Estimation of Control Parameters of Self-Excited Induction Generator

K S Sandhu , Dheeraj Joshi

***Abstract*—** Operation of induction generator in self-excited mode is found to be useful in contrast to grid connected mode due to its ability to generate power for wide range of operating speeds. However such operations results in to a frequent variations in terminal voltage and frequency in the absence of any control strategy. Therefore such machines need a proper control to maintain its output quality in terms of generated voltage and frequency. In the present paper a new model has been proposed to estimate the control parameters of self-excited induction generators. Proposed modeling requires the solution of quadratic equation in operating speed and a simple expression for excitation capacitance. Simulated results as obtained using proposed model are compared with experimental results on two test machines. A close agreement between simulated and experimental results proves the validity of proposed modeling.

***Keywords*—** Induction Generator, Non-Conventional Sources, Self- Excited Mode, Steady-State Analysis, Wind Energy.

NOMENCLATURE

a per unit frequency

b per unit speed

C excitation capacitance per phase

E_1 air gap voltage per phase at rated frequency

I_1 stator current per phase

I_2 rotor current per phase, referred to stator

I_C capacitor current per phase

I_r load current per phase

I_{rc} core loss current per phase

I_m magnetizing current per phase

R load resistance per phase

R_1 stator resistance per phase

R_c core loss resistance per phase

R_2 rotor resistance per phase, referred to stator

V terminal voltage per phase

X load reactance per phase

X_1 stator reactance per phase

X_2 rotor reactance per phase, referred to stator

X_C capacitive reactance due to C at rated frequency

X_m magnetizing reactance per phase at rated frequency

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I. INTRODUCTION

Due to industrial, agricultural and economic developments across the world, electrical power demand is increasing day by day. Such fast growing power demand and continuous depletion of fossil fuels has compelled the researchers to think in a new direction of power generation. This has resulted the movement of scientists on a new track, full of non conventional resources such as wind, solar, biogas, tidal and geothermal. It has been felt that wind energy is emerging as potential source among various non conventional energy sources. Almost every country across the world is promoting such wind energy generating units.

Induction generators with cage rotor [1-3] are found to be most suitable for wind energy conversion due to their advantages such as simple and rugged construction, low cost and no need of synchronization with existing grid. Wound rotor induction generators [4] have its own advantage due to rotor resistance as additional control parameter. These machines can be operated in grid connected or self-excited mode. Induction generator in self-excited mode is capable to generate the power even in the absence of power grid. This makes it to be most useful generator for the remote windy locations.

Researchers [1-11] used the conventional equivalent circuit of induction machine for the steady-state analysis of self-excited induction generators. Whereas, [12-13] suggested a new circuit model which includes a power source in rotor circuit. Irrespective of representation and modeling technique, researchers observed a lot of variations in generated voltage and frequency due to variations in operating speed and load conditions. Few researchers [6-9] tried to estimate the minimum capacitance requirement for self-excitation and effects of capacitance on terminal conditions.

A detailed literature survey reveals the importance of speed and capacitance control to maintain terminal conditions. Researchers [14] attempted in this direction using genetic algorithm and results so obtained have been found to be very close to rated values.

In this paper a new model based on phasor diagram is proposed to estimate the control parameters (i.e. operating speed and excitation capacitance) of a self-excited induction generator. A new strategy is developed using conventional equivalent circuit model including the core loss branch (generally omitted). Proposed modeling as presented results in a single quadratic equation in terms of operating speed and a simple expression to compute excitation capacitance. Comparison of computed results using proposed model with experimental results on two test machines confirms the validity of proposed modeling.

II. Modeling Of SEIG

The steady-state operation of the self-excited generator may be analyzed by using the equivalent circuit representation as shown in Fig.1. In this circuit all parameters are assumed to be constant except magnetizing reactance.

