Wind Driven Induction Generator Study with Static and Dynamic Loads

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***Abstract*-This paper presents the performance of a stand-alone self-excited induction generator (SEIG) under balanced/ un-balanced excitation with balanced RLC and dynamic load. Squirrel cage induction motor has been taken as a dynamic load. SEIG is driven with fixed pitch wind energy system. An approach based on three-phase induction machine model is employed to derive dynamic equations of an isolated SEIG under balanced/unbalanced conditions of excitation and balanced static and dynamic loads. The SEIG model with balanced/un-balanced excitation and balanced load has been simulated using MATLAB/SIMULINK.**

Keywords-Dynamic induction motor load; wind turbine; balanced loads; balanced/un-balanced excitation capacitor; Self-excited induction generator

NOMENCLATURE

Vds Vqs Vdr Vqr	: Stator and rotor d and q axis voltages
ids iqs idr iqr	: Stator and rotor d and q axis currents
im	: Magnetising current
Te	: Electromagnetic torque
Lm	: Magnetizing inductance
Vld, Vlq	:d and q axis excitation voltage per phase
i1d and i1q	:d and q axis load currents per phase
icd and icq	:d and q axis capacitor currents per phase
ppole	: pole pair
ψm	: Magnetising flux
Rs and Rr	: Stator and rotor resistance
Xls and Xlr	: Stator and rotor leakage reactance
L	: Load imductance
C	: Excitation capacitance
R	: Load resistance per phase
ωr	: Rotor angular speed in rad/sec
p	: Differential operator

I. INTRODUCTION

With increasing concern about the environment and the depletion of natural resources such as fossil fuels, much research is now focused on obtaining new environmentally friendly sources of power. Wind energy is environmentally friendly, inexhaustible, safe, and capable of supplying substantial amounts of power. Electric power generation using non-conventional sources is receiving considerable attention throughout the world. The use of induction motor as a generator has gained considerable importance to harness energy from wind. Self excited induction generator has become popular for energy conversion from wind and has advantages of reduced cost, size, and ruggedness. Self excited phenomenon in induction generator has been well documented in [1-3]. The process of voltage buildup in an induction generator is very much similar to that of a dc generator and a suitable value of residual magnetism should be present in the rotor for the process of machine excitation. With wound rotor or squirrel cage rotor, the induction generators can be driven by constant speed or variable speed drives and can have various configurations of different types as: constant-speed constant-frequency (CSCF), variable-speed constant-frequency (VSCF), and variable-speed variable-frequency (VSVF) [4-5].

Tremendous literature is available in the journals and conference proceedings on steady state and dynamic operation of induction generator under different operating conditions of a system. The authors have proposed different models of induction generators based on d-q reference theory, impedance based approach for model development, admittance based models, operational circuit based models, and power equations based models [6-11]. Many Authors have reported detailed analysis and modeling of induction generator with static as well as dynamic model of induction generators. Steady state analysis being important both from design and operational point of view has been presented by many authors [13-22]. These authors proposed steady state analysis technique for analysis of induction generator using equivalent circuit of the machine, nodal admittance technique, iterative technique etc. to analyze the performance of the SEIG. A simple and comprehensive approach for steady state analysis was presented [19]. Some authors utilized symmetrical components theory as an optimization based approached for analysis of SEIG [21-22]. Many authors presented transient and dynamic analysis of SEIG related to the voltage build up process under self-excitation, load perturbation, switching, dynamic load, and unbalanced excitation [23-40]. The comprehensive overview of self excited induction generator and many related issues has been presented nicely [41].

Authors have started working in the direction of wind turbine driven SEIG in early 90's in [42-45]. The literature is expanded by many researchers in this direction and has been reported by many researchers recently on wind driven self excited induction generator and dynamic analysis of SEIG

[46-49]. State space model of self excited induction generator has been presented in [50-53].

A. Kishore et al. [51] proposed a generalized state-space dynamic modeling of a three phase SEIG has been developed using d-q variables in stationary reference frame for transient analysis. The state space approach has been found better representation of transient operation of SEIG. The d-q axes stator-rotor current are the functions of machine parameters. The solution of such equation has been obtained assuming all the non linear parameters as it is. The modelling of excitation system under balanced/un-balanced conditions has been developed in terms of d-q. Different constraints such as variation of excitation, wind speed and load have been taken into account and accordingly the effect on generated voltage and current has been analyzed. The effect of excitation capacitance on generated voltage has been analyzed.

In this paper work, an attempt has been made for an analysis of fixed pitch based wind driven SEIG and its dynamic behavior has been analyzed under no-load, with balanced RLC load as well induction motor dynamic load under balanced and unbalanced excitation. The simulations have been carried out developing model in MATLAB/SIMULINK [54]. The results of SEIG under balanced/un-balanced loads, balanced/un-balanced excitation are presented in section IV.

II. SEIG MODEL

Figure 1 shows the d-q axes equivalent circuit of a (SEIG) supplying an inductive load. Equation (18) is a classical matrix formulation using d-q axes model is used to represent the dynamics of conventional induction machine operating as a generator [52]. Using such a matrix representation, one can obtain the instantaneous voltages and currents during the self-excitation process, as well as during load variations.

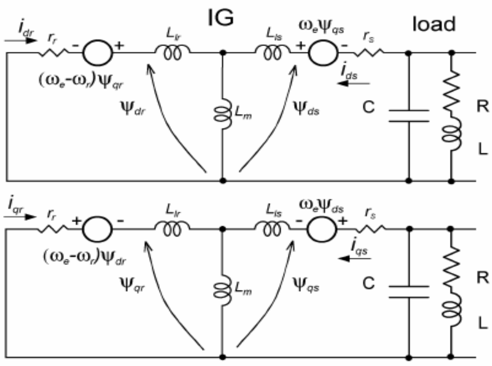


Fig.1 d-q axes equivalent circuit of SEIG

A. Mathematical Model

The complete dynamic model is represented by the set of eight differential equations corresponding to variables ids, iqs , idr, iqr, Vld, Vlq as shown in equation (18) is the generalized state space representation of a SEIG model. That is in the form of classical state-space equation.

