Performance Optimization of Self Excited Induction Generator Using Simulated Annealing Technique

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***Abstract*- A robust meta-heurtics optimization technique, Simulated Annealing, is applied in this paper for analyzing the performance of separate-excited induction generator under different speed/load levels. The simulated annealing technique is utilized to define the minimum value of excitation capacitor required for providing maximum output power from the generator under different load types/operating conditions.**

***Index terms*- Induction Generator, Simulated Annealing Technique, Critical Capacitance, Magnetizing Reactance.**

I. INTRODUCTION

Induction Generator (IG) is considered the preferred option for harvesting electrical power from non-conventional energy sources, particularly wind. This is attributed to the salient features of IG such as: robustness, maintenance free, and absence of separate DC excitation system [1-9].

IG could be operated either grid-connected or off-line; for the case of grid-connected, the reactive power requirements for maintaining constant voltage at generator terminals under different load/speed conditions are supplied by the grid. However, for the case of stand-alone operation, which is the case for remote and rural locations, the capacitive excitation is indispensable to regulate the voltage across the machine terminal [5-14]. For example, for fixed excitation capacitor and speed, the machine terminal voltage decreases/increases with the load increase/reduction. For regulating the terminal voltage, the excitation capacitance has to vary simultaneously with the load. This is costly and complicated solution. However, if the terminal voltage is allowed to vary within a narrow range, attractive, in-expensive and simple approach is to use stepped switched capacitors with the possibility of switching them on/off with the loads.

The principle of self-excitation could also be adopted in other research areas as dynamic braking of three-phase induction motor; therefore, techniques for analyzing the behavior of such machines are of significant practical interest [2, 4]. In general, there are two scenarios for analyzing the steady-state performance of self-excited cage induction generator. The first scenario is to determine terminal voltage, output power, stator and rotor current for given value of capacitance, load and speed, while the second is to determine the required excitation capacitance for desired voltage at given load and speed level [2-6].

Extensive research efforts were draft in the past decades [1-14] for computation of the steady state performance of self excited induction generator using steady state equivalent circuit of the machine. For example, in [5] a mathematical model was developed for obtaining the steady state performance of self-excited induction generator using equivalent circuit. In this approach, the complex impedance is segregated into real and imaginary parts. The resulted nonlinear equations are arranged for unknown variables such as magnetizing reactance (X_m) and frequency (F), while the remaining machine parameters and operating variables are assumed constants. Numerical techniques as Newton Raphson were employed for solving the equations. This approach, however, requires sophisticated computation capabilities in terms of speed and storage.

In [6] an approach for computing steady state performance of the self excited induction generator is proposed; 4^{th} order polynomial is derived from the loop equation of equivalent circuit of the machine. The roots of this polynomial are determined to check occurrence of self excitation and to get the corresponding value of magnetizing reactance. The approach proposed in [6] has the advantages of predicting the performance of the machine for given capacitance/load/speed level. However, the load considered in this approach is pure resistive, which has less practical significance.

A mathematical formula using steady state equivalent circuit of the machine was proposed in [8] for computing the minimum value of the capacitance required for self excitation and the threshold speed below which self excitation could not be established. Another mathematical formula is proposed in [9] for computing the static performance of the induction generator under wide range of operating conditions. In [10], the performance of separate-excited induction generator is investigated to evaluate the range of different parameters as voltage, speed and excitation capacitance, within which self excitation is possible.

Most of the approaches reported in the literature on the evaluation of the steady-state performance of self-excited cage induction generators require splitting the equivalent impedance into real and imaginary components. Moreover, the model becomes rather complicated, if the core losses are included. Accordingly, several assumptions are taken to simplify the analysis. Furthermore, different models are used for modeling the machine with different types of loads/excitation capacitor arrangements. The coefficients of the mathematical models vary, which complicate the problem even further.

In this paper, a robust optimization technique is employed for analyzing the steady-state performance of self-excited cage induction generator. The proposed technique uses a generic mathematic model for self-excited IG; this model is used for any load type/excitation capacitor arrangement. In simulated annealing technique, the complex impedance is formulated as the objective function. Two scenarios are considered: In the first scenario, the magnetizing reactance and frequency are selected as independent variables, while in the second, capacitive reactance and frequency are taken as independent variables. The upper/lower limits of the unknown variables are selected to achieve practically acceptable values. The results from simulated annealing technique are used for predicting the generator performance under different load/speed levels.

