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# Study of self-excited induction generator with unbalanced loads

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## Abstract

There are many applications where the induction generator use is advantageous. So in those cases the detailed analysis of induction generator under various conditions like variation in excitation as well as the loads gives the better performance of the entire system. This paper analyses the steady state performance of self-excited induction generator with unbalanced loads by considering an equivalent sequence circuit much easier and well-organized. Experiments have been carried out to validate the proposed analytical two port network circuit model. Good agreement among analytical and experimental results has to be obtained. In this paper we are analyzing the performance of SEIG with balanced and unbalanced loads and they are comparing the results using MATLAB.

## 1 Introduction

Considering the increasing power demand with present environmental conditions and exhausting of conventional resources made an interest towards renewable and non-conventional energy sources like wind, solar, hydro, biogas for power generation. Normally renewable energy sources are independent power systems which uses a squirrel cage induction motors as generators. Therefore, the study of single phase and three phase self-excited induction generators has reclaimed significance, especially suitable for wind and small hydro power plants.

The steady state analysis of induction generator was studied based on an per-unit equivalent circuit to solve the per-unit frequency (F) and magnetising reactance ($X_M$) with the given machine parameters, excitation capacitance and load impedance by using either nodal admittance method or loop impedance method [1]. An iterative algorithm is proposed by Chan.T.F [2], this algorithm is very efficient because in a per-unit equivalent Circuit of the SEIG, the per-unit frequency is calculated initially and then for finding the magnetising reactance. Instead of solving a set of simultaneous nonlinear equations, which is time consuming, the algorithm solves in sequence two single-unknown nonlinear equations, which is much faster and more accurate.

Many researchers have undertaken this problem in the past period of years and the following two solution techniques based on the steady-state equivalent circuit have been developed:

### 1.1 Loop impedance method

For a specified load and speed, two non-linear simultaneous equations in per-unit frequency F and magnetising reactance $X_m$ are found by equating the real and imaginary terms of the complex loop impedances respectively to zero. These equations are then solved by the Newton-Raphson method [2]. Once F and $X_m$ values are known and with the aid of the magnetization curve, the equivalent circuit is completely explained and the steady-state performance of the SElG can be determined.

### 1.2 Nodal admittance method

This method deals with admittances connected across the nodes which explains the air gap. By equating the sum of real parts to zero (which is equivalent to active power balance), a polynomial equation in F is obtained. $X_m$ can be determined upon equating the sum of imaginary parts to zero, using the value of F obtained after solving the polynomial.

## 2 Model Designing

The designing of an equivalent circuit can be divided into three parts they are load modelling, generator modelling and combination of both load and generator modelling. Now load and generator modelling is converting the unbalanced circuits to phase sequence circuits therefore, it is easy use the symmetrical components to analyse the self –excited induction generator with unbalanced loads.

### 2.1 Load modelling

A delta connected three phase load represents the model of unbalanced loads as shown in fig.1, where $y_1$, $y_2$ and $y_3$ are load admittances. A mixture of Y-connected and single-phase loads can also be converted to this model by appropriate transformation formulae. In fig1, Va, Vb and Vc refer to the phase voltages at the load terminals, and Ia, Ib and Ic to the line currents flowing into the load.

The relation between the three-phase voltages and currents can be written as

$$I=\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}=\begin{bmatrix} y_{3.}+y_1 & -y_1 & -y_3 \\ -y_1 & y_1+y_2 & -y_2 \\ -y_3 & -y_2 & y_2+y_3 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (1)$$
$$=YV$$

Where I and V are current and voltage vectors, respectively, and Y is the nodal admittance matrix. Let the resultant symmetrical voltage and current component vectors be Vs and Is, respectively. Vs and Is can be expressed as

$$V_s=\begin{bmatrix} V_0 & V_p & V_n \end{bmatrix}^T, I_s=\begin{bmatrix} I_0 & I_p & I_n \end{bmatrix}^T \; (2)$$