The dynamic model of the three-phase squirrel cage induction generator is developed by using stationary d-q axes reference frame and the relevant volt-ampere equations are as descried as [12]:

$$[V]=[R][I]+Lp[I]+\omega_r[G][I] \tag{1}$$

From which, the current derivative can be expressed as:

$$p[I]=[L]^{-1}([V]-[R][I]-\omega_r[G][I])$$
$$p[I]=-[L]^{-1}([R][I]+\omega_r[G][I]-[V]) \tag{2}$$

where [V], [i],[R],[L] and [G] defined below:

$$[V]=[\ V_{ds}\ V_{qs}\ V_{dr}\ V_{qr}\ ]^T \tag{3}$$

$$[i]=[\ i_{ds}\ i_{qs}\ i_{dr}\ i_{qr}\ ] \tag{4}$$

$$[R]=\text{diag}[\ R_s\ R_s\ R_r\ \ R_r\ ] \tag{5}$$

$$L=\begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \tag{6}$$

$$G=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & L_m & 0 & L_r \\ -L_m & 0 & -L_r & 0 \end{bmatrix} \tag{7}$$

The SEIG operates in the saturation region and its magnetizing characteristics are non-linear in nature. Magnetizing current should be calculated in every step of integration in terms of stator and rotor d-q currents as defined by:

$$i_m=\sqrt{(i_{ds}+i_{dr})^2+(i_{ds}+i_{dr})^2} \tag{8}$$

Magnetizing inductance is calculated from the magnetizing characteristics which can be obtained by synchronous speed test for the machine under test. This characteristics can be defined as:

$$L_m= 0.1407 +0.0014\ i_m - 0.0012\ i_m^2 + 0.00005\ i_m^3 \tag{9}$$

Developed electromagnetic torque of the SEIG is:

$$T_e=(3P_{pole}/4)L_m(i_{qs}i_{dr}-i_{ds}i_{qr}) \tag{10}$$

Torque balance equation is:

$$T_{shaft}=T_e + j(2/p)\ p\omega_r \tag{11}$$

The derivative of the rotor speed is:

$$p\omega_r = (p/2)\ (T_{shaft}-T_e)/j \tag{12}$$

The residual magnetism in the machine is taken into account in simulation process as it is necessarily required for the generator to self excite. Initial voltage in the capacitor is considered as 2 volts for build-up of voltage for excitation for SEIG.

B. Load and Capacitor Modeling

Load: Here the modeling of load has been developed in terms of d-q reference frame under balanced conditions. The load currents in terms of their respective voltages have been discussed in below:

RLC-Load Modeling:

$$i_{ld}=\int((1/L)V_{ld}\ -(R/L)i_{ld}-(1/LC)\int i_{ld}) \quad (13)$$

$$i_{lq}=\int((1/L)V_{lq}\ -(R/L)i_{lq}-(1/LC)\int i_{lq} \quad (14)$$

The SIMULINK model of RLC load is shown in Fig.2.

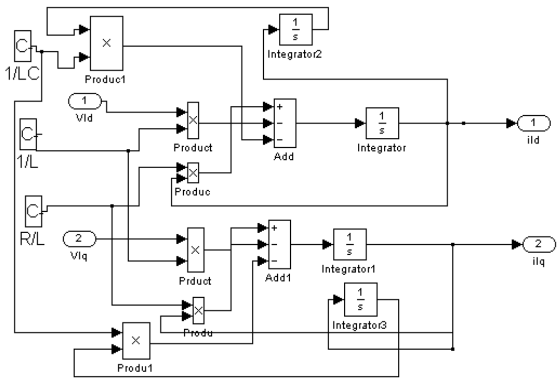


Fig.2 SIMULINK model of RLC load

Capacitor model:

The capacitor model has been developed based on the equations (15), (16), (17) and (18) which represents the self excitation Capacitor currents and voltages in d-q axes representation as:

$$i_{ds}=i_{cd}+i_{ld} \quad (15)$$

$$i_{qs}=i_{cq}+i_{lq} \quad (16)$$

$$pv_{ld}=\left(\frac{3}{2K_3}\right)\left(\frac{1}{c_b}+\frac{1}{c_c}\right)i_{ds}+\left(\frac{\sqrt{3}}{2K_3}\right)\left(\frac{1}{c_b}-\frac{1}{c_c}\right)i_{qs} -\left(\frac{3}{2K_3}\right)\left(\frac{1}{c_b}+\frac{1}{c_c}\right)i_{ld}-\left(\frac{\sqrt{3}}{2K_3}\right)\left(\frac{1}{c_b}-\frac{1}{c_c}\right)i_{lq} \quad (17)$$

$$pV_{lq}=\left(\frac{\sqrt{3}}{C_b}\right)\left\{\left(\frac{K_1}{K_3}\right)\left(\frac{1}{C_b}+\frac{1}{C_c}\right)-1\right\}i_{ds}-\left(\frac{\sqrt{3}}{C_b}\right)\left\{\left(\frac{K_1}{K_3}\right)\left(\frac{1}{C_b}+\frac{1}{C_c}\right)-1\right\}i_{qs} -\left(\frac{\sqrt{3}}{C_b}\right)\left\{\left(\frac{K_1}{K_3}\right)\left(\frac{1}{C_b}+\frac{1}{C_c}\right)-1\right\}i_{ld}+\left(\frac{\sqrt{3}}{C_b}\right)\left\{\left(\frac{K_1}{K_3}\right)\left(\frac{1}{C_b}+\frac{1}{C_c}\right)-1\right\}i_{lq} \quad (18)$$

Where： K1= Ca + (Cb/2), K2 = Ca + (Cc/2) and K3 = (K1/Cb) + (K2/Cc)

This model has been considered for excitation. This model is used for both balanced excitation and un-balanced excitation. If Ca=Cb=Cc=C then it's called as balanced self-excitation otherwise it's called as un-balanced excitation.

The SIMULINK model of excitation capacitor is shown in Fig. 3. This model describes the capacitor model for both balanced and unbalanced excitation conditions.

This is the total block diagram of capacitor model. This has been implemented by using equations from (15) to (18). This consists two subsystems, these sub systems has been explained below from Fig. 4.5(a) to 4.5(b). The developed model in SIMULINK for excitation is the proposed new model based on the derived equations in section 3.