II. ANALYSIS OF STAND-ALONE IG

The following analysis is valid for self-excited IG, squirrel-cage or wound rotor, provided that the capacitor bank is allocated in the stator side. . The equivalent circuit of self-excited IG, Figure 1, is normalized to base frequency.

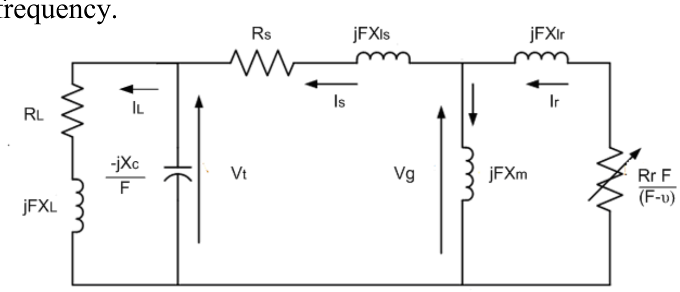

Fig. 1: Equivalent circuit of self excited induction generator

R_s and R_r are per phase stator and rotor resistances. X_{ls} and X_{lr} are per phase leakage reactance of stator and rotor. The X_m is the magnetizing reactance per phase and X_c is the per phase capacitive reactance of the capacitance C connected across the machine terminals at base frequency. R_L is the per phase load resistance. F and υ are p.u. frequency and speed. I_s, I_r and I_l are per phase stator, rotor and load currents respectively. The resistance, reactance, current and voltage of the rotor are referred to the stator. X_m, the magnetizing reactance, is a function in the air-gap voltage Vg and frequency as,

$$X_m=3*(1.6275-V_g/F)$$

(1)

Applying loop-impedance method [2] in the equivalent circuit, Fig. 1, the following equation results,

$$Z_t\, I_s = 0 \quad (2)$$

Z_t is given by,

$$Z_t = Z_1 + Z_c\, Z_L/\,(Z_c+Z_L) + Z_2\, Z_m/\,(Z_L+Z_m) \quad (3)$$

where $Z_1 = R_s + jF\, X_1$, $Z_c = -j\, X_c/F$, $Z_2 = Rr\, F\,/\,(F-\upsilon) + jF\, X_1$ $Z_L = R_L + j\, X_L$ and $Z_m = jF\, X_m$

Under steady-state self excitation, I_s # 0, thus Z_t in (1) is equal to zero.

There are two scenarios for solving (1).

a. SCENARIO 1

For computation of the performance of the self excited induction generator for a given value of capacitance, load and speed, the mathematical formulation of the problem is,

$$\text{Minimize } \left| Z_t\,(F,\, X_c) \right| \quad (4)$$

The frequency and excitation reactances are bounded such as:

$$F_l \le F \le F_u \quad (5)$$

$$X_{cl} \le X_c \le X_{cu}$$

The upper and lower limits of the frequency and reactance are chosen to depict practical constraints.

To fulfill (4), Z_t has to be segregated into real and imaginary parts; accordingly two nonlinear equations are obtained with X_c and F as unknown variables,

$$f(X_c,F) = F^3\, a_1 + F^2 a_2 + F(\, a_3 X_c + a_4) + (a_5 X_c) \quad (6)$$

$$g(X_c,F) = F^4 b_1 + F^3 b_2 + F^2 (b_3 X_c + b_4) + F(X_c b_5 + b_6) + (b_7 X_c) \quad (7)$$

where the coefficients a_1-a_5 and b_1-b_7 are given in appendix A

b. SCENARIO 2

For given magnetizing reactance, load and speed, the performance of the self excited induction generator could be predicted; the mathematical formulation of the problem under these conditions is given by,

$$\text{Minimize} \left| Z_t(F, X_m) \right|$$
(8)

Also for this scenario the frequency and excitation reactance are bounded such as:

$$F_l \leq F \leq F_u \quad (9)$$
$$X_{ml} \leq X_m \leq X_{mu}$$

Again the upper and lower limits of the frequency and reactance are chosen to depict practical constraints.

The equivalent impedance Z_t, after being separated into real and imaginary parts is given by,

$$f(X_m, F)=F^3(c_1X_m+c_2)+F^2(c_3X_m+c_4)+F(c_5X_m+c_6)+(c_7X_m)+c_8 \quad (10)$$

$$g(X_m,F)=F^4(d_1X_m+d_2)+F^3(d_3X_m+d_4)+F^2(d_5X_m+d_6)+F(d_7X_m+d_8)+d_9 \quad (11)$$

where the coefficients c_1-c_8 and d_1-d_9 are given in appendix A

For the both scenarios, the optimization problem is solved using a meta-heurtics technique, Simulated Annealing technique.

