# Fuzzy Technique for Analysis of Self Excited Induction Generator for Varying Capacitance Under Constant Speed and Load

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**Abstract— In general, the conventional techniques like loop impedance and nodal admittance methods are used to find the parameters of SEIG for finding performance under various conditions. In these approaches, long mathematical calculations are involved. With the recent development, ANN and fuzzy logic are used for finding various parameters for different values of machine parameters. By finding these parameters in less time and for variable range of machine parameters the performance of SEIG can easily be analyzed. An approach employed for the evaluation of parameters of self excited induction generator (SEIG) using fuzzy logic, which needs a simple modelling, is proposed in this paper. Here a fully fuzzy based approach is used to evaluate the performance. The results from fuzzy logic approach are found to be accurate in comparison with analytical results.**

**Keywords— Capacitance, Fuzzy Logic, Generated frequency, Magnetizing reactance, Self Excited Induction Generator.**

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
$X_m$ = Per phase 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 corresponding to rated frequency
$I_s$ = Stator current
$I_L$ = Load current
$I_r$ = Rotor current
Ic = Capacitive current
$E_1$ = Air gap voltage per phase
Z = Impedance of complete circuit

## I. INTRODUCTION

We can use electricity to run just about everything. It is the unique form of energy that enables technical innovation and productivity growth. The important achievements of electrification remain still unused by many people of the world because population is growing faster with respect to rate of electrification. Today, most of the electricity generated comes from coal, oil and natural gas. These fuels have very low reserves and will finish in the future. Also there is negative effect of these fuels. They produce pollutant gases when they are burned in the process to generate electricity. To overcome the problems of conventional energy sources we are shifting towards non-conventional energy sources. These sources include wind energy, bio-gas, solar and hydro potential, etc. Renewable resources are able to provide us with limitless energy. Practical action has developed the reliable and cost effective wind energy systems for charging batteries to help meet the electrical energy needs of these people. With the renewed interest in wind turbines and micro-hydro-generators as best energy source, the induction generators can be taken as a choice to the well-developed synchronous generators because induction generator has many advantages like it has brushless construction, reduced size, absence of DC power supply, self short circuit protection capability and no synchronizing problem of induction generator. The use of an induction machine as a generator is becoming more and more popular for renewable energy applications. Squirrel cage induction generators with excitation capacitors (known as SEIGs) are popular in isolated nonconventional energy systems. Basset and Potter first discovered SEIG from an induction machine in 1930. An induction machine operates as a generator only if an appropriate supply of inductive reactive power is available to provide the machine's excitation at a certain rotational speed. Self-excitation can be provided by the connection of suitable capacitors at the machine's stator terminals. The lagging VArs supplied by the capacitors is consumed by the machine's excitation, leakage reactance and the reactance of the inductive load. 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 (SEIG) is more attractive than a conventional synchronous generator because of its low unit cost, brushless cage rotor construction, absence of DC excitation source and lower maintenance requirement. 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 (SEIG) .To determine the performance analysis of SEIG, various researchers used different methods [1-5] to determine the parameters of induction generator. The evaluation of magnetizing reactance and generated frequency is done using fuzzy logic and the results obtained are compared with the analytical, which shows close agreement signifying the uniqueness of fuzzy logic approach.

## II. ANALYTICAL TECHNIQUE TO FIND MAGNETIZING REACTANCE AND GENERATED FREQUENCY OF SEIG

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. The model used in this has 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 2 methods mainly – loop impedance method and nodal admittance method. Two non-linear simultaneous equations in a and $X_m$ can be 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 with the aid of the magnetization curve, the equivalent circuit is completely solved and the steady-state performance of the SElG can be determined. [6] Similarly in Nodal admittance method, we consider the admittances connected across the nodes which define the air gap. This model is analyzed in a similar manner as that of impedance model but a little difference is that here in this method instead of impedances, it used the admittances. For the determination of generating frequency a and magnetizing reactance $X_m$, real and imaginary parts of the sum of admittances of the rotor, magnetizing, and stator branches are equated to zero. This method gives an algebraic expression for magnetizing reactance in terms generator frequency and other machines parameters and given speed. On equating the sum of real parts to zero and the sum of imaginary parts to zero, $X_m$ and a can be evaluated. In order to estimate the performance of a SEIG, researchers have made use of 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 test on the machine such as no load test, blocked rotor test.

