Modelling and Simulation of Stand-Alone Self-Excited Induction Generator for Wind Power Application

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MAY 2014

Modelling and Simulation of Stand-Alone Self-Excited Induction Generator for Wind Power Application

Thesis

Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology

In

Electrical Engineering

Specialization (PED)

By

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled "**Modelling and Simulation of Stand-Alone Self-Excited Induction Generator for Wind Power Application**" in partial fulfilment of the requirements for the award of Master Of Technology Degree in Power Electronics & Drives submitted in department of Electrical Engineering at National Institute of Technology, Rourkela is an authentic record of my own work carried out under the supervision of Dr. Monalisa Pattnaik, Assistant Professor, EE department. The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

(**Ashish kumar Swain**)

This is certify that the above statement made by candidate is correct and true to the best of my knowledge.

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ACKNOWLEDGMENTS

This dissertation would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparing and completion this study. First and foremost, my utmost gratitude to Dr. Monalisa Pattnaik whose sincerity and encouragement I will never forget. Dr. Monalisa Pattnaik has been my inspiration as I hurdle all the obstacles in the completion of this research work.

My sincere thanks to Prof. A.K. Panda, HOD of Electrical Engineering Department, and NIT Rourkela for providing valuable co-operation and needed advice generously all along my M.Tech study.

I would like to extend my gratefulness to Dr. S.K. Sarangi, Director of NIT Rourkela for providing necessary facilities for my research work.

I also want to convey sincere thanks to all my friends at NIT, Rourkela for making my stay in the campus a pleasant one. The co-operation shown by S.K. Senapati, S.K. Panda, D. Samajpati, R. Tikadar, S. Datta my batch mates of Power electronics & Drives Specialization cannot be ignored.

Last but not the least, my parents and the above all of us, the omnipresent God, for answering my prayers for giving me the strength and courage always.

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Abstract

Wind energy is one of the most important and promising source of renewable energy all over the world. Throughout the globe in last three or four decades generation of electricity from wind energy has created a wide interest. At the same time there has been a rapid development of wind energy related technology. The control and estimation of wind energy conversion system constitute a vast subject and are more complex than those of dc drives. Induction generators are widely preferable in wind farms because of its brushless construction, robustness, low maintenance requirements and self-protection against short circuits. However poor voltage regulation and low power factor are its weaknesses. This thesis covers the analysis, dynamic modelling and control of an isolated self-excited induction generator (SEIG) driven by a variable speed prime mover. 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, with load and perturbation of load. To predict the performance of the purposed system, a MATLAB/ SIMULINK based simulation study was carried out. Viability of the excitation process is ascertained through experimental results obtained from the laboratory prototype machine. It also includes Dynamic analysis of voltage controller for SEIG using current control voltage source inverter (CC-VSI).

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LIST OF SYMBOLS AND ABBREVIATIONS

v_{ds}	d- axes stator voltage
v_{qs}	q- axes stator voltage
v_{qr}	q-axes rotor voltage
v_{dr}	d-axes rotor voltage
i_{ds}	d- axes stator current
i_{qs}	q- axes stator current
i_{dr}	d-axes rotor current
i_{qr}	q-axes rotor current
λ_{ds}	d- axes stator flux linkage, web-turn
λ_{qs}	q- axes stator flux linkage, web-turn
λ_{qr}	q- axes rotor flux linkage, web-turn
λ_{dr}	d- axes rotor flux linkage, web-turn
θ	Angle between two axes and three axes
ω_e	Angular speed of the excitation reference frame, synchronous speed rad/sec
R_s	Stator winding resistance
R_r	rotor winding resistance
L_{ls}	Stator leakage inductance
L_{lr}	Rotor leakage inductance
L_m	Magnetizing inductance
L_s	Stator inductance

L_r	rotor inductance
T_e	Electromagnetic torque
J	Inertia constant
T_m	Mechanical torque

IGBT	Insulated Gate Bipolar Transistor
PI	Proportional and Integral controller
PMSG	Permanent magnet Synchronous Generator
PWM	Pulse Width Modulation
SEIG	Self-Excited Induction Generator
VAR	Volt amper reactive
VSI	Voltage Source Inverter
WESC	Wind energy conversion system

CHAPTER 1

INTRODUCTION

In recent years, the environmental pollution has become a major concern in people daily life and energy crisis has led people to develop new technologies for generating clean and renewable energy [1]. Wind power along with solar energy, hydro power and tidal energy are possible solutions for an environmentally-friendly energy production. Out of these renewable energy sources wind is endless and auspicious sources of renewable energy. It is a clean resource that can produce electricity without affecting environment and economically viable also. Wind energy being investigated a supplemental source is suitable to meet extra demand. The nature of wind energy is much different from conventional sources like hydro and thermal. Due to its intermittency one cannot guarantee that there will be enough mechanical power converted to electrical and supplied to load. However, when interconnected with power grid having higher capacity than that of Wind energy conversion system, the fluctuation in power input to WECS taken care by other power station connected to the grid. In case of standalone system, uncertainty of wind availability presents more serious problem requiring some sort of storage element, supplemental source or even capacity of load shedding. The disadvantages of wind power in the view of economic constrain ere due to high capital costs and the uncertainty of the wind.

Synchronous generator are used in conventional energy power plant but in wind power plant induction generator are preferred either in grid connected mode or isolated mode. Induction generators have relative advantageous features over traditional synchronous generators. These features are brush less rugged construction, low cost, less maintenance, simple operation, self-protection against faults, good dynamic response and capability to generate power at varying speed. The use of SEIG are noble methodology for generating electricity from wind energy, there is no extra power supply needed to produce the magnetic field it is convenient especially in remote areas.

1.1 Motivation

Wind power is the most reliable and developed renewable energy source over past decades. The previous work of researchers on clean renewable energy like wind for electrical power generation is the prime motivation to take up this project. Though the induction generator self-excitation phenomena is known since 1935, till date the work in the area of dynamic analysis, steady state analysis, control of voltage and frequency is concern. The use of isolated induction generator is preferable especially where extension of national grid is not feasible.

1.2 Thesis Objective

- Modelling and simulation of self-excited induction generator in d-q axes reference frame particularly in stationary reference frame.
- Determination of minimum excitation capacitance required for SEIG. To analyse the effect of variation of speed and excitation capacitance on generated terminal voltage.
- Analysis of closed loop voltage control scheme for SEIG using current controlled voltage source inverter (CC-VSI) with a dc link capacitor.
- Experimental investigation of self-excitation process in SEIG.

