemented in this paper is shown in Fig. 3

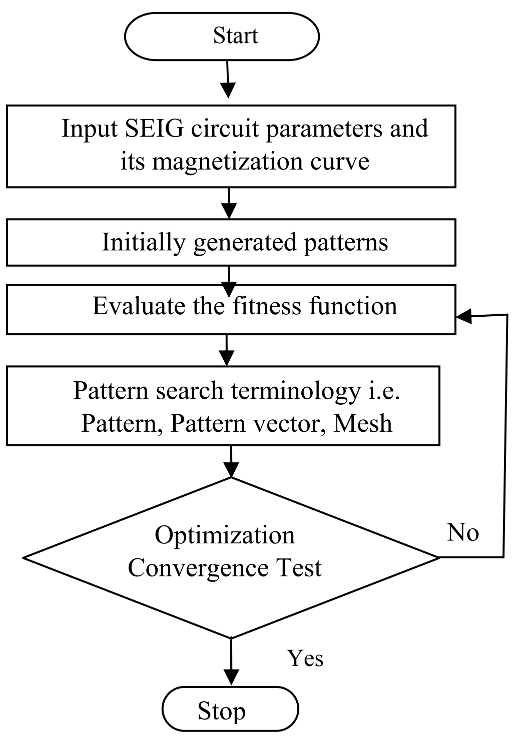

Fig.3 Flow chart of pattern search

C. *Quasi-Newton*

Quasi-Newton methods, which are currently the most robust and effective algorithms for unconstrained optimization, are based on the following set of ideas.

If B_k (definite matrix) is positive definite, the direction $-B_k^{-1}\,\Delta f\,(x^k)$ is always a descent direction at x^k, and we can perhaps get global convergence (i.e. convergence starting anywhere) by searching in those directions.

As long as B_k approximates the second derivative matrix at least asymptotically, the method is likely to work well locally (i.e. fast convergence).

For a quadratic function, a set of conjugate directions, when searched sequentially, gives the optimum solution in at most n iterations.

In terms of numerical computations for the inverse of a matrix, the following formula is used for a low rank update to a matrix

$[A + uv^T]^{-1} = A^{-1}+(1/1+k)\ A^{-1}\ uv^T\ A^{-1}$, where $k = v^TA^{-1}u$

Note that if A^{-1} is known, this is much faster than computing $[A + uv^T]^{-1}$ directly. This is a rank one update (uv^T is a rank one matrix) of the original matrix A. In particular, $A + uv^T$ is a symmetric rank one update.

If B_k is updated by a small rank correction to get B_{k+1} then B_{k+1}^{-1} can be computed easily by the above argument.

Quasi-Newton methods put all these ideas together to construct approximations B_k to the Hessian matrix at each stage. In QN some updates work on B_k and update B_k and then find its inverse, whereas some work directly on the inverse of the second derivative approximation (H_k).

General QN optimization algorithm flow chart is as shown in Fig. 4

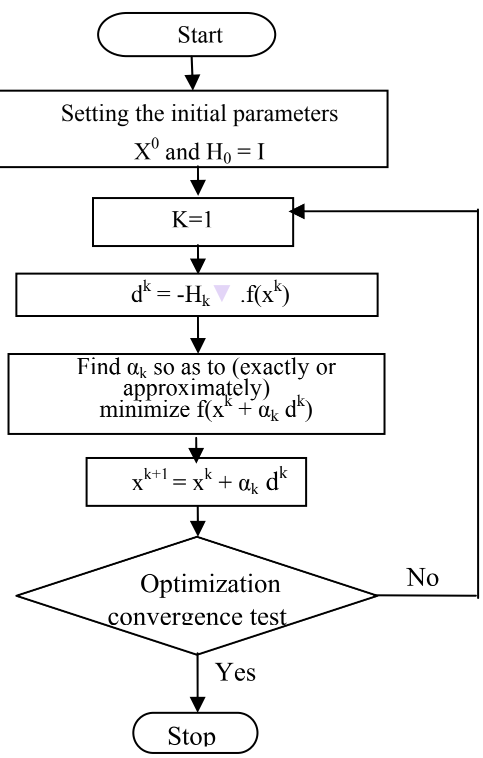

Fig. 4 Flow chart of quasi-newton

IV. RESULTS AND DISCUSSIONS

Fig. 5 to Fig. 8 shows the simulated results for stator current, efficiency, frequency, minimum capacitance requirement and reactive power with output for an induction machine (Appendix-2), using Genetic Algorithm. During simulation terminal voltage is maintained at rated value.

