A Simple Approach to Estimate the Steady-State Performance of Self-Excited Induction Generator

K S Sandhu, Dheeraj Joshi
Department of Electrical Engineering
National Institute of Technology
Kurukshetra,Haryana
INDIA
kjssandhu@yahoo.com, dheeraj_joshi@rediffmail.com

Abstract: This paper presents a new and simple model for the steady-state analysis of single and parallel operated self-excited induction generators (SEIG). In this paper an attempt has been made to incorporate the unjustified assumptions in an existing (Watson's) model. This has resulted into an improved model for the estimation of performance of SEIG. A close agreement of simulated results using proposed modeling with experimental values on test machines proves the validity and superiority of proposed model. Further proposed model is extended for the analysis of a system comprising of number of such machines operating in parallel.

Keywords*:* Parallel operation, steady state analysis, self-excited induction generator (SEIG), wind energy conversion.

Nomenclature

a	per unit frequency
b	per unit speed
C	terminal excitation capacitance per phase
I_m	magnetizing current per phase
R_L	load resistance per phase
R_s	stator resistance per phase
R_r	rotor resistance per phase
V	load voltage per phase
X_s	stator reactance per phase
X_r	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
R_c	Core loss resistance

Sub

1. Introduction

Self-excited induction generators have attained a lot of attraction in recent years, due to the suitability of these machines in many applications including wind energy and small hydro energy systems. Further, these machines and specially cage induction machines pocesses many advantages such as low cost, brushless and rugged construction, self protection capability etc.

To estimate the steady-state performance of a SEIG, most of the researchers used the conventional equivalent circuit representation of an induction motor [1-13]. Some of the researchers used the impedance model, and a few used the admittance-based

model for the treatment of these circuits. Whereas [10, 12] developed a new circuit representation, which includes an active power source in the rotor circuit.
Apart from this, [14] developed the simple most approach to describe the autonomous and parallel operation of self excited induction generators. Simplicity is the main attraction of Watson's [14] model.
Different models are suggested by researchers for analysis and control of parallel operated self-excited induction generators in steady state. Al-Bahrani et al [15] suggests Newton Raphson technique for voltage control of two or more parallel operated SEIG. Various control parameters were found simultaneously. The results are better but with lengthy and complex terms. Chakraborty et al [16,17] suggests T and inverse Γ models for the analysis and control of parallel operated SEIG. More than one iterative loops were used to find the various parameters.
Sandhu [18] suggests a simple model having balanced resistive loads for the analysis of parallel operated SEIG. Methodology adopted needs an estimation of capacitance sharing by individual machine. Classical and conventional control techniques are described by [19-20]. P. Haiguo et al [21] presents an Fuzzy-PID based approach to control the wind turbine system. It is found that the vector control in combination with Fuzzy-PID control enhances the system stability. Such developments are the indication of current research in the area of wind energy generation through induction machines.
In the present paper an attempt has been made to improve the results of [14] with few modifications but without loosing the simplicity of the approach. Close agreement of simulated results with experimental results, confirms the validity of proposed modeling. Model is found to be suitable for the steady-state analysis of single as well as for multi machine systems.

2. Steady-State Analysis

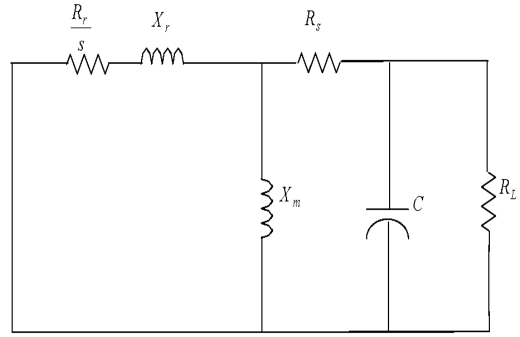

Fig.1 Equivalent circuit representation.

Fig.1 shows the equivalent circuit as adopted by Watson [14].
This circuit representation may be modified as given in Fig.2 with the provision of followings, which were found to be missing;

- Inclusion of stator reactance
- Inclusion of pu frequency to make all leakage reactances and excitation capacitance more effective.
- Further magnetizing branch has been shifted to stator side, as usually adopted in motoring case.