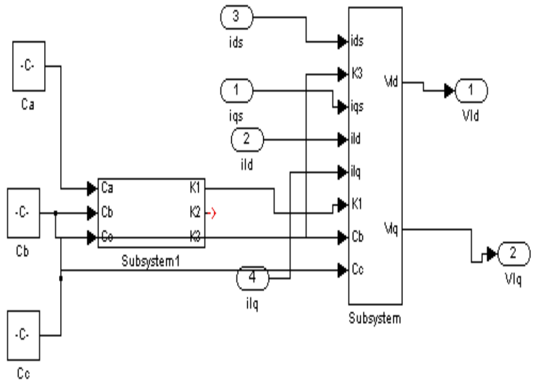


Fig.3 block diagram of capacitor model

The following assumptions are made in this analysis:

- Core and mechanical losses in the machine are neglected.
- All machine parameters, except the magnetizing inductance (L_m), are assumed to be constant.
- The rotor should have sufficient residual magnetism.
- The three capacitor bank should be of sufficient value
- Stator voltage in terms of d-q, V_{ds} and V_{qs} should have some initial voltage i.e 1 volts.

The complete model of SEIG with inductive load and excitation is given in (19) and with capacitor model is given in (20) .

Where:

$$P=\left(\frac{3}{2K_3}\right)\left(\frac{1}{C_b}+\frac{1}{C_c}\right) \qquad Q=\left(\frac{\sqrt{3}}{2K_3}\right)\left(\frac{1}{C_b}-\frac{1}{C_c}\right)$$

$$R=\left(\frac{\sqrt{3}}{C_b}\right)\left\{\left(\frac{K_1}{K_3}\right)\left(\frac{1}{C_b}+\frac{1}{C_c}\right)-1\right\} \qquad S=\left(\frac{1}{C_b}\right)\left\{\left(\frac{K_1}{K_3}\right)\left(\frac{1}{C_b}-\frac{1}{C_c}\right)-1\right\}$$

$$\mathbf{K}=1/(L_m^2-L_sL_r)$$

$K_1 = C_a + (C_b/2)$, $K_2 = C_a + (C_c/2)$ and $K_3 = (K_1/C_b) + (K_2/C_c)$

B. Dynamic Load Model

The dynamic model of three-phase squirrel cage induction motor as dynamic load is similar to that of the induction generator but the parameters concerned is related to the motor. The volt-current equations of a three-phase induction motor in the current derivative can be expressed as:

$$pi_m=[L_M]([V_M]-[R_M][I_M]\omega_m[G_M][I_M]) \quad (21)$$

Where [vM], [iM], [RM], [LM] and [GM] can be defined similar manner as defined for SEIG.

The developed electromagnetic torque of the I. M. is as:

$$T_{eM}=\frac{3P_M}{4}L_{mM}\left(i_{qsM}i_{drM}-i_{dsM}i_{qrM}\right) \quad (22)$$

$$\rho\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ V_{ld} \\ V_{lq} \\ i_{ld} \\ i_{lq} \end{bmatrix} = K\begin{bmatrix} L_rR_s & -\omega_rL_m^2 & -L_mR_r & -\omega_rL_mL_r & L_r & 0 & 0 & 0 \\ \omega_rL_m^2 & L_rR_s & \omega_rL_mL_r & -L_mR_r & 0 & L_r & 0 & 0 \\ -L_mR_s & \omega_rL_mL_s & L_sR_r & \omega_rL_rL_s & -L_m & 0 & 0 & 0 \\ -\omega_rL_mL_s & -L_mR_s & -\omega_rL_rL_s & L_sR_r & 0 & -L_m & 0 & 0 \\ P/K & Q/K & 0 & 0 & 0 & 0 & -P/K & -Q/K \\ R/K & -S/K & 0 & 0 & 0 & 0 & -R/K & S/K \\ 0 & 0 & 0 & 0 & 1/R_aK & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{0.577}{K}\left(\frac{1}{R_a}-\frac{1}{R_b}\right) & 1/R_bK & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ V_{ld} \\ V_{lq} \\ i_{ld} \\ i_{lq} \end{bmatrix} +$$

$$K\begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} V_{ds} \\ V_{qs} \\ 0 \\ 0 \end{bmatrix} \tag{19}$$

$$p\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ V_{ld} \\ V_{lq} \end{bmatrix} = K\begin{bmatrix} L_rR_s & -\omega_rL_m^2 & -L_mR_r & -\omega_rL_mL_r & L_r & 0 \\ \omega_rL_m^2 & L_rR_s & \omega_rL_mL_r & -L_mR_r & 0 & L_r \\ -L_mR_s & \omega_rL_mL_s & L_sR_r & \omega_rL_rL_s & -L_m & 0 \\ -\omega_rL_mL_s & -L_mR_s & -\omega_rL_rL_s & L_sR_r & 0 & -L_m \\ \left(\frac{3}{2KK_3}\right)\left(\frac{1}{C_b}+\frac{1}{C_c}\right) & \left(\frac{\sqrt{3}}{2KK_3}\right)\left(\frac{1}{C_b}-\frac{1}{C_c}\right) & 0 & 0 & 0 & 0 \\ \left(\frac{\sqrt{3}}{KC_b}\right)\left\{\left(\frac{K_1}{K_3}\right)\left(\frac{1}{C_b}+\frac{1}{C_c}\right)-1\right\} & -\left(\frac{1}{KC_b}\right)\left\{\left(\frac{K_1}{K_3}\right)\left(\frac{1}{C_b}-\frac{1}{C_c}\right)-1\right\} & 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ V_{ld} \\ V_{lq} \end{bmatrix} +$$

$$K\begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} V_{ds} \\ V_{qs} \\ 0 \\ 0 \end{bmatrix} \tag{20}$$

The derivative of electromechanical torque of motor speed can be expressed as:

$$p\omega_m = P_M\left(2J_M\right)\left(T_L - T_{eM}\right) \tag{23}$$

Here suffixes d, q refers to D and Q axis (in stationary reference frame), s and r refers to stator and rotor, m refers to magnetizing component.

Developed electromagnetic torque of the motor is:

$$T_e = \frac{3p}{4}L_m\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right) \tag{24}$$

Torque balance equation is:

$$T_{shaft} = T_e = j\left(\frac{2}{p}\right)p\omega_r \tag{25}$$

The derivative of the rotor speed from (25) is

$$p\omega_r = \left(\frac{p}{2}\right)\frac{\left(T_{shaft} - Te\right)}{j} \tag{26}$$

Here Tshaft is the input torque to SEIG from the turbine, j is moment of inertia and p is the number of poles. The SEIG operates in the saturation region and its magnetizing characteristics are non-liner in nature. So the magnetizing current should be calculated in every step of integration in terms of stator and rotor D-Q currents as: (reference no):

$$i_m = \sqrt{\left(i_{ds} + i_{dr}\right)^2 + \left(i_{ds} + i_{dr}\right)^2} \tag{27}$$

Magnetizing inductance is calculated from the magnetizing characteristics which is obtained by synchronous speed test for the machine under test (7.5 kW) and defined as:

$$L_m = 0.1407 + 0.0014\, i_m - 0.0012\, i_m^2 + 0.00005\, i_m^3 \tag{28}$$

Three phase generator voltages and currents are obtained from D-Q axes components using the relation as: Matrices similar relation hold for currents ia, ib and ic. The dynamic load model of induction motor has been implemented in SIMULINK model using MATLAB. The SIMULINK model is shown in Fig. 4.

