

Performance Evaluation of Self Excited Induction Generator Using Fuzzy Logic with Variable Machine Parameter

¹Er Ashish Sharma, ² Raja Singh Khela

¹Research scholar, Punjab Technical University Kapurthala, Punjab, India

² Director –Principal Doaba Group of Colleges Kharar Mohai, India

ashishdpr@rediffmail.com, rskhela@rediffmail.com

Abstract: This paper presents a MATLAB based generalized algorithm to predict the dynamic and steady state performance of Self Excited Induction Generators (SEIG) under any fix combination of speed, excitation capacitor and loading and by varying the other machine parameters such as rotor and stator resistance. The another parameters changed are rotor and stator reactance. The Fuzzy rules are also implemented to model the behavior of SEIG with lagging power factor loads under three operating conditions i.e. variable load operation, variable speed operation and variable capacitance operation. The usual techniques like loop impedance and nodal admittance methods are used to evaluate per unit Magnetizing Reactance (X_m) and Generated Frequency(ω) of Self Excited Induction Generator (SEIG) under varying terminal conditions. These mathematical calculations involve complex equations, are time consuming. With the recent technological advancements, Artificial Neural Networks (ANN) and Fuzzy Logic (FL) techniques are being used in various industrial applications to determine & control the performance of machines replacing the conventional methods. The algorithms are implemented as MATLAB user friendly Tool boxes resulting in considerable simplification over earlier methods. The advantages of using fuzzy logic approach are universal control algorithm, fast converging, accepting of noise and inaccurate signals. At the end of the paper the theoretical and fuzzy logic results are verified with ANN and analytical data.

Keywords: Self excited induction generators, fuzzy logic, artificial neural networks

1 INTRODUCTION

To rise above the problems faced in generation of power from conventional energy sources, government and non-government generating companies have focused their attention towards non-conventional energy sources. These sources include wind energy, bio-gas, solar and hydro potential, etc. In renewable energy applications of low and medium power, the induction motor operated as a generator offers considerable advantages due to its ruggedness, low cost, brush-less squirrel cage rotor, manufacturing simplicity, low maintenance and wide off-the-shelf range. In addition, it does not require synchronizing conditions to be met before connecting it to the existing electric lines supplying power to the network. Squirrel cage induction motor, generates power when driven by prime mover and connected across excitation capacitors. The SEIG system is composed of four main items: the prime mover, the induction machine, the load and the self-excitation capacitor bank. The self excitation capacitors connected at the stator terminals of the induction machine must produce sufficient reactive power to supply the needs of the load and the induction generator. A self excited induction generator is more cheaper than a conventional synchronous generator and has brushless cage rotor construction, absence of DC excitation source and lower maintenance requirement are its attracting features. A suitably sized three-phase capacitor bank connected at the generator terminals is used as variable lagging VAR source to meet the excitation demand of the machine and the load. The operation of machine in this mode is called Self-excited Induction Generator. While operation of the induction motor in the generating mode while connected to the grid is straightforward to analyze using the standard equivalent circuit due to the rigid frequency and voltage of the grid, its analysis and operation as a stand-alone power source is complicated since both the voltage and frequency are now variables and involves solving non linear equations of higher order. Under these conditions proper selection of equipment and the prediction of the system performance are essential for successful implementation of the scheme. To determine the performance analysis of SEIG, various

researchers used different methods [1-5] to determine the parameters of induction generator. The present work takes advantage of the MATLAB software package to make the numerical computations easier, by combining all the available methods into a user-friendly toolbox for MATLAB as it results in considerable ease of analysis. Results are presented for various combinations of inputs, thus enabling the designer to decide on the best setup. The performance of any machine with given parameters as shown in Appendix-II has been evaluated. The evaluation is done using fuzzy logic and the results obtained are compared with the analytical and ANN, which shows close agreement signifying the uniqueness of fuzzy logic approach.