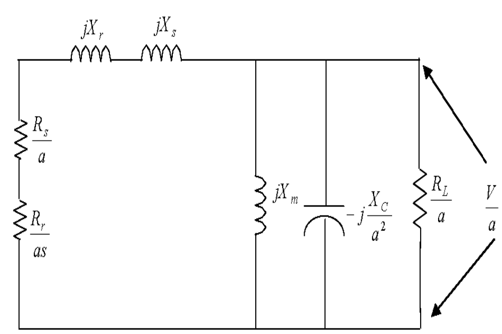

Fig.2 Modified equivalent circuit.

Analysis of circuit as given in Fig.2, in terms of real power gives;

$$P = \left(\frac{k\left(\frac{V}{a}\right)^2}{\frac{R_s}{a} + \frac{R_r}{as}} \right) + \left(\frac{\left(\frac{V}{a}\right)^2}{\frac{R_L}{a}} \right) \quad (1)$$

Where k is a fractional value and for a single machine is

$$k = \frac{\frac{R_s}{a} + \frac{R_r}{as}}{\left[\left(\frac{R_s}{a} + \frac{R_r}{as}\right)^2 + (X_s + X_r)^2\right]^{\frac{1}{2}}}$$

In the absence of power source (1) may be written as;

$$s = -\frac{R_r}{R_s + kR_L} \quad (2)$$

It can be also written as follows;

$$s = \frac{a-b}{a} \quad (3)$$

Rotor speed and slip determines the frequency of the generated voltage.

$$a = \left(\frac{b}{1-s}\right) \quad (4)$$

At no-load ($R_L \to \infty$), therefore the generated frequency is same as the driven frequency. However, as evident from above expressions, generated frequency falls with load.

For self-excitation, magnetizing current is supplied by the capacitor and is given as;

$$I_m = Va\omega C \quad (5)$$

Further, magnetization characteristics of SEIG (Appendix-I) may be expressed in the form as;

$$I_m = k_1V^2 + k_2V + k_3 \quad (6)$$

Rearrangement of (5) and (6) results in to the quadratic equation in terms of unknown voltage as;

$$k_1V^2 + (k_2 - a\omega C)V + k_3 = 0 \quad (7)$$

Values of k_1,k_2 and k_3 are as per Appendix 1. (1) to (7) may be used to determine the generated frequency and terminal voltage for any operating speed and excitation capacitance. Further analysis of the generator including core loss is given in Appendix 2.

This approach can be extended for 'N' self excited induction generators operating in parallel as shown in Fig.3.

Where

N represents the number of machines operating in parallel.

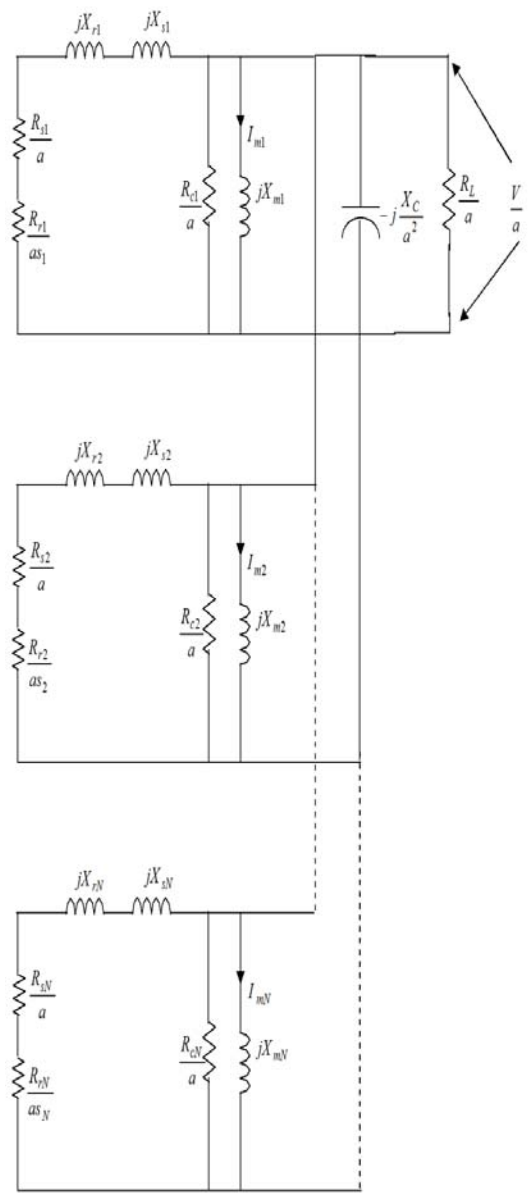

Fig.3. Equivalent circuit representation of parallel operated self-excited induction generators.