The subscripts 0, p and n are denoted to zero-, positive- and negative-sequence components, respectively. From (1) and the symmetrical component equation for currents, we can write

$$I_s=A^{-1}I=A^{-1}YV=A^{-1}YAV_s=Y_sV_s \qquad (3)$$

$$Y_s=A^{-1}YA \qquad (4)$$

$$A=\begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix} \qquad (5)$$

$$a=1\angle 120° \qquad (6)$$

Substituting equation (5) and equation (6) in equation (4) gives

$$Y_s=\frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\begin{bmatrix}y_{3.}+y_1 & -y_1 & -y_3\\ -y_1 & y_1+y_2 & -y_2\\ -y_3 & -y_2 & y_2+y_3\end{bmatrix}$$

$$*\begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix} \qquad (7)$$

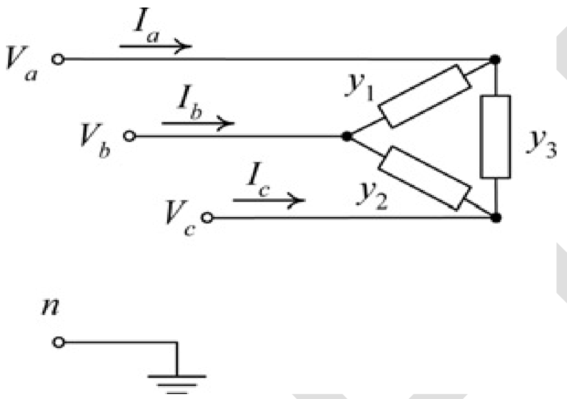

Figure 1 A delta-connected three-phase unbalanced load

Which further simplified as

$$Y_s=\begin{bmatrix}0 & 0 & 0\\ 0 & y_1+y_2+y_3 & -\left(ay_1+y_2+a^2y_3\right)\\ 0 & -\left(a^2y_1+y_2+ay_3\right) & y_1+y_2+y_3\end{bmatrix} \qquad (8)$$

$$=\begin{bmatrix}0 & 0 & 0\\ 0 & y_d & y_\alpha\\ 0 & y_\beta & y_d\end{bmatrix} \qquad (9)$$

Where

$$y_\alpha=-\left(ay_1+y_2+a^2y_3\right)$$

$$y_\beta=-\left(a^2y_1+y_2+ay_3\right) \qquad (10)$$

$$y_d=y_1+y_2+y_3$$

Therefore equation (3) can be written as

$$\begin{bmatrix} I_0 \\ I_p \\ I_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & y_d & y_\alpha \\ 0 & y_\beta & y_d \end{bmatrix} \begin{bmatrix} V_0 \\ V_p \\ V_n \end{bmatrix} \qquad (11)$$

Since the zero sequence current is zero from equation (11) can be expressed as

$$\begin{bmatrix} I_p \\ I_n \end{bmatrix} = \begin{bmatrix} y_d & y_\alpha \\ y_\beta & y_d \end{bmatrix} \begin{bmatrix} V_p \\ V_n \end{bmatrix} \qquad (12)$$

Which implies a two port network as shown in fig.2

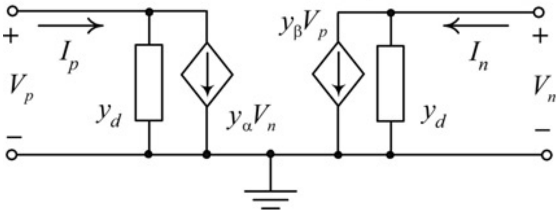

Figure 2 A two port network model for an unbalanced three phase load

## 2.2 Generator Modelling

The single phase steady state equivalent circuit of the SEIG with the positive sequence circuit machine form fig 3,

Whereas
F = frequency,
v = per unit speed,
$R_s$ = stator resistance,
Xs = stator leakage reactance,
Rr = rotor resistance,
$X_r$ = rotor leakage reactance,
$X_m$ = magnetising reactance,
$I_m$ = magnetising current,
$V_g$ = air gap voltage,
$V_p$ = positive sequence voltage,
$X_{mn}$ = negative sequence magnetising Reactance.

Voltages and resistances quantities are modified by frequency and per-unit speed. The only difference from positive sequence and negative sequence circuits are sign of rotor speed and rotor resistance is replaced by (F+v) with (F-v).

Some assumptions are made to help the analysis of SEIG they are:

(a) All the parameters in the equivalent circuit are made constant except magnetising reactance which is a function of magnetising current.

