

# Dynamic Modeling and Analysis of an Isolated Self Excited Induction Generator Driven by a Wind Turbine

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**Abstract** - This paper presents modeling, simulation and transient analysis of three phase self-excited induction generator (SEIG) driven by a wind turbine. Three phase self-excited induction generator is driven by a variable-speed prime mover such as a wind turbine for the clean alternative renewable energy in rural areas. Transients of machine self-excitation under three phase balanced load conditions are simulated using a Matlab/Simulink block diagram for constant, step change in wind speed and random variation in wind speed.

**Keywords** - Induction Generator, modeling, self-excitation, Wind speed, voltage and current transients.

## I. INTRODUCTION

The impact of fossil fuel on the environment, especially the harmful effects of carbon emissions and the global warming have created a new demand for clean and sustainable energy sources. Several new forms of renewable resources such as wind power generation systems (WPGS) and photovoltaic systems (PV) to supplement fossil fuels have been developed and integrated globally. However, the photovoltaic generation has low energy conversion efficiency and very costly as compared to the wind power, wind generators take a particular place; thus, they are considered as the most promising in terms of competitiveness in electric energy production. Three phase self-excited induction generator is driven by a variable-speed prime mover such as a wind turbine for the clean alternative renewable energy in rural areas, because they do not need an external power supply to produce the excitation magnetic field. Based on adaptive models to parameters variation, different studies of the transients of the machine were performed [1-3]. Since the induction generator operating frequency and output voltage are determined by the speed of the generator, the load and the value of excitation capacitor, fixed capacitor values can result in unstable power output under changing load conditions. A self-excited induction generator can operate in a stable manner with an appropriate control strategy and the use of solid state power switching devices to regulate the amount of self-excitation.

The block schematic diagram of a self-excited induction generator driven by wind turbine system is shown in Fig 1. When the induction machine is driven at the required speed, the residual magnetic flux in the rotor will induce a small emf in the stator winding. The appropriate capacitor bank causes this induced voltage to continue to increase until an equilibrium state is attained due to magnetic saturation of the machine. In order for self-excitation to occur for a particular

capacitance value there is a corresponding minimum speed [4,5].

The dynamic d-q model derived in this paper is based on following assumptions: constant air gap, three phase symmetrical stator and rotor windings, sinusoidal distribution of the air gap magnetic field i.e, space harmonics are neglected. Rotor variables and parameters are referred to the stator windings and core losses are neglected [6,7].

In this paper, we develop a dynamic model of SEIG, simulate and analyze the transient response of self-excited induction generator. Also transients of machine self-excitation under three phase loading conditions are simulated for constant, step change in wind speed and random variation in wind speed using a Matlab/Simulink block diagram.

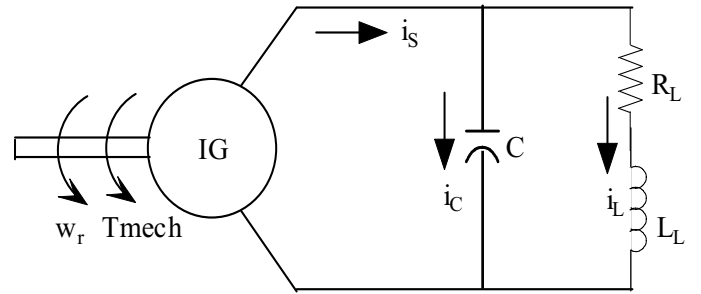


Fig 1. Per phase Equivalent circuit for RL load

This paper is organized as follows: In Section II the modeling of stand-alone SEIG is presented. Section III presents analysis of time domain simulated results of the SEIG system under various values of wind speed under three phase balanced load conditions. Finally, based on the above study the conclusion is drawn in Section IV.

## II. SYSTEM MODELING

### A. Wind turbine power

Wind turbine power depends on both rotor speed and wind speed [8-10]. Aerodynamic power available in the wind can be calculated using equation (1).

$$P = 0.5\rho AC_p V^3 \quad (1)$$

Where P = Power in watts,  $\rho$  = air density, A = rotor swept area, V = wind speed in m/sec,  $C_p$  is coefficient of performance.

