Estimation and Analysis of Optimal Performance Parameters of SEIG for Variable Load Impedance

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***Abstract*: The use of self-excited induction generators (SEIG) are increasing to fulfill the present demand of electricity generation from both conventional and nonconventional energy sources. Optimum values of performance parameters are required for effective operation and precise estimation of various characteristics of SEIG. Nonlinear nature of magnetization curve and higher order equations for solution enhances the complexity of the system. Approximation of nonlinearity of magnetization curve plays an important role in obtaining precise values of performance parameters and different characteristics. This paper intends to calculate precise values of performance parameters at different loading conditions. Different regression functions has been employed to approximate the nonlinearity of magnetization curve and obtain the exact magnetizing reactance. Per unit frequency and excitation capacitance is substantially affect the performance parameters. Therefore, desired performance characteristics can be obtained by controlling the performance parameters. The effectiveness of proposed method is then verified on a machine of rating 2 kW, 380 V.**

I. INTRODUCTION

Steady-state analysis of SEIG is important from design and operational points of view. Optimum value of magnetizing reactance is used for computation of optimal values of performance parameters through steady state analysis of SEIG. Terminal voltage and frequency both are unknown and have to be computed for a given speed, capacitance, and load impedance. Murthy et al. [1] developed a mathematical model to obtain steady-state performance of SEIG using equivalent circuit impedance of machine. Two nonlinear equations, formed by separating real and imaginary parts of impedance, are solved for two unknowns i.e. f and X_m using Newton–Raphson method. Quazene et al. [2] used a nodal admittance technique. Two nonlinear equations, formed by separating real and imaginary parts of admittance, are solved first for f and then for X_m. Algebraic equation is solved for initial value of f and then Secant method is used for the exact solution [3]. An iterative technique by initialize f and increase it in small steps until the result converges is proposed by Chan [4]. This technique, however, lacks in making a judicious choice of an initial value and number of iterations required. An iterative technique by using approximate equivalent circuit and a mathematical model for B-H curve, reduces the solution to a nonlinear equation in f, is reported by Rajakaruna et al. [5]. An optimization technique by expressing it as a multivariate unconstrained nonlinear optimization problem tried by Singh et al. [6], in which impedance of machine is taken as objective function. Independent variables f and X_m varies within their upper and lower bounds to attain practically acceptable values of variables using Rosenbrock's method of rotating coordinates.

Joshi et al. [7] have proposed an approach, which leads to a quadratic equation in slip making the steady-state analysis simple and comprehensive. Eigenvalue-based approach to predict both minimum and maximum values of required excitation capacitance for SEIG is presented by Wang et al. [8]. Performance of SEIG driven by regulated and unregulated turbines is reported in [9-11]. Per unit (p.u.) speed is determined directly by solving a quadratic equation in regulated turbines for constant-speed constant-frequency operation. Whereas, an additional iteration process using Secant method is employed to deal with variable-speed nature of turbine in case of unregulated turbines. Steady state analysis and performance characteristics of SEIG has been investigated by Alghuwainem [12], when a transformer is connected to stator terminals to supply the load at different voltage levels. Transformer tends to saturate at higher rotor speeds, thus absorbs excess reactive power, limits increase in terminal voltage, and improves voltage regulation of SEIG. Simultaneously, transformer introduces additional nonlinearity, which substantially complicates the analysis of SEIG. A technique is proposed that care about transformer saturation and applicable for nonlinear loads.

Performance of wind-driven SEIG is compared for shunt capacitor alone with combination of series and shunt capacitors [13]. Reluctance generator is a synchronous machine with salient or segment rotor, which does not needs any dc rotor excitation. Steady state performance of self-excited reluctance generator and self-excited induction generators has been compared [14]. Analysis of three phase SEIG with asymmetrical load and excitation capacitance using method of symmetrical components is reported [15-18]. Performance analysis of SEIG by optimization-based approach is presented by Alolah et al. [19]. Problem is formulated as objective function for optimization, which does not require derivation of analytical equation. Optimal value of magnetizing reactance is essential to calculate optimal values of performance parameters. Conventionally, piecewise linearized model and lower order polynomial has been used to solve the nonlinearity of magnetization curve. Significance of precise approximation of nonlinear magnetization curve to obtain optimum value of magnetizing reactance has been discussed [20]. Least square method and Levenberg-Marquardt Algorithm have been used for proper fitting of nonlinear magnetization curve [21].

