Generalized State-Space Modeling of Three Phase Self-Excited Induction Generator For Dynamic Characteristics and Analysis

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Abstract - This paper presents the generalized dynamic modeling of self-excited induction generator (SEIG) using state-space approach. The proposed dynamic model consists of induction generator; self-excitation capacitance and load model are expressed in stationary d-q reference frame with the actual saturation curve of the machine. An artificial neural network model is implemented to estimate the machine magnetizing inductance based on the knowledge of magnetizing current. The dynamic performance of SEIG is investigated under no load, with the load, perturbation of load, short circuit at stator terminals, and variation of prime mover speed, variation of capacitance value by considering the effect of main and cross-flux saturation. During voltage buildup the variation in magnetizing inductance is taken into consideration. The performance of SEIG system under various conditions as mentioned above is simulated using MATLAB/SIMULINK and the simulation results demonstrates the feasibility of the proposed system.

1. Introduction

It is well known that the three phase induction machine can be made to work as a self-excited induction generator [1]-[2] provided capacitance should have sufficient charge to provide necessary initial magnetizing current. For self-excitation to occur, the following two conditions must be satisfied [3]-[5].

1. The rotor should have sufficient residual magnetism.
2. The three-capacitor bank should be of sufficient value.

To start with transient analysis the dynamic modeling of induction motor has been used which further converted into induction generator [4]. Magnetizing inductance is the main factor for voltage buildup and stabilization of generated voltage for unloaded and loaded conditions. The dynamic Model of Self Excited Induction Generator is helpful to analyze all characteristic especially dynamic characteristics.

In this paper d-q modeling of three phase SEIG has been Proposed. The d-q equivalent circuit with inductive load is shown in Fig.1. The state space approach is implemented for better representation for transient response of SEIG. The d-q axes stator-rotor voltage and current (5) is the functions of machine parameters. This is four first order differential equations. The solution of such an equation has been obtained assuming all the non-linear parameters as it

is. The effect of main flux and cross flux has been taken into consideration, which in many of previous researches has been considered [6]- [9] as a constant parameter. Different constraints such as variation of prime mover speed and loads has been taken into accounts and accordingly the effects on generated voltages and currents has been analyzed. The effect of excitation capacitance on generated voltage has also been analyzed.

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Different constraints for analyzing transient conditions:

1. The machine is run as an induction motor and then increased the speed above synchronous speed to make it as a generator, after complete excitation the variation of generated voltages observed by application of various loads.
2. The machine is started as induction generator with no load and the voltage variations has been observed by applying the load after complete excitation.
3. The transient periods of voltage build up and voltage collapses has been observed with the application of heavy load and short circuit conditions.

2. SEIG Modelling

Fig.1 shows the d-q axes equivalent circuit of a (SEIG) supplying an inductive load. The classical matrix formulation (5) derived from equivalent circuit of Self-

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Excited Induction Generator. A d-q ax modeling [12] is used to represent the dynamics of conventional induction machine operating as a generator. Using such a matrix representation, one can obtain the instantaneous voltages and currents during the self- excitation process, as well as during load variations [11].

Fig. 1 d-q axes equivalent circuit of Self-Excited Induction Generator

2.1 Self-Excitation capacitor and load model

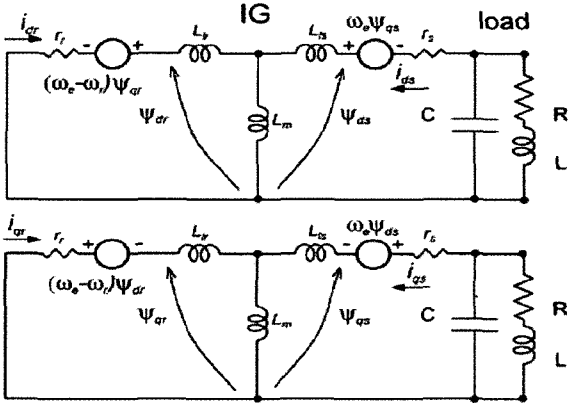The equations (1) and (4) represent the self-excitation capacitor currents and voltages in d-q axes representation.

