ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 6, June 2016

The Dynamic Modelling of Self Excited Induction Generator

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ABSTRACT: Throughout the globe in last four decades generation of electricity from renewable energy sources has created a wide interest. At the same time there has been a rapid development of renewable energy related technology. Induction generators are preferable in wind farms because of their brushless construction, robustness, low maintenance requirements and self-protection against short circuits. However poor voltage regulation and low power factor are their weaknesses. This paper covers the analysis and dynamic modelling of an isolated self-excited induction generator (SEIG). The proposed dynamic model consists of induction generator, self-excitation capacitance and load model which are expressed in stationary d-q reference frame. The dynamic performance of SEIG is investigated under no load and with load. To predict the performance of the system, a SIMULINK based simulation study was carried out.[1]

KEYWORDS: SEIG, dynamic modelling, dq modelling, SIMULINK/MATLAB, induction generator.

I.INTRODUCTION

In recent years, environmental pollution has become a major concern and energy crisis has led people to develop new technologies for generating clean and renewable energy. Wind power, solar energy, hydro power and tidal energy are possible solutions for producing ecofriendly energy.In the past four decades methods of harnessing hydro and wind energy for electric power generation and the technology for such alternate systems are developed. From the recent scenario it is evident that wind energy is drawing attention in the power generation sector. If wind energy could be effectively captured it could solve the problems of environmental pollution and unavailability of fossil fuels in future.

Induction generators are increasingly being used these days because of their being more advantageous over conventional synchronous generators. Some of their useful features are brushless rugged construction, low cost, less maintenance, simple operation, self-protection against faults, good dynamic response and capability to generate power at varying speed. The small-scale power generating system for areas like remotely located single community, a military post or remote industry where extension of grid is not feasible may be termed as stand-alone generating system. Portable gen-sets, stand-by/emergency generators and captive power plants required for critical applications like hospitals, computer centres, and continuous industrial process come under the category of stand-alone generating systems. Self-excited induction generator is best suitable for generating electricity from wind, especially in remote areas, because they do not need an external power supply to produce the excitation magnetic field.[1]

II.SYSTEM MODEL AND ASSUMPTIONS

2.1 MODELLING OF SELF EXCITED INDUCTION GENERATOR

For the development of an induction machine model in stationary frame, the d-q arbitrary reference frame model of machine is transformed into stationary reference frame. Fig 2.1 shows the schematic d-q axes diagram of SEIG. Capacitors are connected across the stator terminal to make the machine self-excited; the reference directions of currents and voltages are indicated in Fig 2.2 (a) and (b). Using d-q components of stator current (i_{sd} and i_{sq}) and rotor current (i_{rd} and i_{rq}) as stator variables, the above differential equations are derived from the equivalent circuit shown in Fig. 2.2.

DOI:10.15662/IJAREEIE.2016.0506072

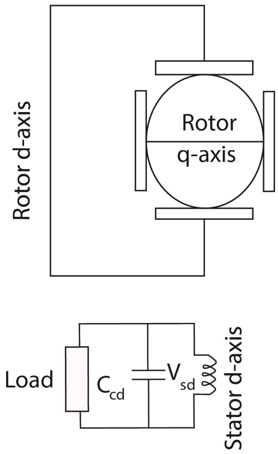

Fig 2.1 Schematic d-q axes diagram of SEIG

In stationary reference frame the dynamic machine model can be derived by substituting $w_e = 0$ in synchronously rotating reference frame d-q model equations. The d-q axes equivalent circuit of a (SEIG) supplying an inductive load is shown in Fig. 2.2.

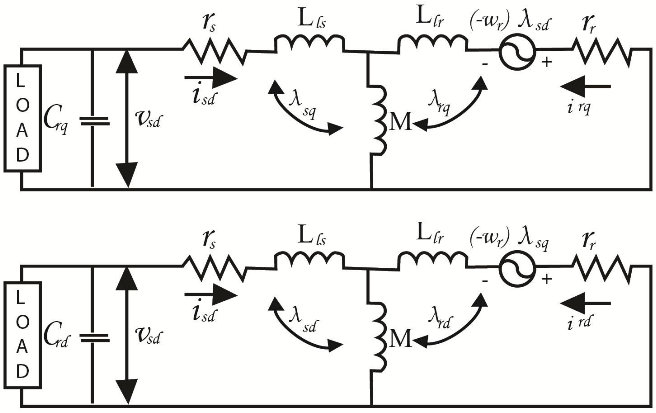

Fig. 2.2 d-q model of induction machine in the stationary reference frame

The mathematical modelling of the induction generator is represented by the following equations:

