Numerical Routine based Optimization of Performance Parameters of a Self Excited Induction Generator

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ABSTRACT
Isolated areas often depend on an independent generation system for its electrical power requirements from both conventional and non-conventional sources due to weak nature of power grid and the difficulty to connect to the power grids. These windy locations are suitable for wind energy conversion systems. The study of behaviour of a self excited induction generator under different operating condition mostly depends on its steady state characteristics which are found generally solving non linear equations by iterative techniques manually or using a tedious long computer programme. This paper draws the attention of solving the equations based on a numerical optimization routine. The effectiveness of the said method is then evaluated on a 220V, 1.5kW induction generator for different operating conditions.

Keywords
Induction generator, self excited induction generator (SEIG), steady-state analysis, wind energy conversion, optimization, power quality.

1. INTRODUCTION
The world is witnessing very critical environmental changes pushing nations to enact new laws and policies safeguarding the environment. While the existing technologies putting lot of efforts to upgrade the modes of generation and distribution systems, researchers around the globe too busy in finding out the possibilities of new and novel techniques to study the steady and transient behaviour of different renewable generation system [1]. Synchronous generators are commonly used for generating voltages in conventional large power plants. Mini and micro generation systems utilizing wind or hydro resources rely on induction machine or a permanent magnet synchronous machine. An induction machine run as an induction generator is preferably used in wind energy conversion systems whether grid connected or isolated for its obvious rugged construction, maintenance and operational simplicity, low cost, self protection against faults and overloads [2, 3]. As the operation of an induction generator in grid connected mode functions at constant voltage and frequency, the calculation of performance characteristics is simple. But the fluctuating nature of the terminal voltage and frequency of a self excited induction generator put constraints on analysis of steady state and transient state behaviours. The steady state behaviour is found by its equivalent circuit using loop impedance or nodal admittance approach. As the behaviour depends on excitation capacitor, speed of rotation of prime mover and continuously varying magnetizing reactance, the nonlinear equations are solved by iterative techniques like Newton-Raphson method or using a symbolic programming technique. These methods are generally cumbersome, time consuming and prone to human error. Inbuilt software routines and functions in software packages are used recently to solve the non linear equations without writing separate codes for iterative techniques [3, 4]. An SEIG operates in variable voltage variable frequency mode or fixed voltage variable frequency mode else in constant voltage constant frequency mode [5]. In this regard the performance evaluation of an SEIG before implementation at a potential site is of great importance. This motivates the author to further investigate the possibility and viability of a numerical optimization routine. The variation of terminal voltage, frequency, along with the exciting current which is a necessary source of reactive power is found for different output powers by optimizing the unknown parameters frequency and magnetizing reactance. The parameter updation is performed by a weight updation procedure suggested by Levenberg-Marquardt.

2. MODEL OF A SEIG
The operation of a normal squirrel cage induction motor operating as an induction generator with excitation capacitance is shown below.

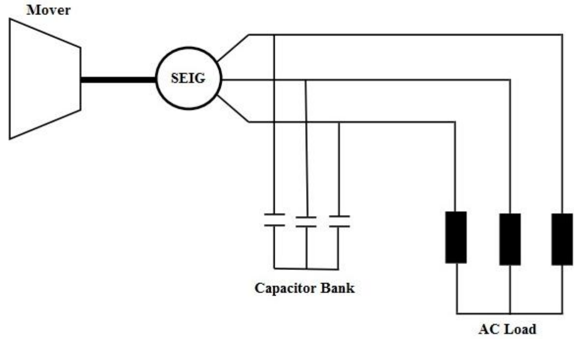

Figure 1: A three phase SEIG operation

The per phase equivalent circuit of a three phase SEIG with an R-L load and an excitation capacitor is shown in figure 2, where R_1, X_1, R_2, X_2, R_c, X_m represent the stator resistance, stator leakage reactance, rotor resistance, rotor leakage reactance, core loss resistance and magnetizing reactance, respectively. F and v represent the per unit (p.u.) frequency and speed respectively. The reactances are specified at a base or rated frequency. All parameters except the magnetizing reactance are considered as constant which is variable and depends on magnetic saturation. Other variable or adjustable parameters in the circuit are X_c, v, F and load impedance.