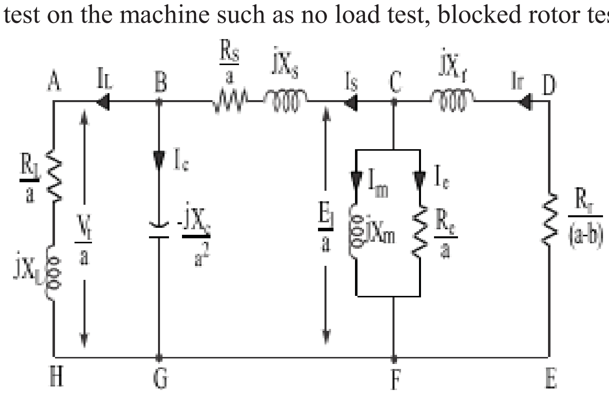


Figure 1.Per phase equivalent circuit of self-excited induction generator

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

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

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

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

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

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

When we solve the equivalent circuit of Figure 1 it results into a single loop equation i.e $I_s * Z = 0$.
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.

$$\text{Real}\,(X_m, a) = P_1X_ma^5 + P_2X_ma^4 + (P_3X_m + P_4)a^3 + (P_5X_m + P_6)a^2 + (P_7X_m + P_8)a + P_9\,X_m + P_{10} \quad (2)$$

$$\text{Imaginary}(X_m, a) = (Q_1X_m + Q_2)a^4 + (Q_3X_m + Q_4)a^3 + (Q_5X_m + Q_6)a^2 + (Q_7X_m + Q_8)a + Q_9 \quad (3)$$

The coefficients $(P_1 – P_{10})$ and $(Q_1 – Q_9)$ of two characteristics equations are obtained using MATLAB and are given in Appendix 2.These are solved using Newton raphson method in MATLAB and the values of $X_m$ and a are calculated .Per unit air-gap voltage $(E_1)$ of SEIG is determined from its magnetic characteristics as given in Appendix 1.Various currents and terminal voltage can be computed as follows :

$$I_r = \frac{-E_1/a}{R_r/(a-b) + jX_r}$$

$$I_s = \frac{aE_1}{jZ_L}$$

$$I_L = I_s\,\frac{-jX_C/a}{R_L + j(aX_L - X_C/a)}$$

$$V_t = aE_1 - I_s(R_s + jaX_s)$$

## III. FUZZY TECHNIQUE TO FIND MAGNETIZING REACTANCE AND GENERATED FREQUENCY OF SEIG

The above Polynomial equations are to be solved 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 and using ANN techniques.[9-11]

### *A. Fuzzy model: Block diagram*

This approach involves 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, stator resistance, rotor and stator leakage reactance, core loss resistance, power factor, speed, capacitance and load admittance in per unit .The two outputs as magnetic reactance and generated frequency. Membership function for all parameters except capacitance is taken as constant as these are terminal conditions .We took six membership function for capacitance as extreme low, very low, low, medium, high and very high .[14] Output variables $X_m$ & a has also six membership functions as extreme low, very low, low, medium, high and very high. To evaluate the $X_m$

& a for the given capacitance, input and output membership functions are formed. Fuzzification and defuzzification processes are carried out with the help of rule matrix. The Proposed Fuzzy model is given in Figure 2