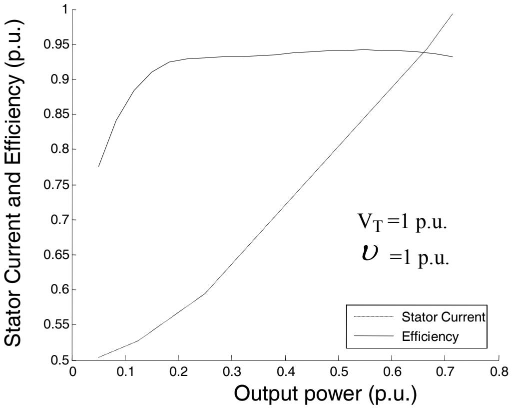

Fig.5 Variation of stator current and efficiency with output power.

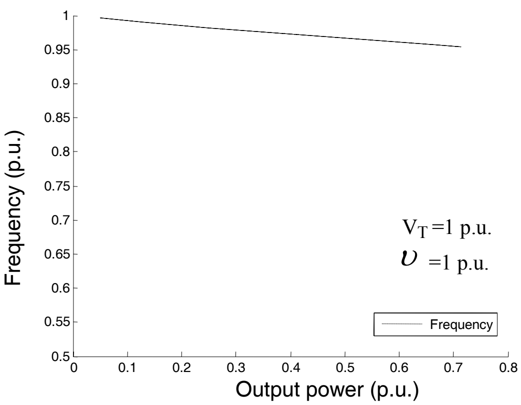

Fig.6 Variation of frequency with output power.

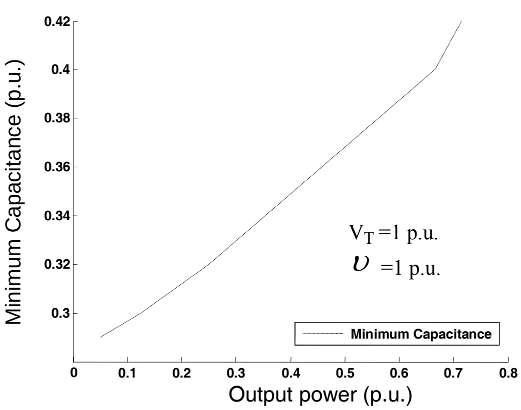

Fig.7 Variation of minimum capacitance with output power.

From Fig.5 it can be observed that the efficiency can be maintained throughout the power range by controlling the terminal voltage. However as per Fig.6 frequency falls slightly from no load to full load. As evident from Fig.7, minimum capacitance requirement of the machine increases with load. Fig.8 to Fig.11 reflects the effects of the machine parameters on the reactive power requirement of generation, in order to maintain the terminal voltage.

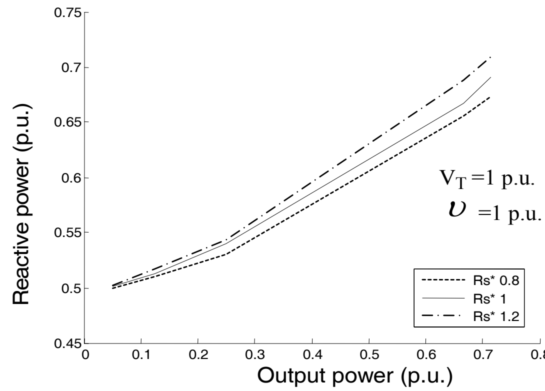

Fig.8 Variation of Reactive power with output power for different values of stator resistance.

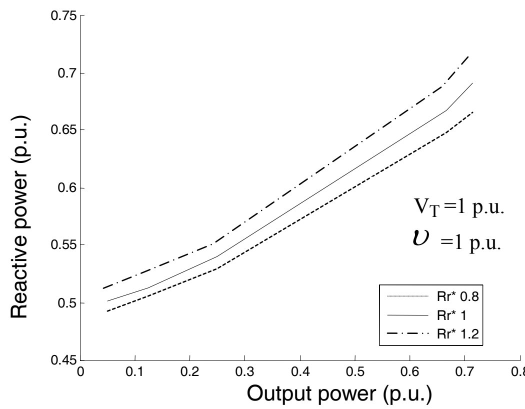

Fig.9 Variation of Reactive power with output power for different values of rotor resistance.

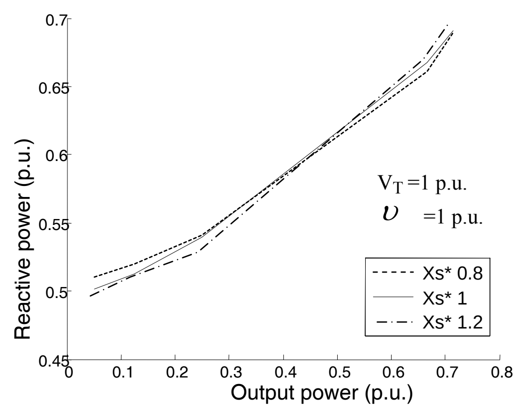

Fig.10 Variation of Reactive power with output power for different values of stator leakage reactance.