2 EQUIVALENT CIRCUIT OF SEIG AND ANALYTICAL TECHNIQUE

The performance of the SEIG using an analytical model based on a conventional single-phase equivalent circuit with per-unit (p.u.) parameter has been studied in the past. The model used has also been extended for the evaluation of various steady-state performance characteristics of stand-alone generators, like the effect of shaft variation, change in generator pole number and parallel operation etc. In analytical techniques, there are two methods mainly – loop impedance method and nodal admittance method. Two non-linear simultaneous equations in term of generated frequency ‘a’ and magnetizing reactance ‘X_m’ is obtained by equating the real and imaginary terms of the complex loop impedances respectively to zero, for any given load and speed. These equations are then solved by the Newton-Raphson method. After knowing the values of ‘a’ and ‘X_m’ and further with the help of the magnetization curve of machine, the equivalent circuit is completely solved and the steady-state performance of the SEIG can be easily determined. Similarly in Nodal admittance method, we consider the admittances connected across the nodes which define the air gap. This method gives an algebraic expression as function of magnetizing reactance ‘X_m’ and frequency ‘a’. On equating the sum of real parts to zero and the sum of imaginary parts to zero, ‘X_m’ and ‘a’ are evaluated mathematically. In order to estimate the performance of a SEIG, The conventional equivalent circuit of an induction motor shown in Figure 1. Various parameters like Stator resistance, leakage reactance, rotor resistance, leakage reactance referred to stator, un-saturated magnetizing reactance representing core loss branch of the machine are to be found using various tests on the machine such as no load test and blocked rotor test.

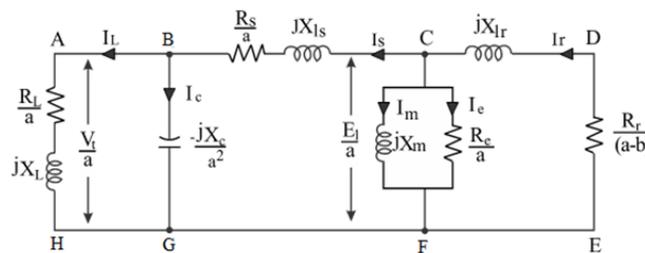


Fig 1: Per phase equivalent circuit of self-excited induction generator

$$Z_{AH} = R_L/a + j X_L$$

$$Z_{BG} = -j X_c / a^2$$

$$Z_{BC} = R_s/a + jX_s$$

$$Z_{CF} = R_c/a \parallel j X_m$$

$$Z_{CE} = (R_r / (a-b) + j X_r)$$

$$Z = (Z_{CF} \parallel Z_{CE}) + Z_{BC} + (Z_{AH} + Z_{BG}) \tag{1}$$

Solving the equivalent circuit of Figure 1, the results in a single loop equation comes to be $I_s * Z = 0$.

For successful voltage build up in SEIG, I_s cannot be zero hence Z should be zero. Thus by separating the real and imaginary components of Z and by putting all the values of parameters we get two non-linear simultaneous

equations. These two equations are obtained in terms of machine parameters, speed, capacitive reactance, load resistance/reactance, magnetizing reactance X_m and generated frequency a .

$$\text{Real}(X_m, a) = P_1 X_m a^5 + P_2 X_m a^4 + (P_3 X_m + P_4) a^3 + (P_5 X_m + P_6) a^2 + (P_7 X_m + A_8) a + P_9 X_m + P_{10} \quad (2)$$

$$\text{Imaginary}(X_m, a) = (Q_1 X_m + Q_2) a^4 + (Q_3 X_m + Q_4) a^3 + (Q_5 X_m + Q_6) a^2 + (Q_7 X_m + Q_8) a + Q_9 \quad (3)$$

The coefficients $(P_1 - P_{10})$ and $(Q_1 - Q_9)$ of two characteristics equations are obtained using MATLAB and are given in Appendix -III. The values of ' X_m ' and ' a ' are determined from polynomials represented by equation 2 & 3 using Newton Raphson Method in MATLAB [6].

3 FUZZY TECHNIQUE FOR SOLVING EQUIVALENT CIRCUIT

Attempt is made to solve the polynomial equations with Fuzzy logic technique to determine the per unit value of saturated magnetizing reactance ' X_m ' and generated frequency ' a '. Fuzzy logic is a simple, rule based approach to solve a problem rather than attempting mathematical modeling. These values are calculated by ANN, genetic algorithm by another authors also [9-12]. The values of saturated magnetic reactance and generated frequency are compared with ANN approach by varying the machine parameters like stator resistance, stator reactance, rotor resistance and rotor reactance. The Fuzzy model is also implemented to model the behavior of SEIG with lagging power factor loads under three operating conditions i.e. variable load operation, variable speed operation and variable capacitance operation.