1.3 Literature Survey

In this section previous work carried out in the area of self-excited induction generator and different control schemes for voltage and frequency regulation are reviewed.

Basset and Potter in 1935 first reported that the induction machine can be operated as an induction generator in isolated mode by using excitation capacitors [2-3]. SEIG can represented either in steady state model or in dynamic model. The basic models of SEIG are impedance based model, admittance based model, d-q reference frame model, operational circuit based model, and power equations based model [4-12]. The per-phase steady state circuit model of SEIG can't be utilized to illuminate transient progress because of the fact that the model was determined from the steady state conditions of induction machine. For dynamic analysis, SEIG in three axes model is transformed to two axes (D-Q) model. The SEIG represented in D-Q axes model and analysed under steady state conditions are reported [12-16]. Different analytical methods are found in literature to calculate minimum capacitance required for self-excitation process [16-19]. A simple and direct method for calculation of excitation capacitance without involvement of iteration method has reported [20].

The main drawback of SEIG is that the terminal voltage and frequency are sensitive to load and speed variation. The disadvantages of voltage control method using switched capacitors is that, it regulates terminal voltage in steps. A voltage controller for standalone induction generator using PWM-VSI is reported [21]. Inverter based static compensator (STATCOM) dynamically regulate the SEIG terminal voltage [22]. To enhance the performance of the system, utilization of advanced control strategies, for example, vector control and sliding mode control have been recommended [23-24].

1.4 Organization of the thesis

The thesis is organized into five chapters, each of these is summarized below.

Chapter 1: Includes importance of renewable energy system to present world and motivation behind this project. In this chapter the literature related to isolated induction generator is reviewed. This involves strength and limitations of the previous work.

Chapter 2: Describes about the modelling of SEIG system. This chapter initially gives an idea of self-excitation phenomena in SEIG and followed by system performance and its operational problems. Describes the method to determine the minimum capacitance required for self-excitation process of SEIG.

Chapter 3: This chapter presents an experimental study of an induction machine being run as self-excited induction generator. Open and short circuit test are carried out to find machine parameters. The magnetizing characteristic curve of induction machine is determined from synchronous speed test.

Chapter 4: In this chapter terminal voltage control of an isolated induction generator using an current controlled voltage source inverter (CC-VSI) is discussed.

Chapter 5: In this chapter conclusion and future work are given.

CHAPTER 2

ANALYSIS AND MODELING OF SEIG SYSTEM

2.1 Introduction

SEIG system consist of a squirrel cage induction motor, prime mover, excitation capacitor and three phase load. The layout diagram of SEIG system shown in fig.2.1. The primary requirement for the induction machine to work as an induction generator is excitation current to produce rotating magnetic field. For grid connected machine it takes reactive current from grid whereas for a standalone machine reactive power is supplied locally by the help of shunt and series passive elements.

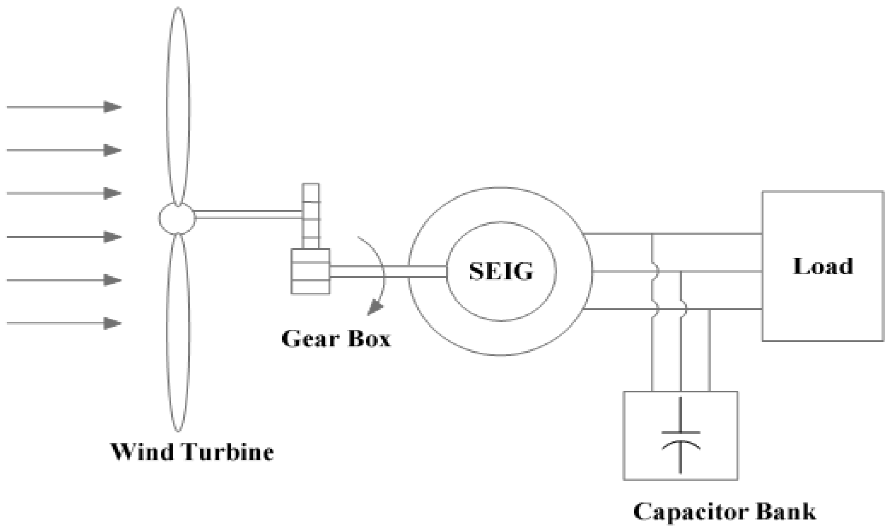


Fig. 2.1 – SEIG with a capacitor excitation system driven by a wind turbine

2.2 Modelling of Self-Excited Induction Generator

In electrical machine analysis a three-axes to two axes transformation is applied to produce simpler expressions that make complex systems simple to analyse and solutions easy to find. The three axes are representing the real three phase supply system. However, the two axes are fictitious axes representing two fictitious phases, displaced by 90^0, to each other. Here the assumption taken is that the three-axes and the two-axes are in a stationary reference frame. It can be rephrased as a transformation between abc and stationary dq0 axes. The conventional per-phase equivalent circuit representation of an induction machine is convenient to use for steady state analysis. However, the d-q representation is used to model the SEIG under dynamic conditions. The d-q representation of a SEIG with capacitors connected at the terminals of the stator windings and without any electrical input from the rotor side is shown in Fig. 2.2. Fig. 2.3 represents the stationary stator reference frame model in direct and quadrature axes separately.