Equation (1) to (7) referred to multi machine system comprising of N such machines may be modified as;

$$\sum P = \sum_{i=1}^{N} \frac{k_i \left(\frac{V}{a}\right)^2}{\frac{R_{si}}{a} + \frac{R_{ri}}{as_i}} + \frac{\left(\frac{V}{a}\right)^2}{\frac{R_L}{a}} \tag{8}$$

$$\sum_{i=1}^{N} s_i = -\frac{R_{ri}}{R_{si} + k_i R_L} \tag{9}$$

$$s_i = \frac{a - b_i}{a} \tag{10}$$

$$a = \left(\frac{b_i}{1 - s_i}\right) \tag{11}$$

$$\sum_{i=1}^{N} I_{mi} = Va\omega C \tag{12}$$

and

$$\sum_{i=1}^{N} I_{mi} = k_{1i} V^2 + k_{2i} V + k_{3i} \tag{13}$$

(8) to (13) may be used to estimate the generated voltage and frequency as given in Appendix-3.

3. Results and Discussions

TABLE 1 Comparison of results for single machine.

Sr. No.	R (pu)	b	Using Wattson Model		Using Modified Model		Experimental Results	
			V(pu)	a	V(pu)	a	V(pu)	a
1.	6.4951	0.9760	0.8885	0.9657	0.9065	0.9616	1.0	0.9606
2.	2.5980	1.0330	0.8807	1.0060	0.9331	0.9967	1.0	0.9992
3.	2.5114	1.0366	0.8803	1.0087	0.9349	0.9990	1.0	1.0022
4.	2.4248	1.0400	0.8792	1.0109	0.9363	1.0010	1.0	1.0040
5.	2.3382	1.0440	0.8784	1.0138	0.9382	1.0035	1.0	1.0080
6.	2.1910	1.0553	0.8796	1.0228	0.9443	1.0119	1.0	1.0164
7.	2.0871	1.0613	0.8782	1.0270	0.9470	1.0157	1.0	1.0196
8.	2.0005	1.0677	0.8774	1.0318	0.9501	1.0201	1.0	1.0242
9.	1.9139	1.0746	0.8765	1.0369	0.9535	1.0247	1.0	1.0292
10.	1.8143	1.0840	0.8755	1.0439	0.9580	1.0312	1.0	1.0360
11.	1.7233	1.0916	0.8730	1.0492	0.9614	1.0360	1.0	1.0416

Table 1 gives the comparison of simulated results with experimental results on a test machine, SEIG-1 (Appendix 1). Simulated results with modifications as suggested in this paper are found to be more close to experimental one in comparison to simulated results as obtained using Watson model. This proves the validity and superiority of the proposed modeling. Fig.4 to Fig.7 gives the variation of terminal voltage and frequency with load for different values of excitation capacitance and operating speed. It is observed that excitation capacitance at stator terminals and operating speed of the machine effect the performance to a great extent and thus may be used to control the terminal conditions.

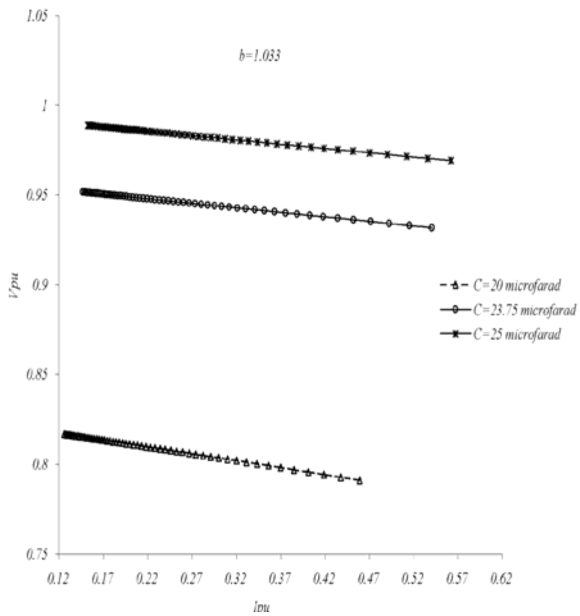

Fig.4. Variation of terminal voltage with load for different excitation capacitance.

