Voltage Control of Self-Excited Induction Generator using Genetic Algorithm

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Abstract

Self-excited induction generators (SEIG) are found to be most suitable candidate for wind energy conversion application required at remote windy locations. Such generators are not able to maintain the terminal voltage with load as, a literature survey reveals, the voltage profile falls sharply with load. In this paper an attempt has been made to improve the voltage profile of a self-excited induction generator. A new methodology based upon Genetic Algorithm (GA) is proposed to compute the steady state performance of the model including core loss branch. Further efforts are made to control the terminal voltage under loaded conditions. Simulated results using proposed modeling have been compared with experimental results. A close agreement between the computed and experimental results confirms the validity of the approach adopted.

Key Words: *Asychronous generators, Genetic Algorithm, Self-excited induction generator, Voltage regulation.*

1. Introduction

The self-excited induction generators (SEIG) have been found suitable for energy conversion for remote locations. Such generators may be commonly used in the remote rural areas where it is not possible to draw from transmission lines. These machines can be used to meet the local demand of remote areas in the absence of a grid. SEIG has many advantages such as simple construction (especially in squirrel-cage rotor), absence of DC power supply for excitation, reduced maintenance cost, good overspeed capability, self short-circuit protection capability and no synchronizing problem.

To compute the steady state performance of SEIG, researchers [1–8] adopted loop impedance or nodal admittance with iterative models. [7–8] proposed a new equivalent circuit model which includes a power source on rotor side. Irrespective of analytical technique or representation, it has been found that the major drawback of the SEIG is its poor voltage regulation. The terminal voltage varies with load and operating speed and fixed capacitor alone cannot provide the adequate amount of reactive power needed by the induction generator [9]. Reference [10] has presented a controller architecture with three phase, four-wire shunt active filter for a stand alone SEIG under varying wind speed conditions. A mathematical model has been developed for voltage control

purpose by [11] with STATCOM for SEIG. It has been shown that STATCOM acts as voltage regulator, load balancer and harmonic eliminator.

The variation in voltage may be controlled through excitation capacitance, as the load or speed varies. Reference [12] proposed a regulating scheme using constant frequency model with proper control of operating speed and excitation capacitance.

In the present study, a new and unique genetic algorithm-based modeling approach has been adopted to compute the unknown generated frequency, magnetizing reactance and excitation capacitance, simultaneously, for self-excited induction generators. The proposed modeling approach may be used to predict and control the excitation capacitance to maintain a constant terminal voltage for changing load conditions. This makes the analysis simple and effective. In addition, iron/core losses of the induction generator have taken into consideration during analysis and such inclusion makes analysis more realistic.

2.   Genetic Algorithm

The genetic algorithm (GA) [13] is an optimization technique that performs a parallel, stochastic and directed search to evolve the fittest (best) solution. Different from conventional optimization methods, GA employs the principles of evolution, natural selection and genetics, as inspired by natural biological systems, in a computer algorithm to simulate evolution.

Performance evaluation variables a and C in SEIG may take any real number. Thus following the many researchers who have been paying attention to real-coded evolutionary algorithms, particularly for solving real-world optimization problems (as is SEIG), we use a real-coded GA [14-15] to investigate performance parameter space. Three main operators comprising GAs are: reproduction, crossover, and mutation.

Reproduction: - Evolution is, in effect, a method of searching among an enormous number of possibilities for solutions. For the analysis and control of SEIG, tournament selection is used for reproduction. A string is permitted reproduction based on fitness for productivity, where productivity of an individual is defined as the value of a string's non-negative objective function.

Crossover: - The crossover operator exchanges genetic information between strings. There are a number of commonly used crossover operators: such as blend crossover (BLX), simulated binary crossover (SBX), unimodal normal distribution crossover (UNDX) and simplex crossover (SPX) and parent centric recombination operator (PCX) [14]. In the present paper PCX operator has been used because this particular operator assigns more probability keeping an offspring closer to the parents than away from parents.