$$V_{cd} = V_{ds} \,,\ V_{cq} = V_{qs} \tag{1}$$

$$i_{cd} = i_{ds} - i_{Ld} \,,\quad i_{cq} = i_{qs} - i_{Lq} \tag{2}$$

$$V_{cd} = \frac{1}{C}\int i_{cd}\,dt + V_{cd}\,|_{t=0} \tag{3}$$

$$V_{cq} = \frac{1}{C}\int i_{cq}\,dt + V_{cq}\,|_{t=0} \tag{4}$$

Where $V_{cd}\,|t=0$, $V_{cq}\,|t=0$, are the initial voltages of the self-excitation capacitor without which voltages cannot be build up in SEIG.

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p + \left(\dfrac{R+Lp}{RCp+LCp^2+1}\right) & 0 & L_m p & 0 \\ 0 & R_s + L_s p + \left(\dfrac{R+Lp}{RCp+LCp^2+1}\right) & 0 & L_m p \\ L_m p & \omega_r L_m & R_r + L_r p & \omega_r L_2 \\ -\omega_r L_m & L_m p & -\omega_r L_2 & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{5}$$

$$p\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ v_{Ld} \\ v_{Lq} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} = K \left\{ \begin{bmatrix} R_s L_r & -\omega_r L_m^2 & -R_r L_m & -\omega_r L_m L_r & L_r & 0 & 0 & 0 \\ \omega_r L_m^2 & R_s L_r & \omega_r L_m L_r & -R_r L_m & 0 & L_r & 0 & 0 \\ -R_s L_m & \omega_r L_m L_s & R_r L_s & \omega_r L_s L_r & -L_m & 0 & 0 & 0 \\ -\omega_r L_m L_s & -R_s L_m & -\omega_r L_s L_r & R_r L_s & 0 & -L_m & 0 & 0 \\ 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK & 0 \\ 0 & 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK \\ 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ v_{Ld} \\ v_{Lq} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} + \begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} \right\} \tag{6}$$

$$[B] = \begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

$$K = \frac{1}{L_m^2 - L_s L_r} \tag{8}$$

The d-q axes load voltages and currents are represented as

$$V_{Ld} = R.i_{Ld} + L\frac{d}{dt}i_{Ld},$$ (9)

$$V_{Lq} = R.i_{Lq} + L\frac{d}{dt}i_{Lq}$$ (10)

$$\frac{d}{dt}i_{Ld} = \frac{1}{L}V_{Ld} - \frac{R}{L}i_{Ld}$$ (11)

$$\frac{d}{dt}i_{Lq} = \frac{1}{L}V_{Lq} - \frac{R}{L}i_{Lq}$$ (12)

2.2 Generalized SEIG modeling

The complete dynamic model is represented by the set of eight differential equations corresponding to variables i_{ds}, i_{qs}, i_{dr}, i_{qr}, v_{ld}, v_{lq}, i_{ld}, i_{lq} are the generalized state space representation (6) of a SEIG model.

That is in the form of classical state-space equation

$$p[x] = [A][x] + [B][u]$$ (13)

$$p\begin{bmatrix} i_G \\ v_C \\ i_L \end{bmatrix} = \begin{bmatrix} G \\ C \\ L \end{bmatrix}\begin{bmatrix} i_G \\ v_C \\ i_L \end{bmatrix} + [B][v_G]$$ (14)

Where G, C and L refer, respectively, to the partition of matrix (6) into matrices for the induction generator parameters, the self-excitation capacitance, and the load. Vector $[x]$ is the transposed matrix $[i_G \, v_C \, i_L]$. The excitation vector $[u] = [v_G]$ of (14) is multiplied by the excitation parameter matrix $[B]$ described by equation (7). Therefore, $[B][u] = [v_G][u]$ defines the voltage corresponding to the residual magnetism in the machine core and K in (6) represents the multiplication variable (8) that varies with the magnetizing inductance (L_m).

