

# Performance Analysis of Self Excited Induction Generator Using Artificial Bee Colony Algorithm

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**Abstract**—This paper presents the performance state analysis of Self-Excited Induction Generator (SEIG) using Artificial Bee Colony (ABC) optimization technique. The total admittance of the induction machine is minimized to calculate the frequency and magnetizing reactance corresponding to any rotor speed, load impedance and excitation capacitance. The performance of SEIG is calculated using the optimized parameter found. The results obtained by ABC algorithm are compared with results from numerical method. The results obtained coincide with the numerical method results. This technique proves to be efficient in solving nonlinear constrained optimization problems and analyzing the performance of SEIG.

**Keywords**—Artificial bee colony, Steady state analysis, Self-excited induction generator, Nonlinear constrained optimization.

## I. INTRODUCTION

**D**UE to rapid depletion of fossil fuels, non-conventional sources of energy have made their presence felt increasingly such as wind energy, nuclear energy and solar energy. Induction generators have been used in Wind Energy Conversion Systems (WECS) due to their relative merits such as low maintenance, brushless construction, low cost, no synchronization problems, no requirement of DC supply for excitation. They just require magnetizing current for excitation and external prime-over. When these generators are connected in power systems, then reactive power for magnetization can be obtained by grid itself. But a stand-alone operation generator can be operated in self-excitation mode by connecting a capacitor in parallel with magnetizing reactance. Induction generators can be used in village and remote areas where power supply is not available. Also energy from them is cheaper from the supply coming from grid in such areas. Main drawback of induction generators is no control on terminal voltage and frequency and reactive power consumption.

To estimate the performance of self-excited induction generators, researchers have used steady state model. Murthy et al. [1] has given loop impedance modelling based on conventional single phase equivalent circuit. It separates real and imaginary part, forming two simultaneous equation in terms of magnetizing reactance ( $X_m$ ) and frequency ( $F$ ) and then solving for  $X_m$  and  $F$ . Raina and Malik [2] used the thyristor controlled self-excited induction generator to obtain dc supply. Malik and Haque [3] considered the core losses while carrying out constant voltage constant frequency

analysis of SEIG. Quazene et al. [4] suggested admittance-based model using single phase equivalent model to determine generated frequency and magnetic reactance of machine over resistive loading. In this method, two non-linear equations are obtained, real part of equivalent admittance expressed by a higher order polynomial of  $F$  and is independent of  $X_m$ . Imaginary part of admittance is equation, consisting both  $X_m$  and  $F$ . Once  $F$  is obtained from the real part equation, it is substituted into imaginary part equation to get the value of  $X_m$ . Using values of  $X_m$  and  $F$  steady state performance of the machine can be found using the magnetizing curve of machine. Ammasaigounden et al. used admittance model [5] in which performance equations becomes quadratic, variables being speed and other machine parameters. Alolah and Alkanhal used GA to calculate the capacitance for excitation for a single phase load connected to SEIG [6]. Loop impedance and node admittance method [7] is used to find out generated frequency and magnetic reactance of the machine. Genetic Algorithm (GA) has been used as a global optimization algorithm in [12] for steady state performance of SEIG considering the admittance model. Search space should be narrowed which require prior knowledge of the solution problem solution in order to get accurate results, which is not always possible.

In earlier reported works, it is cumbersome to separate the real and imaginary parts of admittance function. Also, appropriate initial guess [7]-[11] is required. If algorithm is not furnished with correct initial guess, the convergence and true solution it not guaranteed. There is need to calculate the cost function's jacobian matrix [1]. Prior knowledge of solution is needed [12]. The application of Artificial Bee Colony Algorithm (ABC) in this paper eliminates these difficulties.

This paper deals with the performance analysis of SEIG using ABC algorithm based on the intelligent foraging behavior of honey bees by D. Karaboga [14] in 2005. ABC is applied to the SEIG model formulated as numerical optimization problem

## II. ANALYSIS OF SEIG

The steady state model of SEIG [4] using the per phase equivalent circuit model is shown in Fig 1. The circuit described is used to prepare the expressions for estimation of generated voltage and frequency.

While implementing the model following assumptions have been considered.

- Iron losses are neglected
- Only magnetizing reactance varies with magnetic saturation

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characteristics of machine, while all other parameters of machine remain same.