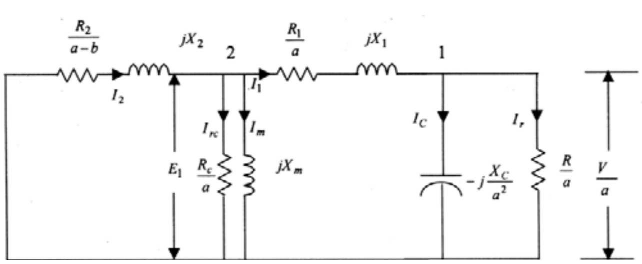

Fig. 1. Per phase equivalent circuit representation for self-excited induction generator.

Nodal analysis at node ‘1’ in Fig.1 results in the following;

$$-I_1 + I_C + I_r = 0 \qquad (1)$$

Where

$$I_C = j\frac{aV}{X_C} \text{ and } I_r = \frac{V}{R}$$

Similarly, nodal analysis at node ‘2’ in Fig.1 results in the following;

$$I_1 + I_m + I_{rc} - I_2 = 0 \qquad (2)$$

Where

$$I_m = \frac{E_1}{jX_m},\ I_{rc} = \frac{aE_1}{R_c} \text{ and } I_2 = -\frac{E_1}{\frac{R_2}{a-b} + jX_2}$$

Equation (1) and (2) gives;

$$\frac{aE_1}{R_c} + \frac{\frac{E_1R_2}{a-b}}{\left(\frac{R_2}{a-b}\right)^2 + X_2^2} + \frac{V}{R} + j\left(-\frac{E_1X_2}{\left(\frac{R_2}{a-b}\right)^2 + X_2^2} + \frac{aV}{X_C} - \frac{E_1}{X_m}\right) = 0 \qquad (3)$$

Separation of real and imaginary parts of (3), results in the following;

$$\frac{aE_1}{R_c} + \frac{\frac{E_1R_2}{a-b}}{\left(\frac{R_2}{a-b}\right)^2 + X_2^2} + \frac{V}{R} = 0 \qquad (4)$$

and

$$-\frac{E_1X_2}{\left(\frac{R_2}{a-b}\right)^2 + X_2^2} + \frac{aV}{X_C} - \frac{E_1}{X_m} = 0 \qquad (5)$$

Simplification of (4) gives a quadratic equation in b as;

$$A_2b^2 + A_1b + A_0 = 0 \qquad (6)$$

Where

$A_2 = aE_1X_2^2R + VR_cX_2^2$

$A_1 = -2E_1a^2RX_2^2 - E_1R_2RR_c - 2aVR_cX_2^2$

$A_0 = E_1a^3RX_2^2 + aE_1RR_2^2 + aE_1R_2RR_c + VR_cR_2^2 + VR_cX_2^2a^2$

Solution of (6) gives two values of *b* and lower one is found to be feasible. The expressions for coefficients as used in (6) gets modified with nature of load [see Appendix-I].

Simplification of (5) gives the value of excitation capacitance as;

$$C = \frac{E_1}{a\omega V}\left(\frac{1}{X_m} + \frac{X_2}{\left(\frac{R_2}{a-b}\right)^2 + X_2^2}\right) \qquad (7)$$

Equation (6) and (7) may be used to determine the rotor speed and excitation capacitance for a known value of generated terminal voltage and frequency for any load. The magnitude of E_1 and X_m to be estimated as explained in preceding section.

III. Iterative Technique

Phasor diagram of SEIG as shown in Fig. 2, gives the expression for air gap voltage as;

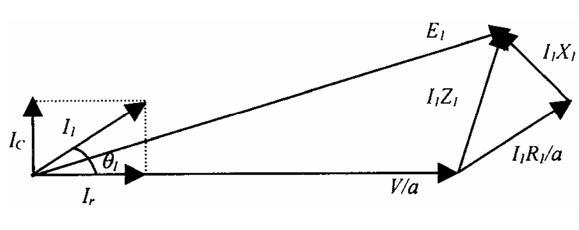

Fig. 2. SEIG phasor diagram under resistive load.

$$E_1 = \sqrt{\left(\frac{V}{a} + \frac{I_1R_1\cos\theta_1}{a} - I_1X_1\sin\theta_1\right)^2 + \left(\frac{I_1R_1\sin\theta_1}{a} + I_1X_1\cos\theta_1\right)^2} \qquad (8)$$

Real part of (1) may be used to compute the initial value of air gap voltage E_0 (to start the iteration process) as;

$$E_0 = \frac{V}{aRR_1}\left(R_1^2 + a^2X_1^2 + RR_1\right) \qquad (9)$$

Once the initial value for air gap voltage is known, the iteration process may be followed as;

Step1. Computation of initial value of air gap voltage E_0 from (9).