$$v_{qs}^{s} = R_s i_{qs}^{s} + \frac{d\lambda_{qs}^{s}}{dt}$$

$$v_{qs}^{s} = R_s i_{ds}^{s} + \frac{d\lambda_{qs}^{s}}{dt}$$

$$0 = R_r i_{qr}^{s} + \frac{d\lambda_{qr}^{s}}{dt} - w_r \lambda_{qr}^{s}$$

$$0 = R_r i_{dr}^{s} + \frac{d\lambda_{dr}^{s}}{dt} - w_r \lambda_{dr}^{s}$$

$$0 = R_r i_{qr}^{s} + \frac{d\lambda_{qr}^{s}}{dt} - w_r \lambda_{qr}^{s}$$

Where $V_{dr} = V_{qr} = 0$
The flux linkage expressions in terms of the currents can be written from Figure 2.2

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\lambda_{qr} = L_s i_{qr} + L_m i_{qs} \lambda_{dr} = L_s i_{dr} + L_m i_{ds}$$

$$\frac{di_{qs}}{dt} = \frac{1}{L_s L_r - L_m^2}[-L_s r_s i_{sq} - w_r L_m^2 i_{sd} + L_m r_r i_{rq} - w_r L_m L_r i_{rd} + L_r v_{sq}]$$

$$\frac{di_{sd}}{dt} = \frac{1}{L_s L_r - L_m^2}[w_r L_m^2 i_{sq} - L_r r_s i_{sd} + w_r L_m L_r i_{rq} + L_m r_r i_{rd} + L_r v_{sd}]$$

$$\frac{di_{rq}}{dt} = \frac{1}{L_s L_r - L_m^2}[L_m r_s i_{sq} + w_r L_m L_s i_{sd} - L_s r_r i_{rq} + w_r L_s L_r i_{rd} + L_m v_{sq}]$$

$$\frac{di_{rq}}{dt} = \frac{1}{L_s L_r - L_m^2}[-w_r L_m L_s i_{sq} + L_m r_s i_{sd} - w_r L_s L_r i_{rq} + L_s r_r i_{rd} + L_m v_{sd}]$$

Where $L_s = L_{ls} + L_{lm} L_s = L_{lr} + L_m$
$\lambda_{sq} = L_s i_{sq} + L_m i_{rq}$, $\lambda_{sq} = L_s i_{sd} + L_m i_{rd}$
The electromagnetic torque can be computed as a function of q and d axes stator and rotor currents and represented in equation given below.

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right) L_m [i_{sq} i_{rd} - i_{sd} i_{rq}]$$

The subscripts q and d denote quadrature and direct axes; subscripts s and r represents stator and rotor variables; l is the leakage component; v and i instantaneous voltage and current; λ flux linkage; Im magnetizing current; Lm magnetizing inductance; R resistance; L inductance; P number of poles; ω_r electrical rotor speed; and Te electromagnetic torque. The magnetization characteristic of the SEIG is nonlinear. The magnetizing inductance “Lm” is not a constant but a function depends on the instantaneous value of magnetizing current “Im” given by Lm=f (Im).

During simulation, in each step, the magnetizing inductance “Lm” is updated as a function of the magnetizing current “Im”. The magnetizing current is represented by equation given below.

$$i_m = \sqrt{(i_{sd} + i_{rd})^2 + \left(i_{sq} + i_{rq}\right)^2}$$

The magnetizing inductance “Lm” is calculated from the magnetizing characteristics fourth order polynomial for the test machine “Im”. The 4th order polynomial is arrived at, by applying curve fit technique to the relationship between “Lm” and “Im”, obtained by performing synchronous speed test on the test induction machine. Torque balance equation is represented by the following equation.[3]

$$T_{shaft} = T_e + J\left(\frac{2}{P}\right)\frac{dw_r}{dt}$$

The torque balance equation given in here may be expressed in speed derivative form as

$$\frac{dw_r}{dt} = (\frac{P}{2J})(T_e - T_{shaft})$$

DOI:10.15662/IJAREEIE.2016.0506072

2.2 MODELLING OF EXCITATION CAPACITOR

The excitation system introduces the following state equations using d-q components of stator voltage (V*sd*&V*sq*) as state variables.