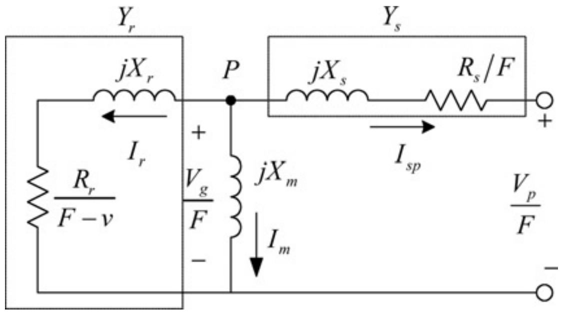

Figure 3 positive sequence equivalent circuit

(b) Ignoring core loss resistance in equivalent circuit.
(c) Harmonic effects are not taken into consideration.

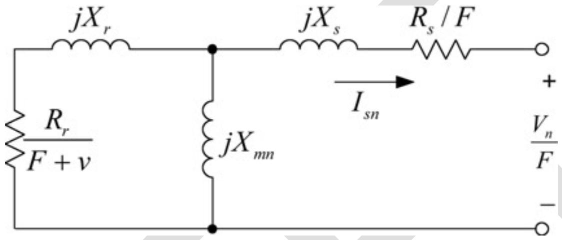

Figure 4 negative sequence equivalent circuit

## 2.3 Combination of load and generator models

The combination of fig 2, fig 3 and fig 4 of load modelling and generator modelling together represents the SEIG with unbalanced loads. Therefore the complete sequence equivalent network of SEIG with unbalanced loads is represented in fig 5. Here the left part of network represents positive sequence network and right side of circuit represents negative sequence network and the combining each other through two dependent current sources. The effects of unbalanced loads can be explained by $y_{\alpha}$, $y_{\beta}$ and $y_d$ are functions of F. if the three phase loads are balanced then the admittances $y_1$, $y_2$ and $y_3$ are equal then $y_{\alpha}$, $y_{\beta}$ will be equal to 0 this implies there is no connection between positive and negative sequence network. By analysing the equivalent circuit the performance of SEIG can be calculated with unbalanced loads.

From the fig 5 $Y_r$ and $Y_s$ are rotor and stator admittances and $Y_L$ is the admittance at right side terminals of load. Now from the negative sequence network considering all parameters into a single admittance $Y_{nth}$ which is parallel to the current dependent source $y_{\beta}V_p/F$ and by eliminating $jX_{mn}$ because it is a smaller value and parallel branches of rotor terminals and stator terminals of negative Sequence network are very close then $Y_{nth}$ is calculated easily.

$$Y_{nth} = y_d + \left[\frac{R_s}{F} + \frac{R_r}{F+v} + j\left(X_s + X_r\right)\right]^{-1} \quad (13)$$

$$I_{sp} = Y_L\left(\frac{V_p}{F}\right) = y_d\left(\frac{V_p}{F}\right) + y_{\alpha}\left(\frac{V_n}{F}\right) \qquad (14)$$

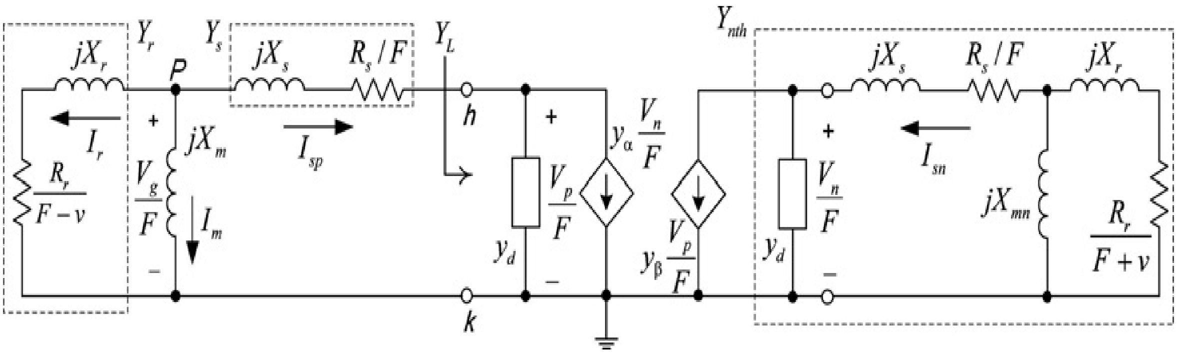

Figure 5 sequence network of SEIG with unbalanced loads

Where $V_n/F$ can be written as

$$\frac{V_n}{F} = -\left(\frac{1}{Y_{nth}}\right) y_\beta \left(\frac{V_p}{F}\right) \qquad (15)$$