- Working slip has no effect on rotor resistance.
- Leakage reactance and rotor reactance are same.
- There is no harmonic components in flux

Applying Kirchoff's laws to the node consisting magnetizing branch that is node 'a', in Fig. 1 and making the total admittance to be zero as the voltage across the capacitor should not be zero for successful self-excitation.

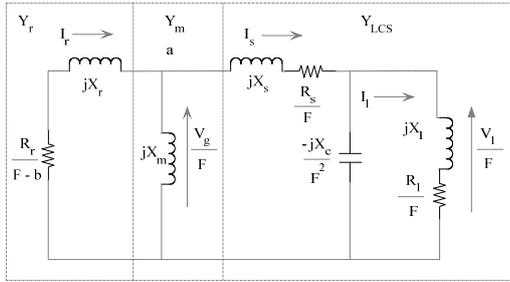


Fig. 1 Per phase equivalent circuit of SEIG

$$\bar{Y} = 0 \quad (1)$$

$$\bar{Y} = \bar{Y}_{LCS} + \bar{Y}_m + \bar{Y}_r \quad (2)$$

$$\bar{Y}_m = -\frac{j}{X_m} \quad (3)$$

$$\bar{Y}_r = \frac{1}{(R_r/F-b) + jX_r} \quad (4)$$

$$\bar{Y}_c = -\frac{jF^2}{X_c} \quad (5)$$

$$\bar{Y}_L = \frac{1}{(R_l/F_q) + jX_l} \quad (6)$$

$$\bar{Y}_s = \frac{1}{(R_s/F) + jX_s} \quad (7)$$

$$\bar{Y}_{LCS} = \frac{\bar{Y}_s \cdot (\bar{Y}_c + \bar{Y}_L)}{\bar{Y}_s + \bar{Y}_c + \bar{Y}_L} \quad (8)$$

$$\bar{Y} = \sqrt{\text{Re}(\bar{Y}) + \text{Im}(\bar{Y})} \quad (9)$$

Differentiating the real part and imaginary part of (1) and equating the real part to zero, a polynomial of frequency of the order of 7 can be obtained [13].

$$P_7F^7 + P_6F^6 + P_5F^5 + P_4F^4 + P_3F^3 + P_2F^2 + P_1F + P_0 = 0 \quad (10)$$

and equating the imaginary part to zero, an expression that corresponds to the magnetizing reactance is obtained.

$$X_m = \frac{\left[ (X_1 - X_L)^2 + \left[ R_1 + \left( \frac{R_r}{F} \right) \right] \right] \left[ X_2^2 + \left( \frac{R_s}{(F-b)} \right)^2 \right]}{\left\{ (X_1 - X_L) \left[ X_2^2 + \left( \frac{R_s}{(F-b)} \right)^2 \right] - X_2 \left\{ (X_1 - X_L)^2 + \left[ R_1 + \left( \frac{R_r}{F} \right) \right] \right\} \right\}} \quad (11)$$

where, coefficients  $P_0$  to  $P_7$  are given in [13]. For numerical method equation of seventh order is solved for  $F$  and then  $X_m$  is calculated from (11).

#### A. ABC Method

Total admittance  $\bar{Y}$  function given in (1) can be observed as a black-box function and is taken as the objective function for optimization with constraints. Benefits of using this black-box function are that, there is no need to separate the real and imaginary parts as well as no requirement of initial guess to start the algorithm.

#### B. Performance Analysis

From the synchronous speed test magnetizing characteristics curve can be obtained. After  $X_m$  and  $F$  are computed from (1), Air gap voltage can be found using magnetizing characteristics curve, given in Appendix. After that the performance parameters can be obtained with the help of known machine parameters. These are stator current, terminal voltage and load current.

Stator Current is expressed as

$$\bar{I}_s = \frac{V_g}{F} \cdot (\bar{Y}_m + \bar{Y}_r) \quad (12)$$

Terminal voltage is given by

$$\bar{V}_1 = \frac{\bar{I}_s \cdot F}{(Y_L + Y_c)} \quad (13)$$

Load Current is given by

$$\bar{I}_L = \frac{\bar{V}_1}{F} \cdot \bar{Y}_L \quad (14)$$

Real Output Power

$$P = 3 \cdot R_L \cdot |\bar{I}_L|^2 \quad (15)$$

For different values of excitation capacitor, rotor speed and load impedance the steady state performance of the machine can be derived by equations mentioned above.