Mutation: - Real coded mutation (RCM) operator [15] has been used to protect the irrecoverable or premature loss of important notions. Since continuous variables are coded directly, RCM is flexible in nature. PCX and RCM operator have been used in conjunction and attain search power similar to the individual methodologies, yet the overall algorithm performs better than binary-coded GAs.

3.   Steady-State Analysis

Steady-state operation of the self-excited generator with shunt capacitors may be analyzed using the equivalent circuit representation shown in Figure 1. In this circuit model, all parameters are assumed to be independent of saturation, except for magnetizing reactance. However, core loss branch has been accounted for, using the
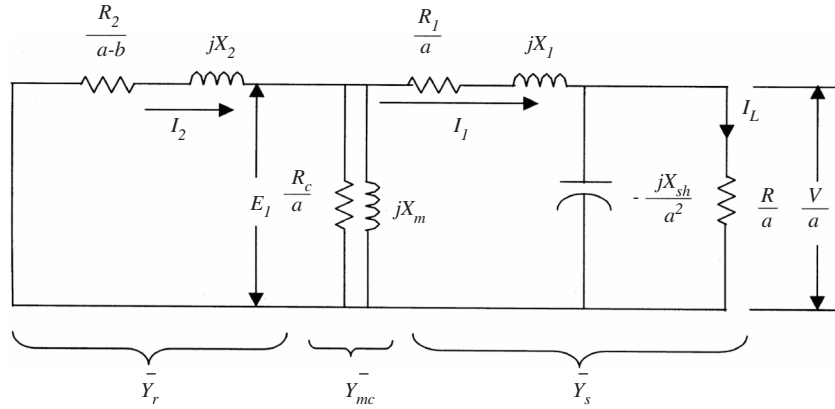
algorithm as shown in the Figure 2.

Figure 1. Per phase equivalent circuit representation for capacitor self-excited induction generator.
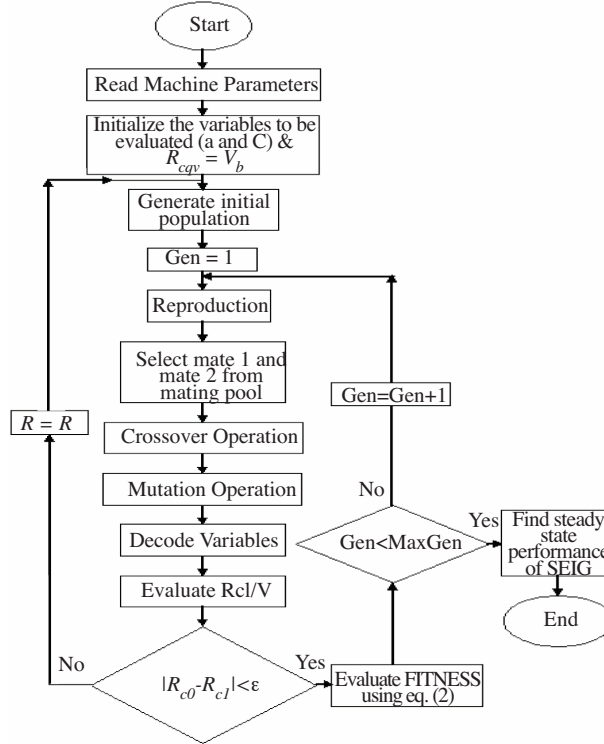

Figure 2. Flow Chart.