$$i_{ds} = i_{ld} + i_{cd}$$

$$i_{qs} = i_{lq} + i_{cq}$$

$$\frac{dv_{ld}}{dt} = (\frac{i_{dc}}{C} - \frac{i_{ld}}{C})$$

$$\frac{dv_{lq}}{dt} = (\frac{i_{qc}}{C} - \frac{i_{lq}}{C})$$

2.3 MODELLING OF LOAD IMPEDANCE

An induction generator is self-excited by providing the magnetizing reactive power by a capacitor bank and the d and q axes current equations for the balanced resistive load can be given by the following equations.

$$i_{Rq} = \frac{v_{sq}}{R_L}$$

$$i_{Rd} = \frac{v_{sd}}{R_L}$$

And asthe load considered is R-L load,The load equations of the induction generator are represented in the same reference frame as given below.

$$v_{ld} = Ri_{ld} + \frac{di_{ld}}{dt}L$$

$$i_{ld} = \int [\left(\frac{1}{L}\right) v_{ld} - \left(\frac{R}{L}\right) i_{ld}]$$

$$v_{lq} = Ri_{lq} + \frac{di_{lq}}{dt}L$$

$$i_{lq} = \int [\left(\frac{1}{L}\right) v_{lq} - \left(\frac{R}{L}\right) i_{lq}]$$

If the load is capacitive in nature, then the capacitor value will be added to the excitation capacitor value.

A classical matrix formulation using d-q axes model is used to represent the dynamics of conventional induction machine operating as a generator. Using this matrix representation, we can obtain the instantaneous voltages and currents during the self-excitation process, as well as during load variations.[4]

$$p\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ v_{LD} \\ v_{LQ} \\ i_{LD} \\ i_{LQ} \end{bmatrix}=\mathrm{K}\{\begin{bmatrix} R_sL_r & -\omega L_m^2 & -R_rL_m & -\omega L_mL_r & L_r & 0 & 0 & 0 \\ \omega_rL_m^2 & R_sL_r & \omega_rL_ml_r & -R_rL_m & 0 & L_r & 0 & 0 \\ -R_sL_m & \omega_rL_mL_s & R_r & \omega L_sL_r & -L_m & 0 & 0 & 0 \\ -\omega_rL_mL_s & -R_sL_m & -\omega L_sL_r & R_rL_s & 0 & -L_m & 0 & 0 \\ \frac{1}{CK} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{CK} & 0 \\ 0 & \frac{1}{CK} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{CK} \\ 0 & 0 & 0 & 0 & \frac{1}{LK} & 0 & -\frac{R}{LK} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{LK} & 0 & -\frac{R}{LK} \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{qr} \\ i_{dr} \\ v_{LD} \\ v_{LQ} \\ i_{LD} \\ i_{LQ} \end{bmatrix}+\begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix}\}$$

Where i_{ds}, i_{dr} , i_{qs} , i_{qr} are respectively the stator and rotor currents in direct and quadrature axis and v_{ds} and v_{qs} are the initial direct axis and quadrature axis applied voltage and

$$K = \frac{1}{L_m^2 - L_sL_r}$$

Combining the above expressions, the electrical transient model in terms of voltages and currents can be given in matrix form as [1]

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix}=\begin{bmatrix} R_s + L_sp + (\frac{R+L_p}{RCp+LCp^2+1}) & 0 & L_mp & 0 \\ 0 & R_s + L_sp + (\frac{R+L_p}{RCp+LCp^2+1}) & 0 & L_mp \\ L_mp & \omega_rL_m & R + L_rp & \omega_rL_r \\ -\omega_rL_m & L_mp & -\omega_rL_r & R_r + L_rp \end{bmatrix}$$