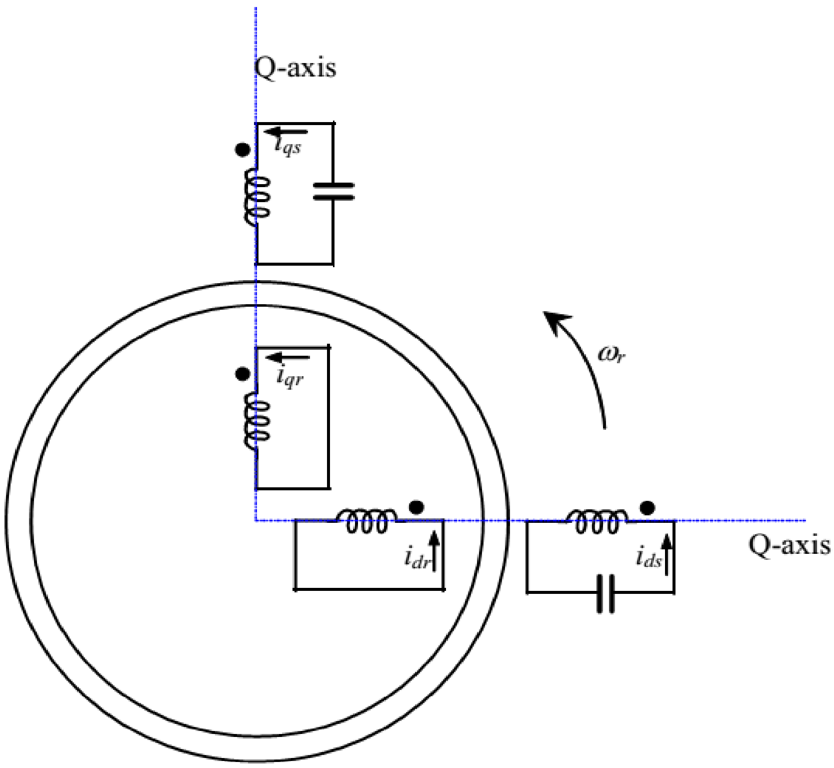


Fig. 2.2 – D-Q representation of self-excited induction generator

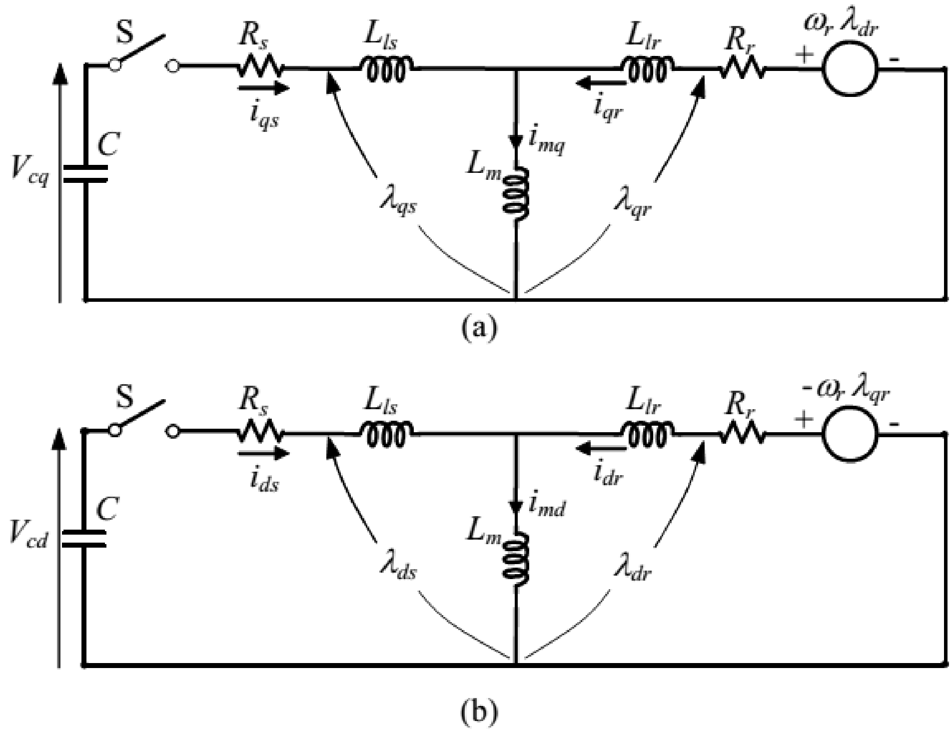


Fig. 2.3 – Circuit model of SEIG in dq stationary reference frame (a) q-axis circuit (b) d-axis circuit

The capacitor voltages in Fig. 2.3 can be represented as

$$v_{cq} = \frac{1}{C}\int i_{qs}dt + v_{cq0} \tag{2.1}$$

$$v_{cd} = \frac{1}{C}\int i_{ds}dt + v_{cd0} \tag{2.2}$$

Where $v_{cq0} = v_{cq}$, at t=0 and $v_{cd0} = v_{cd}$, at t=0 are the initial voltage along the q-axis and d-axis capacitors, respectively.

The rotor flux linkage is given by

$$\lambda_{qr} = L_m i_{qs} + L_r i_{qr} + \lambda_{qr0} \tag{2.3}$$

$$\lambda_{dr} = L_m i_{ds} + L_r i_{dr} + \lambda_{dr0} \tag{2.4}$$

Where

$L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$,

$\lambda_{qr0} = \lambda_{qr}$ at t=0, and $\lambda_{qr0} = \lambda_{qr}$ at t=0 are the remnant or residual rotor flux linkages along the q-axis and d-axis, respectively.

Let ω_r is the electrical angular speed of rotor, the rotational voltage in the rotor circuit along the q-axis is given by

$$\omega_r \lambda_{qr} = \omega_r \left(L_m i_{qs} + L_r i_{qr}\right) + \omega_r K_{dr0} \tag{2.5}$$

$$\omega_r \lambda_{dr} = \omega_r \left(L_m i_{ds} + L_r i_{dr}\right) + \omega_r K_{qr0} \tag{2.6}$$

Similarly the rotational voltage in the d axis of the rotor circuit is

$$\omega_r \lambda_{dr} = \omega_r (L_m i_{ds} + L_r i_{dr}) + \omega_r K_{qr0} \tag{2.7}$$

$$\omega_r \lambda_{qr} = \omega_r (L_m i_{qs} + L_r i_{qr}) + \omega_r K_{dr0} \tag{2.8}$$

Where $K_{dr0} = \omega_r \lambda_{qr0}$ and $K_{qr0} = \omega_r \lambda_{dr0}$ represent the initial d-axis and q-axis induced voltages respectively. The constant K_{dr0} and K_{qr0} are due to the remnant or residual magnetic flux in the core. ω_r is the equivalent electrical rotor speed in radians per second. That is,

Electrical speed = number of pole pairs × mechanical speed

The matrix equation for the d-q model of a self-excited induction generator, in the stationary stator reference frame, using equations (2.1-2.8) is given as:

$$\begin{bmatrix} R_s + pL_s + \frac{1}{pC} & 0 & pL_m & 0 \\ 0 & R_s + pL_s + \frac{1}{pC} & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_m \\ \omega_r L_m & pL_m & \omega_r L_m & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} v_{cq0} \\ v_{cd0} \\ -K_{qr0} \\ K_{dr0} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{2.9}$$

$$[Z][I_v] + [V_v] = [0] \tag{2.10}$$

Where Z is the impedance matrix, I_v is the stator and rotor currents vector and V_v is the voltage vector due to initial condition

2.2.1 Modelling of SEIG under Different Loading

The development of an induction generator model in dq reference frame involves transformation of variables from three axes to two axes. While transformation the per phase value of machine parameter, shunt capacitance and load impedances remains unaffected. Equivalent circuit model in dq reference frame is shown in fig.2.4. Each element of equivalent circuit in dq reference frame is same as per phase value of three phase machine.