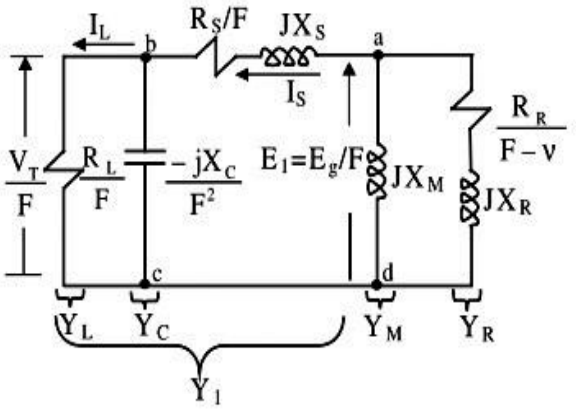

Figure 2: Per phase equivalent circuit of a three phase SEIG

The magnetization characteristic of the motor is governed by the following equation. The circuit of above shown figure has five variables (X_m, X_c, F, v, Z_L) and information of all variables is necessary to evaluate the performance of a generator.

3. STEADY STATE MODELLING

As the task of evaluation depends on information of five variables, fixed possible values can be assigned to some of the variables by considering them as fixed parameters. This reduces the number of independent equations needed in formulating the problem.

The problem equation is formulated here by a loop impedance approach using three series impedances where,

$$\bar{Z}_{a0} = \left(\frac{1}{-jX_C / F^2} + \frac{1}{R_L / F + jX_L} \right)^{-1} \quad (1)$$

$$\bar{Z}_{ab} = \left(R_1 / F + jX_1 \right) \quad (2)$$

$$\bar{Z}_{b0} = \left(\frac{1}{R_C / F} + \frac{1}{jX_m} + \frac{1}{R_2 (F - v) + jX_2} \right)^{-1} \quad (3)$$

Applying Kirchhoff's voltage law in figure 2, it yields

$$\bar{I}_1 = \bar{Z}_{a0} + \bar{Z}_{ab} + \bar{Z}_{b0} \quad (4)$$

Under normal operating condition, the stator current $\bar{I}_1 \neq 0$.Thus

$$\bar{Z}_{a0} + \bar{Z}_{ab} + \bar{Z}_{b0} = 0 \quad (5)$$

In most of the previous method of analysis, the above equation is solved for X_m and F by separating it into real and imaginary parts for fixed values of X_C, v and Z_L.

The above equation in general form can be written as

$$G(x) = 0 \quad (6)$$

Here $G = [g_1 \; g_2]^T$ and x is an unknown vector $[X_m \;\; F]^T$. By evaluating V_g / F from equation (1) after estimating $[X_m \;\; F]^T$, the performance of the generator (voltage, current, power at various points of the circuit) can easily be determined. The two important characteristics that is to be determined is mentioned as follows:

A. No-load Characteristic
It is the variation of no-load terminal voltage against the excitation capacitor C for a const speed v.

B. Load Characteristic
It is the variation of terminal voltage against the generator output power by taking X_C and v as fixed parameters.

4. EVALUATION PROCEDURE

Instead of going through rigorous algebraic manipulations followed by Newton-Raphson method, a numerical based routine is used to solve for X_m and F without expressing them explicitly. In addition partial derivatives of the equations are also not needed in numerical based routine. It uses non-linear least-square algorithm that employs the Levenberg-Marquardt method. Levenberg-Marquardt optimization is a virtual standard in non-linear optimization which significantly out performes gradient descent and conjugate gradient methods for medium sized problems. It estimates the hessian matrix using the sum of outer products of the gradients. To predict the behaviour of an unknown target function for fixed parameters (weights) it is first modelled as deterministic model $f(x:w)$ to obtain the required data sets x. Then an average error gradient matrix d and a hessian matrix H is formed as

$$d = \left\langle \left(f(x; w_0) - y \right) \Delta f(x; w_0) \right\rangle \quad (7)$$

$$H = \left\langle \Delta f(x; w_0) \Delta f(x; w_0)^T \right\rangle \quad (8)$$

Here H is an approximation to the hessian which is obtained by averaging outer products of the first order derivative. The Levenberg weight updation rule is given by

$$w_{i+1} = w_i - (H + \lambda I) ^1 d \quad (9)$$

where I is the identity matrix, and λ is a blending factor that determines the mix between steepest descent and the quadratic approximation. For a large value of λ, the rule approaches

$$w_{i+1} = w_i - \frac{1}{\lambda} d \quad (10)$$

which is steepest descent.