C. *Wind Turbine Model*

Fixed pitch wind turbine model has been utilized to drive induction motor. The fixed pitch model of the wind turbine has been considered with number of blades as 3, blade radius equal to 13m, and the gear ratio is taken as 30 with fixed pitch as $(\beta = 0)$. Since the power coefficient characteristic of wind turbine is a non-linear curve that reflects the aerodynamic behavior a wind turbine. The characteristic forms the basis for the custom turbine model. The non-linear, dimensionless Cp characteristic is represented as [9].

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \tag{29}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{30}$$

where,

$C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$

The power coefficient function given by (21),

$$P_m = 0.5\rho A(0.5176(\frac{116}{\lambda} - 9.06)e^{\frac{-21}{\lambda}+0.735} + 0.0068\lambda)v_w^{\ 3} \tag{31}$$

The mechanical torque is given by (22),

$$t_m = 0.5\rho A(0.5176(\frac{116}{\lambda} - 9.06)e^{\frac{-21}{\lambda}+0.735} + 0.0068\lambda)v_w^{\ 3}\frac{R}{G\lambda v_w} \tag{32}$$

The Cp curve is obtained developing the wind turbine model in Mat lab SIMULINK. The SIMULINK model of wind turbine is shown in Fig. 5. The mechanical power output at air density of 1.1kpa is obtained as shown in Fig. 6.

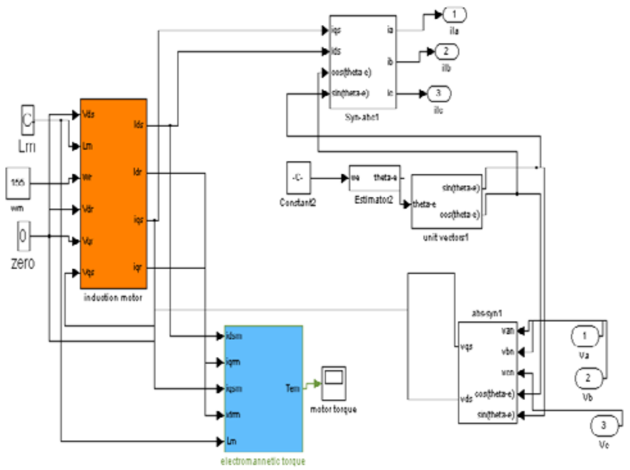


Fig.4. SIMULINK model of dynamic load

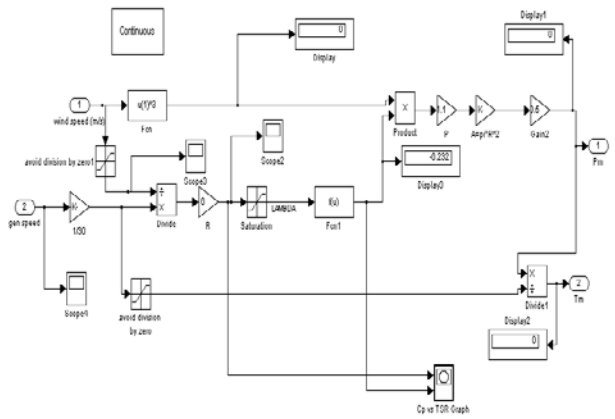


Fig. 5 Custom wind turbine model (Air Density: 1.1 kpa)

III. SIMULINK MODEL OF SEIG WITH STATIC AND DYNAMIC LOAD

MATAB SIMULINK is powerful software tool which has needed utilized for modeling and simulation of SEIG with RLC load and dynamic load under balanced and unbalanced excitation. The equations of self-excited induction generator (7.5 kW, 4 poles, Rs=Ω, Rr=0.77 Ω, Xlr=Xls=1mh.J=0.23 Kg/m2) described above have been implemented in MATLAB/SIMULINK. The equation (19) has been implemented in subsystem “Induction Generator” whose outputs are currents. The MATLAB SIMULINK model is shown in Fig. 7 with subsystems component shown in color. Equation (19) shows the eight first order differential equations, for which the solutions gives the four currents (stator d-q axis currents and rotor d-q axis currents), load currents and capacitor voltages. Further these currents are the function of constants viz. stator and rotor inductances, resistances, speed, excitation capacitance and load impedance. And also variables like magnetizing inductance, magnetizing currents and electromagnetic torque generated, has been evaluated using equations described in the section II. The constraints of non linear magnetizing inductance have been taken into account. The wind turbine is implemented in subsystem ‘wind turbine’ as shown in SIMULINK model of SEIG in Fig. 7 by using equations as described in section II.

IV. RESULTS AND DISCUSSIONS

In this work, the results have been determined for SEIG (under no-load, with RLC balanced load under balanced and constant unbalanced conditions of excitation. In addition to RLC load, a dynamic load of induction motor has also been considered for study of behavior of SEIG with balanced and constant un-balanced excitation.

The simulations have been obtained using MATLAB/SIMULINK model developed for SEIG with RLC load as well induction motor load as dynamic load using MATLAB 7.0 version. This model has been discussed in the previous section. The residual magnetism in the machine is taken into account in simulation process as it is necessary required for the generator to self excite. Initial voltage in the capacitor is considered as 1 volt for build-up of voltage for excitation for SEIG. The results of SEIG under balanced and dynamic load with balanced/constant un- balanced excitation have been determined. Results have been also been obtained under no load condition and are discussed in the next section.