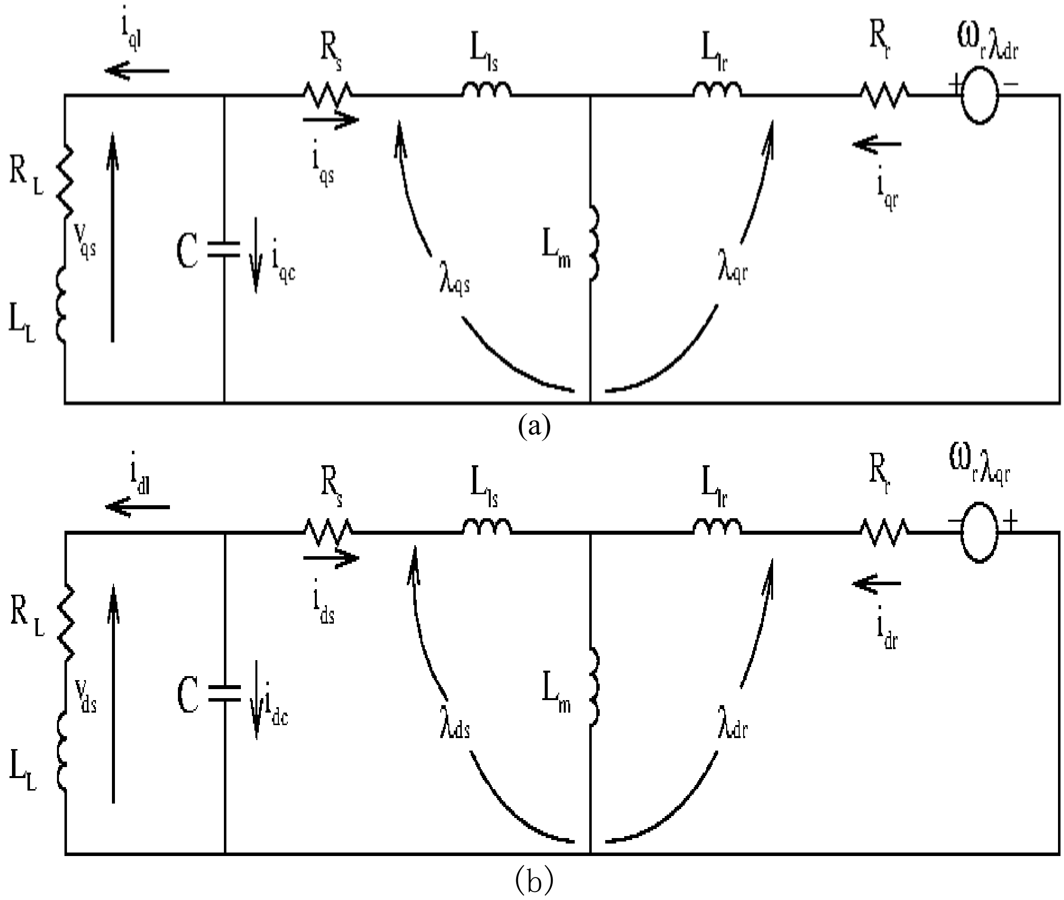


Fig. 2.4 – Circuit model of SEIG in dq stationary reference frame (a) q-axis circuit (b) d-axis circuit

From above circuit by applying KVL we can get the voltage equations as follows

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} \tag{2.11}$$

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} \tag{2.12}$$

$$0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} - \omega_r \lambda_{qr} \tag{2.13}$$

$$0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - \omega_r \lambda_{dr} \tag{2.15}$$

Where $v_{qr} = v_{dr} = 0$ (short circuited rotor)

The flux linkage expressions in terms of the currents can be written a

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

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

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

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

The following differential equation can be derived from eqn.(2.11-2.15)

$$\frac{di_{sq}}{dt} = \frac{1}{L_s L_r - L_m^2}\left[-L_s R_s i_{sq} - \omega_r L_m^2 i_{sd} + L_m R_r i_{qr} - \omega_r L_m L_r i_{rd} + L_r v_{sq}\right] \tag{2.16}$$

$$\frac{di_{sd}}{dt} = \frac{1}{L_s L_r - L_m^2}\left[-L_r R_s i_{sd} - \omega_r L_m^2 i_{sq} + L_m R_r i_{dr} + \omega_r L_m L_r i_{qr} + L_r v_{sd}\right] \tag{2.17}$$

$$\frac{di_{rq}}{dt} = \frac{1}{L_s L_r - L_m^2}\left[L_m R_s i_{sq} + \omega_r L_m L_s i_{sd} - L_s R_r i_{qr} + \omega_r L_s L_r i_{dr} + L_m v_{sq}\right] \tag{2.18}$$

$$\frac{di_{rd}}{dt} = \frac{1}{L_s L_r - L_m^2}\left[L_m R_s i_{sd} - \omega_r L_m L_s i_{sq} - L_s R_r i_{dr} - \omega_r L_s L_r i_{qr} + L_m v_{sd}\right] \tag{2.19}$$

Where

$$L_s = L_{ls} + L_m,\ L_r = L_{lr} + L_m$$

The expression for electromagnetic torque is given by

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)L_m\left[i_{qs}i_{qr} - i_{ds}i_{qr}\right] \tag{2.20}$$

Torque balance equation is represented by equation

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

The subscript d and q indication direct and quadrature axes variables of stator and rotor respectively; l for leakage component; v and i instantaneous voltage and current; λ flux linkage; i_m magnetizing current; L_m magnetizing inductance; r resistance; L inductance; P number of poles; ω_r electrical rotor speed; and T_e electromagnetic torque.