This paper presents the steady state analysis of SEIG including computation of optimal performance variables. Per-phase equivalent circuit model is used to determine various parameters. Eigenvalue computation approach is applied to solve equations of nodal admittance method to get the values of performance parameters. Eight regression functions viz. exponential, Gaussian, polynomial, power series and sum of sine series are employed in place of conventional models. A comparative analysis is furnished between conventional and proposed regression approximation methods on the basis of graphical and numerical values of goodness of fit statistics for each fitting. This process is employed on a test induction machine of rating 2 kW, 380V, 4-pole, star, 50 Hz. Best fitted function is selected on the basis of goodness of fit statistics for all functions. It gives optimum value of magnetizing reactance at any desired value of terminal voltage. The values of per unit frequency, magnetizing reactance and excitation capacitance required to generate rated voltage is computed for all regression functions. Variation in performance variables with load impedance is also presents. This paper deals with determination of performance variables corresponding to different regression functions and select the optimal values of parameters.

II. STEADY STATE MODEL OF SEIG

(a) Per-Phase Equivalent Circuit Model

Per-phase equivalent circuit feeding resistive and inductive load is used for calculating performance variables at the given operating conditions is shown in Fig. 1 [22]. All the reactance and voltages are referred to stator at base frequency. All the design parameters of machine are assumed to be constant and unaffected by saturation except magnetizing reactance. Simplified per-phase equivalent circuit and final equations of nodal Admittance method used for steady state analysis of SEIG are re-written for calculation of performance parameters [22].

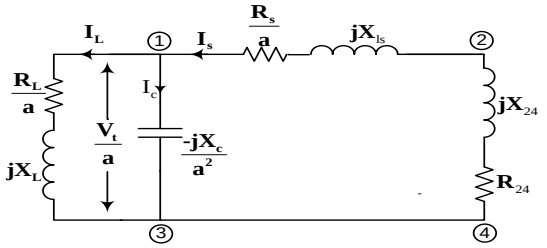


Fig. 1 Simplified per-phase equivalent circuit of SEIG

$$\left(Y_L + Y_{14} + Y_c\right) = 0 \tag{1}$$

$$\frac{aR_L}{R_L^2 + a^2 X_L^2} + \frac{R_{14}}{R_{14}^2 + X_{14}^2} = 0 \tag{2}$$

$$\frac{a^2}{X_c} - \frac{a^2 X_L}{R_L^2 + a^2 X_L^2} - \frac{X_{14}}{R_{14}^2 + X_{14}^2} = 0 \tag{3}$$

Equation (2) does not contain capacitive reactance. Therefore, per unit frequency is determined by this equation for specific terminal voltage, rotor speed and load. Magnetizing reactance is obtained from magnetization curve of machine. Size of excitation capacitance is computed by equation (3) using per unit frequency determined from equation (2). It can be expressed as a 6th degree polynomial as follows after a series of algebraic manipulations;

$$h_6 a^6 + h_5 a^5 + h_4 a^4 + h_3 a^3 + h_2 a^2 + h_1 a + h_0 = 0 \tag{4}$$

Solution of a 6th degree polynomial by conventional solution technique i.e. Newton-Raphson method, iterative method etc. needs complicated mathematical derivations for coefficients of equation. It is a tedious and time consuming task and prone to human errors. Determination of optimal value of performance parameters by some simple technique is required for the proper design and operation of induction machine as SEIG. Eigenvalue and eigenvalue sensitivity approach is employed to solve the polynomial.

(b) Solution Methodology

Eigen value problem is of substantial theoretical importance and wide-ranging application viz. solving systems of differential equations, analyzing population growth models, and calculating powers of matrices [21]. The eigenvalue problem is to determine the nontrivial solutions of the equation

$$Ax = \lambda Bx \tag{5}$$

Where both A and B are $n \times n$ matrices, x is a length n column vector, and λ is a scalar.

n values of λ that satisfy the equation (5) are generalized eigenvalues, and corresponding values of x are generalized right eigenvectors. If B is nonsingular, the problem could be solved by reducing it to a standard eigenvalue problem

$$B^{-1}Ax = \lambda x \tag{6}$$

The characteristic polynomial of degree n is represented by a $n \times n$ matrix A, has exactly n complex roots (with zero or nonzero imaginary part). The polynomial can be factored into the product of n linear terms;

$$\det(\lambda I - A) = (\lambda - \lambda_1)(\lambda - \lambda_2)(\lambda - \lambda_3)\ldots(\lambda - \lambda_n) \tag{7}$$

$$= c_1\lambda^n + c_2\lambda^{n-1} + \ldots + c_n\lambda + c_{n+1} \tag{8}$$

Where, each λ_i is a complex number. The numbers $\lambda_1, \lambda_2, \lambda_3, \ldots \lambda_n$ (which may not be all distinct) are roots of the polynomial, and are represented as eigen values of A. $c_1, c_2, \ldots, c_n, c_{n+1}$ are coefficients of polynomial A.