The simultaneous solution of this system of equation can be obtained using the Runge-Kutta 4th order integration method with automatic adjustment of step. This gives the instantaneous values of d-q axes voltages and currents for stator and rotor.

The following assumptions are made in this analysis:

1. Core and mechanical losses in the machine are neglected.
2. All machine parameters, except the magnetizing inductance (L_m), are assumed to be constant.
3. Stator windings, self-excitation capacitors and the load are star connected.

3. ANN -Modeling of Magnetic Core Saturation

The experimental data is taken from the reference [10]. Using this data, the authors had derived the nonlinear equation of magnetizing inductance (L_m) as a function of magnetizing current (I_m), using the 6th order curve fitting. But it is not an effective approximation of magnetizing inductance,

The magnetizing current is given as

$$I_m = \sqrt{(i_{ds} + i_{dr})^2 + (i_{qs} + i_{qr})^2}$$ (15)

So a precise mathematical model to evaluate the nonlinear behavior of the magnetizing inductance as a function of capacitance, load impendence and saturation is quite difficult to obtain. However an Artificial Neural Network (ANN) model [14] can simulate the variation of the magnetizing inductance as a function of magnetizing current. Since the saturation is a nonlinear phenomenon then the sigmoidal function is used to model the nonlinear variation of the L_m as a function of Im. The sigmoidal transfer function (16) is given as

$$f(x) = \frac{1}{1 + e^{-\alpha x}} \quad , (0 < f(x) < 1)$$ (16)

Where α is the gain that adjusts the slope of the function.

Fig.2. Shows the typical two-layer architecture, which is used for the approximation of the magnetizing inductance (L_m). It has a hidden layer of sigmoidal neuron (tan-sigmoid neurons), which receives input (magnetizing current) directly and then broadcast their outputs to a layer of linear neurons, which computes the network output (magnetizing inductance). The Back-propagation–training algorithm [13] is used for function approximation of magnetizing inductance.

$a_1 = \text{tansig } (IW_{1,1}p_1 + b_1)$ $a_2 = \text{purelin } (LW_{2,1}a_1 + b_2)$
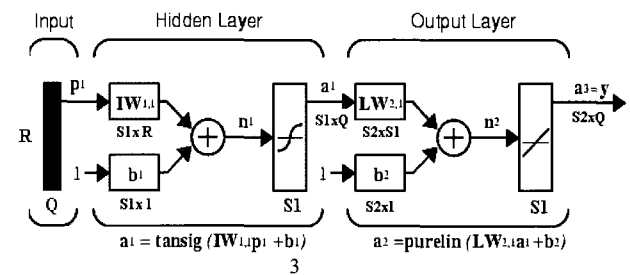
R = 1: Input, Q = Input Vector, $a^3 = y = 1$: Output

IW = Initial Weight Vector, LW=Latest Weight Vector, b^1, b^2 = bias vector

S1= 2: Hidden Layer Neurons, S2 = 2: Output Layer Neurons

Fig.2 Block Diagram of ANN Model for Estimation of Magnetizing Inductance.

The training is automated with MATLAB simulation program that uses a certain number of input-output example patterns. At completion of the training the weights are downloaded to the magnetizing inductance ANN-model built in the SEIG simulation.

4. Simulation

Simulation work has been implemented in MATLAB/ SIMULINK programming toolboxes. The induction generator model is implemented with the (6), whose outputs are current. The load and excitation model is implemented using (9) to (12) and (1) to (4).