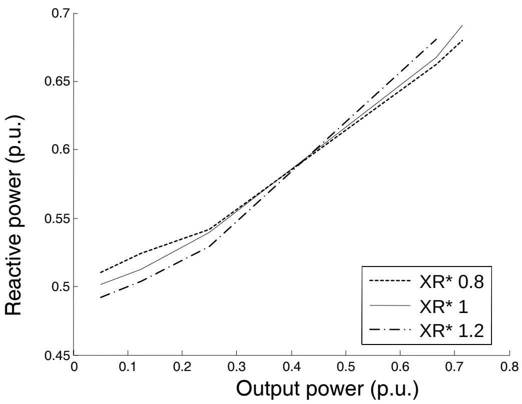

Fig.11 Variation of Reactive power with output power for different values of rotor leakage reactance.

It is seen from Fig.8 and 9 that reactive power requirements are significantly affected with changes in rotor resistances in contrast to stator resistances. However lower values for stator and rotor resistance seems to be best selection for reduction of reactive power requirements. Fig.10 and 11shows that the change in reactive power requirements due to any variation in stator and rotor leakage reactance.

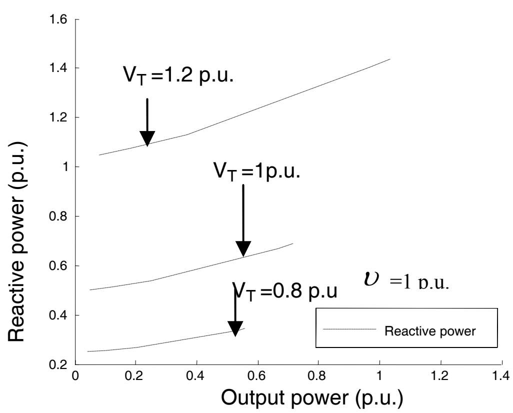

Fig.12 Variation of reactive power with output power for different values of terminal voltage.

Fig.12 and 14 shows the simulated results on the same machine using GA, but at different values of terminal voltage. As observed from Fig.12, reactive power requirement is greatly influenced by terminal voltage. In other words it can be stated that the terminal voltage may be controlled easily by controlling the excitation capacitance or reactive power source.

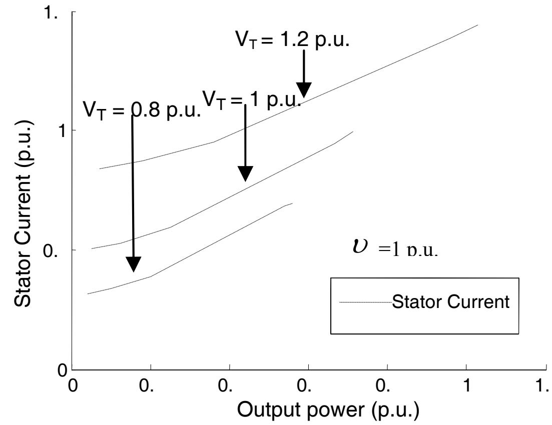

Fig.13 Variation of stator current with output power for different values of terminal voltage.

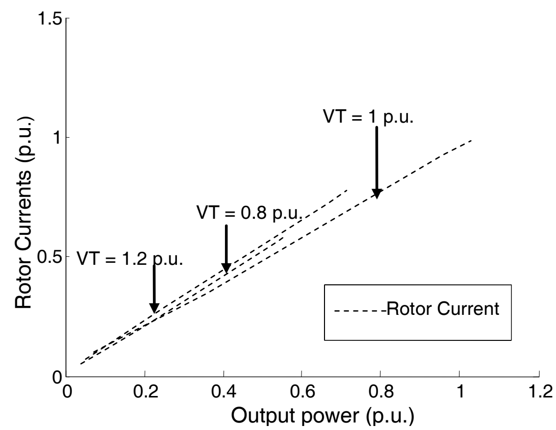

Fig.14 Variation of rotor current with output power for different values of terminal voltage.

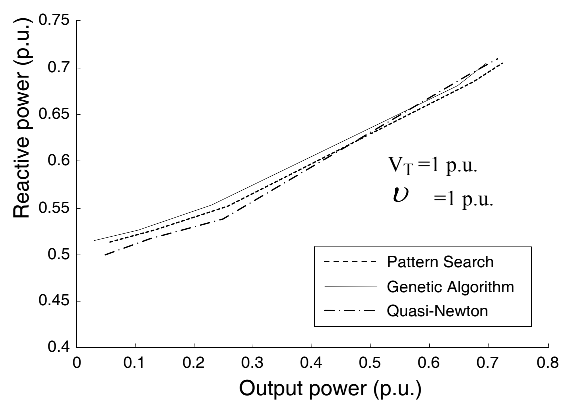

Fig.15 Variation of reactive power with output power using different optimization tools.