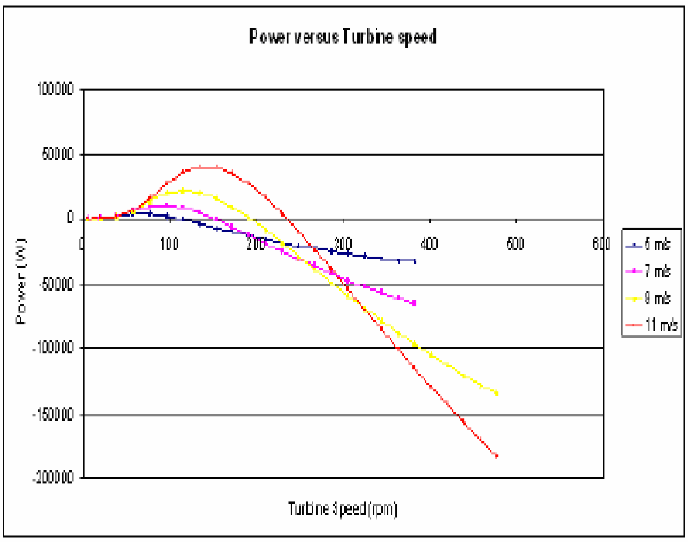


Fig. 6 Output Mechanical Power of Turbine versus the Turbine Speed

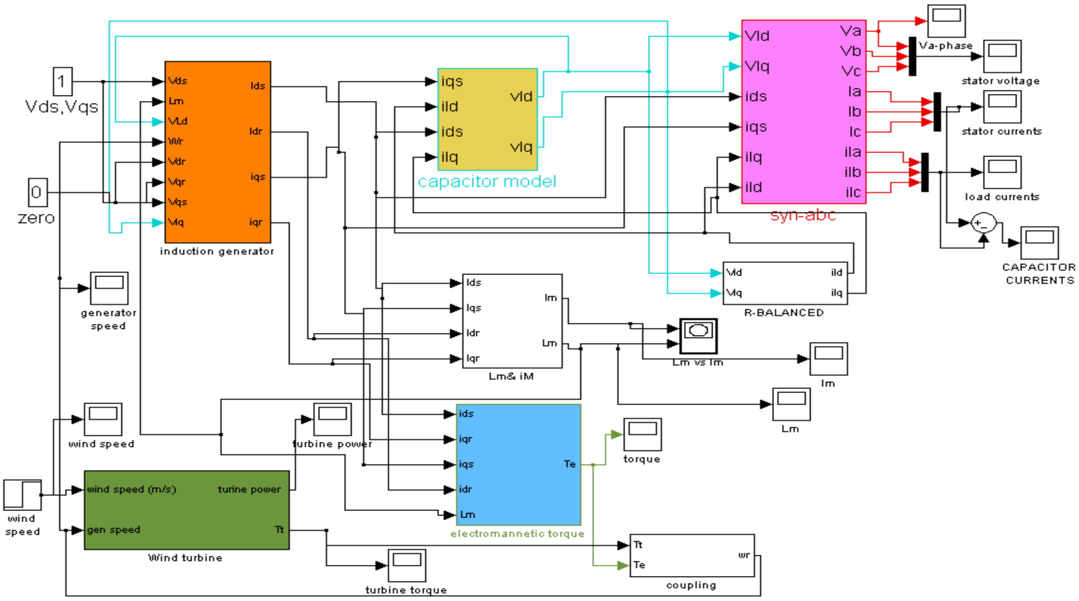
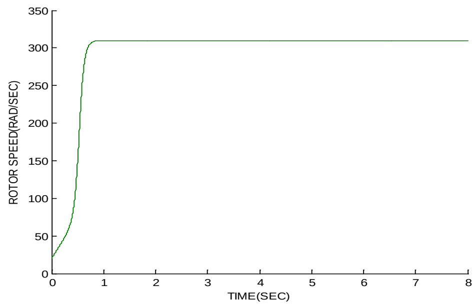


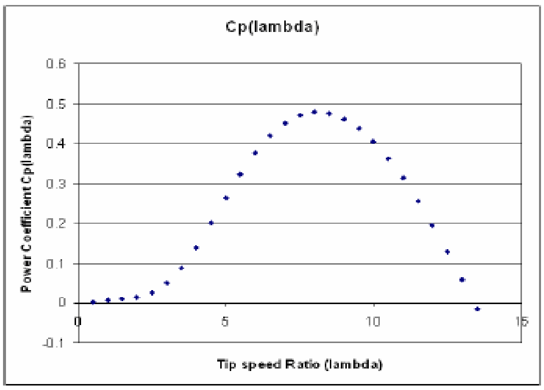
Fig.7. Complete simulink model of wind driven SEIG with load

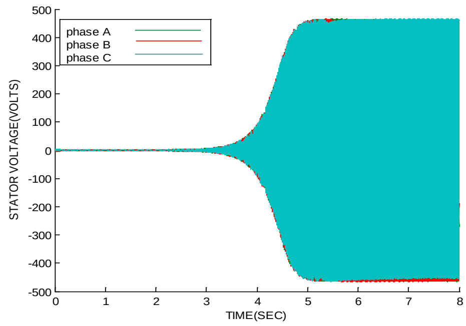
A. SEIG Under No-load

When generator is excited with capacitance value C=110 µF and rotor speed increased to 310 rad/sec from 50 rad/sec, the generated voltage and current attains their steady state value of 410 volts and 15 amps in 4.6 sec. Cp v/s TSR curve has been shown in Fig.8 (graphs 1-4).

It is observed from the graphs that stator voltage and stator currents are balanced and attain their steady state value at 5 sec. Rotor speed attains its steady state value in 1 sec. The variation of coefficient of power (Cp) vs. tip speed ratio (TSR) for wind turbine is shown in Fig. 8 (graph 2)







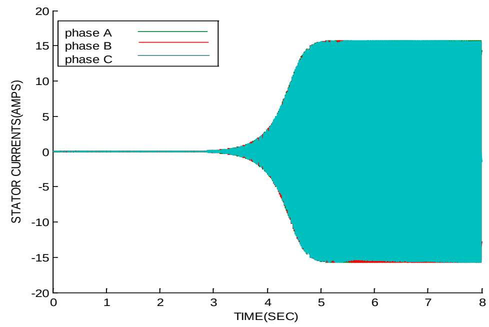


Fig.8 Graphs (1. rotor speed 2. Cp v/s TSR curve 3.stator voltage 4.stator currents)

B. SEIG Operation with RLC Load

In this case, the behavior of the system connected to RLC load is studied. The results have been obtained for two different cases. The cases are:

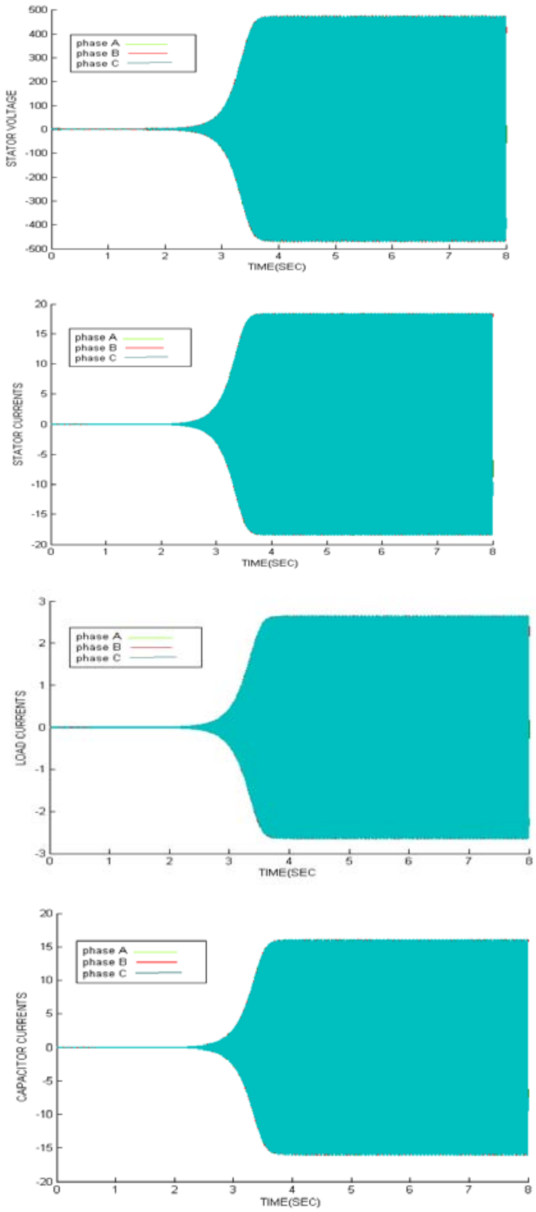
Case-1: RLC load with balanced excitation

Case-2: RLC load under constant un-balanced excitation

Thus, using (3.25), and (3.26), the operation of the SEIG is simulated with R=80Ω, L= 12mH, C= 20 µf under balanced conditions. Generator is excited with C=110 μf and unexcited with Ca= 110 μf, Cb= 80 μf, Cc= 103 μf.

Case-1: RLC-balanced load with constant balanced excitation

In Case 1: balanced exaction with balanced RLC-load all the currents, i.e. stator currents, capacitor currents and load currents are balanced. Voltage is also balanced as shown in Fig.8. It is observed from the Fig. 8 (graphs 1, 2 3, 4) that the stator voltage, currents, load currents, and capacitor currents attain their steady state value at 3.5 sec. The variation of electromagnetic torque with time and magnetizing inductance with time of SEIG has also been shown in Fig. 8 (graphs 5 and 6). The electromagnetic torque is zero initially and then it increases exponentially and attains steady values at about 4.2 sec. It is observed that the magnetizing inductance is constant of value 0.14 H up to 3.2 sec. and then reduces to 0.081 H and become constant at 4.5 sec. and remains constant.



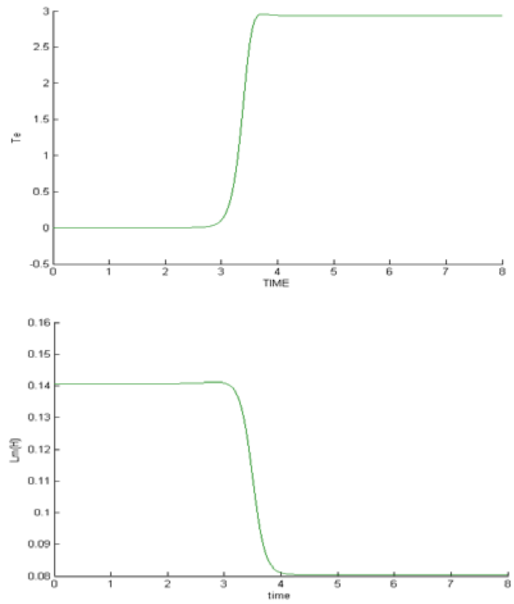


Fig. 8. SEIG at RLC-load with constant excitation (graphs: 1. Stator line voltages 2.Stator currents 3. Load currents 4.Capacitor currents. 5. Electromagnetic torque 6.Magnetizing inductance)

Case-2: RLC-balanced load with constant unbalanced excitation

In Case 2: constant unbalanced excitation and balanced RLC load, the load currents are balanced but stator currents and capacitor currents are un- balanced as shown in Fig. 9. It is observed from the Fig. 9 (graphs 1, 2, 3, 4) that the stator voltage, currents, load currents, and capacitor currents attain their steady state value at 4.3 sec. The variation of electromagnetic torque with time and magnetizing inductance with time of SEIG has also been shown in Fig. 9 (graphs 5 and 6). The electromagnetic torque is zero initially and then it increases exponentially and it is observed that Te is having oscillations due to unbalanced excitation. It is observed that the magnetizing inductance is constant of value 0.14 H up to 3.5 sec. and then reduces to 0.087 H and become constant at 5.0 sec. and remains constant.

C. SEIG Operation with Dynamic Load

In this case, the behavior of the system connected to an induction motor load is studied. The results have been obtained for two different cases. The cases are:

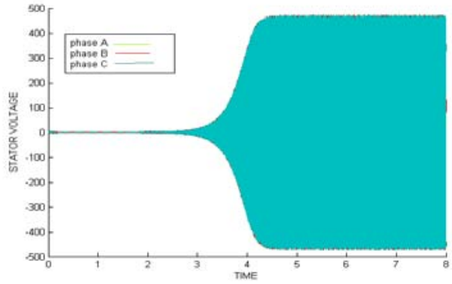
Case-1: Dynamic load with balanced excitation

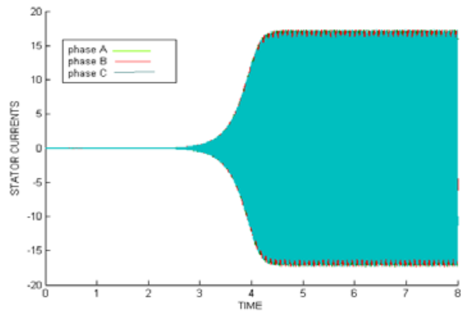
Case-2: Dynamic load under constant un- balanced excitation