The relationship between rotor speed and wind speed can be

$$\text{given by } \lambda = \frac{\omega R}{V} \quad (2)$$

Where  $R$  = wind machine rotor radius,  $\omega$  = rotor speed in rad/sec,  $\lambda$  = tip speed ratio = ratio between the linear speed of the tip of the blade with respect to the wind speed.

### B. Modeling of Self Excited Induction Generator

The Simulink block diagram of the dynamic model of induction generator driven by wind turbine system is shown in Fig 2. In d-q synchronously rotating frame, the d-q components of stator and rotor voltage equations [11,12] are as follows:

$$v_{ds} = R_s i_{ds} + \frac{1}{\omega_b} \frac{dF_{ds}}{dt} - \frac{\omega_\lambda}{\omega_b} F_{qs} \quad (3)$$

$$v_{qs} = R_s i_{qs} + \frac{1}{\omega_b} \frac{dF_{qs}}{dt} + \frac{\omega_\lambda}{\omega_b} F_{ds} \quad (4)$$

$$v_{dr} = R_r i_{dr} + \frac{1}{\omega_b} \frac{dF_{dr}}{dt} - \frac{(\omega_\lambda - \omega)}{\omega_b} F_{qr} \quad (5)$$

$$v_{qr} = R_r i_{qr} + \frac{1}{\omega_b} \frac{dF_{qr}}{dt} + \frac{(\omega_\lambda - \omega)}{\omega_b} F_{dr} \quad (6)$$

Where  $\omega_b$  is the base angular frequency of the machine,  $F_{ds}, F_{qs}, F_{dr}, F_{qr}$ : d-q components of stator and rotor transient flux linkages,  $R_s, R_r$  are stator and rotor ohmic resistances.

For a cage rotor type induction machine,  $v_{dr}$  and  $v_{qr}$  are zero. Because the machine parameters are given in ohms or per unit of base impedance, it is often convenient to express the flux linkage equations in terms of reactances. The currents can be expressed as

$$i_{ds} = \frac{1}{X_{ls}} \left[ F_{ds} - \frac{X_{lm} F_{ds}}{X_{ls}} - \frac{X_{lm} F_{dr}}{X_{lr}} \right]$$

$$i_{qs} = \frac{1}{X_{ls}} \left[ F_{qs} - \frac{X_{lm} F_{qs}}{X_{ls}} - \frac{X_{lm} F_{qr}}{X_{lr}} \right]$$

$$i_{dr} = \frac{1}{X_{lr}} \left[ F_{dr} - \frac{X_{lm} F_{ds}}{X_{ls}} - \frac{X_{lm} F_{dr}}{X_{lr}} \right]$$

$$i_{qr} = \frac{1}{X_{lr}} \left[ F_{qr} - \frac{X_{lm} F_{qs}}{X_{ls}} - \frac{X_{lm} F_{qr}}{X_{lr}} \right]$$

Where

$$X_{lm} = \left( \frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}} \right)^{-1}; X_{ls}, X_{lr}, X_m \text{ are stator, rotor leakage reactances and magnetization reactance.}$$

The d-q axis voltage of the induction machine are derived in state space form by substituting the above current equations into the equations (3)-(6) as

$$\frac{dF_{ds}}{dt} = \omega_b \left[ v_{ds} - \frac{R_s}{X_{ls}} F_{ds} + \frac{\omega_\lambda}{\omega_b} F_{qs} + \frac{R_s X_{lm}}{X_{ls}} \left( \frac{F_{ds}}{X_{ls}} + \frac{F_{dr}}{X_{lr}} \right) \right]$$

$$\frac{dF_{qs}}{dt} = \omega_b \left[ v_{qs} - \frac{R_s}{X_{ls}} F_{qs} - \frac{\omega_\lambda}{\omega_b} F_{ds} + \frac{R_s X_{lm}}{X_{ls}} \left( \frac{F_{qs}}{X_{ls}} + \frac{F_{qr}}{X_{lr}} \right) \right]$$