Now substituting eqn (15) in eqn (14) gives

$$I_{sp} = \left(y_d - \frac{y_\alpha y_\beta}{Y_{nth}}\right)\left(\frac{V_p}{F}\right) = Y_L \frac{V_p}{F} \qquad (16)$$

Where $Y_L = \left(y_d - \frac{y_\alpha y_\beta}{Y_{nth}}\right)$ (17)

## 3 Analysing the Equivalent Network

To analyse the performance of the SEIG at a specified operating conditions, voltages and currents should be calculated from the equivalent circuit fig 5. With this values frequency F and magnetising reactance $X_m$ can be solved. The two step method is used for finding F and $X_m$ i.e. in first step per-unit frequency is calculated then with the help of F magnetising reactance is calculated and this method was proposed by chan.T.F. [2].

### 3.1 Calculation of F and $X_m$

From fig 5 the air gap voltage $V_g$ as a reference phasor i.e. $V_g = V_g0$. The magnetising current should be an imaginary quantity because the magnetising reactance is an imaginary quantity. The sum of currents pass through node P equals to 0, i.e. $I_r+I_{sp} = -I_m$ is also an imaginary number. It is written as

$$I_r + I_{sp} = \frac{V_g}{F} Y_r + \frac{\left(\frac{V_p}{F}\right)}{Y_L^{-1} + Y_s^{-1}} = \frac{V_g}{F}\left[Y_r + \frac{Y_L Y_s}{Y_L + Y_s}\right] \qquad (18)$$

Here $V_g$ is a real number and $I_r+I_{sp}$ is an imaginary number, the equation is written as. i.e.

$$Y_T\left(F\right)=\left[Y_r+\frac{Y_LY_s}{Y_L+Y_s}\right] \qquad (19)$$

From the above equation real part is separated and made equal to zero i.e.

$$\mathrm{Re}\left[Y_T\left(F\right)\right]=\mathrm{Re}\left[Y_r+\frac{Y_LY_s}{Y_L+Y_s}\right]=0 \qquad (20)$$

Here $Y_T$ is a combination of $Y_r$ , $Y_s$ and $Y_L$ as they are function of F. from equation 20 there is only one unknown value F, which is solved by basic numerical methods and other methods like false position method or bisection method or secant method. Per-unit frequency F value doesn't depend on magnetising reactance $X_m$. After finding F from above equation then substitute in equation 19 we get $Y_T$ which is total admittance parallel with magnetising reactance $jX_m$. Hence the equation can be written as

$$I_m\left(jX_m+\frac{1}{Y_T}\right)=0 \qquad (21)$$

As $I_m \neq 0$, so the above equation turns to

$$jX_m=-\frac{1}{Y_T} \qquad (22)$$

### 3.2 Determination of air-gap voltage

Air-gap voltage is determined by the found per-unit frequency value. And an intersection point between a straight line equation and magnetising curve represents an equation which shown in fig6 i.e.

$$\frac{V_g}{F}=I_m jX_m=-\frac{I_m}{Y_T} \qquad (23)$$

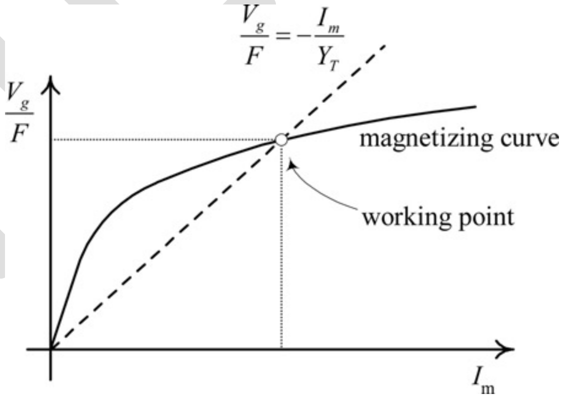

Figure 6 Air-gap voltage $V_g$

Where $Y_T$ is parallel with $jX_m$ shows the expression of $Y_T$ in equation 19. To find the working point an iteration method has to be taken as unknown variables are $V_g$ and $I_m$ so the iteration procedure starts from initial values of any of them and finally an intersection point occurs. The magnetising curve obtains from the experimental values which is discussed below.

Once the values of $V_g$, F and $I_m$ are known then all the voltages and currents from the sequence network can be found easily. After finding voltages and currents from positive and negative sequence network convert them to phase domain by multiplying with symmetrical matrix which represents three phase quantities.