### III. ARTIFICIAL BEE COLONY ALGORITHM

D. Karaboga proposed an Artificial Bee Colony algorithm (ABC) based on the foraging behavior of honey bees for optimization problems [14], [15]. In the ABC algorithm, the artificial population of bees consists of three types of bees: employed bees, onlooker bees and scouts. Half of the population is employed bees and rest is onlooker bees. Each employed bees represents a food source or in other words, number of food sources and number of employed bees is same. An employed bee turns into a scout if its food source is discarded or abandoned by the other bees of hive.

The position of any employed bee corresponds to a possible solution for the optimization problem. The fitness or the nectar

amount of any food solution represents the quality of that solution. In the beginning of the algorithm a randomly generated population is distributed across the search space, which consists of  $N_f$  food solutions. Here,  $N_f$  denotes the number of employed bees or onlooker bees as both is equal. Each solution  $x_i$  is a D dimensional vector, D being the total number of parameter to be optimized or the number of variables of the objective function. Next this population is subjected to repetitive iterations  $iter=1,2,\dots,max\_iter$  of search mechanism carried out by employed bees, onlooker bees and scout bee. An employed bee makes alterations in the positions of food sources in her memory depending upon the local information and checks the nectar amount (fitness) of the new position (new solution). If the nectar amount of new food source rules out the older one then, the bee memorizes the new solution and forgets the old one. When all the employed bees have searched out all the food sources, they share the information of food sources (position and nectar amount) with the other members of the hive through a specific way of dance called "waggle dance". Here onlooker bees evaluate the nectar amount of all food sources gained from employed bees and select a food source on the basis of probability related to its nectar amount. Just like the employed bees, they also produce some modifications in the selected food source and check the nectar amount of new food source. If the nectar amount of the new source is better, then they memorize the new source else retain the old source in their memory.

An onlooker bee selects the food source on the basis of probability value associated with the individual food source calculate  $p_i$ , calculated as follows:

$$p_i = \frac{fit_i}{\sum_{n=1}^N fit_n} \quad (16)$$

here,  $fit_i$  is the fitness value of solution  $I$  which is proportional to the nectar amount of food source in position  $i$ ,  $N_f$  being the number of food sources.

In ABC algorithm, there are three steps in each iteration: dispersion of employed bees to different food sources and evaluation of their nectar amount; sharing of the food sources and their selection by onlooker bees in order to make some modifications in them for better nectar amount; determination of scout bee and sending it to find a random food source from the whole search space.

For producing the new food source from the old one, artificial bees use the following expression:

$$x_{ij}^{new} = x_{ij}^{old} + \phi_{ij}(x_{ij}^{old} - x_{kj}^{old}) \quad (17)$$

here,  $k$  and  $j$  are randomly chosen indexes and  $k \in \{1,2,\dots,N_f\}$ ,  $j \in \{1,2,\dots,D\}$ . In order to get a new solution  $k$  should be different from  $i$ .  $\phi_{ij}$  is an arbit number in range of  $[-1, 1]$ . Its function is to control the modification of new source and represents the comparison of two food sources by bee. As the difference between  $x_{ij}$  and  $x_{kj}$  increases, the disturbance of the position of  $x_{ij}$  decreases. Hence, the solution progresses

towards the optimum solution.

If a food source is not updated for a certain number of trials, it is abandoned by the bees and it is replaced by a new random food source by scouts. The value of predetermined number of trials is an important control parameter in ABC and is called "limit" for abandonment. For a scout bee to obtain a new food source following expression is used.

$$x_i^j = x_{min}^j + rand[0,1](x_{max}^j - x_{min}^j) \quad (18)$$

#### IV. ABC ALGORITHM TO ANALYZE THE SEIG PERFORMANCE

For analyzing the SEIG performance the absolute value of the admittance is taken to be zero as described in (9). This can be treated as multivariable nonlinear constrained optimization problem.

$$\text{Minimize } \bar{Y} \text{ subjected to: } 0 \leq F \leq b \text{ and } 0 \leq X_m \leq X_o$$

To implement ABC on SEIG, control parameters are taken as per unit speed, per unit load (resistive) and excitation capacitance. ABC is initialized with taking objective function as  $\bar{Y}$  and inputs are control parameters mentioned above. A population size set by user starts finding solutions in the search space. The number of employed bees  $N_f$  is taken to be 20 that is also equal to number of onlooker bees. The value of limit, criteria to declare a solution abandoned is taken to be 100. Total number of iterations N is taken to be 500.