III. RESULTS AND DISCUSSIONS

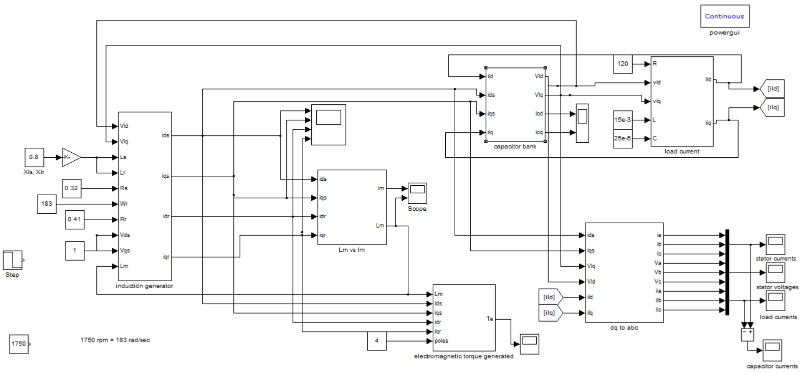

Fig. 3.1 simulink model of the SEIG system

The Simulink model of the proposed SEIG system has been shown in fig. 3.1, which has been developed in SIMULINK/MATLAB software.

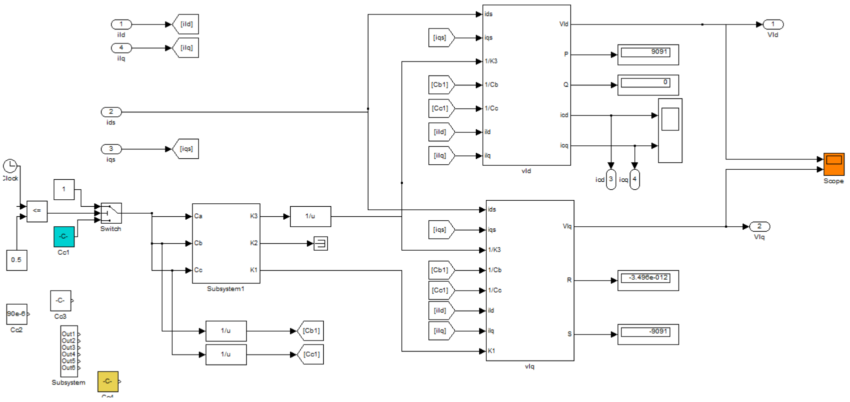

Fig. 3.2 the three phase excitation capacitor model

Also, the three phase excitation capacitor model and stator and rotor dq axes current has been shown in fig. 3.2 and fig. 3.3 respectively.

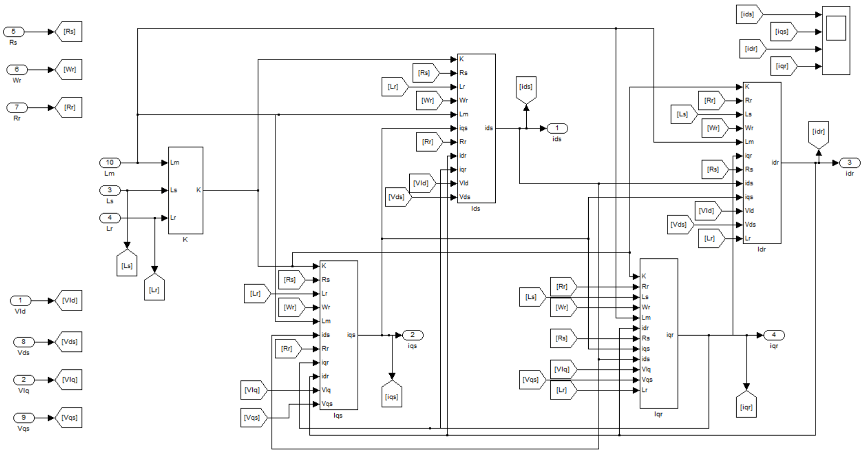

Fig. 3.3 calculation of stator and rotor d,q axes currents

The parameters of the machine are shown in the following table :

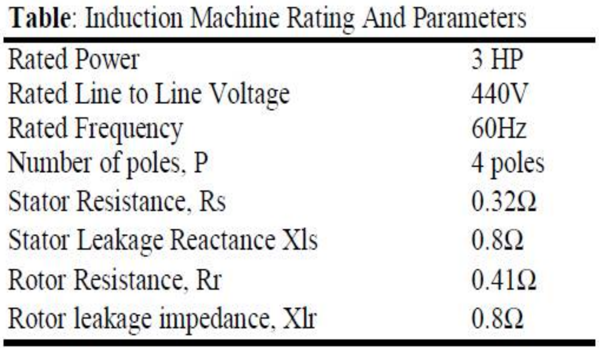

Table: Induction Machine Rating And Parameters

Rated Power	3 HP
Rated Line to Line Voltage	440V
Rated Frequency	60Hz
Number of poles, P	4 poles
Stator Resistance, Rs	0.32Ω
Stator Leakage Reactance Xls	0.8Ω
Rotor Resistance, Rr	0.41Ω
Rotor leakage impedance, Xlr	0.8Ω

The transient behavior of SEIG, specifications are given in the above table having balanced star-connected excitation capacitor across the terminal of SEIG has been studied. The transient behavior of the SEIG under the following condition has been observed.