The expression for magnetizing current is given as

$$i_m = \sqrt{(i_{sd} + i_{rd})^2 + (i_{sq} + i_{rq})^2} \tag{2.21}$$

2.2.2 Modelling of Excitation Capacitor

The following state equations are involved in excitation system using d-q components of stator voltage $(v_{sd}\ \&\ v_{sq})$as state variables, from the circuit shown in Fig 2.4.

$$i_{dc} = i_{ld} + i_{cd} \tag{2.23}$$

$$i_{qc} = i_{lq} + i_{cq} \tag{2.24}$$

$$\frac{dv_{ld}}{dt} = \frac{1}{C}(i_{dc} - i_{ld}) \tag{2.25}$$

$$\frac{dv_{lq}}{dt} = \frac{1}{C}(i_{qc} - i_{lq}) \tag{2.26}$$

2.2.3 Modelling of Load Impedance

A balance load connected at the terminal of the induction generator can be represent symmetrically in dq reference frame shown in fig.2.4. The current equations for the balanced resistive load in d and q axes given by

$$i_{rq} = \frac{v_{sq}}{R_l} \tag{4.27}$$

$$i_{rd} = \frac{v_{sd}}{R_l} \tag{4.28}$$

And for R-L load. Voltage current relationship are given below.

$$v_{ld} = R_l i_{ld} + L_l \frac{di_{ld}}{dt}$$

$$i_{ld} = \frac{1}{L_l}\int v_{ld} + \frac{R_l}{L_l}\int i_{ld} \tag{4.29}$$

$$v_{lq} = R_l i_{lq} + L_l \frac{di_{lq}}{dt}$$

$$i_{lq} = \frac{1}{L_l}\int v_{lq} + \frac{R_l}{L_l}\int i_{lq} \tag{4.30}$$

The dynamics of induction generator competently represented by state space matrix formulation using d-q axes model. Solving these state variables, we can obtain the instantaneous voltages and currents during the self-excitation process, as well as during load variations. The state space matrix is shown below.

$$
\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \\ v_{sd} \\ v_{sq} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} = K\begin{bmatrix}
R_sL_r & -\omega L_m^2 & -R_rL_m & -\omega L_mL_r & L_r & 0 & 0 & 0 \\
\omega L_m^2 & R_sL_r & \omega L_mL_r & -R_rL_m & 0 & L_r & 0 & 0 \\
-R_sL_m & \omega L_mL_s & R_rL_s & \omega L_sL_r & -L_m & 0 & 0 & 0 \\
-\omega L_mL_s & -R_sL_m & -\omega L_sL_r & R_rL_s & 0 & -L_m & 0 & 0 \\
1/C_{cd}K & 0 & 0 & 0 & 0 & 0 & -1/C_{cd}K & 0 \\
0 & 1/C_{cq}K & 0 & 0 & 0 & 0 & 0 & -1/C_{cq}K \\
0 & 0 & 0 & 0 & 1/L_LK & 0 & -R_L/L_LK & 0 \\
0 & 0 & 0 & 0 & 0 & 1/L_LK & 0 & -R_L/L_LK
\end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \\ v_{sd} \\ v_{sq} \\ i_{Ld} \\ i_{Lq} \end{bmatrix}
$$

$$
+\begin{bmatrix}
-L_r & 0 & L_m & 0 \\
0 & -L_r & 0 & L_m \\
L_m & 0 & -L_s & 0 \\
0 & L_m & 0 & -L_s \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}\begin{bmatrix} v_{sd} \\ v_{sq} \\ v_{rd} \\ v_{rq} \end{bmatrix}
$$

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

Where C_{cd}, C_{cq} are the d-axis and q-axis equivalent capacitor value.

2.3 Conditions for Self-Excitation in Induction Generator

Basically an induction machine can be modelled using RLC circuit elements. Self-excitation in an induction generator is the growth of current and the associated increase in the voltage across the capacitor without an external excitation system. Transients that grow in magnitude can only happen if there is an external energy source that is able to supply all the power losses associated with the increasing current. The SEIG is able to have a growing transient because of the external mechanical energy source that is driving the induction generator. The transient process of terminal voltage growth continues until the iron parts gets saturate. The saturation changes the magnitude of magnetisation inductance L_m. Variation in L_m changes the roots of stator current characteristics equation of SEIG. If the real part of root is positive response is over damped as real part of root becomes zero the response becomes undammed with certain magnitude and frequency. Unlike the simple *RLC* circuit, the roots for the self-excited induction generator which can be derived from Equation (2.31). Magnitude of roots dependent on induction machine parameters, shunt capacitor and the rotor speed. Determination of the roots of the characteristic equation of the currents in the induction generator is the key to finding out whether the induction generator will self-excite or not.

Equation (2.9) can be re written as

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + pL_s + 1/pC & 0 & pL_m & 0 \\ 0 & R_s + pL_s + 1/pC & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} -v_{cq0} \\ -v_{cd0} \\ K_{qr} \\ -K_{dr} \end{bmatrix} \qquad (2.31)$$

The equation (2.31) representing a self-excited induction generator, can be solved by applying Cramer's rule.

Applying Cramer's rule to equation (2.31) results in

$$i_{ds} = \frac{\begin{bmatrix} R_s + pL_s + \frac{1}{pC} & -v_{cq0} & pL_m & 0 \\ 0 & -v_{cd0} & 0 & pL_m \\ pL_m & K_m & R_r + pL_r & -\omega_r L_r \\ \omega_r L_m & -K_{dr} & \omega_r L_r & R_r + pL_r \end{bmatrix}}{\begin{bmatrix} R_s + pL_s + \frac{1}{pC} & 0 & pL_m & 0 \\ 0 & R_s + pL_s + \frac{1}{pC} & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_r & R_r + pL_r \end{bmatrix}} \tag{2.32}$$

Since the characteristic equation of the d-axis stator current is the determinant of the denominator, only the denominator part of i_{ds} will be expanded. The determinant of the numerator will be represented by a variable *U*, which is dependent on the machine parameters, initial conditions, capacitance and electrical rotor speed. *U* affects only the magnitude of the current i_{ds} and does not contain any information on the behaviour of the resulting current. The determinants in Equation (2.32) can be evaluated to give

$$i_{ds} = \frac{U}{\left(A_6 P^6 + A_5 P^5 + A_4 P^4 + A_3 P^3 + A_2 P^2 + A_1 P^1 + A_0\right)\left(P^2 C^2\right)} \tag{2.33}$$