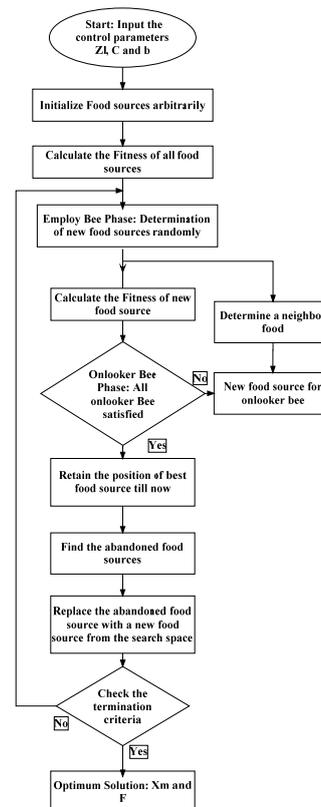


Fig. 2 Flowchart of ABC

V.RESULTS

The method as described in section II is used to compute the performance characteristics of 3-phase induction machine whose parameters are given in [7]. There are three parameters which define the working of the SEIG. These are rotor speed, excitation capacitance and load impedance. The output voltage, frequency and generated power also depend on them.

**Case 1:** Rotor speed is kept constant at 1 p.u. and magnetizing reactance and frequency are observed for different values of load impedance and capacitances. Fig. 3 shows the variation of the magnetizing reactance  $X_m$  with increasing load impedance. Fig. 4 depicts frequency variation on increasing impedance at different capacitances. In Fig. 3 at lower impedances magnetizing reactance goes beyond the unsaturated value  $X_o$ , which indicates failure to get self-excitation. Also in Fig. 4, there is not much difference in the frequency, with different capacitances. The different capacitances are chosen to be 20  $\mu$ F, 30  $\mu$ F and 40  $\mu$ F. In Fig. 9 the variation of output voltage with respect to the power delivered. It can be seen from the graph that, increasing the value of capacitance increases the maximum power that can be delivered.

**Case 2:** Here, for a particular value of excitation capacitance, the variation is noted in magnetizing reactance and frequency with increasing load, for different rotor speeds. Fig. 5 shows different curve lines of  $X_m$  for different rotor speeds. The excitation capacitance here is taken to be 30 $\mu$ F. With increasing rotor speed, magnetizing reactance decreases. In Fig. 6, the plot describes the curves of frequency for different rotor speeds. Increasing the rotor speed also decreases the frequency of the machine. Different rotor speed is chosen to be 0.9 p.u., 1 p.u. and 1.1 p.u.

**Case 3:** In this case rotor speed is kept constant to 1 p.u. and variation in magnetizing reactance and frequency is seen for different loads. Curves are plotted for different loads that are 1 p.u., 3 p.u. and 1.5 p.u. at 0.8 p.f.. Fig. 7 shows the magnetizing reactance varying with increasing capacitance. From the curve, it can be seen that for certain range of capacitances the value of magnetizing reactance lies under the unsaturated magnetizing reactance value, hence the self-exciting region. Beyond this range, the machine fails to get self-excited. Also, increasing the load increases the  $X_m$ . In Fig. 8, it can be seen that, there is not much difference in the frequency with respect to the load.