1. Self-excitation process
2. Insertion of load
3. Loss of excitation due to heavy-load
4. Insertion of excitation capacitor

3.1Self-excitation Process

The SEIG at no load and the simulation results are shown in following figures. It is observed that the residual magnetism taken in terms of Vsd and Vsq as 1 volt for the simulation induces a voltage across the self-exciting capacitor and produces a capacitive current or a lagging magnetizing current in the stator winding and results in a higher voltage. This procedure goes on until the saturation of the magnetic field occurs as observed in the simulation results shown in Fig 3.4. It is also observed that for SEIG rotor speed of 1750 r.p.m , the voltage and current waveform of SEIG reaches the steady state condition following the voltage build up process.

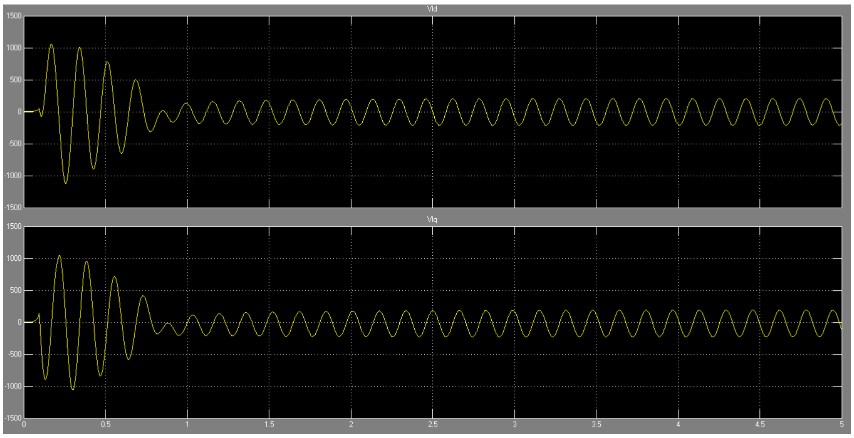

Fig.3.4 the self excitation phenomenon

The voltage build up process has been clearly shown to go up to a final output of 200 V in figure 3.5 whereas the figure 3.4 shows the self-excitation phenomenon exhibited by the induction generator.

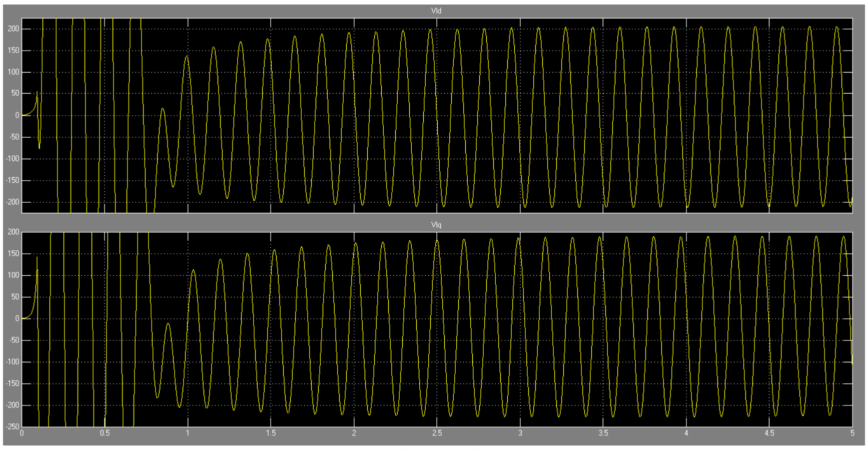

Fig. 3.5 the voltage build up process

3.2 Insertion of Load

Here are the simulation results of 3 HP induction machine for R-L load having p.f 0.8 applied at t=6 seconds. When the SEIG is operating at no-load, the load current is zero, hence the load current reaches a steady-state value. Loading decreases the magnetizing current Im shown which results in the reduced flux. Reduced flux implies reduced voltage, which has been shown in figure 3.6.