Where

$$A_6 = C^2 (L_s^2 L_r^2 - 2L_s R_r L_m^2 + L_m^4)$$

$$A_5 = 2C^2 (R_s L_s L_r^2 - L_s R_r L_m^2 + L_r L_s^2 R_r - L_s R_r L_m^2)$$

$$A_4 = C^2 \left(L_s^2 \left(\omega_r^2 L_r^2 + R_r^2\right) L_r^2 R_s^5 + 4L_r R_s R_r L_s - 2L_r L_s L_m^2 \omega_r^2 + L_m^4 \omega_r^2 - 2R_s R_r L_m^2\right) + 2C\left(L_s L_r^2 - L_r L_m^2\right)$$

$$A_3 = 2\left(C^2 \left(L_s L_r^2 R_s \omega_r^2 - L_r L_m^2 R_s \omega_r^2 + L_s L_r R_s^2 + R_s L_s R_r^2\right) + C\left(R_s L_r^2 + 2L_s L_r R_r - R_r L_m^2\right)\right)$$

$$A_2 = 2L_s C\left(\omega_r^2 L_r^2 + R_r^2\right) + R_s^2 C^2 \left(\omega_r^2 L_r^2 R_r^2\right) - 2L_r C L_m^2 \omega_r^2 + L_r^2 + 4L_r R_s C R_r$$

$$A_1 = 2R_s C\left(\omega_r^2 L_r^2 + L_r^2\right) + 2R_r L_r$$

$$A_0 = \omega_r^2 L_r^2 + R_r^2$$

To determine roots of the characteristics equation, the denominator of Equation (2.33) is set to zero.

$$\left(A_6 P^6 + A_5 P^5 + A_4 P^4 + A_3 P^3 + A_2 P^2 + A_1 P^1 + A_0\right) = 0 \qquad (2.34)$$

$$(p - \sigma_1 + \omega_1)(p - \sigma_2 + \omega_2)(p - \sigma_3 \omega_3)(p - \sigma_4 + \omega_4)(p - \sigma_5 + \omega_5)(p - \sigma_6 + \omega_6) = 0 \qquad (2.35)$$

The transient and steady state solution due to each of the roots can be obtained by using partial fraction expansion. If there exists a root with a positive real part, then due to that specific root there will be self-excitation. The current and voltage will grow until the magnetising inductance saturate. Saturated value of magnetizing inductance makes the real part of the roots zero which shows that circuit is operating like undamped RLC circuit. From there on wards voltage and current shall oscillate with particular magnitude and frequency.

2.4 Method to Determine Minimum Capacitance Required for SEIG

The self-excitation process to initiate, a capacitor bank of suitable size must be connected across the terminals of induction motor, the core of which retains some residual flux. For a particular speed and given load, excitation capacitor should sufficient enough to provide VAR to produce rated voltage. An uncontrolled self-excited induction generator shows considerable variation in its terminal voltage, and output frequency under varying load. For symmetrical study the behaviour of such a standalone induction generator with a variable frequency output, it is convenient to analyse its steady state circuit model whose parameters are defined in terms of the base frequency. The new efficient and direct method is proposed to calculate required minimum capacitance and output frequencies under diversity of load. The per phase steady state, stator referred equivalent circuit of a SEIG normalised to the base frequency connected to a resistive- inductive load is shown in Fig.2.5. A capacitor of capacitance C is connected to provide the excitation VAR.

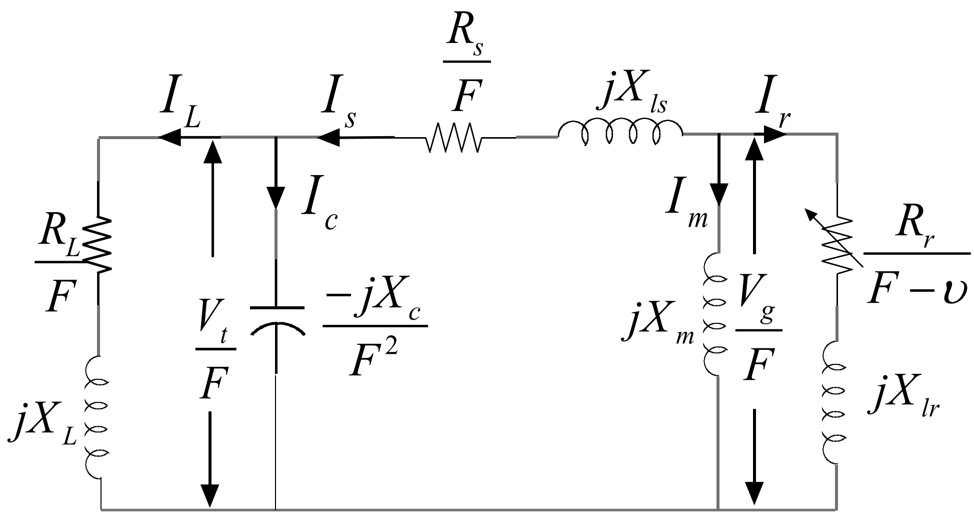


Fig. 2.5 – the stator referred circuit model of SEIG normalized to the base frequency

Applying KCL in inner loop of circuit shown in Fig. (2.5)**,** the loop equation for the current I_s can be written as

$$I_s Z = 0 \tag{2.35}$$

Where Z is the net loop impedance.

Since under steady-state excitation $I_s \neq 0$, it follows that $Z = 0$. By equating Z to zero value of unknown parameter that is capacitor is calculated.

Separating both real and imaginary parts by equating Z to zero.

The real part yields

$$-a_1F^3 + a_2F^2 + (a_3X_c + a_4) - a_5X_c = 0 \tag{2.36}$$

and the imaginary part yields

$$-b_1F^4 + b_2F^3 + (b_3X_c + b_4)F^2 - (b_5X_c + b_6)F - X_c b_7 = 0 \tag{2.37}$$

Where **a**$_i$, i = **1, 2. . .** 5 and b_i, i = **1,** 2... 7 are positive real constants

Stable operating point occurs in saturation region hence for steady state analysis saturated value of magnetizing reactance must be consider.

Solving eqns. (2.36) and (2.37).

For no load condition, $Z_L=\infty$. The value of excitation capacitive reactance is given as

$$X_{C\max} = \left(\frac{R_S}{F} + \frac{R_r}{F-v}\right)(X_{ls} + X_m)\frac{F^2(F-v)}{R_r} \tag{2.38}$$

$$\left(2X_{ls}X_m + X_1^2\right)F^3 - v\left(2X_1X_m + X_1^2\right)F^2 - \left(X_C\left(X_m + X_{ls}\right) + R_sR_r\right)F + vX_C\left(X_m + X_{ls}\right) = 0 \tag{2.39}$$

For no load operation slip is almost zero

$$F \approx V$$

$$F - V \approx 0$$

$$X_{C\max} \approx (X_{ls} + X_m)v^2 \tag{2.40}$$

For maximum value of capacitive reactance the value of capacitance is minimum. From eqn.(2.40) minimum value capacitor can be calculated.