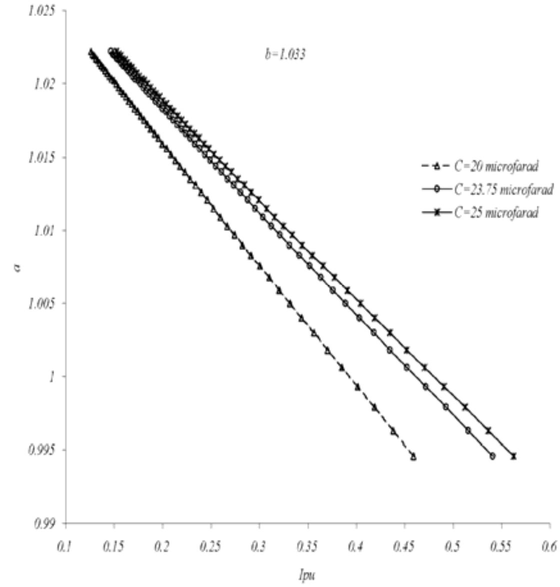

Fig.5. Variation of generated frequency with load for different excitation capacitance.

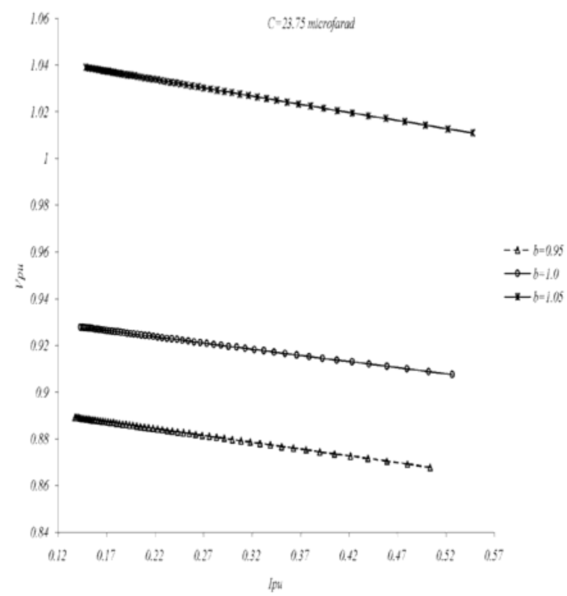

Fig.6. Variation of terminal voltage with load for different operating speed.

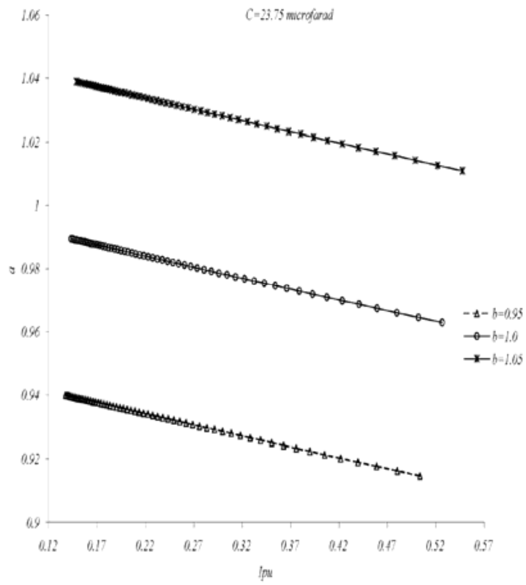

Fig.7. Variation of terminal voltage with load for different operating speed.

TABLE 2 Comparison of results for two machines operating in parallel.