The eigenvalues may have non-zero imaginary parts even for all real values of A. Also, eigenvalues may be irrational numbers for all rational or integer values of A. The non-real roots of a real polynomial with real coefficients can be grouped into pairs of complex conjugate values, namely with two members of each pair having same real part and imaginary parts that differ only in sign. If the degree is odd, then at least one of the roots is real. Therefore, any real matrix with odd order has at least one real eigenvalue—whereas, a

real matrix with even order may have no real eigenvalues. When a matrix has no repeated eigenvalues, the eigenvectors are independent and eigenvector matrix V diagonalizes the original matrix A. Whereas, if a matrix has repeated eigenvalues, it is not similar to a diagonal matrix unless it has a full (independent) set of eigenvectors. If the eigenvectors are not independent then the original matrix is defective. Even if a matrix is defective, the solution satisfies $A \times X = X \times D$, where D is matrix of eigenvalues. Eigenvalue computation approach is carried out in MATLAB environment.

The choice of the excitation capacitance, the rotor speed and the load impedance not only affect the self-excitation process but also the induction generator steady state performance parameters, such as the output voltage, the frequency, the generated power and the efficiency. Roots of equation (4) is evaluated for various load impedance, speed and power factor condition for reactive loads.

III. DETERMINATION OF PERFORMANCE PARAMETERS OF SEIG

(a) Estimation of Magnetization Reactance

Magnetizing reactance decides the value of capacitance to generate specific terminal voltage. Excitation capacitance influences frequency, stator current and efficiency of SEIG. Therefore, determination of precise magnetizing reactance is essential to compute optimal performance parameters of SEIG. Magnetizing reactance can be obtained from nonlinear magnetization curve. Conventional piecewise linearized model provides approximate value of magnetizing reactance. Precise value of magnetizing reactance can be obtained by employing different regression function to solve the nonlinearity of magnetization curve. Eight regression functions has been employed on magnetization curve of test induction machine. The rating and different parameters of that induction machine are given in Table – 1.

Table – 1 Details of Induction Machine

Rated Power	7.5 HP
Base Voltage	380 Volts
Base Current	5.4 amp
Base Impedance	40.63 Ω
Number of Poles	4
Type of Connection	Star
Rated Frequency	50
Rated Speed	1500 r.p.m.
Per unit Stator Resistance	0.0982
Per unit Stator Reactance	0.112
Per unit Rotor Resistance (referred to stator)	0.0621
Per unit Rotor Reactance (referred to stator)	0.0952

To get the optimum value of magnetizing reactance, different regression function are to be employed to solve the nonlinearity of magnetization curve. Eight regression functions, given in Table - 2, have been used on test machine. Precise magnetizing reactance with best goodness of fit among eight regression functions.

TABLE – 2 Different Regression Functions

Fitting Type	**Type of Regression**	**Equation**
Fitting – I	One-Term Exponential Regression	$V_g = ae^{bX_m}$
Fitting – II	Two-Term Exponential Regression	$V_g = ae^{bX_m} + ce^{dX_m}$
Fitting – III	Gaussian Regression	$V_g = ae^{-\left(\frac{X_m - b}{c}\right)^2}$
Fitting – IV	First Order Polynomial Regression	$V_g = aX_m + b$
Fitting – V	Second Order Polynomial Regression	$V_g = aX_m^2 + bX_m + c$
Fitting – VI	Third Order Polynomial Regression	$V_g = aX_m^3 + bX_m^2 + cX_m + d$
Fitting – VII	Power Series Regression	$V_g = aX_m^b + c$
Fitting – VIII	Sum of Sine Regression	$V_g = aSin(bX_m + c)$

(b) Computation of per-unit Frequency

Equation (1) is minimized to calculate p.u. frequency and capacitance required for self-excitation from per-phase equivalent circuit model and it is divided in to real and imaginary parts as equation (2) and (3). Rotor speed and load impedance is assumed to be constant for calculation of p.u. frequency and required excitation capacitance to generate a given terminal voltage. Thus, equation (2) is independent of capacitance term and the only variable is per unit frequency a. It can be expressed as equation (4) in the form of polynomial in p.u. frequency a, which is solved using eigenvalue computation approach to yield all the real and complex roots of p.u. frequency at a given load, rotor speed and terminal voltage. Only real roots have physical significance and used for further calculations. The simulation has been carried out in MATLAB environment.