Equation (6) shown has eight first order differential equations, for which the solutions gives the four currents (stator and rotor d-q axis currents), load currents and capacitor voltages. Remnant magnetism in the machine is taken in to account, without which it is not possible for the generator to self excite. An impulse function is used to represent the remnant magnetic flux in the core.

An ANN-model of the non-linear relation between magnetizing inductance and magnetizing current is used in SEIG simulation model.

5. Results and Discussion

The simulation has been developed in MATLAB/ SIMULINK. The residual magnetism in the machine and the charging of capacitor to its rated value is taken into account in simulation process without which it is not possible for the generator to self-excite.

5.1 Estimation of Magnetizing Inductance with the Artificial Neural Network (Ann)-Model

The training of the ANN-model for estimation of the magnetizing inductance with six hidden neurons took about 100 epochs to reach a sum-squared error of magnetizing inductance (L_m) of 1e-005. The ANN simulation-training program trains the network and generates the ANN-SIMULATION block. The generated ANN-model with six hidden neurons is shown in Fig.3 is placed in SEIG SIMULATION model. This ANN-model enhances the accurate estimation of magnetizing inductance with high precision and accuracy for a given non-linear magnetizing current. A Comparison between the actual values of magnetizing inductance (L_m) and the ANN calculated values, is shown in Fig.4. It can be observed that there is a good fitting between the two values for different values of the magnetizing current.
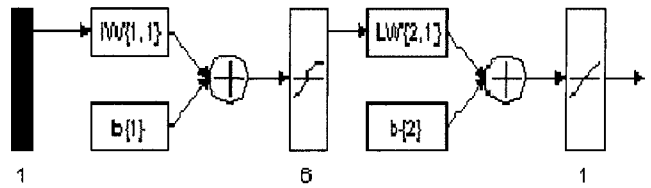

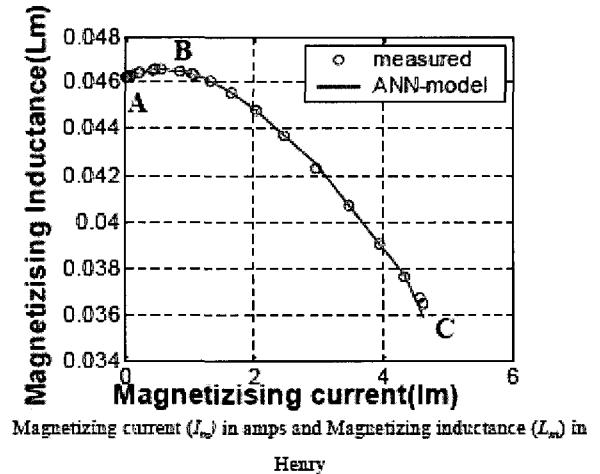Fig.3 ANN- simulation model block (neural networks)

Magnetizing current (I_m) in amps and Magnetizing inductance (L_m) in Henry

Fig.4 Comparison between Measured and ANN-based Values of magnetizing inductance (L_m)

The weights and biases obtained from the training are used in the ANN- simulation block (Neural Network block) .For each epoch, weights are updated; when sum squared error reaches the goal the training is stopped and generated ANN-model is placed in SEIG simulation model to estimate magnetizing inductance.

As it can be seen in Fig.4. At the start of self-excitation point A, where the magnetizing current is close to zero i.e. the voltage is zero, L_m is close to 0.046 H. once the self excitation starts the magnetizing current increase which causes the generated voltage to grow and then L_m also increase up to point B. beyond point B, up to point C, L_m decreases while the voltage continues to grow until it reaches its steady state value. Between points A and B is the unstable region.

If the SEIG starts to generate in this region, a small decrease in speed will cause a decrease in voltage and this will bring a decrease in L_m, which in turn decreases the voltage, and finally the voltage will collapse to zero. Once the voltage collapse there is no transient phenomenon and there will not be voltage buildup even if the speed increases once again to its initial value as shown in Fig. 5.This condition can cause demagnetization of the core. When the core is demagnetized there will not be self-excitation. In order to initiate self-excitation the core should be magnetized by running the generator as a motor or excite the windings from a dc supply. The other

arrangement is to charge the exciting capacitors from a DC supply. Between point B and C is a stable operating region.