C=90μF ,R_L=90Ω

Sr. No.	b_1	b_2	Using Modified Model		Experimental Results	
			V(pu)	a	V(pu)	a
1.	0.9413	0.9520	1.0107	0.9189	1.0041	0.9242
2.	0.9693	0.9653	1.0231	0.9332	1.0543	0.9472
3.	0.9653	0.9573	1.0416	0.9290	1.0543	0.9414
4.	0.9266	0.9186	1.0766	0.9020	1.0041	0.9120
5.	0.8933	0.9000	1.0706	0.8842	0.9539	0.8820

Table 2 gives the comparison of simulated results with experimental results on a set of two test machines [Appendix-1] operating in parallel. Results are found to be in close agreement especially for low slip operations, justified in case of induction machines.

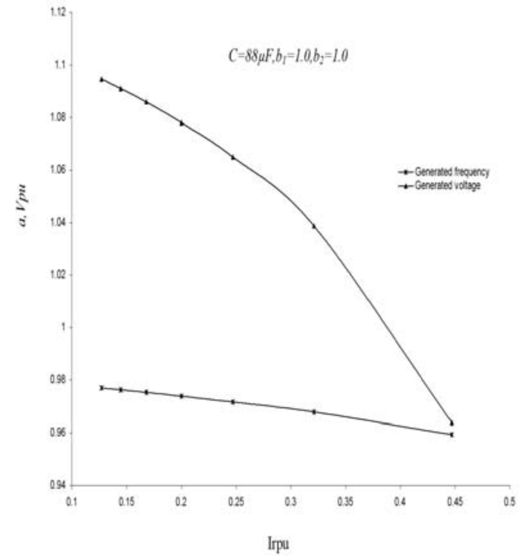

Fig.8 Variation of generated frequency and voltage with load.

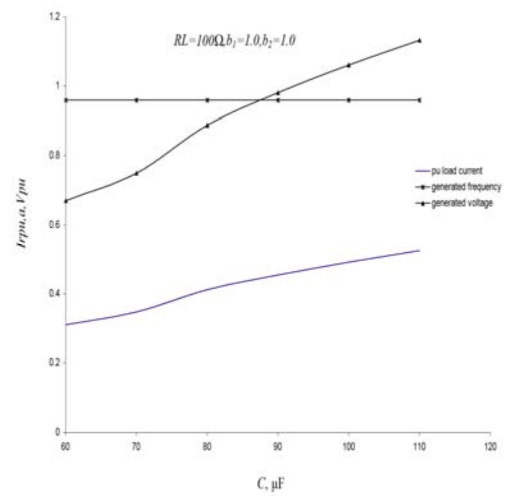

Fig.9 Variation of load ,generated frequency and voltage with excitation capacitance.

Fig. 8 to Fig. 11 shows the simulated results for a system comprising of two self excited induction generators. As observed terminal voltage falls sharply with load. However fall of generated frequency with load is small in comparison with the terminal voltage. This reflects the necessacity to control the terminal voltage with load variations. Fig.9 and Fig.10 shows the effect of excitation capacitance and operating speed on the generated voltage, frequency and load supplied by two machine system operating in parallel. Load capability of the system increases with an increase in excitation capacitance. However it effects the generated voltage and frequency simultaneously.

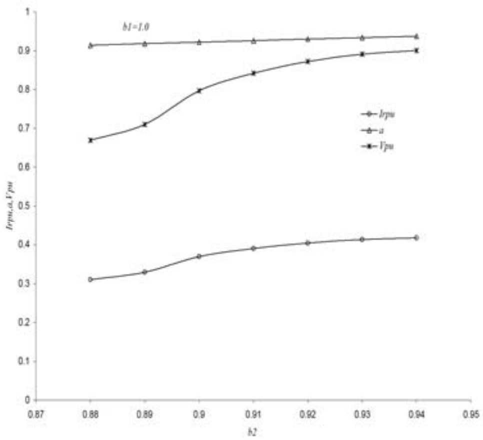

Fig.10. Variation of load, generated frequency and voltage with rotor speed of machine-2.