Levenberg-Marquardt method replaces the identity matrix by diagonal of hessian to move further in the direction in which the gradient is smaller.

$$w_{i+1} = w_i - (H + \lambda diag[H])^{-1} d \quad (11)$$

The algorithm of evaluation procedure is mentioned as follows:

a) Initialize the value of parameters, evaluate the residual and Jacobian J at initial parameter guess.
b) Go for updation
c) Evaluate for error at new weight vector
d) Check for convergence. If the method has converged, return x that is here X_m and F.

One of the characteristics of the least square method is that when the system of equations does not have a zero numerically, the method still converges to a point with a tolerance of the order of 10^{-6}.

5. RESULTS AND DISCUSSION

The performance characteristics of a 220V, 1.5kW delta connected induction motor operating as self excited induction generator is found for the following machine parameters. R_s=4.98 ohm, R_r=4.92 ohm, R_C=38.67 ohm, X_{ls}=5.79 ohm, X_{lr}=5.79 ohm. All the calculations are done on per unit basis for a power base of 2500W, voltage base 500V, current base 5A and impedance base 100ohm. The machine is run at a per unit speed of 1.1 for a synchronous speed of 1500rpm. Apart from variation of air-gap voltage with magnetizing reactance, the variation of output power versus load current, exciting capacitor current and stator current respectively for exciting capacitance value of 24µF, 35µF and 48µF is obtained. The performance evaluation of self excited induction generator is obtained by supplying electrical power to varied resistive loads. The characteristics are first found for varying terminal voltage.

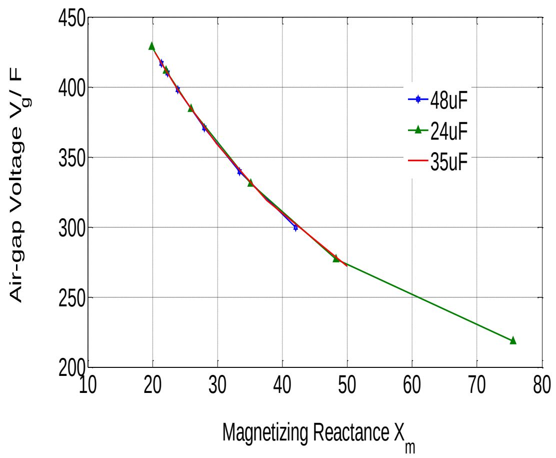

Figure 3: Variation of air-gap voltage with magnetizing reactance

For three different exciting capacitances figure 3 shows the variation of air-gap voltages from around 425V to 225V with magnetizing reactances varying from 20Ω to 75Ω as seen to be varied. As the generator output voltage and power supplied to any load depends on this variation of air-gap voltage with magnetizing reactance it is evaluated first followed by the variation of line frequency with output power. As seen from figure 4 as the output power is varied for three different exciting capacitances from 5W to 74W, the line frequency varies from around 38 Hz to around 53 Hz. Though operating any electrical load is potentially a power quality problem at these frequencies but reliability issues are improved by a continuous power supply for few restricted electrical loads. The generator terminal voltage is not constant rather its varying continuously as the output power is varied as observed from figure 5. The maximum and minimum terminal voltage is restricted to about 335V and 210V respectively. Figure 6 and figure 7 shows the variation of generator currents viz. load current, capacitor current and stator current for 48µF and 24µF respectively. As observed from these two figures, the capacitor current which supplies the reactive power to start and maintain the generating process is a flat characteristic at about 5.5A and 6.5A respectively for 48µF and 24µF.