As Figure 1 contains neither e.m.f. nor current source, nodal analysis of the equivalent circuit results in the following equations:

$$\sum \bar{Y} = 0 \qquad (1)$$

where $\bar{Y} = \bar{Y}_r + \bar{Y}_{mc} + \bar{Y}_s$

Here subscript r, mc and s represents the rotor branch, magnetizing/ core loss branch and stator branch in the equivalent circuit of machine. Further these can be defined as;

$$\bar{Y}_s = \frac{\left(R_L + \frac{R_1}{a}\right)}{\left(X_1 - X_L\right)^2 + \left(R_L + \frac{R_1}{a}\right)^2} - j\frac{\left(X_1 - X_L\right)}{\left(X_1 - X_L\right)^2 + \left(R_L + \frac{R_1}{a}\right)^2}$$

$$\bar{Y}_{mc} = \frac{a}{R_c} - j\frac{1}{X_m}$$

$$\bar{Y}_r = \frac{\frac{R_2}{a-b}}{X_2^2 + \left(\frac{R_2}{a-b}\right)^2} - j\frac{X_2}{X_2^2 + \left(\frac{R_2}{a-b}\right)^2}$$

where,

$$R_L = \frac{RX_{sh}^2}{a^2R^2 + (a^2X - X_{sh})^2}$$

and

$$X_L = \frac{aR^2X_{sh} + a^3X^2X_{sh} - aXX_{sh}^2}{a^2R^2 + (a^2X - X_{sh})^2}$$

Equation (2) must be satisfied to ensure the phenomenon of self-excitation. The SEIG voltage regulation problem may easily be handled by using the objective function

$$OF = Y + V_{err}, \tag{2}$$

where

$$V_{err} = (1 - V_{pu})^2$$

Here 'V'_{pu} is the per unit generated voltage. This objective function may be minimized using GA to maintain power quality. Suitable ranges of a and C are given in Appendix I. Such approach gives a new and unique methodology to compute the values of a and C simultaneously for controlled voltage operation of SEIG.

Figure 3 shows a scheme to control the load voltage of SEIG using the following Genetic Algorithm.

Step 1. Sensing the generated voltage.

Step 2. Comparison of generated voltage with reference voltage.

Step 3. Amplification of error as obtained to a suitable level for processing.

Step 4. Computation of excitation capacitance using Genetic Algorithm for minimizing voltage error as per the fitness/objective function defined.

Step 5. Actuating the control circuit for selection of specific capacitance as estimated in previous step.

Step 6. Computation of steady state performance of SEIG using selected value of excitation capacitance.
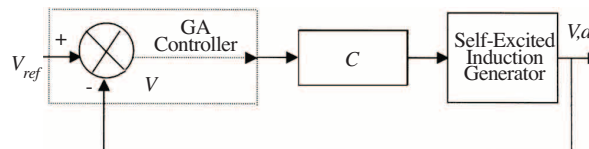

Figure 3. Voltage control of SEIG.

4. Results and Discussions

Table 1 gives a comparison of computed and experimental results on induction machine with resistive load only (Appendix II). In simulations, V_{ref} has been taken as the experimental terminal voltage for each observation. In Table 2 is a comparison of results for lagging power factor load. Close agreement between the computed and experimental results gives validity to the adopted approach. Figures 4 shows variation of computed voltage and Figure 5 shows the variation of generated frequency with load. It is observed that the change in generated voltage (Figure 4) and frequency (Figure 5) with load is almost negligible.

Table 1. Comparison of results.

Sr. No.	N,C,R rpm,μF,Ω	Computed Values		Experimental Values	
		fg,Hz	V, Volts	fg,Hz	V, Volts
1.	1570,36,160	51.66	216.58	51.69	217
2.	1596,36,160	52.52	226.98	52.54	228
3.	1390,51,160	45.70	215.33	45.91	215
4.	1440,51,160	47.34	232.21	47.40	232
5.	1540,36,220	50.84	209.71	50.78	210
6.	1563,36,220	51.60	224.41	51.13	224
7.	1386,51,220	45.72	217.66	45.70	216
8.	1406,51,220	46.37	224.98	46.41	223
9.	1430,51,220	47.15	237.95	47.62	237

Table 2. Comparison of results (R=167.5, C=50μF).