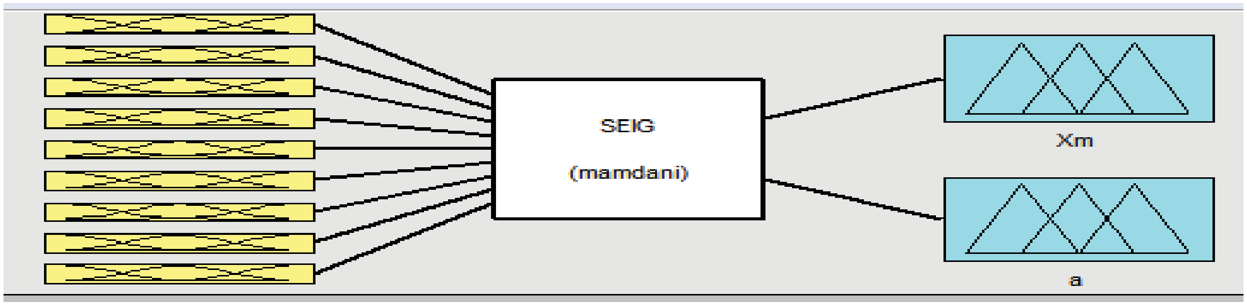


Figure 2 Fuzzy model of SEIG to find $X_m$ and a

### B. *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 as discussed in section II. 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 member ship functions are 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.The first rule is if capacitance is extreme low then magnetizing reactance is extreme high and generated frequency is very high. The other rules can also be interpreted as shown in Table 1.

Table 1: Fuzzy rules

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

### C. *Implementation of Fuzzy rules*

The proposed Fuzzy model of SEIG is implemented to determine the magnetic reactance and generated frequency requirements under varying conditions of capacitance at unity power factor. In this case the induction machine operation is carried with constant speed at unity power factor. The capacitance is varied from 20 microfarad to 29 microfarad 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 given machine parameters and other conditions (speed = 1485 rpm and load = 165 ohm) and varying capacitance as mentioned above. Using the fuzzy rules the values of $X_m$ and a are computed with input data of machine parameters for speed of 1485 rpm. The results obtained from the proposed Fuzzy model for computation of $X_m$ and a with varying capacitance are recorded in Table 2 and Table 3 which gives the comparison of results obtained from analytical technique and fuzzy logic of machine. The variation of magnetizing reactance, generated frequency and terminal voltage corresponding to given conditions of varying capacitance from 0.6082 to 0.8617 pu , speed (1485 rpm) and load (165 ohm) is shown in Figure 4 , Figure 5 and Figure 6.