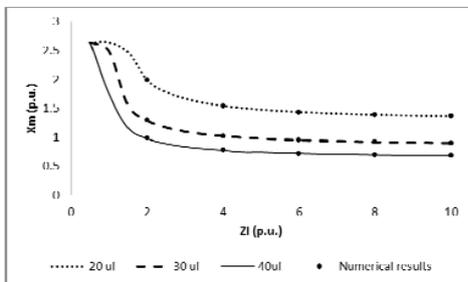


Fig. 3  $X_m$  vs  $Z_L$  for different capacitance

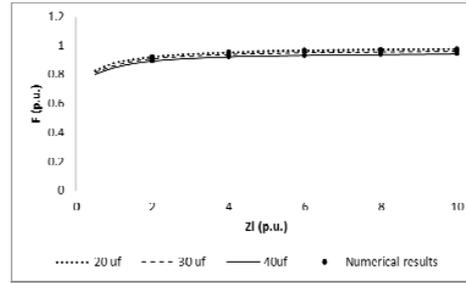


Fig. 4 F vs  $Z_L$  for different capacitance

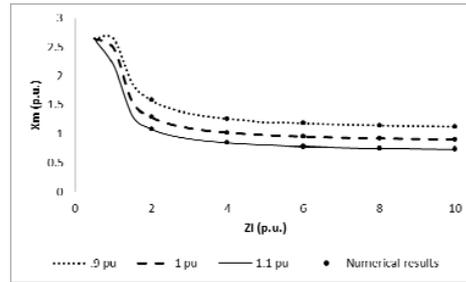


Fig. 5  $X_m$  vs  $Z_L$  for different b

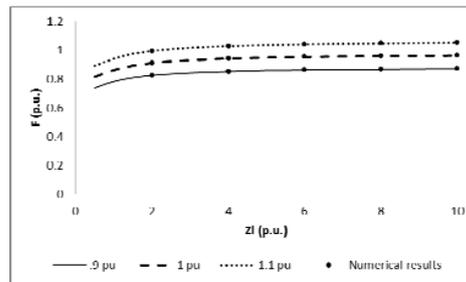


Fig. 6 F vs  $Z_L$  for different b

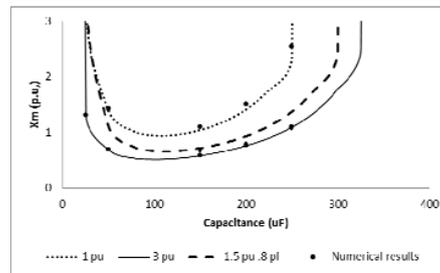


Fig. 7  $X_m$  vs capacitance for different  $Z_L$

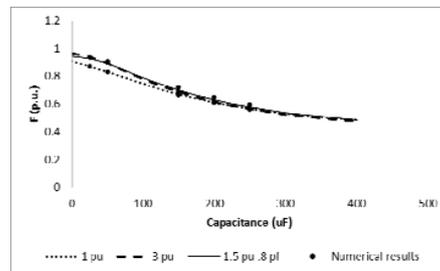


Fig. 8 F vs capacitance for different  $Z_L$

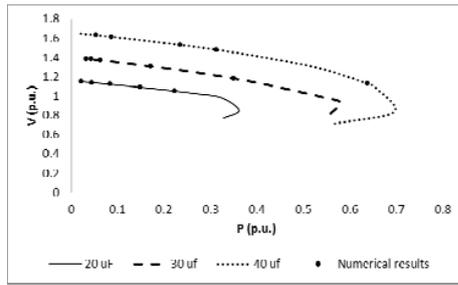


Fig. 9 V vs P for different capacitance

## VI. VALIDATION OF RESULTS

The results obtained from the ABC algorithm are compared with those from the numerical method as explained in Section II. Numerical methods are much complex and tedious to solve. On other hand ABC algorithm, no need to separate out the real and imaginary parts, so it is much easier to solve using them with same accuracy as of numerical methods. The dotted point in all the graphs depicts the numerical solutions and coincides with the ABC solutions in most cases. There competitiveness of ABC can be seen from Tables I and II. In Table I the error in magnetizing reactance is shown and in Table II error in frequency is shown. It is observed that the error is of the order of  $e^{-4}$ . In Table III comparison in terminal voltage calculation is shown.

TABLE I  
COMPARISON OF  $X_m$  OBTAINED FROM ABC AND NUMERICAL METHOD

Load	Magnetizing Reactance $X_m$						Error		
	20 $\mu F$ (Numerical method)	20 $\mu F$ (ABC)	30 $\mu F$ (Numerical method)	30 $\mu F$ (ABC)	40 $\mu F$ (Numerical method)	40 $\mu F$ (ABC)	Error in 20 $\mu F$	Error in 30 $\mu F$	Error in 40 $\mu F$
2	1.99437	1.98848	1.29354	1.28841	0.98041	0.97548	5.89E-03	5.12E-03	4.93E-03
4	1.54391	1.54297	1.01917	1.01824	0.77584	0.77488	9.38E-04	9.20E-04	9.50E-04
6	1.43873	1.43837	0.94954	0.94916	0.72169	0.72130	3.66E-04	3.70E-04	3.90E-04
8	1.39219	1.39199	0.91779	0.91758	0.69664	0.69642	1.94E-04	2.00E-04	2.10E-04
10	1.36599	1.36587	0.89962	0.89950	0.68219	0.68206	1.20E-04	1.20E-04	1.30E-04