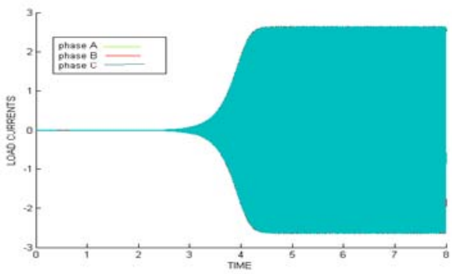
The study of SEIG with induction motor as a dynamic load has been studied and implemented using equation as described in section II. The operation of the SEIG is simulated with induction motor under balanced excitations and constant unbalanced excitation. Generator is excited with C=110 μf and un-balanced excitation has been taken as with Ca=110 μf, Cb= 80 μf, Cc= 103 μf. The results obtained with dynamic load are shown in Fig.6.10 to 6.11.

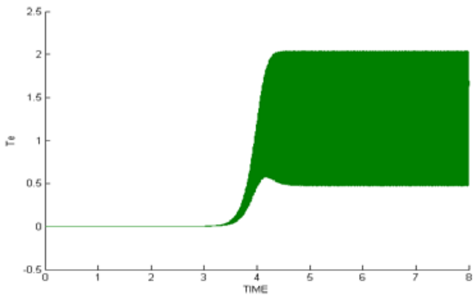
Case-1: Dynamic load with balanced excitation

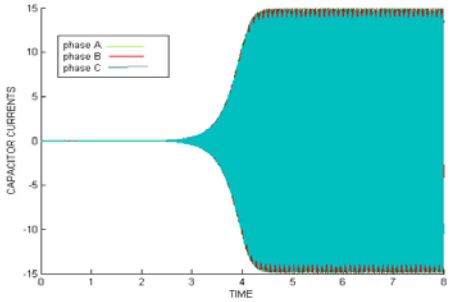
In Case 1: balanced exaction with balanced dynamic load, all the currents, i.e. stator currents, capacitor currents and load currents are balanced. Voltage is also balanced as shown in Fig. 10. It is observed from the Fig. 10 (graphs 1, 2 3, 4) that the stator voltage, currents, load currents, and capacitor currents attain their steady state value at 5.0 sec. The variation of electromagnetic torque of SEIG and motor with time and magnetizing inductance with time of SEIG has also been shown in Fig. 10 (graphs 5, 6 and 7). The electromagnetic torque of SEIG is zero initially and then it increases exponentially and attains steady values at about 5.5 sec. The electromagnetic torque of induction motor is zero initially and then it decreases exponentially and attains steady values at about 5.5 sec. It is observed that the magnetizing inductance is constant of value 0.14 H up to 3.8 sec. and then reduces to 0.095 H and become constant at 5.5 sec. and remains constant.











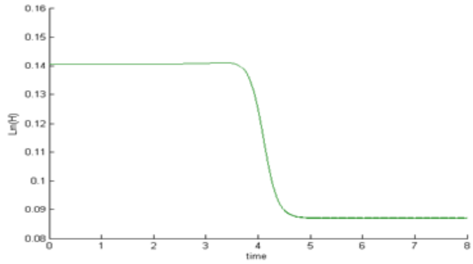
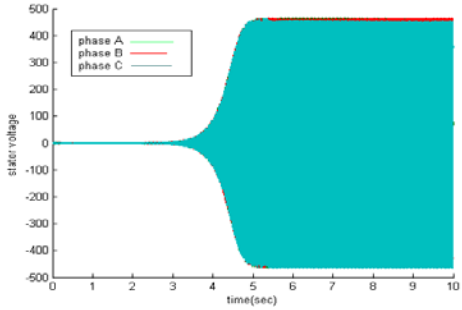
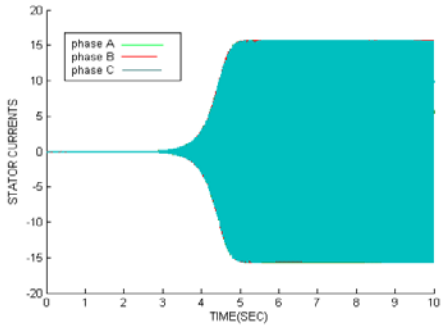
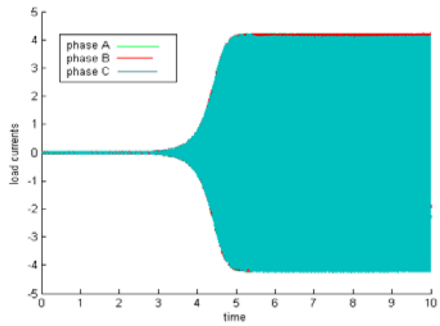


Fig.9. SEIG at RLC-load with constant excitation (graphs: 1. Stator line voltages 2.Stator currents 3. Load currents 4.Capacitor currents. 5. Electromagnetic torque 6.Magnetizing inductance)