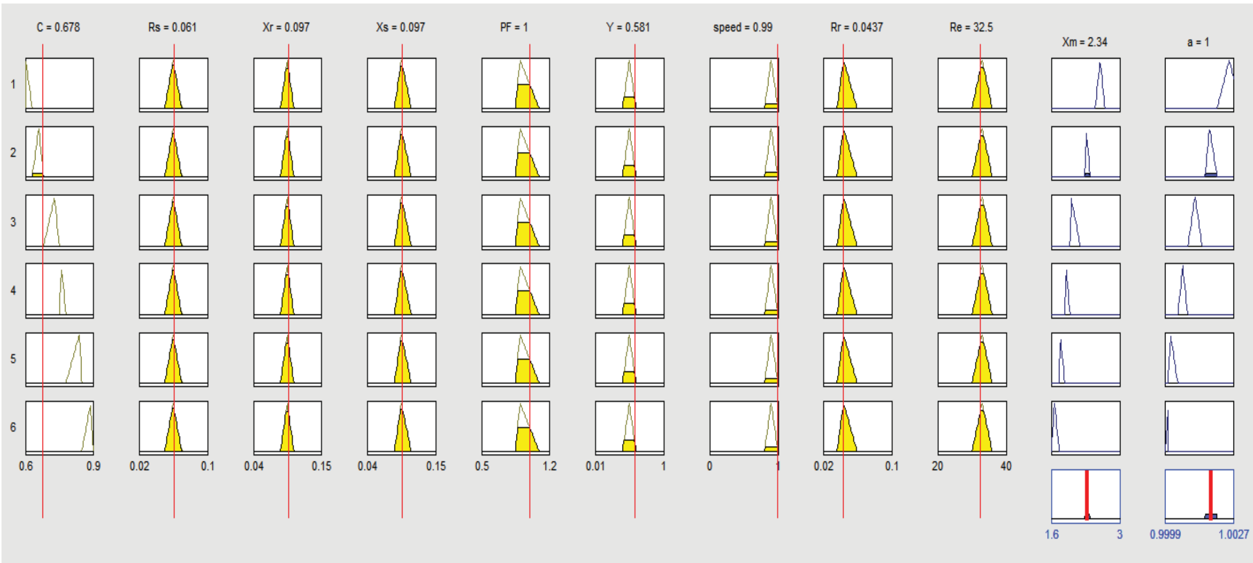


Figure 3 Various fuzzy rules used to find the parameters

Table 2: Magnetizing reactance with varying capacitance and given terminal conditions

| C (pu) | $X_m$(pu) (FL) | $X_m$(pu) (Analytical) |
|---|---|---|
| 0.6082 | 2.6 | 2.6229 |
| 0.6495 | 2.34 | 2.3888 |
| 0.6784 | 2.34 | 2.3481 |
| 0.7437 | 2.09 | 2.1118 |
| 0.7753 | 1.94 | 1.9834 |
| 0.8091 | 1.82 | 1.8764 |
| 0.8408 | 1.82 | 1.7741 |
| 0.8617 | 1.68 | 1.687 |

Table3: Generated frequency under varying capacitance and given terminal conditions

| C (pu) | a (pu) (FL) | a (pu) (Analytical) |
|---|---|---|
| 0.6082 | 1 | 1.0026 |
| 0.6495 | 1 | 1.0022 |
| 0.6784 | 1 | 1.0018 |
| 0.7437 | 1 | 1.0015 |
| 0.7753 | 1 | 1.0011 |
| 0.8091 | 1 | 1.0007 |
| 0.8408 | 1 | 1.0004 |
| 0.8617 | 1 | 0.9999 |

Table 4: Terminal voltage under varying capacitance and given terminal conditions

| C (pu) | $V_t$(pu) (FL) | $V_t$(pu) (Analytical) |
|---|---|---|
| 0.6082 | 0.755 | 0.7524 |
| 0.6495 | 0.8050 | 0.7923 |
| 0.6784 | 0.8050 | 0.8048 |
| 0.7437 | 0.8531 | 0.8501 |
| 0.7753 | 0.8819 | 0.8745 |
| 0.8091 | 0.9050 | 0.8947 |
| 0.8408 | 0.9050 | 0.9139 |
| 0.8617 | 0.9319 | 0.9303 |

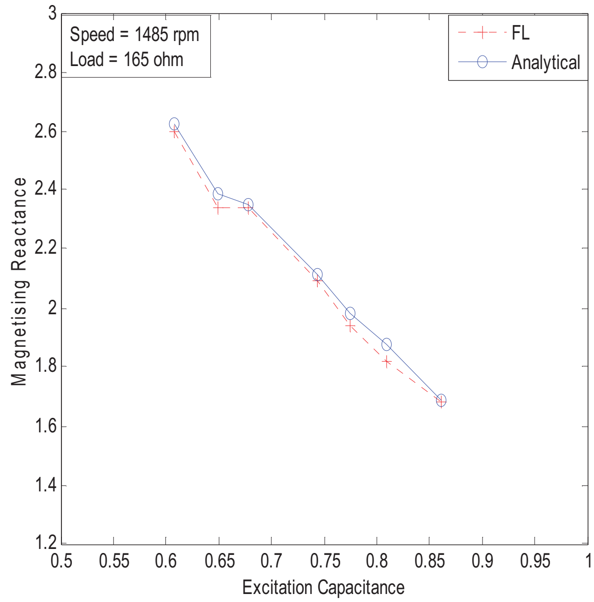


Figure 4 Effect of capacitance on magnetizing reactance for given terminal conditions