S.No.	N,rpm	Load p.f.	Computed Values		Experimental Values	
			fg,Hz	V,Volts	fg,Hz	V,Volts
1.	1496	0.7411	49.4875	226.9075	49.77	226
2.	1491	0.8854	49.1886	228.2978	49.69	227
3.	1506	0.8739	49.6969	229.3975	49.88	230
4.	1476	0.8755	48.7160	219.5752	48.79	220
5.	1441	0.8773	47.5568	210.2636	48.05	210
6.	1432	0.8375	47.2936	199.9104	47.27	200

Analysis of Figure 4 gives rise to the following observations:

(i) Induction generator operating zone marginally increases with operating speed.

(ii) Core loss accounting leads to a slight reduction in terminal voltage.

(iii) Wide variation in load does not lead to significant fluctuation in terminal voltage.

Analysis of Figure 5 gives rise to the following observations:

(i) For a given load (Figure 5), generated frequency is totally dependent upon operating speed, i.e. wind speed.

(ii) Effect of core loss accounting on generated frequency is almost negligible.

(iii) Speed selection is important to generate rated frequency. It is observed that the operating speed of the machine should be slightly above the synchronous speed corresponding to rated frequency.
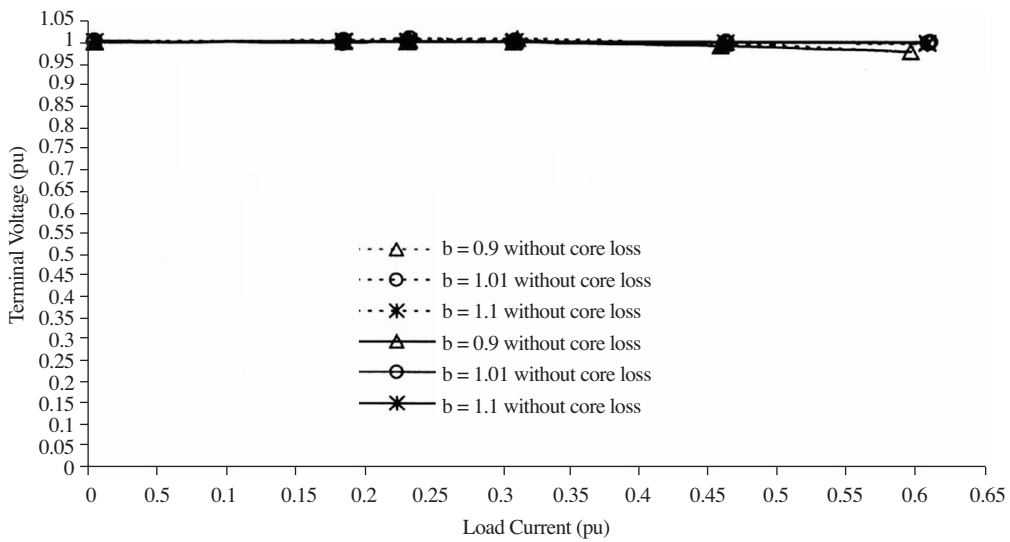
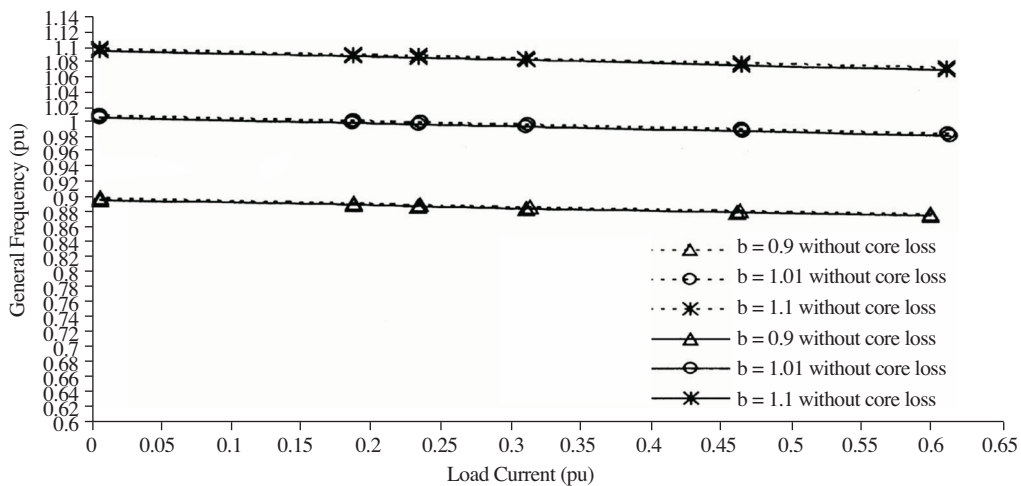**Figure 4.** Variation of terminal voltage with load.