## 4 Analysing models and experimental verification

When an experimental self-excited induction generator model as shown in fig 7. With three phase, 220V, delta connected, 50 Hz, 4- pole, 1/2Hp squirrel cage induction machine. The parameters of the equivalent circuit is taken from no load and a blocked rotor tests and the parameters are $R_s$ = 0.1567, $R_r$ = 0.1204, $X_s$ = 0.1600, $X_r$ = 0.1600. Here by conducting a test magnetising curve is calculated which is shown in fig 8 and a curve of the expression

$$V_g\left(I_m\right)=\frac{a}{1+\left(I_m/b\right)^{-c}} \tag{24}$$

Where the parameters a= 1.15V, b=0.0018, c=0.0057 are found by using a non-linear regression equation. The obtained air gap voltage with intersection point between magnetising curve and straight line equation is

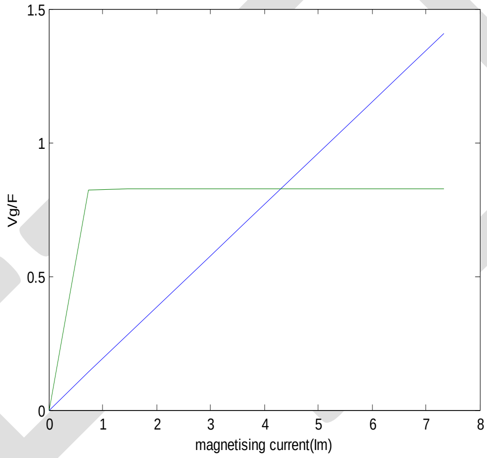

Figure 7 air-gap voltage

## 4 Performance of system at different loads and different excitations

The performance and analysis of self-excited induction generator is obtained by comparing with balanced and unbalanced loads which gives a perfect picture how the system behaves for that the following steps have done they are:

### a) Balanced load and balanced excitation capacitance

The three phase voltages and currents for the balanced excitation of capacitance are $C_1$=$C_2$=$C_3$ = 10μF and balanced resistance loads are $R_1$=$R_2$=$R_3$ = R Ω and resistance vary from 400 Ω to 1800 Ω which results the normal output of the line currents at balanced condition and it results only single phase is shown in figure 8 and line voltages in figure 9.

### b) Unbalanced excitation capacitance and balanced loads

The three phase voltages and currents for the unbalanced excitation of capacitance are $C_1$= 8 μF, $C_2$= 12 μF, $C_3$ = 10 μF and balanced resistance loads are $R_1$=$R_2$=$R_3$ = R Ω and resistance vary from 400 Ω to 1800 Ω for this case the experimental values of voltages and currents are used which shows the difference of balanced excitation and unbalanced excitation of capacitance which shows three phase line currents are shown in figure 10 and line voltages in figure 11 Due to variation in excitation capacitance there will be change in voltages and currents.