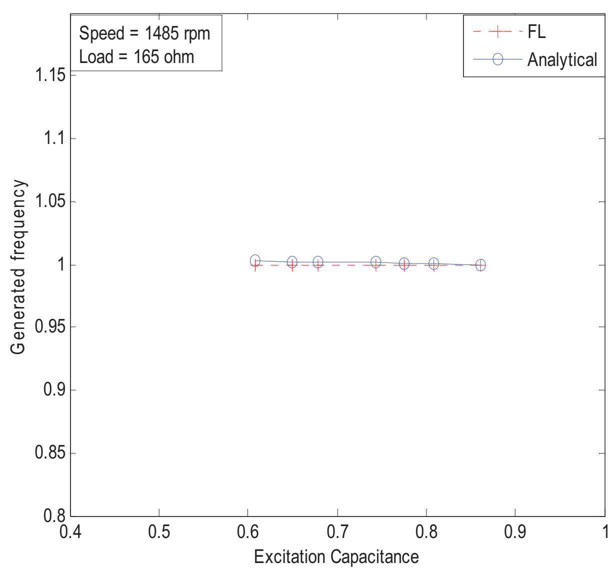


Figure 5 Effect of capacitance on generated frequency for given terminal conditions

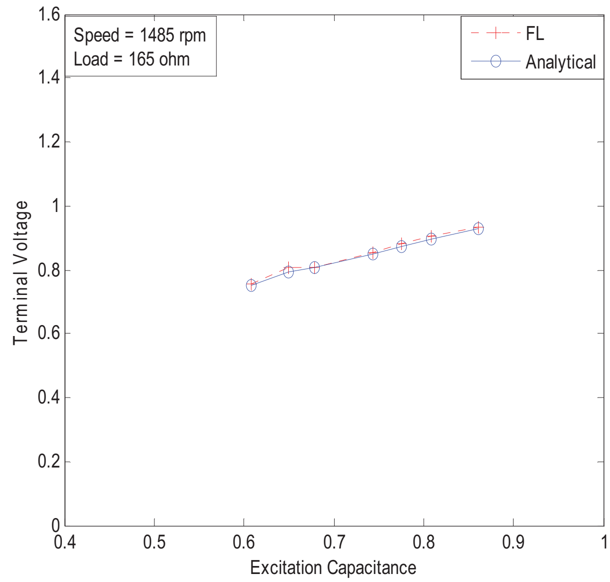


Figure 6 Effect of capacitance on terminal voltage for given terminal conditions

## IV. CONCLUSION

Self-excited induction generators are quite suitable for remote and windy areas where terminal voltage and frequency are controllable. Excitation capacitance connected across the stator terminal of machine plays very important role for the successful operation of induction generator. The terminal voltage, magnetizing reactance and generated frequency are affected by the capacitance when load and speed are kept constant The capacitor bank supplies the reactive power not only to self-excite the machine but also contributes to meet the requirements of reactive power of the load. From the Fig. 4, it is clear that the magnetizing reactance of SEIG is directly influenced by the terminal capacitance i.e. magnetizing reactance decreases sharply with the increase in terminal capacitance. The power generating capability of the machine increases with increase in terminal capacitance but generated frequency of machine practically remains constant. Increased excitation capacitance increases the terminal voltage as shown in Fig. 6. In this paper, an attempt is made for the pre evaluation process using fuzzy logic approach, which is simple. With this technique we can also vary the machine parameters by 4-8 percent. The closeness of the fuzzy results with the analytical data validates this attempt. With this approach the analysis of SEIG can be done under various conditions. Thus it is concluded that fuzzy logic technique is superior in comparison to conventional methods and this technique is applicable to all machines. The accuracy of results can further be improved by using trapezoidal membership function.