III. PROPOSED OPTIMIZATION ALGORITHM

Simulated annealing is a combinatorial optimization technique based on random evaluation of the objective function. The simulated annealing has the capability of finding global optimum with a high probability even for ill-conditioned functions with numerous local optima, albeit with large number of function evaluations. In general, the simulated annealing method resembles the actual cooling process of molten metals through annealing [15]. A Detailed description of the technique is given in [15], however, the technique could be understood from the flowchart below that used for solving the problem under concern. A brief description for simulated Annealing is given in the following:

- Step 1: Set Choose the parameters of the SA method. The initial temperature, the temperature reduction factor is chosen as c = 0.5, number of iterations n, machine data and Xc, F or X_m,F.
- Step 2: Evaluate the objective function value at Xc, F as f_1 or X_m , F as f_1 and set the iteration number as i = 1.
- Step3: Generate a solution from the neighborhood of the current solution. Let this solution be $f_2 = f(Xc_2, F_2)$ or $f_2 = f(X_m, F_2)$ and compute $\Delta f = f_2 - f_1$.
- Step4: Since the value of Δf is positive, we use the Metropolis criterion (P $[Xc_2,F_2]$ or P $[X_m,F_2]$ = $e^{-\Delta f/t}$) to decide whether to accept or reject the current point. For this we choose a random number in the range (0, 1), if random number is smaller than Metropolis criterion we accept (Xc_2, F_2) or (X_m, F_2). Since $\Delta f<0$, we accept the current point as (Xc_3, F_3) or (X_m, F_3) and increase the iteration number to i = 3. Since i > n, we go to step5.
- Step 4: Update the iteration number as i = 2.Since the iteration number i is less than or equal to n, we proceed to step3.
- Step 5: Since a cycle of iterations with the current value of temperature is completed,
- We reduce the temperature to a new value by (t = c*t) and reset the current iteration number as i = 1 and go to step3.
- Step 6: If stop criteria is met, then STOP. Else go to Step 3.

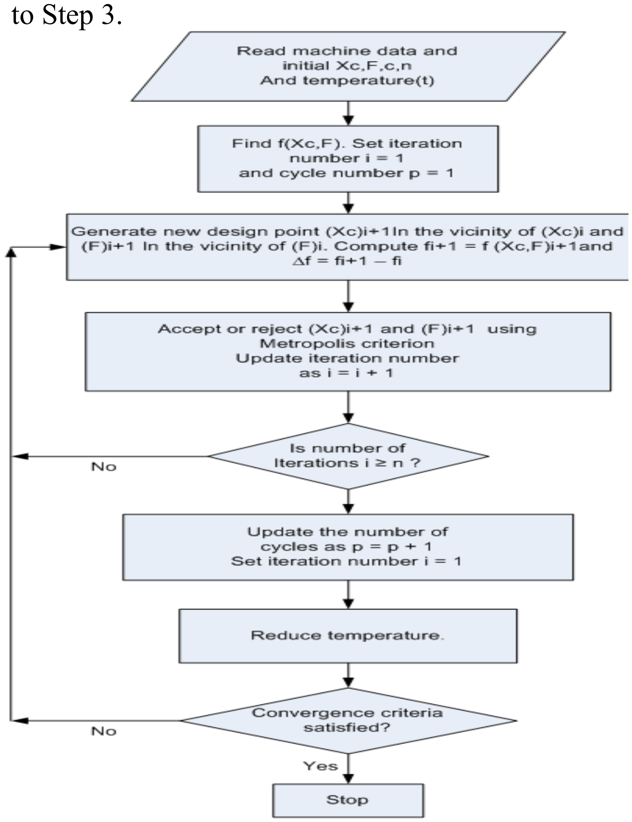

Fig.2: Flow chart of Simulated annealing Algorithm

The number of iteration N in the flowchart is taken around 100, which is considered a good comprise between the accuracy and computation time.