3.1 FUZZY MODE BLOCK DIAGRAM

In this approach the classification of fuzzy sets into various linguistic variables for which different membership functions are to be formed. We take nine inputs and two outputs. The inputs are rotor resistance ' R_r ', stator resistance ' R_s ', rotor leakage reactance ' X_r ' and stator leakage reactance ' X_s ', power factor ' PF ', speed ' N ', capacitance ' C ' and load admittance ' Y ' in per unit and two outputs as magnetic reactance ' X_m ' and generated frequency ' a '. Membership function for all parameters are set for different ranges. Six membership functions are extreme low, very low, low, medium, high and very high are used in this paper so that wide range of output can be taken and extremely close values of all the machine parameters can be used. Output variables ' X_m ' & ' a ' also have six membership functions as extreme low, very low, low, medium, high and very high. In this approach we can vary the range the membership function are as per our requirement. More the range of membership function more rules are made and more accuracy in result can be achieved. The Proposed Fuzzy model is given in Figure 2.

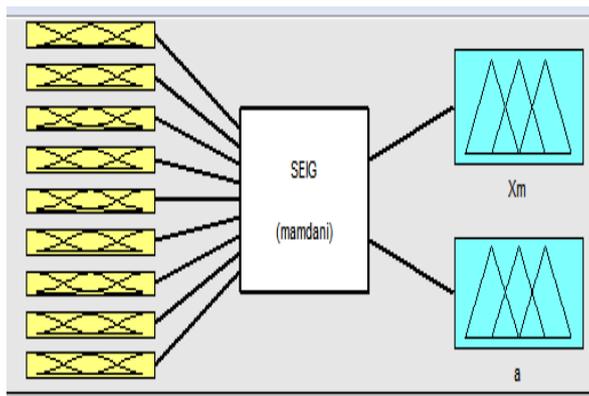


Fig. 2: Fuzzy model of SEIG to find X_m and a

3.2 FUZZY RULES

The proposed Fuzzy model of SEIG is made with input-output parameters obtained from analytical technique using MATLAB programming corresponding to randomly chosen input variables. The range of all input variables must be chosen very carefully and these should be compatible to real life applications of induction machine as self excited induction generator. The range of stator and rotor resistance can be varied from 4-8 percent. Triangular membership function is used to create the rule table for fuzzy approach. The linguistic variables of the membership functions are given as extreme low(EL), very low (VL), low(L), medium (M), high (H), very high(VH) and extreme high (EH) are shown below in Table 1. This table shows rules when rotor resistance is changed. The other rules for varying the parameters are also like that and results are noted for comparison.

R_r (EL)	R_s	X_r	X_s (EH)	R_e	Y	PF	N	C	X_m (EL)	a(VH)
R_r (VH)	R_s	X_r	X_s (VH)	R_e	Y	PF	N	C	X_m (VL)	a(VH)
R_r (H)	R_s	X_r	X_s (VH)	R_e	Y	PF	N	C	X_m (L)	a(H)
R_r (M)	R_s	X_r	X_s (H)	R_e	Y	PF	N	C	X_m (M)	a(M)
R_r (VH)	R_s	X_r	X_s (EH)	R_e	Y	PF	N	C	X_m (H)	a(VH)
R_r (EL)	R_s	X_r	X_s (EL)	R_e	Y	PF	N	C	X_m (VH)	a(VH)