(c) Determination of Optimal Capacitance

A minimum capacitance is required for voltage buildup in induction generator i.e. tangent to the magnetization curve. The machine must operate at threshold of saturation for required minimum capacitance. Only real roots of equation (4) can be used for performance parameters calculation. For determining the minimum capacitance required, the magnetizing reactance, X_m should be equal to the maximum value of the saturated magnetizing reactance $(X_m)_{max}$. Optimum capacitance for self-excitation at a specific voltage generation require precise value of magnetizing reactance. To calculate capacitance required for self-excitation from the steady-state model, equation (1) is minimized by using eigenvalue computation approach. After minimization, the required capacitance is calculated from the equation (3).

Optimal value of excitation capacitance is determined by solving equation (3) at precise value of magnetizing reactance, real roots of p.u. frequency computed by equation (4), given rotor speed and load impedance. Largest positive real value of p.u. frequency a_{max} corresponds to minimum capacitance C_{min} at given operating condition. Similarly,

smallest positive real root a_{min} corresponds to maximum capacitance C_{max}. C_{min} indicates the minimum value of excitation capacitance for voltage generation, below which no voltage generation and the system is under-excited. C_{max} indicates the maximum value of excitation capacitance, above which the system is over-excited and no generation of voltage. Thus, the value of excitation capacitance connected across stator terminals must lie between minimum and maximum capacitance for voltage buildup in SEIG.

(d) Steady State Analysis of SEIG

Magnetization curve provides the value of magnetizing reactance corresponding to required generated voltage. Speed can be vary by changing prime mover speed. Load impedance can be vary in two ways i.e. magnitude and power factor of load. By varying magnitude, excitation capacitor delivers constant reactive power to load. Whereas, reactive power loading on excitation capacitor varies with load power factor. Load impedance affects rotor speed, p.u. frequency and terminal voltage for constant capacitance operation. Whereas, p.u. frequency and excitation capacitance get affected by load impedance for constant voltage operation of SEIG. Equation (2) and (3) provides values of p.u. frequency and excitation capacitance at a definite value of terminal voltage, load impedance, rotor speed, power factor of load impedance. Per unit frequency and excitation capacitance can be computed for different load impedance, terminal voltage and rotor speed. Thus, dependence and relation between different performance parameters carried out.

IV. RESULTS AND DISCUSSION

(a) *Comparative Analysis of Performance Parameters*

Performance variables like air gap voltage, magnetization reactance, excitation capacitance, per unit frequency, per unit speed, load power factor and load impedance are required to study the performance analysis of SEIG. Magnetizing reactance is obtained from magnetization curve which is used to calculate p.u. frequency and required excitation capacitance by equation (2) and (3). The value of magnetizing reactance is largely depends on function employed for approximation of nonlinearity of magnetization curve. Impact of eight regression functions on the magnetizing reactance, p.u frequency and required excitation capacitance has been presented in this section.

Eight regression functions provides eight distinct values of magnetizing reactance. All the other performance parameters are depending on the value of magnetizing reactance. Eight different set of values are computed corresponding to each value of magnetizing reactance. Eigenvalue computation approach is used to calculate performance variables. Table - 3 shows the comparison of magnetizing reactance, p.u. frequency and excitation capacitance required to generate rated terminal voltage ($V_g = 1.0\ p.u.$) at rated rotor speed ($b = 1.0\ p.u.$) and rated load impedance ($Z_L = 1.0\ p.u.$) of unity power factor ($R_L = 1.0\ p.u., X_L = 0.0\ p.u.$) for test machine with proposed eight regression expressions. Optimum value performance parameters are obtained by using optimal value of magnetizing reactance while solving nodal equations. Optimum values of magnetizing reactance, p.u. frequency and excitation capacitance is highlighted in the Table - 3.