IV. STEADY-STATE PERFORMANCE OF SELF-EXCITED INDUCTION GENERATOR

The steady-state performance of self-excited induction generator could be mapped after obtaining X_c, X_m and F. Generally the steady-state performance of the machine is deduced from the following equations:

$$I_s = Vg/ \{F (Z_l+Z_{LC})\} \quad (11)$$
$$I_l = I_s.Z_C/ (Z_L+Z_C) \quad (12)$$
$$Vt=I_l.Z_L \quad (13)$$
$$I_r = I_s.Z_m/ (Z_2 +Z_m) \quad (14)$$
$$VAR = 3\ Vt^2\ F/Xc \quad (15)$$
$$Pin = 3\ 1_r^2.R_r.F/ (F- \upsilon) \quad (16)$$
$$Po = 3\ V_t.1_1 \quad (17)$$

a. STUDY CASE

The steady-state performance of 3.7kW self-excited IG is evaluated through Simulated Annealing. The machine parameters are given in Table 1.

Table 1 Parameters of 3.7kW IG

Induction Machine Data	
Resistances	Reactance
R_s =0.053 p.u	(X_{ls} = X_{lr}) =0.087 p.u.
R_r = 0.061 p.u	Impedance base=94.5ohm
4 pole	Rated power = 3.7 KW
Voltage line to line = 415 Volts	Frequency = 50Hz
Line current =7.6 Amps	Delta

The Simulated Annealing has found that self-excitation is not achievable at all operating speeds/excitation capacitors, and if the excitation capacitor is reduced than a certain value for speed, the generator will not build up irrespective to load type. The values of the threshold capacitor could be obtained for any load type/operating condition. These values were compared with those given in [13]. In this reference, analytical expression for the minimum excitation capacitance was introduced; however it was only for the case of no-load.

The variation of the generated voltage with excitation capacitance at rated speed for no-load case is shown in Figure3.

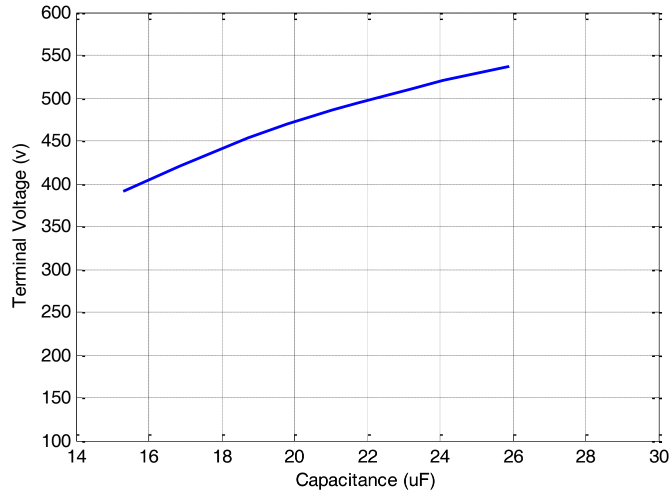

Fig. 3: Terminal voltage versus capacitance at no load and rated speed

Fig. 3 shows that for 3.7kW, 15μf is the minimum value for the excitation capacitor at rated speed, below which the self-excitation is not possible. Moreover, the Figure shows that there is upper limit for the excitation capacitor above which the machine reverts into saturation. In the saturation the increase in the excitation capacitor will not produce significant increase in output power/generated voltage, which could not overwhelm the increase in capacitor size, cost and losses.

The variation of the minimum, critical, capacitance with the speed for different load conditions was shown in Fig. 4.

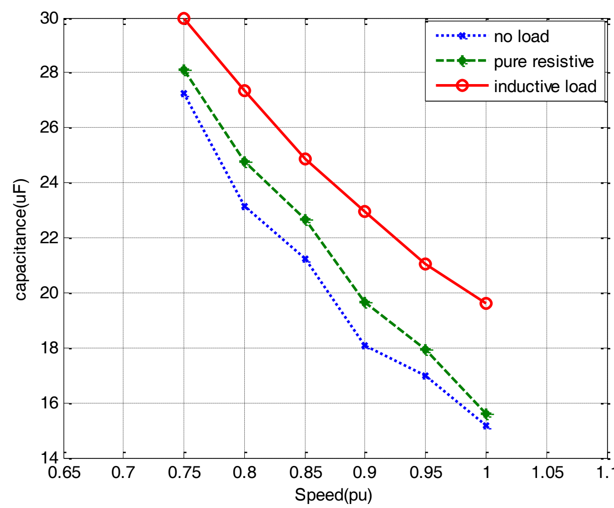

Fig. 4 Critical capacitance with speed for no-load (blue), pure resistive (green) and inductive load (red) for different loading conditions

Fig. 4 shows that the critical capacitance for inductive load is significantly higher than that of resistive load and no-load. Because, the excitation capacitor has to satisfy the reactive power requirements for the load and the generator simultaneously. Accordingly, capacitive load requires less capacitance than no-load case.