Table 1 : Fuzzy Rules for varying machine parameter

3.3 IMPLIMENTATION OF FUZZY RULES

In this section influence of machine parameters (stator and rotor parameters) on its performance of SEIG is predicted using fuzzy model. The proposed Fuzzy model of SEIG is implemented to determine the magnetic reactance and generated frequency requirements under varying conditions stator resistance, stator reactance, rotor resistance and rotor reactance. In the first case the induction machine operation is carried with constant load, constant capacitance and constant speed at unity power factor. The speed is taken as 1554 rpm, capacitance is taken as 26.93 micro farad and load is taken as 120 ohm. The stator resistance is varied from 0.0200 to 0.952 pu in eight steps which can be then easily understood from the tabular form. To investigate the performance of the proposed Fuzzy model, input data is presented to Figure 3, with Variable machine parameters and other conditions (Speed = 1584rpm and capacitance = 26.93 microfarad and load 120 ohm). Using the fuzzy rules the values of ' X_m ' and 'a' are computed with varying input data of machine parameters. The results obtained from the proposed Fuzzy model for computation of X_m and 'a' with varying stator resistance, stator reactance, rotor resistance and rotor reactance are recorded in Table 2,3,4 and 5 which give the comparison of results obtained from analytical technique, ANN and fuzzy logic of machine. The variation of magnetizing reactance, generated frequency and with varying parameters and given conditions is shown in Figure 4, Figure 5, Figure 6 and Figure 7.

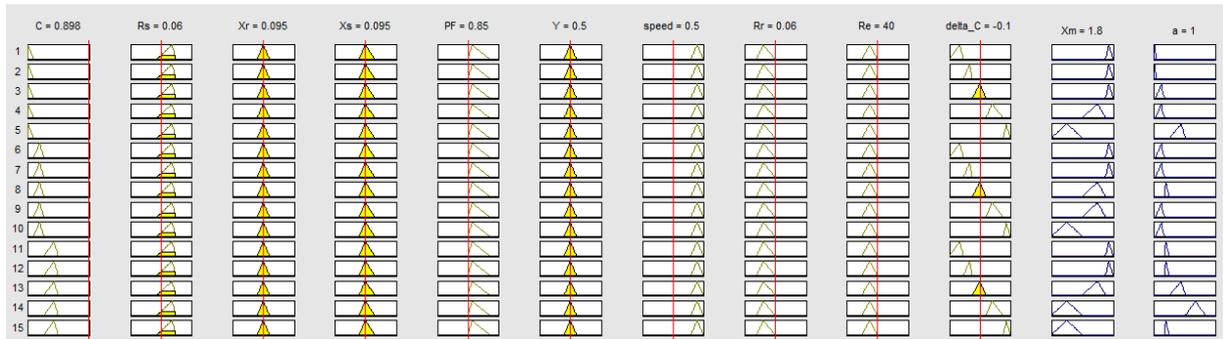


Figure 3: Various fuzzy rules used to find the performance parameters

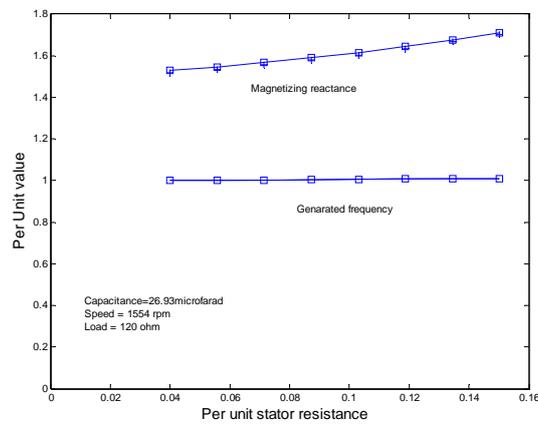


Fig. 4 Effect of Stator Resistance on Magnetizing Reactance and Generated Frequency of SEIG

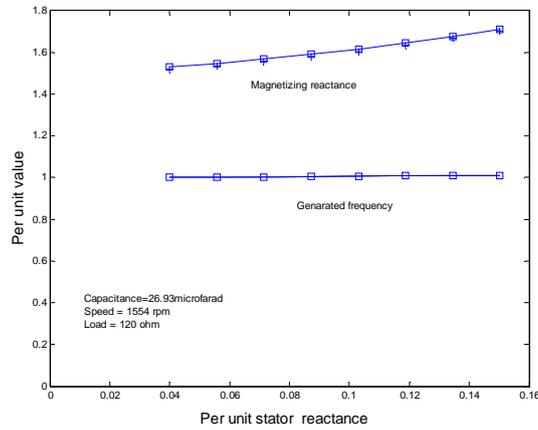


Fig. 5. Effect of Stator Reactance on Magnetizing Reactance and Generated Frequency of SEIG