$$\frac{dF_{dr}}{dt} = \omega_b \left[ -\frac{R_r}{X_{lr}} F_{dr} + \frac{(\omega_\lambda - \omega)}{\omega_b} F_{qr} + \frac{R_r X_{lm}}{X_{lr}} \left( \frac{F_{ds}}{X_{ls}} + \frac{F_{dr}}{X_{lr}} \right) \right]$$

$$\frac{dF_{qr}}{dt} = \omega_b \left[ -\frac{R_r}{X_{lr}} F_{qr} - \frac{(\omega_\lambda - \omega)}{\omega_b} F_{dr} + \frac{R_r X_{lm}}{X_{lr}} \left( \frac{F_{qs}}{X_{ls}} + \frac{F_{qr}}{X_{lr}} \right) \right]$$

The equation of rotational motion of the induction machine is

$$T_{em} = \frac{J}{p} \frac{d\omega}{dt} + \frac{B}{p} \omega + T_{mech};$$

Where  $\omega$  is electrical rotor angular speed,  $J$  is the rotor inertia,  $p$  is number of machine pole pairs;  $T_{mech}$  =externally applied mechanical torque (from wind turbine shaft) and  $T_{em}$  the electromagnetic torque.

The electromagnetic torque equation [11] can be expressed as

$$T_{em} = \frac{3}{2} \frac{X_m}{(X_{lr} + X_m)} \frac{p}{\omega_b} (i_{qs} F_{dr} - i_{ds} F_{qr})$$

Thus, the equation governing the rotational motion can be expressed below in which the viscous frictional torque was neglected.

$$\frac{d\omega}{dt} = \frac{p}{J} (T_{em} - T_{mech})$$

### C. Modeling of Load Impedance

An induction generator is self-excited by providing the magnetizing reactive power by a capacitor bank as shown in Fig 1 and the load considered is R-L load ( $R_L=800\Omega$  and  $L_L=10H$ ). The load equations of the induction generator are represented in the same reference frame are given below [13].

$$\frac{di_{Ld}}{dt} = \frac{1}{L_L} (v_{ds} - R_L i_{Ld}) + \omega_\lambda i_{Lq}$$

$$\frac{di_{Lq}}{dt} = \frac{1}{L_L} (v_{qs} - R_L i_{Lq}) - \omega_\lambda i_{Ld}$$

### D. Modeling of Excitation Capacitor

The capacitor equations are given by

$$\frac{dv_{ds}}{dt} = -\frac{1}{C} i_{ds} + \frac{1}{C} i_{Ld}$$

$$\frac{dv_{qs}}{dt} = -\frac{1}{C} i_{qs} + \frac{1}{C} i_{Lq}$$

Where  $i_s$  is the generator stator currents,  $i_c$  capacitor currents,  $i_L$  load currents and  $i_{Ld}, i_{Lq}$ : d-q components of transient load currents [13].

### III. SIMULATION RESULTS AND DISCUSSIONS

The nine first order system equations described above has been directly implemented in Matlab/Simulink blocksets. The Simulink block diagram of the dynamic model of Self-excited induction generator driven by a wind turbine system is shown in fig 2. The induction generator system in Fig 2 consists of one input, that is the shaft torque  $T_{mech}$  provided by a prime mover (i.e. wind turbine), and nine state variables,  $F_{ds}, F_{qs}, F_{dr}, F_{qr}, \omega, i_{Ld}, i_{Lq}, v_{ds}$  and  $v_{qs}$ . In this section, the simulation results of the stator phase voltages built-up, the stator current transients, the electromagnetic torque of the induction generator and generated output power of the induction generator described by the system of equations and the machine data are 3-phase, 4 pole star connected,  $f_b=50\text{Hz}$ ;  $J= 0.011\text{kgm}^2$ ;  $R_s=7.5\Omega$ ;  $R_r=7\Omega$ ;  $X_{ls}=11.5\Omega$ ;  $X_{lr}=6\Omega$ ;  $X_m=145\Omega$  are presented.