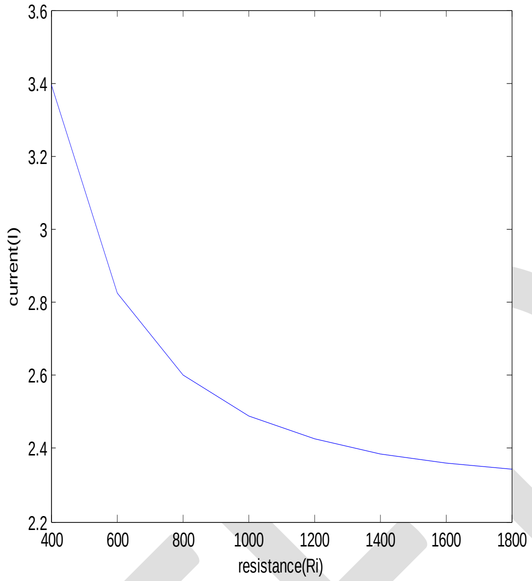

Figure 8 Current for balanced excitation capacitance and loads

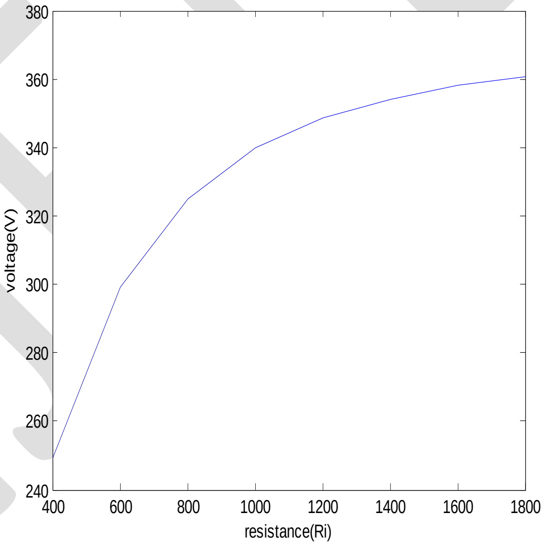

Figure 9 voltage for balanced excitation capacitance and loads

### c) Unbalanced excitation capacitance and unbalanced loads

In this case both excitation and loads are unbalanced, where unbalanced excitation of capacitance are $C_1$= 8 µF, $C_2$= 12 µF, $C_3$ = 10 µF and balanced resistance loads are $R_1$= R **Ω**, $R_2$= R+240 **Ω**, $R_3$ = R+480 **Ω** and resistance vary from 400 **Ω** to 1800 **Ω**, which results three phase differently compare to other cases as they are unbalanced, voltage and current changes according to the change in excitation and loads of the system which differs every time with change in them, then the experimental values of voltages and currents are used which gives three phase line currents are shown in figure 12 and line voltages in figure 13.

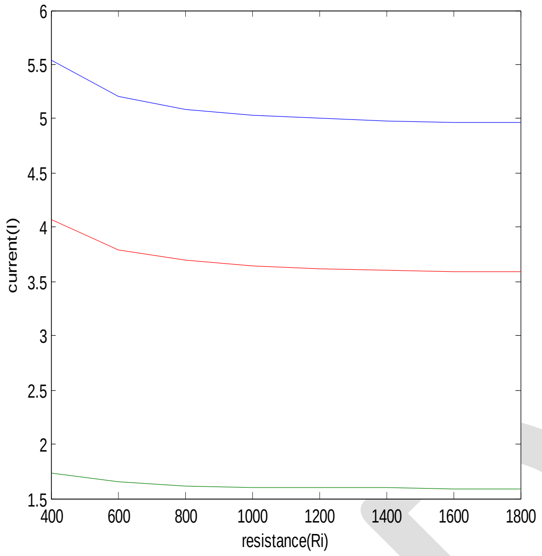

Figure 10 Current for unbalanced excitation capacitance and balanced loads

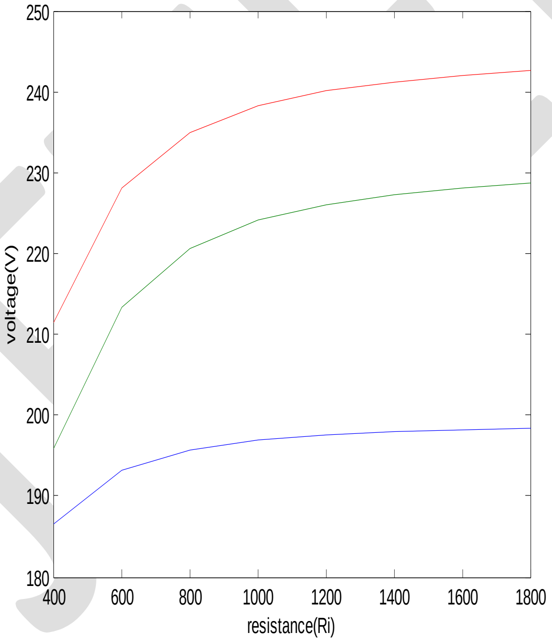

Figure 11 voltage for unbalanced excitation capacitance and balanced loads

### d) Single capacitance and single phase load

In this case to know the system performance at unbalanced conditions the excitation and loads are changed into unbalanced excitation of capacitance are $C_1$= 0 µF, $C_2$= 0 µF, $C_3$ = 20 µF and balanced resistance loads are $R_1$= R Ω, $R_2$= ∞ Ω, $R_3$ = ∞ Ω and resistance vary from 400 Ω to 1800 Ω. This results three phase which consists of zero phase voltage and current due the specified values of excitation and loads rest is shown in figure as load changes the voltage and current changes according to it. Therefore the experimental values of voltages and currents are used which gives single phase line currents are shown in figure 14 and line voltages in figure 15.