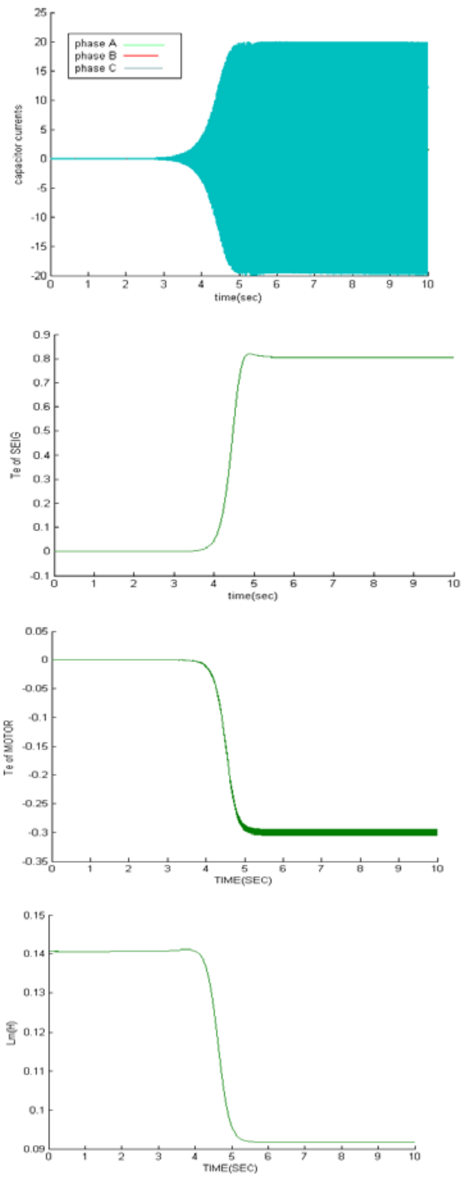
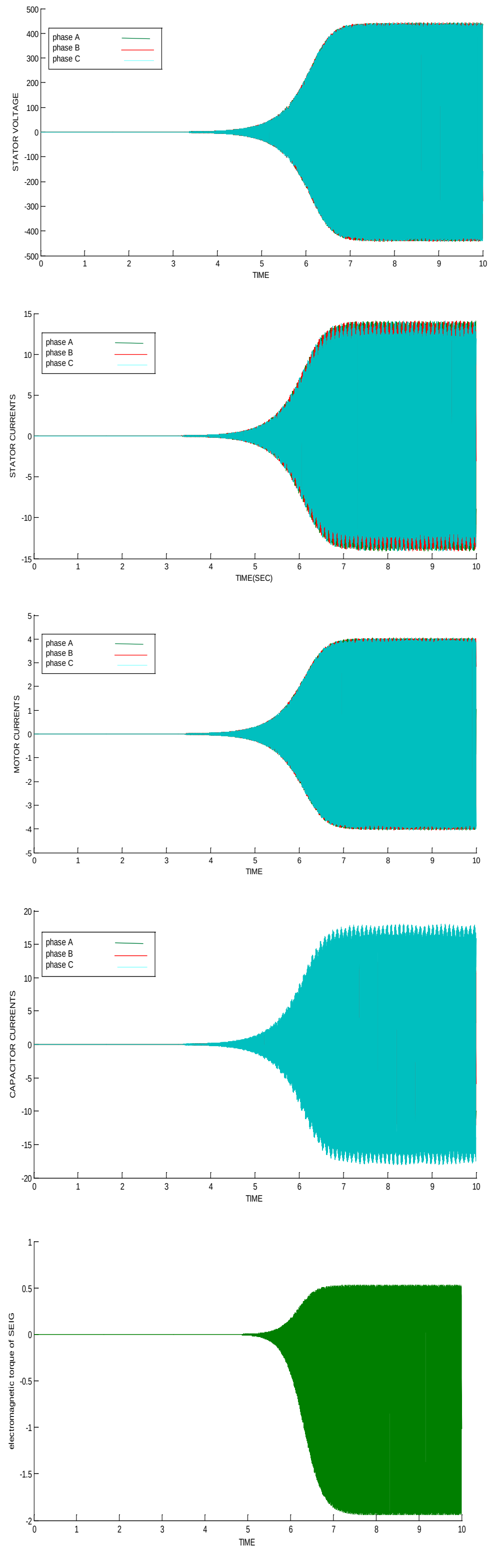


Fig.10. SEIG with Dynamic load with constant excitation (graphs: 1. Stator line voltages 2.Stator currents 3. Load currents 4.Capacitor currents. 5. Electromagnetic torque. 6. Electromagnetic torque of motor 7. Magnetizing inductance)

Case-2: Balanced dynamic load under constant Un-balanced excitation

In Case 2: un-balanced exaction with balanced dynamic load, all the currents, i.e. stator currents, capacitor currents are un-balanced and load currents are balanced. Voltage is also balanced as shown in Fig. 11. It is observed from the Fig. 11 (graphs 1, 2 3, 4) that the stator voltage, currents, load currents, and capacitor currents attain their steady state value at 6.5 sec. The variation of electromagnetic torque of SEIG and motor with time and magnetizing inductance with time of SEIG has also been shown in Fig. 11 (graphs 5, 6 and 7). The electromagnetic torque of SEIG is zero initially and then it increases exponentially and attains steady values at about 6.5 sec. The electromagnetic torque of induction motor is zero initially and then it decreases exponentially and attains steady values at about 6.5 sec. it is observed that Te is having oscillations due to unbalanced excitation. It is observed that the magnetizing inductance is constant of value 0.14 H up to 5 sec. and then reduces to 0.103 H and become constant at 7 sec. and remains constant.



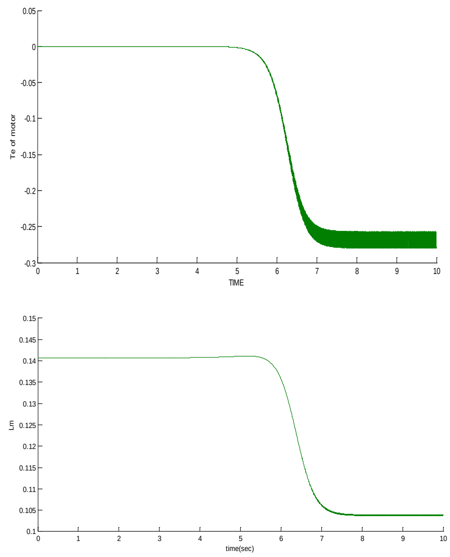


Fig.11. SEIG at Dynamic load with constant UN excitation (graphs: 1. Stator line voltages 2. stator currents 3. Load currents 4.Capacitor currents. 5. Electromagnetic torque of SEIG. 6. Electromagnetic torque of motor 7. Magnetizing inductance)

V. Conclusions

In this paper, the results have been determined for SEIG under no-load, balanced RLC load conditions and dynamic load using balanced and unbalanced excitation conditions. Based on the results for all the cases, the following conclusions can be drawn:

- It is observed that the performance of SEIG under balanced RLC load and balanced excitations, the stator voltage, stator currents, load currents and capacitor currents are balanced.
- Under constant un-balanced excitation with RLC load, the load currents are balanced but stator currents and capacitor currents are un- balanced. The electromagnetic torque is having oscillations under un-balanced excitation.
- Under unbalanced load and un-balanced excitation the oscillations are more as compared to all other cases.
- With balanced exaction with balanced dynamic load, all the currents, i.e. stator currents, capacitor currents and load currents are balanced. They attain their steady values later than compared to balanced RLC load.
- With un-balanced exaction and balanced dynamic load, all the currents, i.e. stator currents, capacitor currents are un-balanced and load currents are balanced. Voltage is also balanced. It is observed that *Te* is having oscillations due to unbalanced excitation.

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