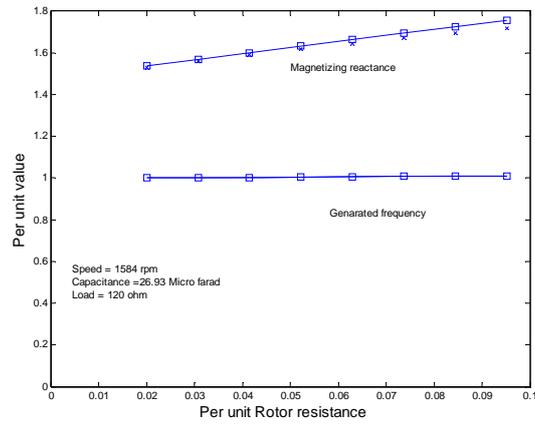


Fig. 6.: Effect of rotor Resistance on Magnetizing Reactance and Generated Frequency of SEIG

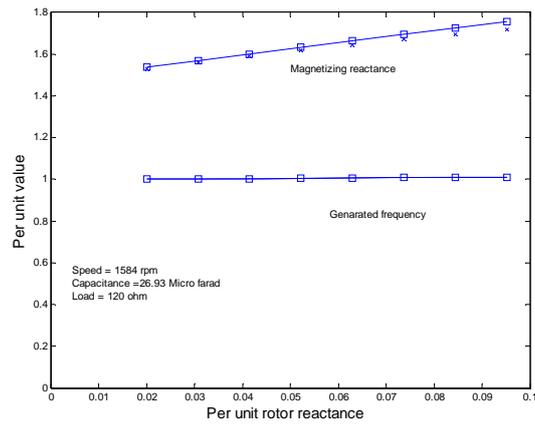


Fig.7: Effect of Rotor Reactance on Magnetizing Reactance and Generated Frequency of SEIG

Stator Resistance (pu)	Analytical Model Xm	Fuzzy Model Xm
0.0200	1.4841	1.4854
0.0308	1.5162	1.5124
0.0415	1.5489	1.5412
0.0522	1.5822	1.5719
0.0630	1.6159	1.6045
0.0737	1.6502	1.6392
0.0845	1.6849	1.6761
0.0952	1.7203	1.7151

Table 2 : Effect of Stator resistance on Magnetizing Reactance of SEIG

Rotor Resistance (pu)	Analytical Model Xm(pu)	Fuzzy Model Xm (pu)
0.0200	1.5383	1.5316
0.0308	1.5692	1.5609
0.0415	1.6003	1.5897
0.0522	1.6315	1.6176
0.0630	1.6628	1.6446
0.0737	1.6942	1.6705
0.0845	1.7256	1.6953
0.0952	1.7573	1.7190

Table 3 : Effect of rotor resistance on Magnetizing Reactance of SEIG

Stator Reactance (pu)	Analytical Model Xm	Fuzzy Model Xm
0.0400	1.5291	1.5185
0.0558	1.5471	1.5356
0.0715	1.5673	1.5555
0.0873	1.5901	1.5785
0.1030	1.6155	1.6045
0.1188	1.6441	1.6340
0.1345	1.6760	1.6670
0.1502	1.7117	1.7038

Table 4 Effect of Stator Reactance on magnetizing Reactance of SEIG

Rotor Reactance (pu)	Analytical Model Xm	Fuzzy Model Xm
0.0400	1.4835	1.4787
0.0558	1.5149	1.5069
0.0715	1.5478	1.5377
0.0873	1.5825	1.5713
0.1030	1.6191	1.6081
0.1188	1.6578	1.6483
0.1345	1.6989	1.6922
0.1502	1.7426	1.7403

Table 5: Effect of rotor Reactance on magnetizing Reactance of SEIG

3.4 IMPLIMENTATION OF FUZZY MODEL OF SEIG ON LAGGING POWER FACTOR LOAD

The Fuzzy rules are also implemented to model the behavior of SEIG with lagging power factor loads under three operating conditions i.e. variable load operation, variable speed operation and variable capacitance operation. The results of fuzzy model depicting the effect of varying load, speed and terminal capacitance on the magnetizing reactance and generated frequency of machine with lagging power factor loads is shown through Fig 7 – Fig 10 .