For resistive load condition

$$Z_L = \frac{R_L}{F}$$

From eqn. (2.31) and (2.32)

$$X_{C\max} = \frac{R_L\left(\dfrac{R_s}{F^2} + \dfrac{R_r}{F(F-v)}\right)(X_{ls} + X_m)}{\dfrac{R_rR_L}{F^3(F-v)} + \dfrac{R_rR_s}{F^3(F-v)} - \dfrac{\left(2X_{ls}X_m + X_{ls}^2\right)}{F^2}} \tag{2.41}$$

For inductive load condition

$$Z_L = \frac{R_L}{F} + jX_L$$

From eqn. (4.36) and (4.37)

$$X_{C\max} = \frac{R_L\left(\frac{R_s}{F^2} + \frac{R_r}{F(F-v)}\right)(X_{ls} + X_m) - \left(2X_{ls}X_m + X_{ls}^2\right)X_L + \frac{R_s R_r X_L}{F(F-v)}}{\frac{R_r R_L}{F^3(F-v)} + \frac{R_r R_s}{F^3(F-v)} - \frac{\left(2X_{ls}X_m + X_{ls}^2\right)}{F^2} - \frac{X_L(X_{ls} + X_m)}{F^2}} \qquad (2.42)$$

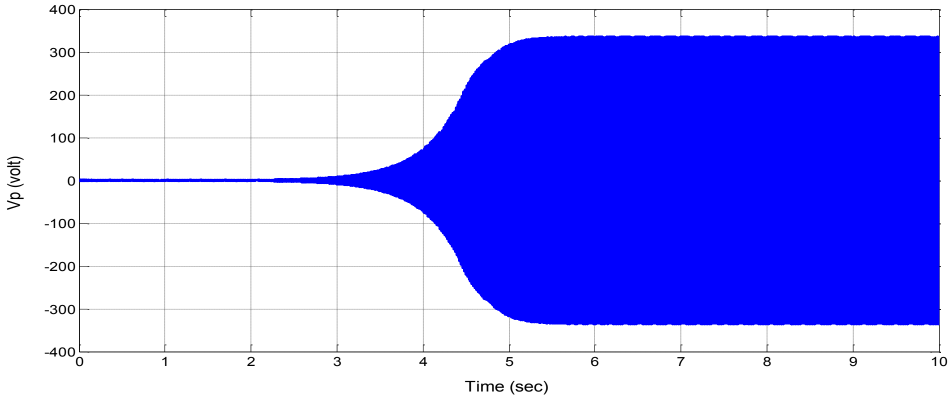
The capacitive reactance inversely proportional to capacitance, for maximum value of capacitive reactance the value of capacitor is minimum.

2.5 Results and Discussion

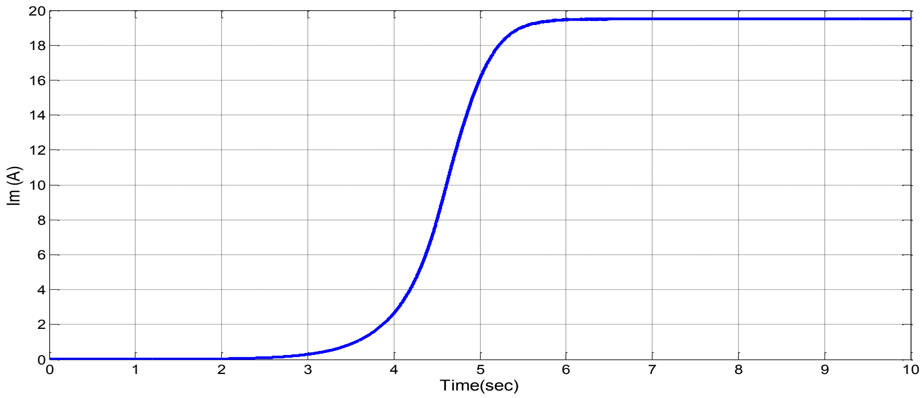
Digital simulation of dynamic model of self-excited induction generator has been carried out using numerical integration technique Rung-kutta fourth order method. For getting accurate result the step length must be as small as possible but on the other hand it will take more time. In this case 50μs is considered as step time. To clearly demonstrate the effect of excitation capacitor and speed on the voltage build up time and on the magnitude of steady state voltage, simulation carried out on the model of a 22KW induction machine whose parameter are given in appendix A.

2.5.1 Self-excitation Process

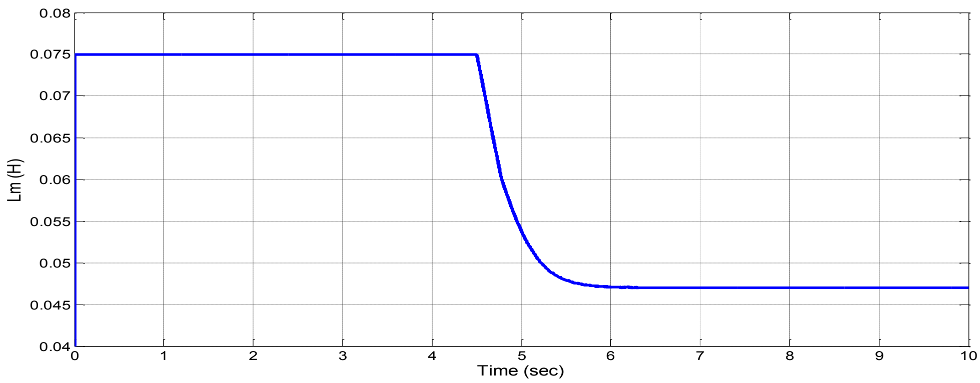
The fixed excitation capacitance is selected as $152\mu f$, for the 22kw induction machine. The SEIG driven by constant speed prime mover with 1700rpm at no load and simulation result are shown in fig 2.6(a,b,c). The voltage and current waveform of SEIG reach the steady state within 5.6 sec .the steady state peak value of SEIG terminal voltage is 335 volts (236 rms) and stator current is 18.44 at no load.