Step2. Computation of magnetizing reactance X_m from expressions (see Appendix-II and Appendix-III).

Step3. Estimation of the of rotor speed *b* and excitation capacitance *C* from (6) and (7) after substituting the value of *E* as E_0 and X_m as obtained in step 2.

Step4. Computation of I_1 and θ_1.

Step5. Finding of the new value of air gap voltage E_1 from (8).

Step6. Comparison of the new value of air gap voltage E_1 with previous air gap voltage used in step 1 i.e. E_0.

If $\left|E_1 - E_0\right| \langle \varepsilon$, Where ε =0.000001, E_1 may be treated as air gap voltage. Otherwise process may be repeated by replacing E_0 with E_1 until difference in the successive values for air gap voltage comes out to be ε .

IV Results and Discussions

Proposed modeling which is found to be useful for estimation of control parameters of SEIG needs the determination of air gap voltage. A simple iterative technique has been proposed for the estimation of exact air-gap voltage. Further inclusion of core loss branch makes the analysis more realistic. Table I shows the computation of air gap voltage for Machine-2 [see Appendix-II] using iterative process as explained in section-II. Five to six iterations are found to be sufficient to achieve accuracy up to third digit after decimal. Table II and Table III shows the comparison of simulated results with experimental results for Machine-1 and Machine-2 [see Appendix-I and Appendix-II]. Comparison has been done for different sets of generated voltage and frequency. Simulated and experimental results are found to be in good agreement. It is observed that a fixed value for excitation capacitance and operating speed results in variations for terminal voltage. This reflects a need for pre-estimation of control parameters in case of self-excited induction generator.

Fig.3 to Fig.6 gives the comparison of computed and experimental results to generate rated voltage across load terminals. A close agreement between the simulated and experimental results proves the validity of proposed modeling.

It is found that irrespective of load power factor (see

Appendix-III), proposed approach results in a quadratic equation in operating speed and a simple expression for excitation capacitance.

TABLE I- COMPUTATION OF AIR GAP VOLTAGE

Cpu =0.5239

Number of iterations	Air gap voltage				
	R=160	R=160	R=220	R=220	R=220
(Initial value)	213.2681307	201.5474252	229.6958800	199.71765123	185.0585109
1.	191.8448722	182.1356134	207.1474430	182.8367067	170.1613610
2.	193.9310957	183.8316351	210.6106198	184.3214324	171.3427590
3.	193.7474070	183.6926319	210.2625166	184.1978047	171.2598170
4.	193.7636925	183.7040867	210.2979232	184.2081473	171.2661567
5.	193.7622495	183.7031431	210.2943262	184.2072824	171.2656723
6.	193.7623774	183.7032209	210.2946916	184.2073547	171.2657093
7.	193.7623660	183.7032145	210.2946545	184.2073487	171.2657064
8.	193.7623670	183.7032150	210.2946583	184.2073492	171.2657067
9.	193.7623669	183.7032150	210.2946579	184.2073492	171.2657067
10.	193.7623669	183.7032150	210.2946579	184.2073492	171.2657067

TABLE II -COMPARISON OF RESULTS FOR MACHINE-1

Sr. No.	Experimental Results (pu)					Computed Results (pu)	
	I_r	V	a	C	b	C	b
1.	0.2894	1.0131	0.9892	0.8472	1.0133	0.8265	1.0095
2	0.2394	1.0578	0.9922	0.8472	1.0133	0.8348	1.0085
3	0.1789	1.0921	0.9960	0.8472	1.0133	0.8356	1.0079
4	0.1648	1.1000	0.9968	0.8472	1.0133	0.8361	1.0077
5	0.1552	1.1052	0.9984	0.8472	1.0133	0.8339	1.0086