Figure 5. Variation of generated frequency with load.

Figure 6 to Figure 8 gives the variation of computed results for reactive power requirement, stator current and efficiency with load.

Analysis of Figure 6 gives rise to the following observations:

(i) Reactive power requirement increases with load for constant speed operation.

(ii) Effect of core loss accounting is found to be insignificant provided speed is maintained. A small change is due to the variation of no load current in shunt branch.

(iii) However, as appears, this reactive requirement may be compensated through speed control at the cost of generated frequency, which is undesirable for frequency sensitive loads.
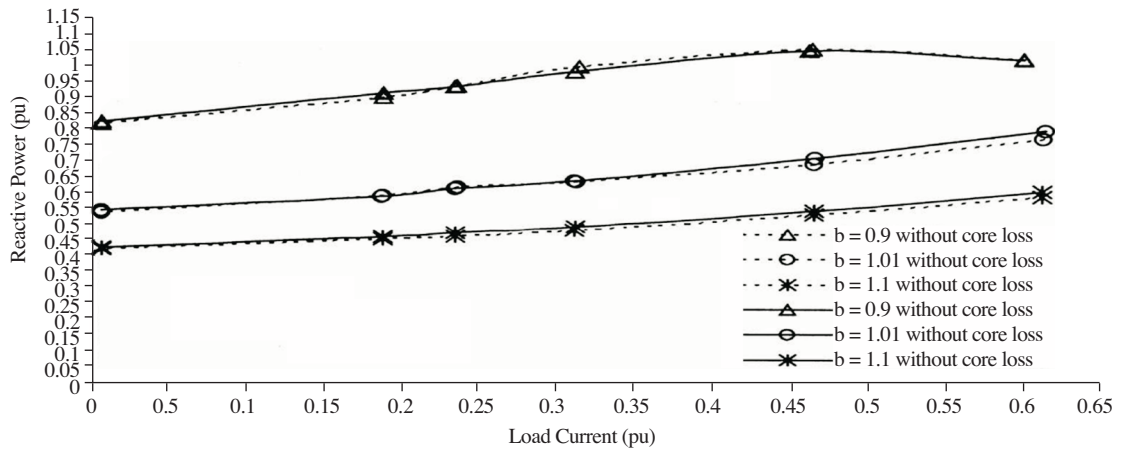
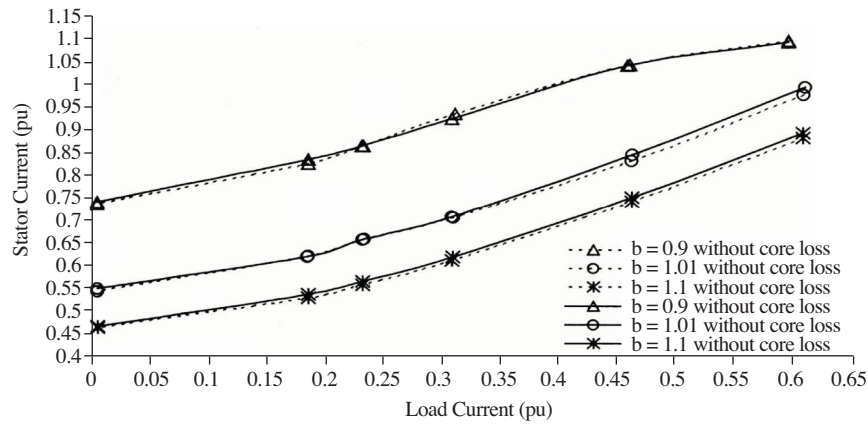**Figure 6.** Variation of reactive power to maintain the terminal voltage.