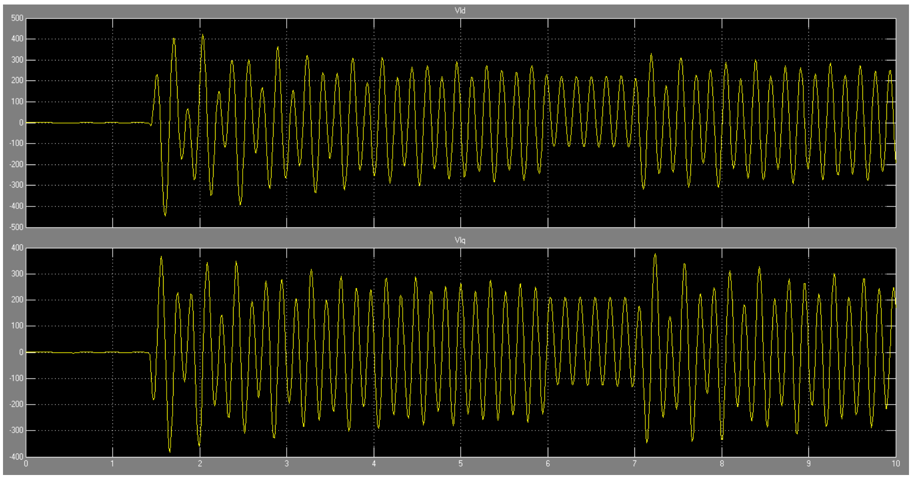

Fig 3.6 insertion of load

3.3 Loss of Excitation due to heavy-load

The SEIG which is initially operated under steady state condition and R-L load is applied at t=6 seconds having p.f 0.8, voltage is reduced and reached a steady state voltage. At t=7 seconds an extra load is applied, the SEIG line voltage collapse is a monotonous decay of the voltage to zero shown in Fig 3.7. Once the voltage collapse occurs, the re-excitation of the generator becomes difficult. Thus it shows the poor overloading capability of the SEIG. Therefore the load connected to the generator should never exceed beyond the maximum load the generator can deliver under steady state condition. But it may be mentioned here that the momentary excess stator current can operate protective relays to isolate the overload condition at the generator terminals to prevent voltage collapse.

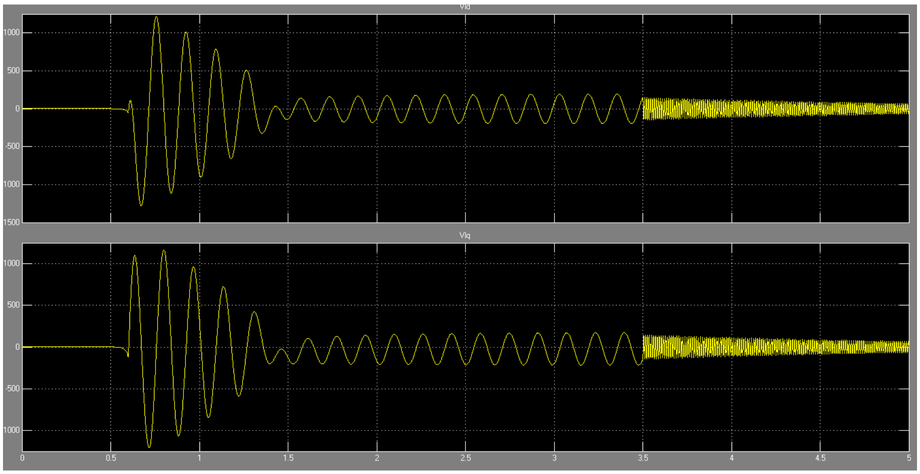

Fig 3.7 loss of excitation

3.4 Insertion of Excitation Capacitor

The SEIG is initially operated under steady state condition with three-phase balanced star connected capacitor bank connected across its stator terminal. when, resistive load is connected at t=3 seconds, the steady state voltage is reduced. The increase in load current should be compensated either by increasing the energy input (drive torque) thereby increasing the rotor speed or by an increase in the reactive power to the generator.