Table III-COMPARISON OF RESULTS FOR MACHINE-2

Sr. No.	Experimental Results (pu)					Computed Results (pu)	
	I_r	V	a	C	b	C	b
1.	0.2557	0.8826	1.0148	0.5239	1.0286	0.5074	1.0287
2	0.2381	0.8217	0.9984	0.5239	1.0106	0.5061	1.0119
3	0.2052	0.9739	1.0226	0.5239	1.0420	0.5219	1.0338
4	0.1722	0.8173	0.9848	0.5239	0.9973	0.5126	0.9951
5	0.1567	0.7434	0.9656	0.5239	0.9780	0.5102	0.9752

Computed results on Machine-2 for different operating condition have been shown in Fig 7 to Fig 10.

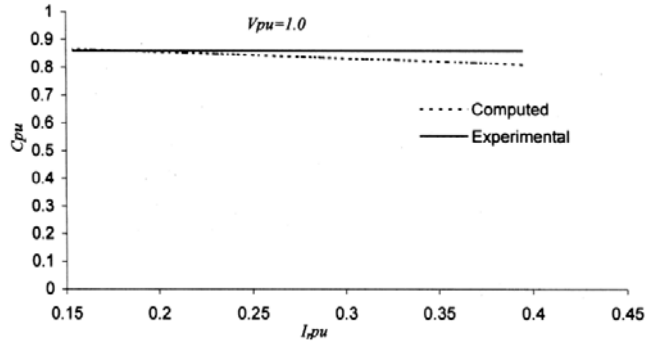

Fig. 3. Variation of excitation capacitance with load for Machine-1.

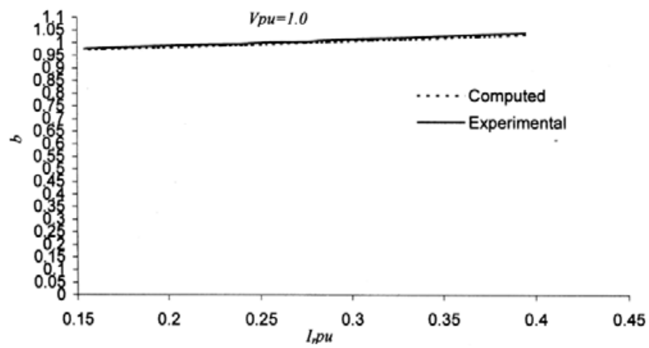

Fig. 4. Variation of rotor speed with load for Machine-1.

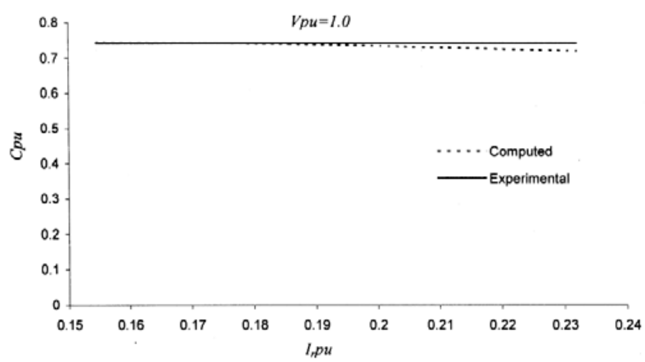

Fig. 5. Variation of excitation capacitance with load for Machine-2.

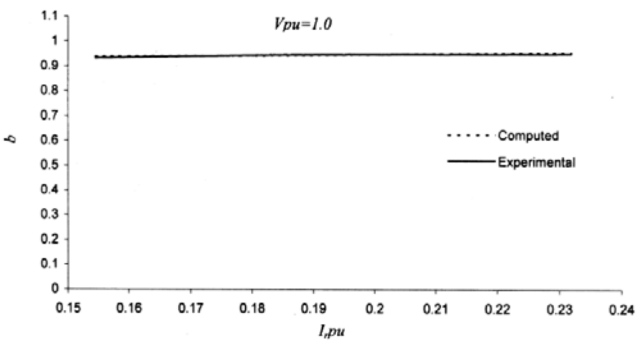

Fig. 6. Variation of rotor speed with load for Machine-2.