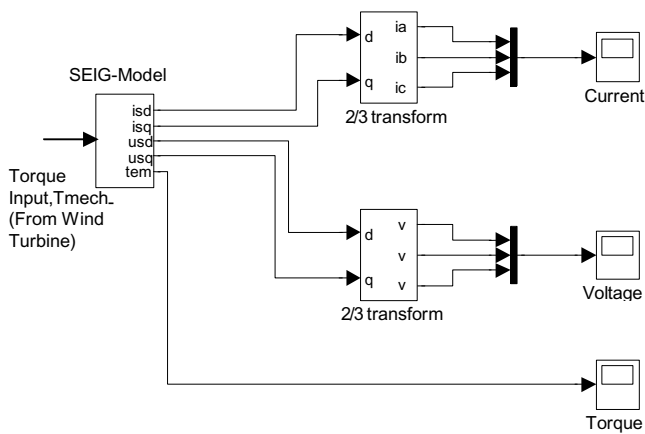


Fig 2. Simulink block diagram of the dynamic model of Self-excited induction generator driven by a wind turbine system

The following three cases are considered for the study and simulation interval of 2 sec for constant wind speed of 11m/sec and 4 sec for varying wind speed profile has been chosen.

Case 1: A constant wind speed of 11m/sec is applied to the generator and simulation results of the stator phase voltages built-up, the corresponding changes in the stator current transients, the electromagnetic torque and generated output power of the induction generator are shown in fig. 3. When the machine is loaded and excited with the capacitance value of  $C=150\mu\text{F}$ , the generated phase voltages and current transients occur at 0.1sec and attains its steady state value in 0.25sec as shown in fig. 3. The negative value of the electromagnetic torque indicates that the machine is working in generating mode.

Case 2: A varying wind speed profile is applied to the generator to investigate its performance. The wind speed at  $t=0$  sec is 10m/sec and the wind speeds are changed at  $t=1, 2$  and 3 seconds to 12m/sec, 13m/sec and 11m/sec respectively. As the wind velocity increases, the mechanical input from the wind turbine increases. This result in the increased rotor speed causing an increase in the stator phase voltage, as faster turning rotor produces higher values of

stator voltage. Fig. 4 shows the simulation results of the stator phase voltages built-up, the corresponding changes in the stator current transients, the electromagnetic torque and generated output power of the induction generator.

Case 3: In this case, during  $0 < t < 2\text{sec}$  the wind speed is 10m/sec and at  $t=2\text{sec}$ , the wind speed is increased to 13m/sec with random variation. The simulation results are shown in fig 5. From the simulation results, it is observed that the self-excited induction generator (SEIG) is inherently capable of operating at variable speeds with random variation.

The dynamic voltages, currents, electromagnetic torque developed and generated output power for an SEIG have been analyzed. All of the characteristics shown are the basic tools required to develop a control system, using power electronics, which will regulate the generated voltage and generated output power for an SEIG over a wide range of speed.