Table - 3 Comparison of X_m, a and C at $V_g = 1.0\ p.u.$

Fitting Type	X_m $(p.u.)$	a $(p.u.)$	C (μF)
I	1.206068	0.924134	35.53018
II	1.19258	0.923904	35.89453
III	1.19650755	0.923972	35.78743
IV	1.206538	0.924142	35.51761
V	1.192469	0.923902	35.89759
VI	1.192873	0.923909	35.88654
VII	1.190571	0.923869	35.94959
VIII	1.193211	0.923915	35.87726

It is observed from Table - 3 that values of magnetizing reactance, p.u. frequency and excitation capacitance are varying with regression function. Estimation of optimal excitation capacitance is prime important for optimum performance of SEIG as voltage build up is depending on the value of excitation capacitance. It is also seen that the variation of magnetizing reactance slightly affects the value of p.u. frequency but extremely affects the value of excitation capacitance. The magnitude of generated terminal voltage depends up on the value of excitation capacitance connected to the stator terminals at a given load and prime mover speed. Hence, method adopted for approximation of nonlinearity of magnetization curve greatly affect the value of excitation capacitance and generated voltage. Optimum value of variables has been determined and highlighted using the function having best fit among all the eight regression functions under study. The deviation in the values of magnetizing reactance, p.u. frequency and excitation capacitance with fitting expression validates the proposed methodology.

(b) Effect of Load Impedance on Performance Parameters

Performance parameters of SEIG are computed for different values of magnetizing reactance obtained by employing eight different regression functions. Terminal voltage generation, prime mover speed, load power factor and connected load is constant for all calculations. Performance variables are dependent on each other. Excitation capacitance and p.u. frequency varies with type of regression function used and also with load impedance.

(c) Variation in Per Unit Frequency with Load Impedance

To analyze the variation in both the real roots of p.u. frequency with load impedance, only higher real root is considered for voltage generation. No real root available below a specific value of load impedance i.e. critical load impedance Z_{LC}. No generation of voltage occurs below this value of load impedance. Fig. 2 is showing variation in p.u. frequency with load impedance for all regression functions. Maintain constant speed of prime mover at rated value ($b = 1.0\ p.u.$) and load power factor at unity ($X_L =$

$0.0\ p.u.$) to generate rated terminal voltage ($V_g = 1.0\ p.u.$) during plotting these characteristics. The range of load impedance for plots is narrow ($0.9\ p.u.$ – $1.1\ p.u.$) for the sake of clarity between eight observations of all regression functions.

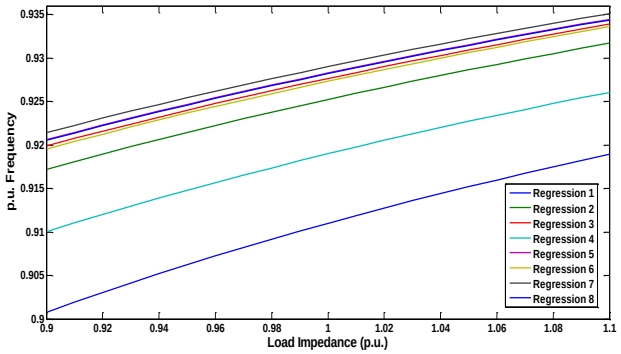


Fig. 2 Variation in p.u. Frequency with Load Impedance

(d) Variation in Excitation Capacitance with Load Impedance

Higher real root of equation (4) gives minimum value of excitation capacitance C_{min} for voltage generation, below which no generation of voltage and the system is under-excited. Lower real root gives the maximum value of excitation capacitance C_{max}, above which the system is over-excited and no generation of voltage. Fig. 3 is showing variation in excitation capacitance with load impedance for all regression functions. Operating conditions and range of load impedance are same as mentioned in the above subsection.

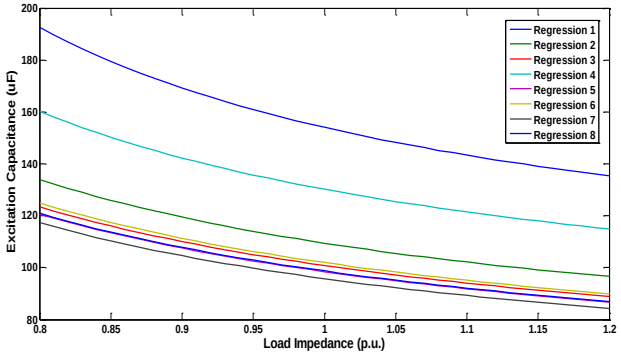


Fig. 3 Variation in Excitation Capacitance with Load Impedance

Variation in per unit frequency and required excitation capacitance at rated prime mover speed with purely resistive load is plotted to generate constant rated terminal voltage. Values of p.u. frequency and excitation capacitance are very close for different regression expressions. As a result, the characteristics of variation in p.u. frequency and excitation capacitance are cumbersome for wide range of load impedance for all regression expressions. Therefore, the range of load impedance is limited for analysis of all characteristics. It is considered near rated load i.e. slightly higher and lower than the rated load conditions.