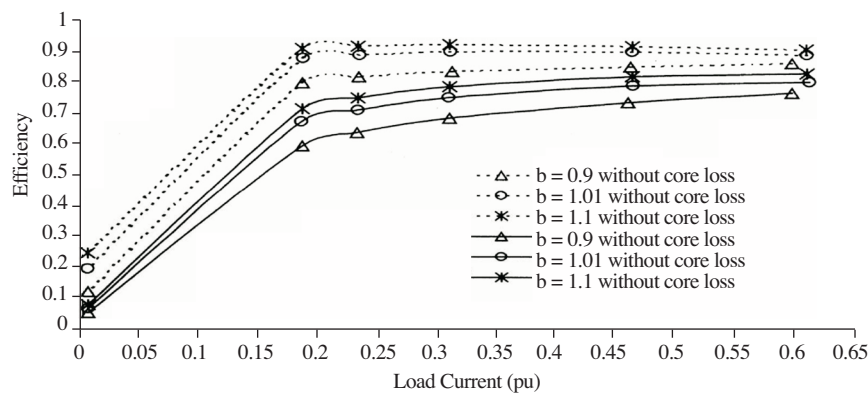**Figure 7.** Variation of stator current with load.

Figure 8. Variation of efficiency with load.

Analysis of Figure 7 gives:

(i) As excitation capacitive reactance decreases with increase in operating speed, there is decrease in capacitive current for a given load. Hence stator current decreases with increase in operating speed.

(ii) For constant speed operation, stator current increases with load due to increase in reactive and active power.

Analysis of Figure 8 gives:

(i) For the same load, efficiency increases with an increase in operating speed. It is due to reduction in stator current or copper losses.

(ii) Effect of core loss accounting is clearly visible from plot. Therefore it is essential to account core loss component for the analysis of SEIG.

(iii) Nature of plot comes out to be same as for induction motor.

Finally, Figure 9 gives the control of excitation capacitance to achieve constant terminal voltage; speed is maintained constant and kept slightly greater then synchronous speed corresponding to rated frequency.
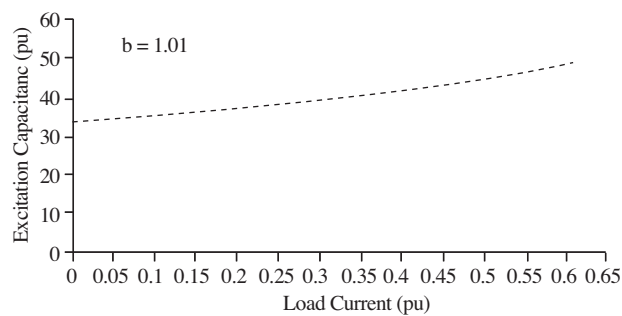

Figure 9. Variation of excitation capacitance with load to maintain the terminal voltage (including core losses).