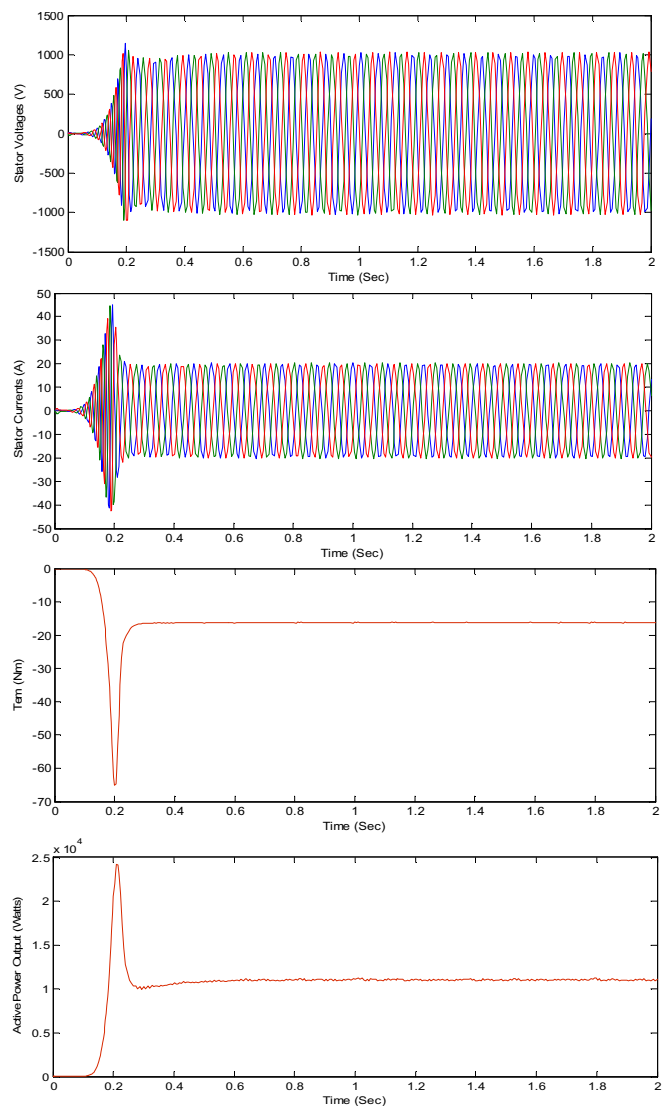


Fig. 3. Simulated results for Case 1: Stator phase voltages built-up, stator current transients, electromagnetic torque and generated output power

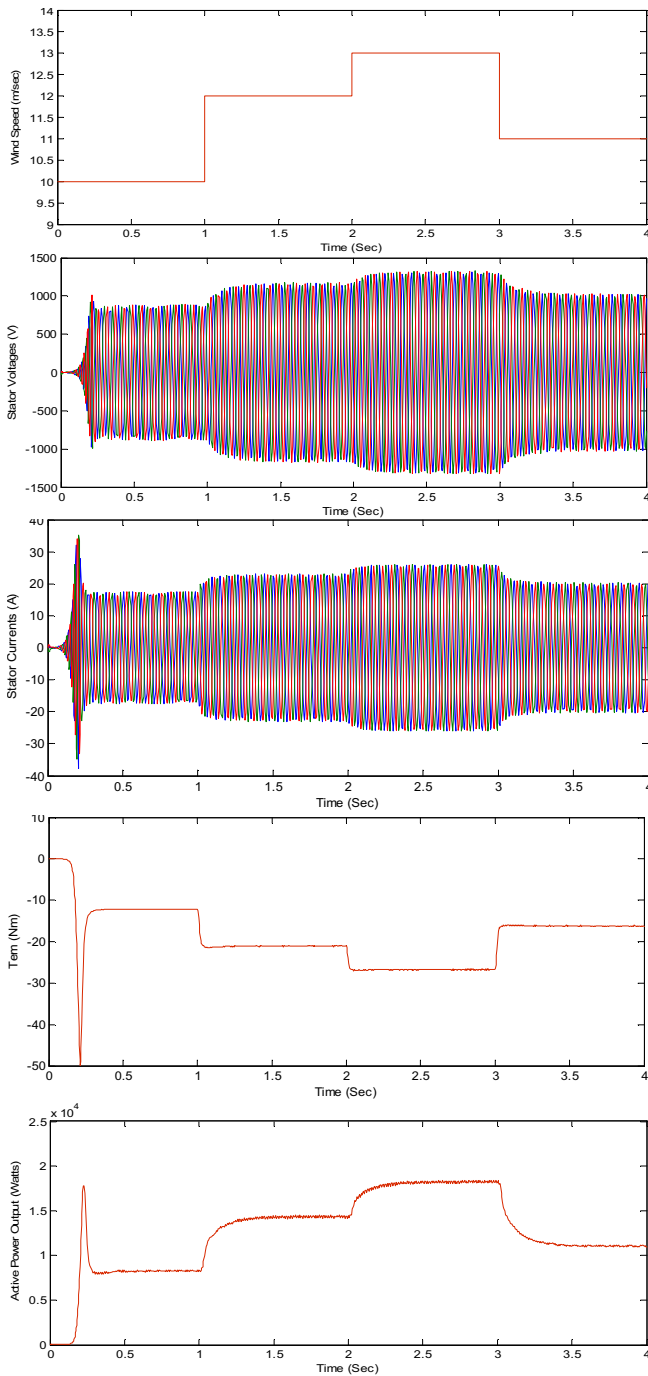


Fig. 4. Simulated results for Case 2: Wind speed m/sec, Stator phase voltages built-up, stator current transients, electromagnetic torque and generated output power