The critical capacitance is a speed dependent, Fig. 4; the capacitance drops nearly by 40% for 25% increase in the speed. The critical capacitance for no-load shown in Fig. 4 is similar to that obtained from analytical expression derived in [13] for no-load.

For a given speed, the performance of self-excited IG is dependent on the excitation capacitance. This is shown clearly in Fig. 5, where the terminal voltage of the generator is illustrated against output power for different load types/capacitor values.

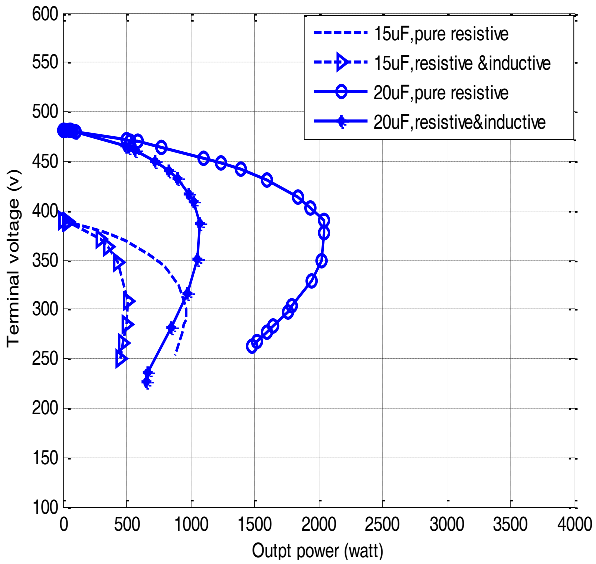

Fig. 5: Terminal voltage versus output power at rated speed for pure resistive load and 15µf capacitor (dashed), inductive load and 15µf capacitor (triangle-dotted), and pure resistive load and 20µf capacitor (white circled-solid), and inductive load and 20µf capacitor (black circled-solid)

The terminal voltage/output power of IG increases/decreases with increase/decrease in the excitation capacitor, Fig. 5, provided that saturation is not reached. The saturation was included in the above analysis through the upper limit of the excitation reactance, X_{cu}. Figure 5 shows that the voltage regulation for the inductive load is inferior to that of the resistive load; this may be attributed to the function of the excitation capacitor in case of inductive load in fulfilling the reactive power requirements of the load and the generator.

The dependency of the output power on the excitation capacitance is exploited in Fig. 6, where the output powers are plotted versus the capacitance for constant terminal voltage/speed.

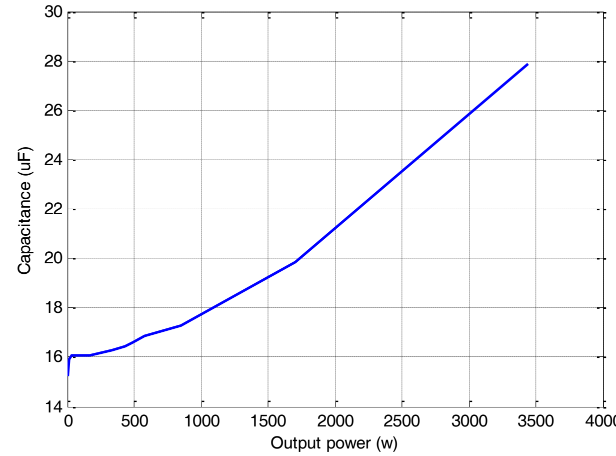

Fig.6: Excitation capacitance with output power at rated terminal voltage and rated speed

For constant terminal voltage/speed, the capacitance has to increase for an increase in the output power. The excitation capacitance in Figs. 4 and 5 is limited to 28µf. This is to avoid the operation in saturation.

The variation of magnetizing reactance X_m, with load at rated voltage and speed for two levels of excitation capacitance is shown in Fig. 7.