When the speed decreases voltage will decreases and L_m increases which enables the self-excited machine to continue to operate at a lower voltages as shown in Fig.6.
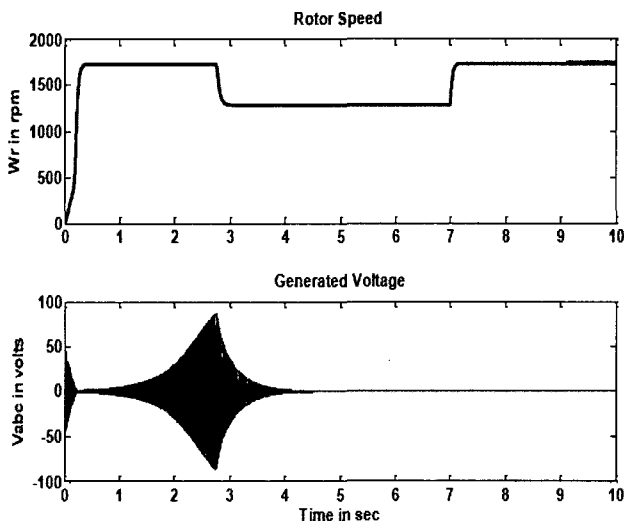

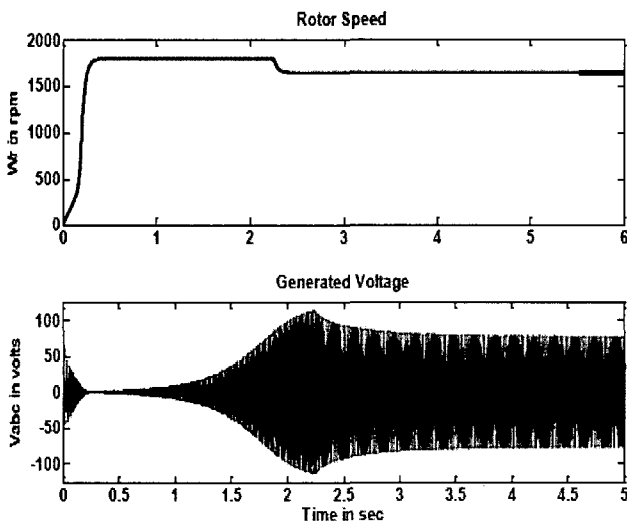**Fig.5** Measured unsuccessful self-excitation at C= 188 μF

Fig. 6 Measured self-excitation at C = 188 μF and reduced speed

5.2 Variation of magnetizing inductance during voltage buildup process

The no-load stator voltage, rotor speed, magnetizing current along with the magnetizing inductance profile is shown in Fig.7. The voltage is continuing to build up and increase gradually as magnetizing current increases until saturation, at which the magnetizing inductance drops from 0.046 H to0.036 H (i.e.21.74 %). Afterwards the voltage settles at rated no-load values.
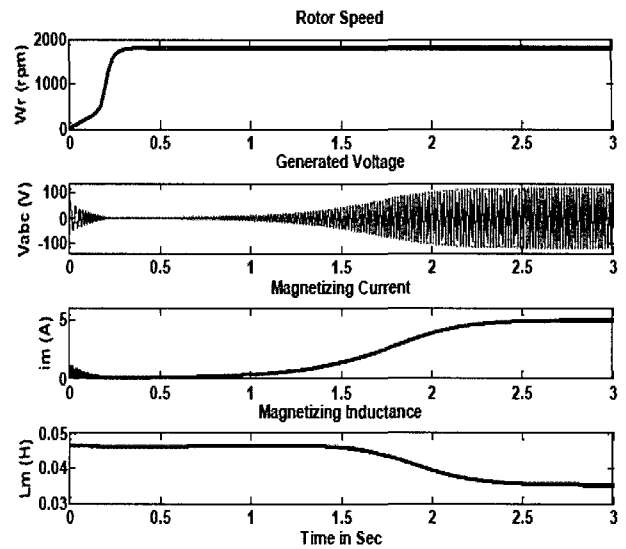