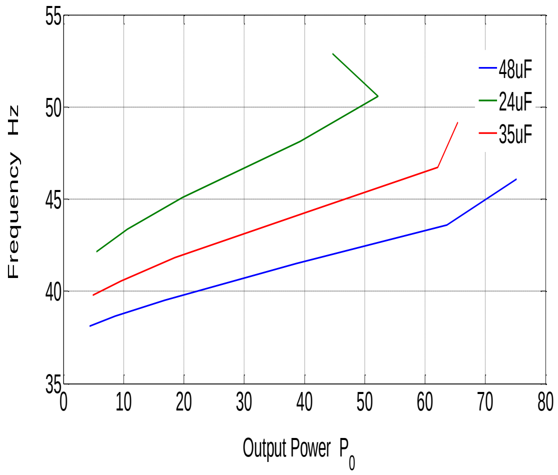

Figure 4: Variation of output frequency with output power

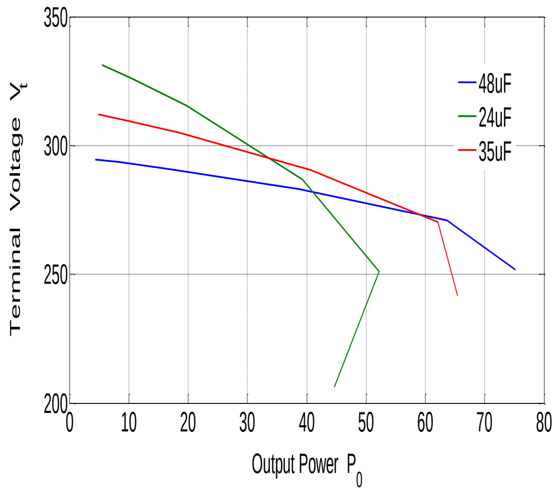

Figure 5: Variation of terminal voltage with output power

From the equivalent diagram and from figure 6 and figure 7 it is quite clear that by applying Kirchhoff's current law the load current and the stator current adds to the exciting capacitor current. More the capacitance value, more is the capacitor current, more is the reactive power supplied. As any induction machine for its normal operation that is to establish a flux in the air gap needs reactive power, this is supplied by an external capacitor in a SEIG but it varies as the mutual inductance is not constant as in a motoring operation.

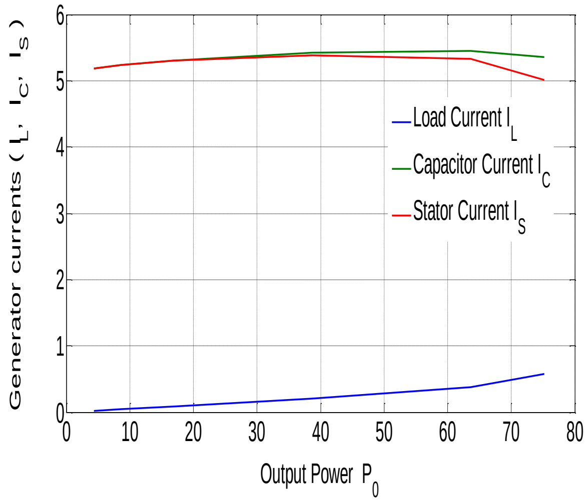

Figure 6: Variation of generator load currents, capacitor currents and stator currents with output power for an exciting capacitance of 48µF

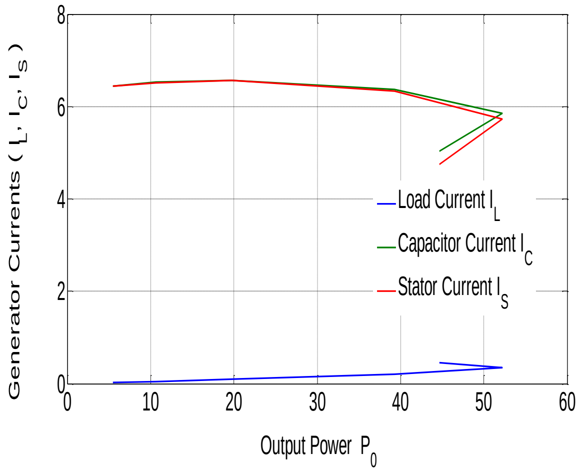

Figure 7: Variation of generator load currents, capacitor currents and stator currents with output power for an exciting capacitance of 24µF

6. CONCLUSION

This paper describes a numerical based routine optimization procedure for performance evaluation of a SEIG. It simplifies the procedure and effort to formulate the problem by eliminating the need of iterative methods like Newton-Raphson and rigorous algebraic manipulations. The parameter updation is performed by a Levenberg-Marquardt weight updation matrix by introducing a hessian diagonal to move the solution further towards where the gradient is still smaller as compared to a steepest descent procedure. Performance characteristics are obtained for step changes in resistive loads for varying terminal voltages. The advantage of Levenberg-Marquardt method is that when the system of equations does not have a zero numerically, the method still converges to a solution with a pre-specified tolerance. The technique could be extended to problem formulation and analysis of SEIG for different operating conditions.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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