TABLE II  
COMPARISON OF F OBTAINED FROM ABC AND NUMERICAL METHOD

Load	Frequency F						Error		
	20 $\mu F$ (Numerical method)	20 $\mu F$ (ABC)	30 $\mu F$ (Numerical method)	30 $\mu F$ (ABC)	40 $\mu F$ (Numerical method)	40 $\mu F$ (ABC)	Error in 20 $\mu F$	Error in 30 $\mu F$	Error in 40 $\mu F$
2	0.92406	0.92463	0.91041	0.91126	0.89369	0.89481	5.69E-04	8.50E-04	1.76E-02
4	0.95483	0.95500	0.94130	0.94155	0.92361	0.92395	1.69E-04	2.50E-04	1.79E-02
6	0.96616	0.96624	0.95274	0.95287	0.93470	0.93486	8.06E-05	1.20E-04	1.82E-02
8	0.97205	0.97210	0.95872	0.95880	0.94050	0.94059	4.61E-05	7.18E-05	1.83E-02
10	0.97567	0.97570	0.96240	0.96244	0.94406	0.94412	3.06E-05	4.68E-05	1.84E-02

TABLE III  
COMPARISON OF TERMINAL VOLTAGE

Load	Voltage						Error		
	20 $\mu F$ (Numerical method)	20 $\mu F$ (ABC)	30 $\mu F$ (Numerical method)	30 $\mu F$ (ABC)	40 $\mu F$ (Numerical method)	40 $\mu F$ (ABC)	Error in 20 $\mu F$	Error in 30 $\mu F$	Error in 40 $\mu F$
2	0.8504	0.8499	1.0187	1.0165	1.1295	1.1289	5.0E-04	2.2E-03	-6.0E-04
4	1.0282	1.0277	1.1814	1.1813	1.36	1.3603	5.0E-04	1.0E-04	3.0E-04
6	1.0694	1.0693	1.2495	1.2495	1.4511	1.4514	1.0E-04	0.0E+00	3.0E-04
8	1.0904	1.0904	1.2861	1.2861	1.4993	1.4995	0.0E+00	0.0E+00	2.0E-04
10	1.1033	1.1033	1.3088	1.3089	1.5292	1.5293	0.0E+00	-1.0E-04	1.0E-04

## VII. CONCLUSION

In this paper, the performance of self-excited induction generator is investigated using artificial bee colony algorithm. The nodal admittance of the machine acquired from the per phase equivalent circuit of self-excited induction generator is minimized. This method produced results with more accuracy without segregating the real and imaginary nonlinear equations of the admittance function. Also, no prior knowledge about the solution is required in this method. The simulated results of ABC algorithm are compared with the results obtained by numerical techniques involving solution of higher degree polynomial. Promising agreement is found

between the two results, hence assuring the effectiveness and ease of implementation of the proposed method.

## APPENDIX

*The Rating of the Induction Machine and Its Parameters [7]:*

Rated Power: 0.75 KW  
 Base voltage: 220 V  
 Base current: 2.31 A  
 Base impedance: 95.238  $\Omega$   
 Rated frequency: 60 Hz  
 Rated speed: 1800 rpm

$R_s=0.111$  pu  
 $R_r=0.132$  pu  
 $X_s=X_r=0.157$  pu  
 $X_o=2.64 \Omega$

*The Magnetizing Curve is a Polynomial of Degree Three and Is Written Below:*

$$V_g / F = 2.594 - 2.92318X_m + 1.8711X_m^2 - 0.418359X_m^3$$

## NOTATIONS

$F$	per unit frequency
$I_s$	stator current per phase, A
$I_r$	rotor current per phase, referred to stator, A
$I_l$	load current per phase, A
$N$	rated speed, rpm
$R_l$	load resistance per phase
$R_s$	stator resistance per phase
$R_r$	rotor resistance per phase, referred to stator
$b$	per unit speed
$V_g$	air-gap voltage per phase at rated f, V
$V_l$	terminal voltage per phase, V
$X_s$	stator reactance per phase
$X_r$	rotor reactance per phase, referred to stator,
$X_C$	capacitive reactance due to 'C' at rated f,
$X_m$	magnetizing reactance per phase at rated f,
$X_o$	unsaturated value of magnetizing reactance
$Y$	total admittance
$Y_s \& Y_r$	stator and rotor admittance
$Y_L$	load admittance
$Y_m$	magnetizing admittance
$Y_C$	capacitive admittance

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