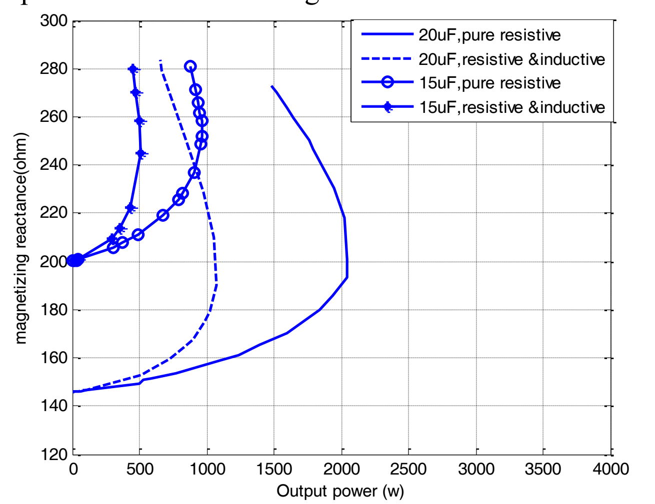

Fig. 7 Magnetizing Reactance with output Power at rated speed/voltage for pure resistive load and 15µf capacitor (dotted-solid), inductive load and 15µf capacitor (triangle-solid), and pure resistive load and 20µf capacitor (dash), and inductive load and 20µf capacitor (solid)

Fig. 7 shows the magnetizing reactance X_m for resistive load is nearly constant. Also it shows that for inductive load there are two values at one load level. The high value is at unstable condition. It is observed from Figure 5, that the characteristic of self-excited induction generator is nearly similar to that of separate-excited DC generator.

V. CONCLUSION

The following conclusions can be drawn:

1. The IG is best option for harvesting electrical power from renewable energy sources, due to its salient advantages: robustness, maintenance free and reduced volumetric dimension/cost.
2. Capacitor banks are essential for stand-alone operation of IG for supplying the machine with reactive power requirements
3. Simulated Annealing predicts with relatively small computation requirements, the minimum capacitor required for self excitation under different load/speed conditions
4. For a speed, there is critical capacitance below which the self-excitation is not possible.
5. The terminal voltage of IG increases/decreases with increase/reduction in the output capacitance
6. For constant terminal voltage and speed, the excitation capacitance has to vary with the load.
7. The performance of self-excited induction generator is investigated here for different loads/operating conditions, which as far as we know is not reported.

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APPENDIX (A)

The coefficients of equation (5)

$a_1 = -((2X_m+X_1)\,X_1\,R_L+X_L\,(X_1+X_m)\,(R_r+R_s))$

$a_2= (2X_m+X_1)\,X_1\,R_L\,\upsilon+R_s\,X_L\,(X_1+X_m)\,\upsilon$

$a_3= (R_L + R_s + R_r)\,(X_m+X_1) + (X_L\,R_L)$, $a_4= R_s\,R_L\,R_r$

$a_5= -(R_s+R_L)\,(X_m+X_1)\,\upsilon$

The coefficients of equation (6)

$b_1= -X_1\,X_L\,(X_1+2X_m)$, $b_2= -B_1\,\upsilon$

$b_3= (X_m+X_1)\,(X_L+X_1)+(X_1X_m)$

$b_4= R_s\,X_L\,R_r+R_L\,(X_m+X_1)\,(R_s+R_r)$

$b_5= -((X_m+X_1)\,(X_L+X_1) +X_1\,X_m)\,\upsilon$

$b_6= -R_s\,R_L\,(X_m+X_1)\,\upsilon$, $b_7= -R_r\,(R_s+R_L)$

The coefficients of equation (9)

$c_1=-X_L\,(R_s+R_r) - (2X_1)\,R_L$, $c_2=-X_LX_1\,(R_s+R_r) - (X_1^2)\,R_L$

$c_3= (2X_1R_L\,\upsilon + R_sX_L\,\upsilon)$, $c_4=X_1(R_sX_L\,\upsilon +X_1R_L\,\upsilon)$

$c_5=X_c(R_L+R_s+R_r)$, $c_6=X_LX_cR_r+R_sR_LR_r+X_1X_c\,(R_L+R_s+R_r)$

$c_7=-X_c\,(R_L+R_s)\,\upsilon$, $c_8=-X_1X_c\,(R_L+R_s)\,\upsilon$;

The coefficients of equation (10)

$d_1=-2X_1X_L$, $d_2=-X_L(X_1^2)$, $d_3=2X_1X_L\,\upsilon$

$d_4=(X_1^2)\,X_L\,\upsilon$, $d_5=(R_sR_L+2X_1X_c+X_LX_c+R_rR_L)$

$d_6=X_L\,(R_sR_r+X_cX_1)+(X_1R_L)\,(R_r+R_s)+(X_1^2)\,X_c$

$d_7=\upsilon\,((-2X_1X_c)-(R_sR_L)-(X_cX_L))$

$d_8=X_1\,\upsilon\,(-R_sR_L-X_1X_c-X_cX_L)$, $d_9=-X_cR_r\,(R_s+R_L)$