Figure 10 shows the effect of load power factor on the excitation requirements of the systems. Value of excitation capacitance for any load varies with load power factor. As evident, reactive power requirement increases as power factor shifts from unity power factor to lagging. This results in the need for more shunt capacitance for lagging power factor load. Therefore operation of such generators is generally recommended only for unity power factor load.
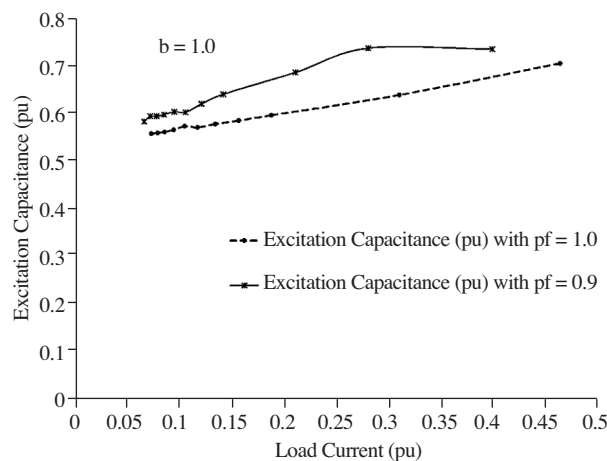

Figure 10. Effect of power factor on excitation capacitance(including core losses).

5. Conclusion

Self excited induction generators seems to be the right choice for remote windy locations provided terminal voltage is maintained with load. In this paper a new and unique GA based modeling has been proposed to improve the voltage profile of SEIG. Genetic Algorithm is proposed for estimation and selection of shunt capacitance. It is found that proposed methodology results in to a simultaneous estimation for generated frequency, magnetizing reactance and excitation capacitance. A control strategy has been worked out to achieve the required performance of SEIG. Simulated results as obtained are compared with experimental results on a test machine. Comparison for unity power factor and lagging power factor load indicates that the proposed modeling is effective and accurate for real world applications. A close agreement between computed and experimental results proves the validity and accuracy of proposed modeling. Analysis proposed may be helpful for researchers to think over the implementation of such generators successfully in windy remote locations.

List of symbols

a per unit frequency
b per unit speed
C excitation capacitance per phase, μF
E_1 air gap voltage per phase, at rated frequency, V
f rated frequency, Hz
f_g generated frequency, Hz
I_1 stator current per phase, A
I_2 rotor current per phase, referred to stator, A
I_L load current per phase, A
N speed, rpm
pf power factor
R load resistance per phase, Ω
R_c core resistance per phase, Ω
R_1 stator resistance per phase, Ω
R_2 rotor resistance per phase, referred to stator, Ω
R_L equivalent series resistance per phase, across stator terminals, Ω
X_L equivalent series reactance per phase, across stator terminals, Ω
V load voltage per phase, V
V_b base voltage per phase, V
X_1 stator reactance per phase, Ω
X_2 rotor reactance per phase, referred to stator, Ω
X_{sh} excitation capacitive reactance due to C at rated frequency, Ω
X_m magnetizing reactance per phase, at rated frequency, Ω
X load reactance per phase, at rated frequency, Ω

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Appendix I.

Lower and upper bounds on the variables used:

Sr. No.	Variables	Bounds	
		Lower	Upper
1.	a	0.6000 b	0.9999 b
2.	C	30 μF	100 μF

$b=$ per unit speed of the machine.

Appendix II.

The details of induction machine are:

•Specifications

3-phase, 4-pole, 50 Hz, delta connected, squirrel cage induction machine

2.2 kW/3HP, 230 V, 8.6 A.

•Parameters

$R_1 = 3.35\Omega, R_2 = 1.76\Omega, X_1 = 4.85\Omega, X_2 = 4.85\Omega$

•Base values

Base voltage =230 V

Base current =4.96 A

Base impedance=46.32 Ω

Base capacitance=68.71 μF

Base power=3422.4 W

Base frequency=50 Hz

Base speed=1500 rpm

•Air gap voltage

Variation of air gap voltage with magnetizing reactance at rated frequency induction machine;

$$X_m < 82.292 \qquad E_1 = 344.411 - 1.61X_m$$
$$95.569 > X_m \geq 82.292 \qquad E_1 = 465.12 - 3.077X_m$$
$$108.00 > X_m \geq 95.569 \qquad E_1 = 579.897 - 4.278X_m$$
$$X_m \geq 108.00 \qquad E_1 = 0$$