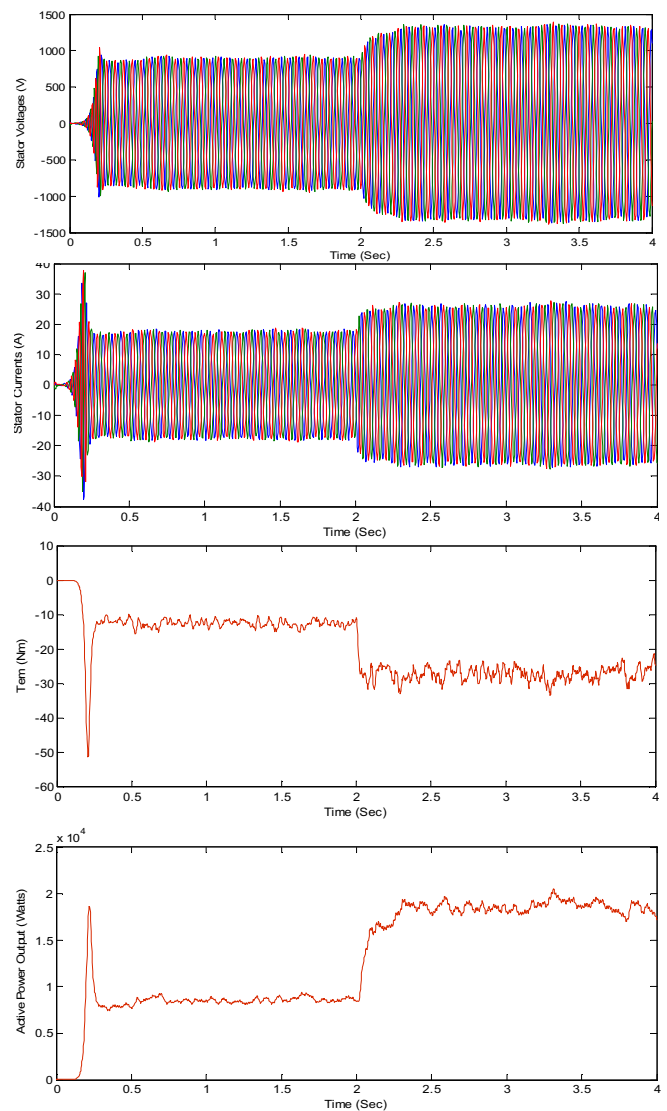
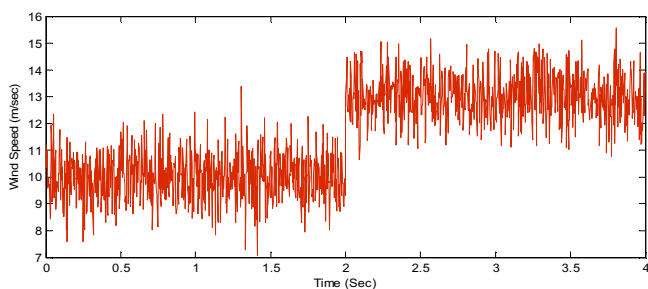


Fig. 5. Simulated results for Case 3: Wind speed m/sec, Stator phase voltages built-up, stator current transients, electromagnetic torque and generated output power

#### IV. CONCLUSION

In this paper, a Simulink model for the transient analysis study of a three phase self-excited induction generator driven by a variable-speed prime mover such as a wind turbine is implemented. Transients of machine self-excitation under three phase balanced load conditions are simulated. The dynamic voltages, currents, electromagnetic torque developed by the induction generator and generated output power have been analyzed for a constant, step change and random variation in wind speed. From the simulation results presented, it can be seen that the self-excited induction generator (SEIG) is inherently capable of operating at variable speeds.

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