**Appendix 1**

Magnetization curve of machine (pu values)

| | |
|---|---|
| $X_m < 2.6930$ | $E_1 = 1.3818-0.2117\ X_m$ |
| $X_m < 2.8386\ \&\ X_m >= 2.6930$ | $E_1 = 2.1697- 0.5057\ X_m$ |
| $X_m < 2.9716\ \&\ X_m >= 2.8386$ | $E_1 = 3.8732- 1.1057\ X_m$ |
| $X_m > 2.9716$ | $E_1 = 0$ |

Machine specifications and its base value parameters

| | |
|---|---|
| $V_B = 415V$ | $I_B = 4.33A$ |
| $P_B = 1797VA$ | $Z_B = 95.84ohm$ |
| $C_B = 33.21\ uF$ | $f_B = 50Hz$ |

Single phase 1.7 kW, 415V, 4.33A, 1500rpm, 50Hz

$R_s$= 5.76ohm, $R_r$ = 4.19 ohm, $R_e$ = 3118 ohm, $X_s$ = 9.37 ohm ,$X_r$ = 9.37 ohm, $X_{mu}$= 285 ohm

## Appendix 2

Coefficients are given as:

$P_1 = -(X_s X_r X_{L)}$

$P_2 = (X_s X_r X_L)*b$

$P_3 = X_s*(R_r*R_L+R_e*R_L+X_r*X_c)+X_r*(R_e*R_s+X_c*X_s+ R_s*R_L)+X_s*(R_e*R_r+ R_e*R_s+ R_s*R_r)$

$P_4 = X_s*R_e*(X_r*R_L +R_r*X_L)+R_e*R_s*X_r*X_L$

$P_5 =-X_s*(X_r*X_c +R_e*R_L)*b- X_r*(R_s*R_L+R_e*R_L+ X_c*X_L)*b-(R_s*R_e*X_L)*b$

$P_6 = -X_r*R_e*(R_s*X_L+X_s*R_L)*b$

$P_7 = -X_c*R_r*(R_s+ R_L)-X_c*R_e* (R_s+ R_L+ R_r)$

$P_8 =-(R_e*X_r*X_c*(R_L+R_s))-(R_e*R_r*X_c*(X_L+X_s))-(R_e*R_s*R_r*R_L)$

$P_9 = R_e*X_c* (R_s+ R_L)*b$

$P_{10} = X_c*X_r*R_e*(R_L+R_s)*b$

$Q_1 = X_s*X_L*(R_e+ R_r)+X_s*X_r*R_L+X_r*X_L*(R_e+ R_s)$

$Q_2 = X_s *X_r*X_L*R_e$

$Q_3 = -X_s*(R_e*X_L+X_r*R_L)*b-X_r*X_L*(R_s+ R_e)*b$

$Q_4 = -(X_s*X_r*X_L*R_e)*b$

$Q_5 =-X_c*R_e*(X_s+X_r+X_L)-R_L*R_e*(R_s+Rr)-R_L*(X_r*X_c+R_r*R_s)-X_c*(R_s*X_r+X_s*R_r+X_L*R_r)$

$Q_6 =-R_e X_r*(X_s*X_c+ X_c*X_L+R_s*R_L)-R_r *R_e*(X_s*R_L+R_s*X_L)$

$Q_7 =R_e*(X_r*X_c+X_s*X_c+ *X_L+R_s*R_L)*b+X_c*X_r*(R_s+ R_L)*b$

$Q_8 = R_e*X_r*(X_s*X_c+ X_c*X_L)*b+ (X_r*R_e*R_L*R_s)*b$

$Q_9 = R_e*X_c* R_r*(R_L+R_s)$

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