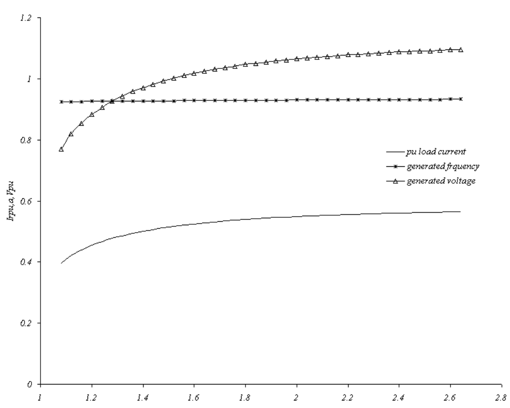

Fig.11. Variation of load, generated frequency and voltage with rotor resistance of machine-2.

Fig.11 gives the effect of variations of rotor resistance of machine-2 on the performance of parallel operation of two machines. It is seen that generated voltage is greatly influenced due to any change of rotor resistance of one of the machines. However variations in generated frequency are negligible in case both machines are running at constant speeds. This provides the opportunity to control the generated voltage of the system through rotor resistance, provided operating speeds are maintained.

4. Conclusion

In this paper an attempt has been made to prepare a new model to investigate the steady-state performance of single as well as parallel operated self-excited induction generators. The main attraction of the model is its simplicity to obtain the final solution. Results obtained are found to be close agreement to the experimental results obtained on a test machine/set of machines. This proves the validity of model proposed for the analysis of single unit or number of units operating in parallel. Efforts are made to include the core loss component which is generally neglected. Inclusion of core loss branch makes the model more realistic. It is found that, to meet the power needs of the world, wind energy is emerging s a potential candidate among renewable energy resources. Therefore future research plans of the authors in the area of wind energy extraction using induction generators is as;

- Analysis and control of power quality of wind energy systems using artificial intelligence.
- Design modifications in the induction generators according to operating constraints of a specific area.

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APPENDIX 1

SPECIFICATIONS OF SEIG-1

Line voltage=380V
Line current=1.9A
Rating=1.0HP
Number of poles= 4
Frequency=50Hz
Base speed =1500 rpm
R_s = 9.5 ohm
R_r = 8.04 ohm
$X_s = X_r$ = 8.84 ohm

SPECIFICATIONS OF SEIG-2

Line voltage=230V
Line current=4.96A
Rating=3.0HP
Frequency=50Hz
Number of poles= 4
Base speed =1500 rpm
R_s = 3.35 ohm
R_r = 1.76 ohm
$X_s = X_r$ = 4.85 ohm

APPENDIX 2

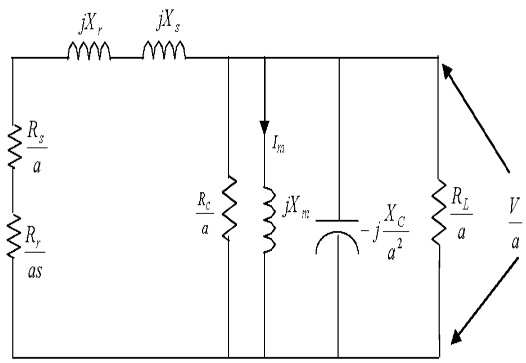

Fig.12. Modified equivalent circuit including core losses.

Analysis of circuit as given in Fig.12, in terms of real power gives;

$$P = \left(\frac{k\left(\frac{V}{a}\right)^2}{\frac{R_s}{a} + \frac{R_r}{as}} \right) + \left(\frac{\left(\frac{V}{a}\right)^2}{\frac{R_c}{a}} \right) + \left(\frac{\left(\frac{V}{a}\right)^2}{\frac{R_L}{a}} \right)$$

Where k is a fractional value and depends upon the design of the machine.
In the absence of power source may be written as;

$$s = -\frac{R_r}{R_s + \frac{k}{a\left(\frac{1}{R_c} + \frac{1}{R_L}\right)}}$$

TABLE 2 Simulated results including core losses.