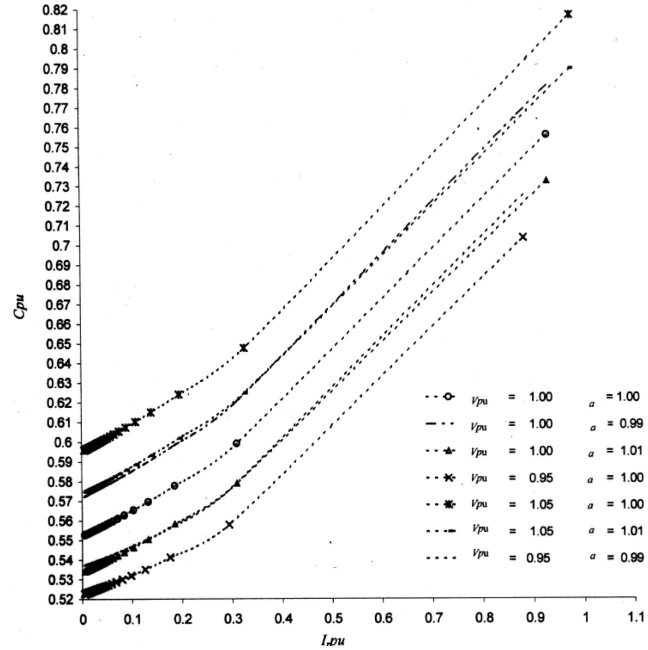

Fig. 8. Variation of excitation capacitance with load for different operating conditions.

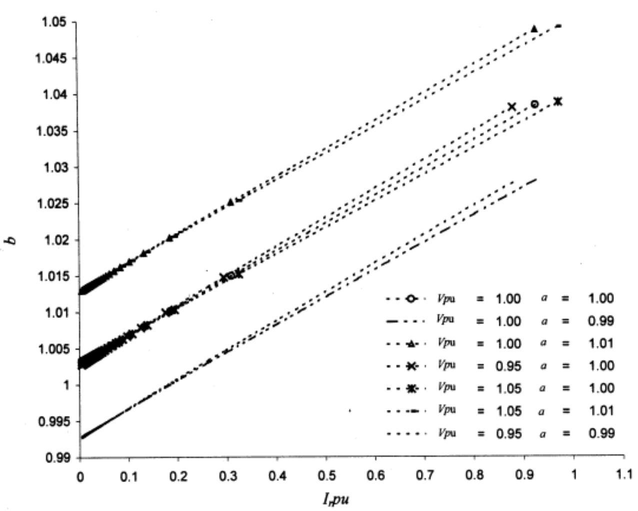

Fig. 7. Variation of rotor speed with load for different operating conditions.

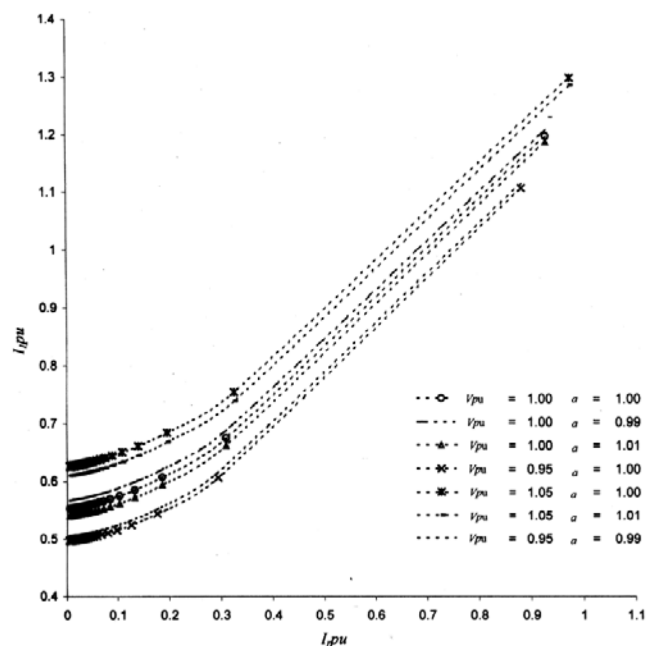

Fig. 9. Variation of stator current with load for different operating conditions.