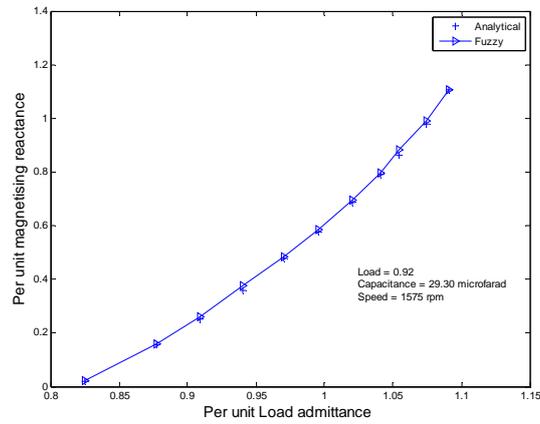


Fig. 7 : Effect of Load Admittance on Magnetizing Reactance for Lagging Power Factor Load

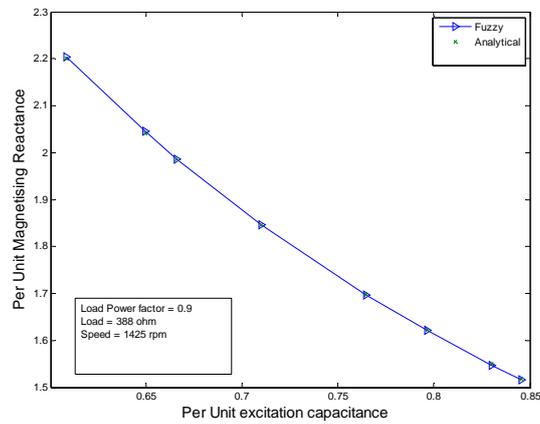


Fig. 8 :Effect of Excitation Capacitance on Magnetizing Reactance for Lagging Power Factor Load

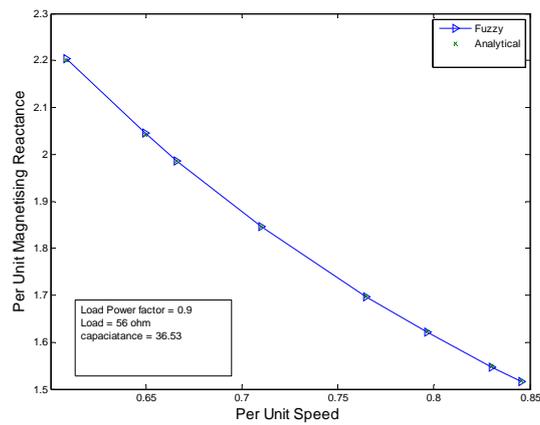


Fig.9 Effect of speed on Generated Frequency for Lagging Power Factor Load

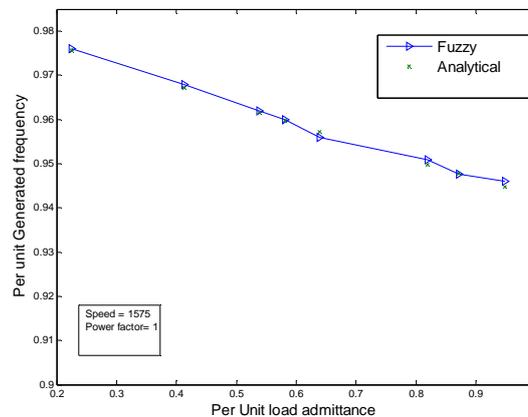


Fig.10: Effect of Load Admittance on Generated Frequency for Lagging Power Factor Load

4 CONCLUSION

In this application, intelligent approach, based on fuzzy logic has been implemented successfully for steady state analysis of self-excited induction generators under different machine parameters. The proposed technique has shown that, it is reliable, accurate and simple compared to the conventional methods. Attempt is made for the pre-evaluation process using fuzzy logic approach, which is simple. In this technique, machine parameters are assumed to be varying from 4 to 8 percent. It is also observed that the saturated magnetizing reactance of self-excited induction generator is more in case of lagging power factor loads. The generated frequency is not affected much with lagging power factor loads. It is observed that frequency with poor power factor is higher than unity power factor for the same value of load impedance. The results obtained from fuzzy results are compared with analytical and found to be in good agreement, thus validating the technique. This technique can be extended to improve the accuracy by using trapezoidal membership function and simultaneously varying the machine parameters involved in the performance evaluation of SEIG. The technique used can be implemented to any machine.