It has been observed from all characteristics, that p.u. frequency increases and excitation capacitance decreases with increase in load impedance. Fig. 3 shows the variation in excitation capacitance with load impedance, which is increased for under-load conditions and decreased for overload conditions. This variation in excitation capacitance increases rapidly at under-load condition. Similarly variation in p.u. frequency increases for under-load conditions and decreases for overload conditions. Performance variables not only depend on the type of regression but also on the operating conditions. Optimum excitation capacitance reduces the current flowing through stator winding. It reduces the heating of machine, which further improves the efficiency of SEIG.

V. COMPARISON WITH EXISTING METHODOLOGY

Performance analysis of SEIG using conventional fitting techniques i.e. piecewise linearized model and polynomial of lower order are to be compared with the results obtained by best fit expression. Table - 4 presents a comparison of performance parameters using conventional fitting models and proposed regression expressions employed to solve nonlinearity of magnetization curve. Solution technique for both the fitting prototypes are same i.e. Eigen value approach. Table - 4 shows the comparison of magnetizing reactance, excitation capacitance and per unit frequency at rated load impedance ($Z_L = 1.0\ p.u.$) of unity power factor ($R_L = 1.0\ p.u., X_L = 0.0\ p.u.$) load and rated rotor speed ($b = 1.0\ p.u.$) to generate rated terminal voltage test machine.

Table - 4 Comparison of Proposed and Existing Methodology

Methodology	**Fitting Type**	X_m **(p.u.)**	a **(p.u.)**	C **(p.u.)**	**Reduction in Capacitance (%)**
Existing	PLM	1.242	0.925754	107.6542	1.668955
Proposed	II	1.219429	0.925244	109.4509	

Piecewise linearized model and polynomial model provides approximate value of magnetizing reactance. This approximate value of magnetizing reactance further gives approximate values of performance parameters. Different regression functions are employed to solve nonlinearity of magnetization curve and to obtain precise value of magnetizing reactance. The regression expression having best fitting provides precise value of magnetizing reactance, which further used for calculation of optimal performance parameters of SEIG.

Polynomial of third order are the best fitting expression for the test machine. Optimum values of performance parameters are then computed for optimal value of magnetizing reactance using eigenvalue computation approach. It has been observed from Table – 4, that the performance parameters significantly varies with proposed regression methodology in comparison to existing conventional PLM technique. Precise value of magnetizing reactance using regression functions, provide optimal value of excitation capacitance at given operating condition. A

considerable variation in the value of excitation capacitor of about 1.67% is observed. Thus, optimal performance parameters are determined using proposed methodology.

VI. CONCLUSION

Performance parameters of SEIG can be determined by solving its per-phase equivalent circuit. It is computed by solving two nonlinear equations using eigenvalue computation approach. Magnetizing reactance is required to solve nodal equations. Conventional piecewise linearized model and lower order polynomial model gives approximate value of magnetizing reactance. Eight regression functions has been employed to obtain precise value of magnetizing reactance. Performance variables are than computed for all regression functions and compare them. Precise value of magnetizing reactance is required to calculate optimal value performance variables of SEIG. Values of magnetizing reactance, p.u. frequency and excitation capacitance are varying with regression function. The variation of magnetizing reactance slightly affects the value of p.u. frequency but extremely affects the value of excitation capacitance. The value of excitation capacitance and p.u. frequency are not maximum or minimum for the same machine simultaneously. Impact of load impedance on the values of p.u. frequency and required excitation capacitance is observed. Compare the values of performance variables obtained by existing and proposed methodologies. The p.u. frequency increases and excitation capacitance decreases with increase in load impedance. The variation in excitation capacitance and p.u. frequency increased for under-load conditions and decreased for overload conditions. Optimum values of performance variables are computed using magnetizing reactance of best fitted curve. A considerable variation in the value of excitation capacitor up to 1.67% is observed while comparing the values of performance parameters using conventional and proposed methodologies.

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