Sr. No.	*R* (pu)	*b*	*V*(pu)	*a*
1.	6.4951	0.9760	0.9060	0.9610
2.	2.5980	1.0330	0.9324	0.9957
3.	2.5114	1.0366	0.9341	0.9980
4.	2.4248	1.0400	0.9356	1.0000
5.	2.3382	1.0440	0.9374	1.0024
6.	2.1910	1.0553	0.9433	1.0105
7.	2.0871	1.0613	0.9459	1.0141
8.	2.0005	1.0677	0.9489	1.0183
9.	1.9139	1.0746	0.9520	1.0227
10.	1.8143	1.0840	0.9564	1.0288
11.	1.7233	1.0916	0.9596	1.0334

APPENDIX 3

Generated frequency for two machine systems including core losses may be calculated using (8) and (10). This results into the solution of 9^{th} order polynomial equation in unknown '*a*' as follows;

$$Q9*a^9+Q8*a^8+Q7*a^7+Q6*a^6+Q5*a^5+Q4*a^4+Q3*a^3+Q2*a^2+Q1*a^1$$

Where

Q9=P9;

*P9=kk*d41*d42;*

Q8=P8;

P8=kk(d41*d32+d31*d42);*

Q7=M7+N7+P7;

*M7=n31*d42;*

*N7=n32*d41;*

P7=kk(d41*d22+d31*d32+d21*d42);*

Q6=M6+N6+P6;

*M6=n31*d32+n21*d42;*

*N6=n32*d31+n22*d41;*

P6=kk(d41*d12+d31*d22+d21*d32+d11*d42);*

Q5=M5+N5+P5;

*M5=n31*d22+n21*d32+n11*d42;*

*N5=n32*d21+n22*d31+n21*d41;*

P5=kk(d41*d02+d31*d12+d21*d22+d11*d32+d01*d42);*

Q4=M4+N4+P4;

*M4=n31*d12+n21*d22+n11*d32;*

*N4=n32*d11+n22*d21+n12*d31;*

P4=kk(d31*d02+d21*d12+d11*d22+d01*d32);*

Q3=M3+N3+P3;

*M3=n31*d02+n21*d12+n11*d22;*

*N3=n32*d01+n22*d11+n12*d21;*

P3=kk(d21*d02+d11*d12+d01*d22);*

Q2=M2+N2+P2;

*M2=n21*d02+n11*d12;*

*N2=n22*d01+n12*d11;*

P2=kk(d11*d02+d01*d12);*

Q1=M1+N1+P1;

*M1=n11*d02;*

*N1=n12*d01;*

*P1=k*d01*d02;*

$kk=(1/R_L)+(1/R_{c1})+(1/R_{c2});$

$n31=R_{s1}+R_{r1};$

$n21=-b_1*(2*R_{s1}+R_{r1});$

$n11=b_1*b_1*R_{s1};$

$d41=(X_{s1}+X_{r1})^\wedge 2;$

$d31=-2*b_1*d41;$

$d21=R_{s1}+R_{r1}+2*R_{s1}*R_{r1}+b_1*b_1*d41;$

$d11=-2*b_1*R_{s1}-2*b_1*R_{s1}*R_{r1};$

$d01=b_1*b_1*R_{s1};$

$n32=R_{s2}+R_{r2};$

$n22=-b_2*(2*R_{s2}+R_{r2});$

$n12=b_2*b_2*R_{s2};$

$d42=(X_{s2}+X_{r2})^\wedge 2;$

$d32=-2*b_2*d42;$

$d22=R_{s2}+R_{r2}+2*R_{s2}*R_{r2}+b_2*b_2*d42;$

$d12=-2*b_2*R_{s2}-2*b_2*R_{s2}*R_{r2};$

$d02=b_2*b_2*R_{s2};$

(12) and (13) may be used to develop the quadratic expression in terms of '*V*' as given below;

$0.00029*V^2-(0.0753+w*a*C-K1-K2)*V+6.8767$

Where

$K1=K1a/K1e;$

and

$K2=K2a/K2e;$

$K1a=a*(a-b_1)*(a-b_1)*(X_{s1}+X_{r1});$

$K1b=R_{s1}*(a-b_1)+a*R_{r1};$

$K1c=K1b*K1b;$

$K1d=a*a*(a-b_1)*(a-b_1)*(X_{s1}+X_{r1})^\wedge 2;$

$K1e=K1c+K1d;$

$K2a=a*(a-b_2)*(a-b_2)*(X_{s2}+X_{r2});$

$K2b=R_{s2}*(a-b_2)+a*R_{r2};$

$K2c=K2b*K2b;$

$K2d=a*a*(a-b_2)*(a-b_2)*(X_{s2}+X_{r2})^\wedge 2;$

$K2e=K2c+K2d;$