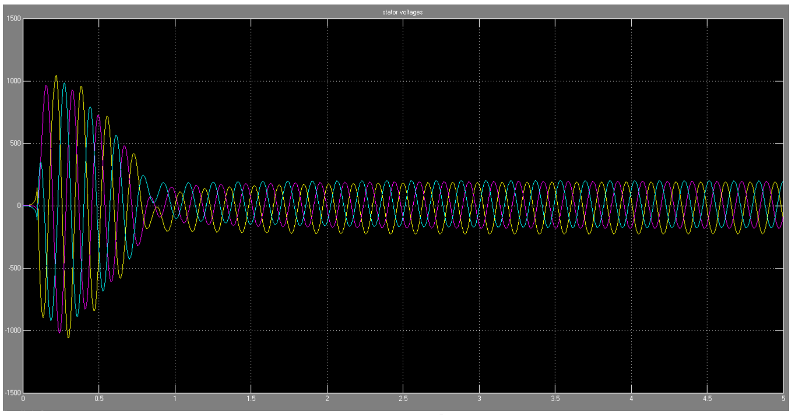

Fig 3.8 stator voltages

Figure 3.8 shows the three phase stator voltages developed by the induction generator after excitation by the capacitor. After initial transient period of 1 second, the graph represents steady state voltages being developed in the stator.

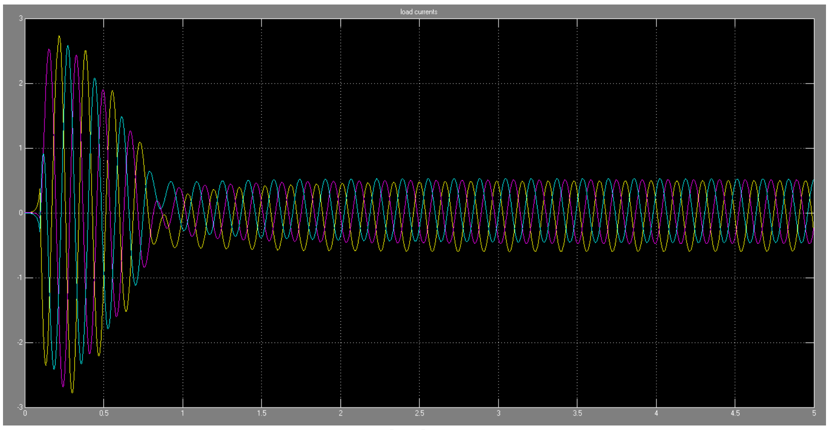

Fig.3.9 load currents

Similarly, fig. 3.9 and fig. 3.10 represent the three phase load currents and three phase capacitor voltages respectively, which shows the same pattern as of stator currents, of initially being in a transient state and later constant at a steady rate.

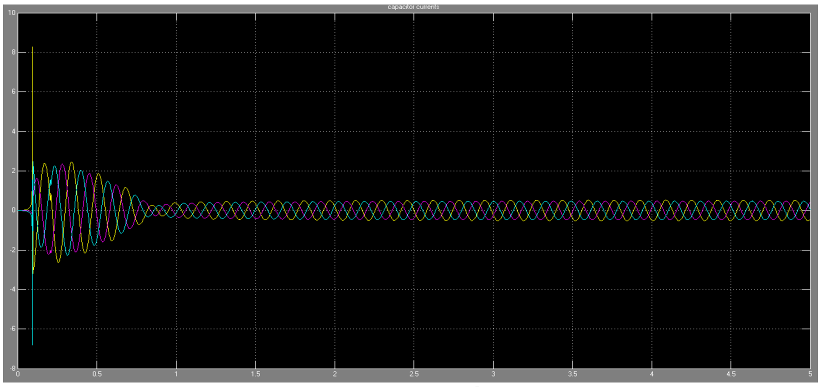

Fig 3.10 capacitor voltages

IV. CONCLUSION

In this paper, d-q model of self-excited induction generator driven by constant speed prime movers in stationary reference frame developed. Voltage build up process of a SEIG is presented both for no load and loaded condition using MATLAB/Simulink and experimental result reveals that magnitude of voltage decreases with load. And it is concluded that voltage developed depends on three factors: (i) speed of the rotor, (ii) capacitor value connected for excitation and (iii) load connected across the stator terminal Experimentally verified the open loop control on self-excited induction generator in the laboratory. It is anticipated that the model presented in this paper would be broadly applicable in any system where the induction machine is used as a generator.

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