Fig.7 Rotor speed, voltage, magnetizing current, magnetizing inductance during voltage buildup at no-load

5.3 Response of SEIG with constant rotor speed under no load

When the generator is excited with capacitance value C= 188 μf and rotor speed is maintained at synchronous speed (1800 r.p.m) without load, the generated voltage and current attains its s steady state value of 120 Volts and 5 amp in 1.7 sec as shown in Fig.8. As the excitation is taking place, the magnetizing current is increasing and at the same time the magnetizing inductance is decreasing and when core is saturated (i.e. at rated phase voltage) the I_m and L_m are also saturated and maintaining a steady state value. This figure also depicts the torque generated by SEIG is 1.4 Nm.
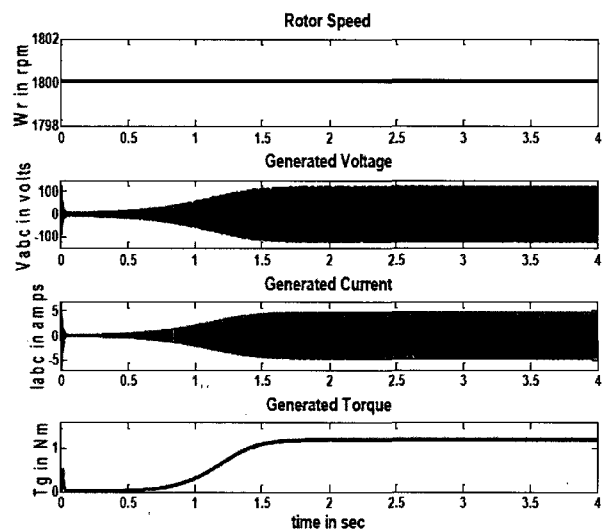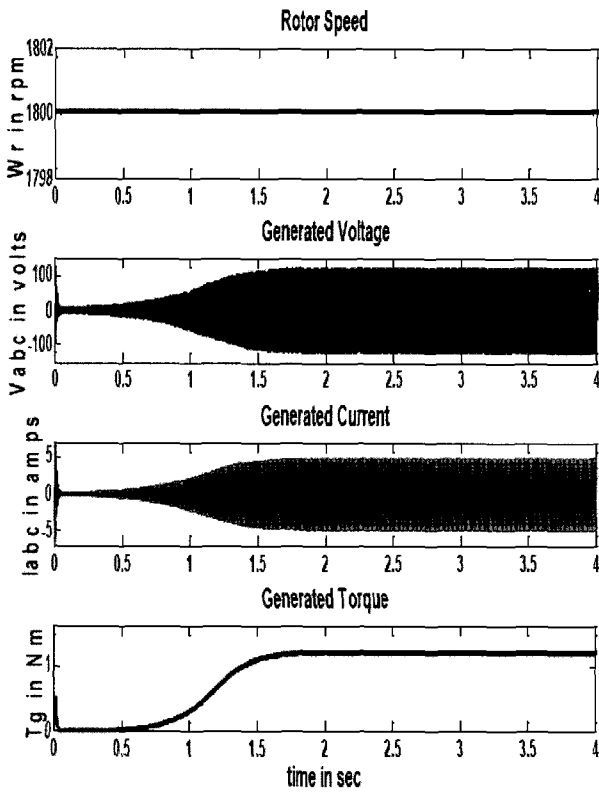

Fig.8 Response of SEIG with constant rotor speed under no load with the excitation capacitance value of 188 μF

5.4 Response of SEIG with constant rotor speed under loaded condition

When the generator is excited with capacitance value C= 188 µf and rotor speed is maintained at synchronous speed (1800 r.p.m) with the RL-load(R=130 Ω, L = 20 mH), the generated voltage and current attains its steady state value of 115 Volts and 4.6 amp in 1.7 sec as shown in Fig.9. It can be observer that when the machine is excited with the load the generated voltage, current and torque attains a steady state value, which is less than the rated no-load values. The generated torque is 1.2 Nm.