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Appendix 1

Nomenclature:

- R_r, X_r = Rotor resistance and reactance
 R_s, X_s = Stator resistance and reactance
 R_L, X_L = Load resistance and reactance
 R_e = Core loss resistance
 X_m = Saturated magnetizing reactance
 X_{mu} = Unsaturated magnetizing reactance
 X_C = Per phase capacitive reactance
 a = Generated frequency
 b = Ratio of actual rotor speed to synchronous speed
 I_s = Stator current
 I_L = Load current
 I_r = Rotor current
 I_c = Capacitive current
 E_1 = Air gap voltage per phase
 Z = Impedance of complete circuit

Appendix -II

Polynomial Coefficients:

- $P_1 = -(X_{1s}X_{1r}X_L)$
 $P_2 = (X_{1s}X_{1r}X_L)b$
 $P_3 = X_{1s}(R_r R_L + R_e R_L + X_{1r}X_C) + X_{1r}(R_e R_r + X_C X_L + R_s R_L) + X_L(R_e R_r + R_e R_s + R_s R_r)$
 $P_4 = X_{1s}R_e(X_{1r}R_L + R_r X_L) + R_e R_s X_{1r}X_L$
 $P_5 = -X_{1s}(X_{1r}X_C + R_e R_L)b - X_{1r}(R_s R_L + R_e R_L + X_C X_L)b - (R_s R_e X_L)b$
 $P_6 = -X_{1r}R_e(R_s X_L + X_{1s}R_L)b$
 $P_7 = -X_e R_r(R_s + R_L) - X_e R_e(R_s + R_L + R_r)$
 $P_8 = -(R_e X_{1r}X_C(R_L + R_s)) - (R_e R_r X_C(X_L + X_{1s})) - (R_e R_s R_r R_L)$
 $P_9 = R_e X_C(R_s + R_L)b$
 $P_{10} = X_C X_{1r}R_e(R_L + R_s)b$
 $Q_1 = X_{1s}X_L(R_e + R_r) + X_{1s}X_{1r}R_L + X_{1r}X_L(R_e + R_s)$
 $Q_2 = X_{1s}X_{1r}X_L R_e$
 $Q_3 = -X_{1s}(R_e X_L + X_{1r}R_L)b - X_{1r}X_L(R_s + R_e)b$
 $Q_4 = -(X_{1s}X_{1r}X_L R_e)b$
 $Q_5 = -X_e R_e(X_{1s} + X_{1r} + X_L) - R_L R_e(R_s + R_r) - R_L(X_{1r}X_C + R_r R_s) - X_C(R_s X_{1r} + X_{1s}R_r + X_L R_r)$
 $Q_6 = -R_e X_{1r}(X_{1s}X_C + X_C X_L + R_s R_L) - R_r R_e(X_{1s}R_L + R_s X_L)$
 $Q_7 = R_e(X_{1r}X_C + X_{1s}X_C + X_L + R_s R_r)b + X_C X_{1r}(R_s + R_L)b$
 $Q_8 = R_e X_{1r}(X_{1s}X_C + X_C X_L)b + (X_{1r}R_e R_L R_s)b$
 $Q_9 = R_e X_C R_r(R_L + R_s)$

AUTHOR PROFILE

¹ **Er.Ashish Sharma** passed B.Tech in 2001 and M.Tech in 2006 from Punjab Technical university Kapurthala. Presently he is working as Astd. Prof. in Department of Electrical DAV Institute of engineering and Technology Jalandhar .He is pursuing his PhD from Punjab Technical University Kapurthala.

² **Dr Raja Singh Khela** He graduated in Electrical Engg. From Institution of Engineers, Calcutta in 1985. He Passed his Masters Degree (with Distinction) from Punjab University, Chandigarh (India) in the year 1990. He did his PhD in 2009 from Punjab Technical University, Jalandhar (India). Presently serving as Director at Doaba group of colleges ,Kharar ,Mohali ,Punjab India