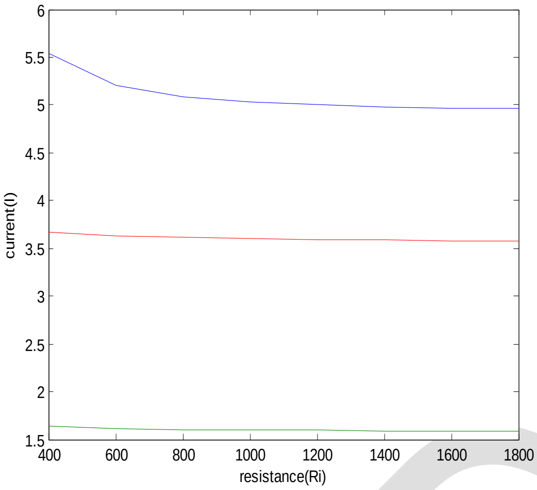

Figure12 Current for unbalanced excitation capacitance and balanced loads

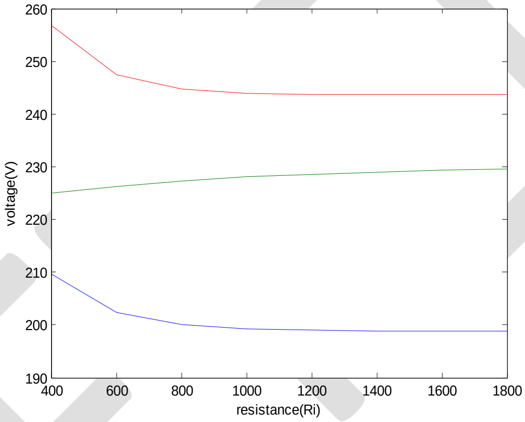

Figure 13 voltage for unbalanced excitation capacitance and balanced loads

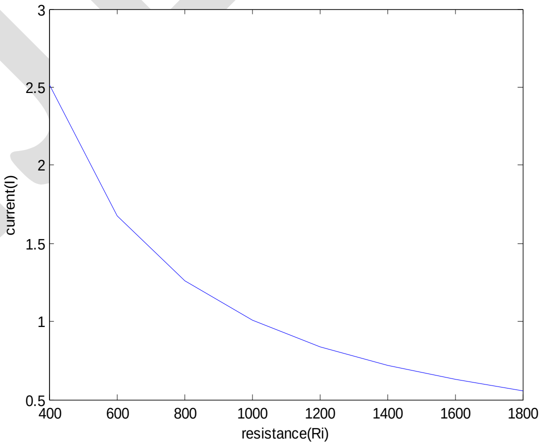

Figure 14 Current of single capacitance and single load

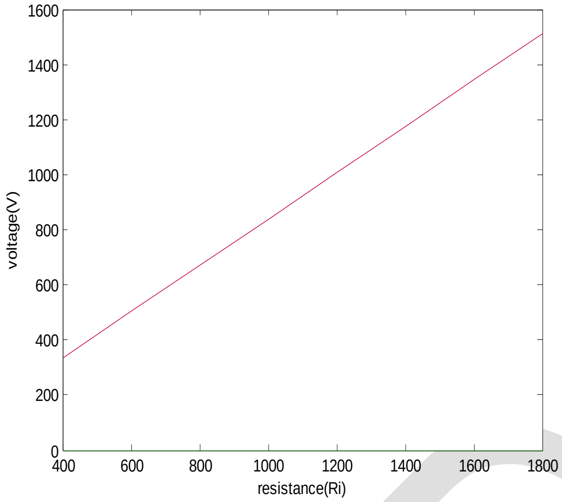

Figure 4.8 voltage of single capacitance and single load

## 5 Conclusion

The analysis and performance of self-excited induction generator with unbalanced loads has been modelled in MATLAB programming. The results have been taken for three phase balanced and unbalanced loads with an equivalent circuit based on concepts of symmetrical components and based on two port network allows the steady state performance of a three phase unbalanced excitation capacitances and unbalanced loads. SEIG is working at the saturated region of magnetizing curve, harmonics are generated because of nonlinearity of magnetization but harmonics are neglected in this modelling. The projected model also delivers improved physical explanation results the currents and voltages of unbalanced loads and excitation capacitance of the SEIG. Now this application can be used with mini hydro plants, wind energy plants and bio-gas plants etc. The projected model gives a two-step method to be used for solving the sequence circuit which improves speed for finding solution. And it is observed that projected model is approximately ten times faster than the existing model.

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