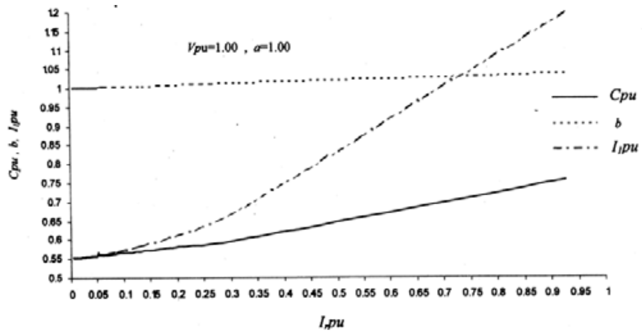

Fig. 10. Constant voltage constant frequency operation of self-excited induction generator.

Observation of Fig. 7 to Fig. 10 leads to the following results;

1. Excitation capacitance and speed requirement increases with load to maintain a particular voltage and frequency across its terminals.
2. Analysis is possible for following modes;
   i) Constant voltage constant frequency
   ii) Constant voltage variable frequency
   iii) Variable voltage constant frequency
   iv) Variable voltage variable frequency
3. It is easy to estimate the percentage permissible loading on machine without exceeding the stator current beyond its rated value.
4. Intercept on Y-axis in Fig. 7 and Fig. 8 gives the minimum value of operating speed, excitation capacitance to generate a particular voltage and frequency across load terminals.
5. Intercept on Y-axis in Fig. 9 gives the charging current. Charging current effects the net loading on the machine.
6. Fig. 10 may be used to find out the minimum and maximum limits for two control parameters for constant voltage constant frequency operation.
7. It is found that *b* must be greater than 1.0 pu to generate rated frequency.

V. Conclusions

Induction generators in self-excited mode are found to be most suitable for wind energy conversion in remote windy locations. These machines suffer from the drawback of poor voltage regulation in the absence of any control strategy. Such machines needs a control over excitation capacitance and operating speed to generate rated voltage and rated frequency from no load to full load operation. In this paper a new model based upon phasor diagram of generator has been proposed to estimate the control parameters of SEIG. Modeling needs simple calculations with a solution of quadratic equation in operating speed, irrespective of nature of load. Closeness between simulated and experimental results on two test machines gives the validity of proposed modeling. Pre-estimation of such parameters may be helpful to decide the control strategy of self-excited induction generator.

Appendix-I

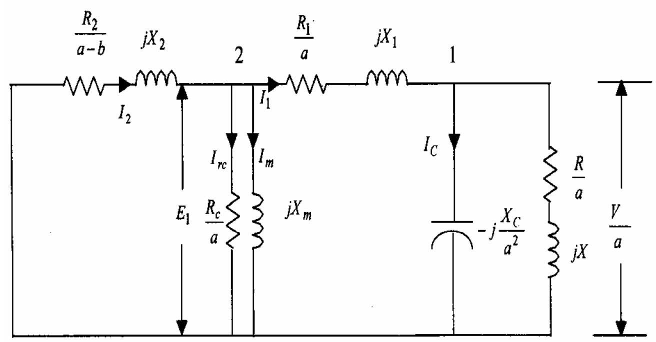

Fig. 11. Per phase equivalent circuit representation for self-excited induction generator for RX load.