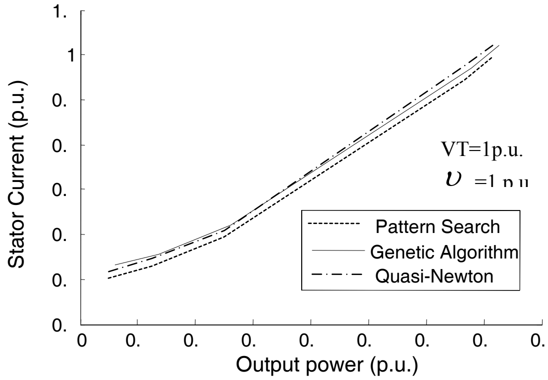

Fig.16 Variation of stator current with output power using different optimization tools.

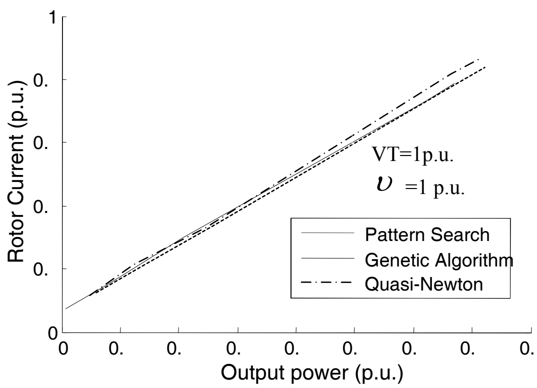

Fig.17 Variation of rotor current with output power using different optimization tools.

Fig. 15 to Fig. 17 shows comparison of simulated results using GA, PS and QN optimization techniques. The simulated results shown in these figures are found to be in good agreement with each other. This reflects that any one of the three optimization techniques as discussed may be used for the solution of problems related to self excited induction generator.

V. CONCLUSION

This paper presents the performance evaluation of SEIG using MATLAB based optimization techniques. Genetic Algorithm is used to determine the excitation capacitance required to maintain the terminal voltage for a given operating speed and load. It has been observed that the value of capacitance varies over a wide range in order to maintain the terminal voltage constant. Simulated results show that the efficiency of the machine may also be maintained by controlling the terminal voltage. Further analysis has been extended to show the effect of machine parameters on the reactive power requirement of machine. Lower values of stator and rotor resistance are suitable for reduction of reactive power requirements of the generator. A close comparison of simulated results using GA, PS and QN optimization techniques leads to the conclusion that any one of the three may be utilized to evaluate the steady state performance of self excited induction generator.

APPENDIX- 1

$$f\left(X_C, F\right) = A_1 F^3 + A_2 F^2 + \left(A_3 X_C + A_4\right)F + A_5 X_C = 0$$

$$g\left(X_C, F\right) = \left(B_1 X_C + B_2\right)F^2 + \left(B_3 X_C + B_4\right)F$$
$$+ B_5 X_C = 0$$

Where the constants are defined as,

$$A_1 = -\left(2\ X_L X_M R_L + X_L^2 R_L\right)$$
$$A_2 = -A_1 \times \upsilon$$
$$A_3 = \left(X_M + X_L\right)\left(R_L + R_S + R_R\right)$$
$$A_4 = R_S R_L R_R$$
$$A_5 = -\left(X_M + X_L\right)\left(R_L + R_S\right) \times \upsilon$$
$$B_1 = 2\ X_L X_M + X_L^2$$
$$B_2 = R_L\left(R_S + R_R\right)\left(X_L + X_M\right)$$
$$B_3 = -B_1 \times \upsilon$$
$$B_4 = -R_S R_L\left(X_M + X_L\right) \times \upsilon$$
$$B_5 = -R_R\left(R_L + R_S\right)$$

APPENDIX- 2

Rating of Machine:
3.7KW/5HP, 3-phase, 415 Volts, 7.6 Amp,
4 poles, 50 Hz, delta connected cage induction motor
Base Quantities:
Currents/phase – 4.39 Amp
Frequency – 50 Hz
Impedance/phase – 94.53 ohms
Power – 1820 Watts
Speed – 1500 r.p.m.
Voltage/phase – 415 Volts
Equivalent Circuit Parameters:
K_1 = 1.6275
K_2 = 0.3418
R_R = 0.061 p.u.
R_S = 0.053 p.u.
X_M (unsaturated) = 2.35 p.u.
X_S = X_R = 0.087 p.u.

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BIOGRAPHIES

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