Fig.9 Response of SEIG with constant rotor speed under loaded condition (R=130 Ω, L = 20 mH) with the excitation capacitance value of 188 µF

5.5 Transient Response of SEIG under sudden switching on load

With the constant rotor speed (1800 rpm) and excitation capacitance value of 188 µF, When the RL-load (R= 25 Ω, L=10.5 mH) is suddenly switched on at t =3 sec after full excitation as shown in Fig.10. There is a sudden decrease in phase voltage from 120 volts to 90 volts, generated current from 5 A to 4.2 A and generated torque from 1.4 Nm to 0.8 Nm as shown in Fig.10.
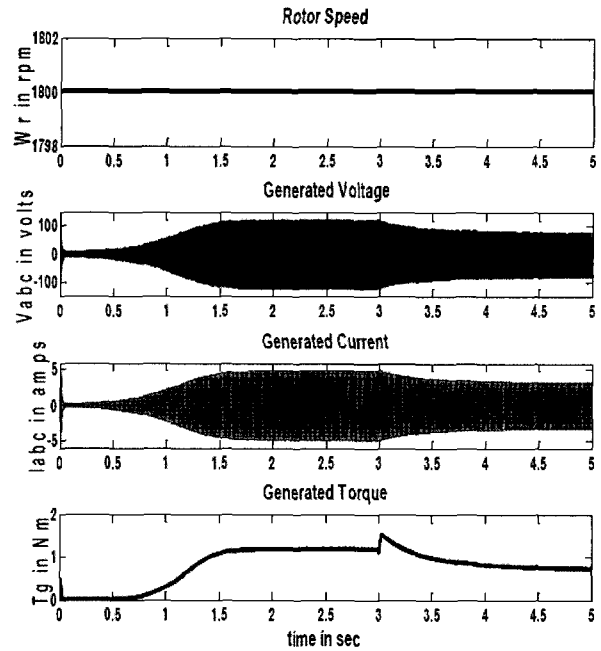
Fig.10 With the constant rotor speed (1800 rpm) and excitation capacitance value of 188 µF, a impedance load(R= 25 Ω, L=10.5 mH) is applied at time T= 3 sec

5.6 Transient Response of SEIG under short circuit condition

With the constant rotor speed (1800 rpm) and excitation capacitance value of 188 µF, at time T= 3 sec short circuiting the stator, There is a complete collapse of phase
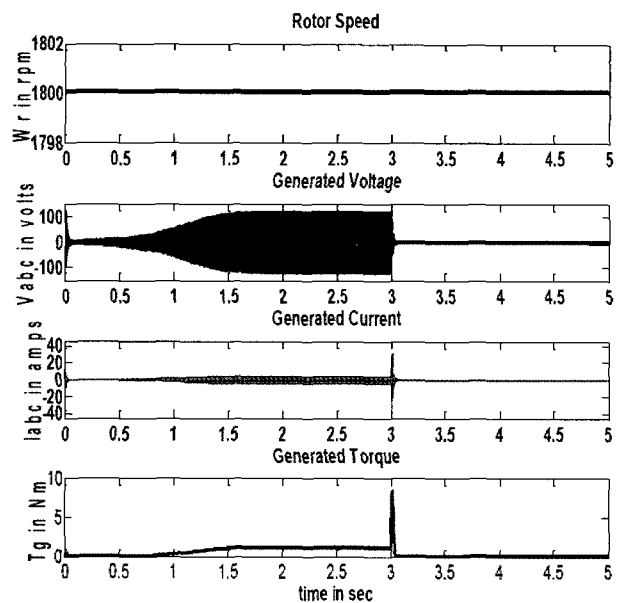
Fig.11 With the constant rotor speed (1800 rpm) and excitation capacitance value of 188 µF, short circuit at stator terminals at time T= 3 sec