Case I: For RL load (including R_c)

Expression in *b* can be written as;

$$A_2 b^2 + A_1 b + A_0 = 0$$

Where

$$A_2 = VRX_2^2 R_c + E_1 a X_2^2 R^2 + E_1 a^3 X_2^2 X^2$$

$$A_1 = -R_c E_1 R_2 R^2 - R_c E_1 R_2 a^2 X^2 - 2aR_c VRX_2^2 - 2a^2 R_c E_1 X_2^2 R^2 - 2a^4 E_1 X_2^2 X^2$$

$$A_0 = a^5 E_1 X_2^2 X^2 + 2a^3 E_1 R_2 X^2 + a^3 E_1 R_2 R^2 + a^2 VRX_2^2 + 2aE_1 R_2 R^2 + VRR_2^2$$

The expression of excitation capacitance can be written as;

$$C = \frac{E_1}{a\omega V}\left(\frac{1}{X_m} + \frac{X_2}{\left(\frac{R_2}{a-b}\right)^2 + X_2^2} + \frac{\frac{V}{a}X}{\left(\frac{R}{a}\right)^2 + X^2}\right)$$

Case II: For RL load (excluding R_c)

Expression in *b* can be written as;

$$A_2 b^2 + A_1 b + A_0 = 0$$

Where

$$A_2 = VRX_2^2$$

$$A_1 = -E_1 R_2 R^2 - E_1 R_2 a^2 X^2 - 2aVRX_2^2$$

$$A_0 = a^3 E_1 R_2 X^2 + a^2 VRX_2^2 + aE_1 R_2 R^2 + VRR_2^2$$

The expression of excitation capacitance can be written as;

$$C=\frac{E_1}{a\omega V}\left(\frac{1}{X_m}+\frac{X_2}{\left(\frac{R_2}{a-b}\right)^2+X_2^2}+\frac{\frac{V}{a}X}{\left(\frac{R}{a}\right)^2+X^2}\right)$$

Case III: For R load (excluding R_c)

Expression in *b* can be written as;

$$A_2b^2+A_1b+A_0=0$$

Where

$$A_2=VX_2^2$$

$$A_1=-E_1RR_2-2aVX_2^2$$

$$A_0=a^2VX_2^2+aE_1RR_2+VR_2^2$$

The expression of excitation capacitance can be written as;

$$C=\frac{E_1}{a\omega V}\left(\frac{X_2}{\left(\frac{R_2}{a-b}\right)^2+X_2^2}+\frac{1}{X_m}\right)$$

APPENDIX-II

MACHINE-1

- Specifications

3-phase, 4-pole, 50 Hz, star connected, squirrel cage induction machine
750W/1HP, 380 V, 1.9 A

- Parameters

The equivalent circuit parameters for the machine in pu are
$R_1=0.0823, R_2=0.0696, X_1=X_2=0.0766$

- Base values

Base voltage =219.3 V
Base current =1.9 A
Base Impedance=115.4 Ω
Base frequency=50 Hz
Base speed=1500rpm

- Air gap voltage

The variation of magnetizing reactance with air gap voltage at rated frequency for the induction machine is as given below.

$88.5=>E_0>0$	$X_m=184.46;$
$107.6=>E_0>88.5$	$X_m=(785.79-E_0)/3.78$
$152.3=>E_0>107.6$	$X_m=(891.66-E_0)/4.37$
$E_0>152.3$	$X_m=(512.69-E_0)/2.13$

APPENDIX-III

MACHINE-1I

- Specifications

3-phase, 4-pole, 50 Hz, delta connected, squirrel cage induction machine
2.2kW/3HP, 230 V, 8.6 A

- Parameters

The equivalent circuit parameters for the machine in pu are
$R_1=0.0723, R_2=0.0379, X_1=X_2=0.1047$.

- Base values

Base voltage =230 V
Base current =4.96 A
Base Impedance=46.32 Ω
Base frequency=50 Hz
Base speed=1500rpm

- Air gap voltage

The variation of magnetizing reactance with air gap voltage at rated frequency for the induction machine is as given below.

$117.873=>E_0>0$	$X_m=108$
$171.0528=>E_0>117.873$	$X_m=(579.897-E_0)/4.278$
$211.9075=>E_0>171.0528$	$X_m=(465.12-E_0)/3.077$
$E_0>211.9075$	$X_m=(344.411-E_0)/1.61$

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BIOGRAPHIES

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