voltage, a sudden rise and fall in stator currents and generated torque to zero values as shown in Fig.11. This shows that generator has natural capability of self-protection from severe short circuits, as stator currents become zero.

5.7 Response of SEIG under random variation of prime mover speed (1750 to 1850 rpm)

When the prime mover speed is varied randomly with 2.7% of synchronous speed, the variation of generated voltage, generated current, and generated torque is depicted in Fig.12. It can be observed that there is a fluctuation at rated values of above-mentioned parameters.
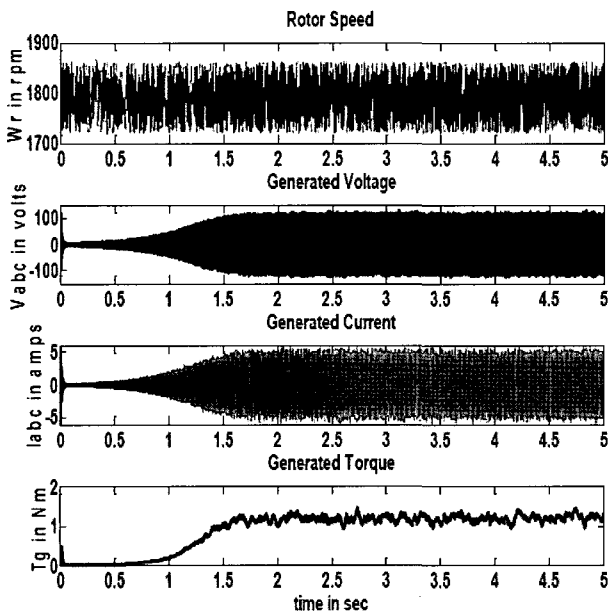

Fig.12 Response of SEIG under random variation of prime mover speed (1750 to 1850 rpm)

6. Conclusions

This paper presents the generalized dynamic modeling of the three-phase self-excited induction generator using state-space approach, an ANN-model of magnetizing inductance. With this proposed model it is possible for isolation of induction generator, excitation and load model. This feature is guaranteed by the separate parameter representation of the machine model, the self-excitation bank of the capacitor and the load. The proposed model analyses the transient characteristics with the variation of load, excitation and speed. The performance of the SEIG system is analyzed during initial self-excitation, load switching, varying prime mover speeds, voltage build-up and voltage collapse. The proposed ANN model enhances the accurate estimation of the SEIG's magnetizing

inductance based on the knowledge of the magnetizing current. This frequency independent magnetizing inductance is used in conjunction with the actual saturation curve of the machine.

The main features of this approach are
1. Representation of SEIG in the form of classical state equation.
2. Separation of machine parameters from the self-excitation capacitors from the load parameters, the transient analysis can be analyzed effectively.
3. This model works effectively even with the consideration of main and cross flux saturation and gives better result.

The proposed ANN-model takes the data of the magnetizing current to estimate the magnetizing inductance with high precision.

Appendix

Table Induction machine Rating and Parameters

Rated Power	1HP
Rated Voltage	120/210 V
Rated Current	5.0 A
Rated Frequency	60Hz
Number of poles, P	4 poles
Stator Resistance, R_s	0.32 Ω
Stator Leakage Reactance, X_{ls}	0.8Ω
Rotor Resistance, R_r	0.41 Ω
Rotor leakage impedance, X_{lr}	0.8 Ω

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