(a). Stator terminal voltage



(b). Magnetizing current

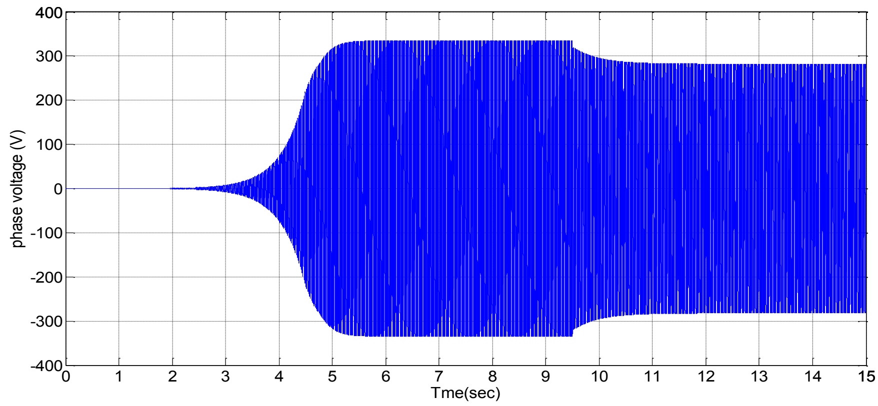


(c). Magnetizing inductance

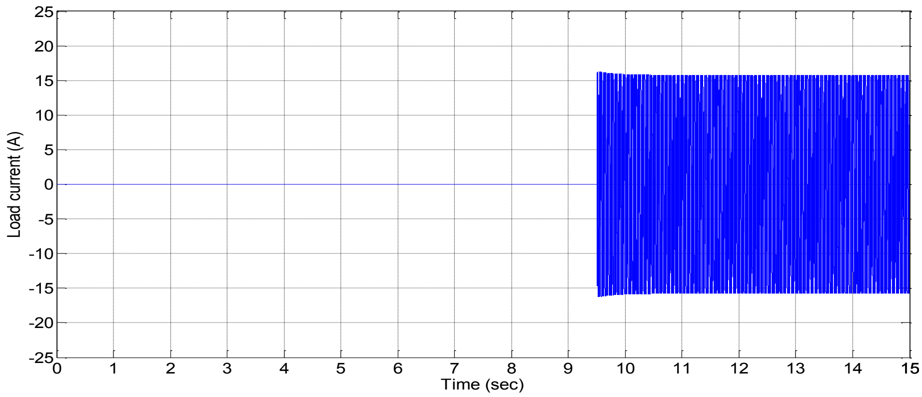
Fig.2.6

2.5.2 Loading condition

A load of 7 kw is applied to SEIG at t=9.5sec. It is observed that steady state peak voltage was 335 volt at no load reduces to 285 volt. The load current reaches steady state peak value of 15 ampere.



(a). Stator terminal voltage



(b). Load current

Fig. 2.7

2.6 Summary

This chapter presents the mathematical modelling of self-excited induction generator, excitation capacitor and load impedance. Using these d-q model equations a matrix has formulated which represents the state space dynamic model of conventional induction generator. Condition for self-excitation process of SEIG have analysed and minimum capacitance value requirement for self-excitation have calculated.

CHAPTER 3

EXPERIMENTAL VERIFICATION OF SEIG

3.1 Introduction

Machine modelling requires knowledge of the parameters of the machine. Whether the three-phase induction machine is modelled using the conventional equivalent circuit model or dq method, it needs information about parameters of the machine. To have an accurate model of the machine, which represents all the characteristics of the physical machine, the parameters need to be determined accurately. Accurate magnetizing characteristics can be obtained by running the machine at synchronous speed with help of a prime mover. Mutual inductance as a function of magnetizing current has determined through accurate curve fitting method. Finally the process of voltage build up in SEIG is studied in detail by performing a series of experiments.

3.2 Determination of Equivalent Circuit parameters of IM

The equivalent circuit parameters of three phase induction motor can be determined from open circuit, short circuit test and stator winding dc resistance test. While measuring dc resistance skin effect must be taken into account.

3.2.1 Open Circuit tests

The open-circuit test is conducted by supplying rated voltage to the stator while driving the induction motor at its synchronous speed using an external prime mover. When the motor runs at synchronous speed the slip, *s*, will be zero and rotor current becomes zero. For the open-circuit test, the conventional equivalent circuit model can be reduced to the one shown in Fig. 3.1.

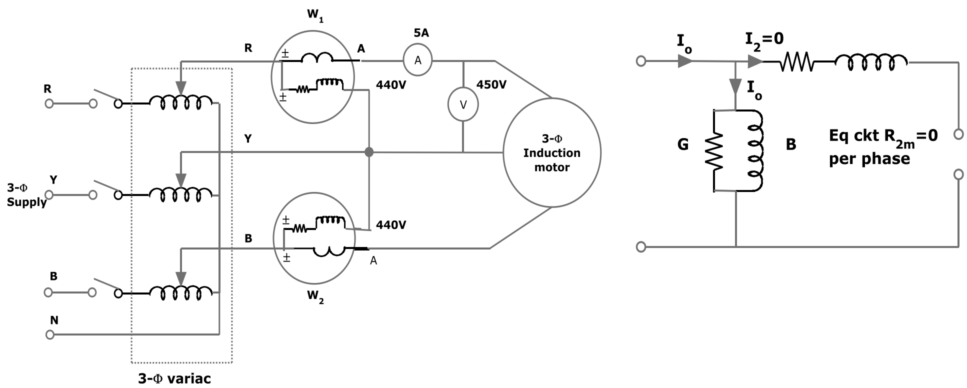


Fig. 3.1circuit connection diagram and equivalent circuit during no load test

Where V_0 - the measured open-circuit phase voltage

I_0 - the measured open-circuit phase current

P_0 - the measured open-circuit three-phase power

So at slip s = 0:

Total input resistance under open-circuit condition $R_0 = \frac{P_0}{3I_0^2}$ (3.1)

Total input impedance under open-circuit condition $Z_0 = \frac{V_0}{I_0}$ (3.2)

Total input reactance under open-circuit condition $X_0 = \sqrt{Z_0^2 - R_0^2}$ (3.3)

From the fig. 3.1 $X_0 = x_1 + X_m$ (3.4)

3.2.2 Short Circuit tests

The short-circuit test (or block rotor or standstill test) is conducted by blocking the motor using a locking mechanism to hold the induction motor at zero speed. At standstill, rated current is supplied to the stator. When the speed of the rotor is zero, the slip will be unity. Fig. 3.2 shows the equivalent circuit for the short circuit or block rotor test.

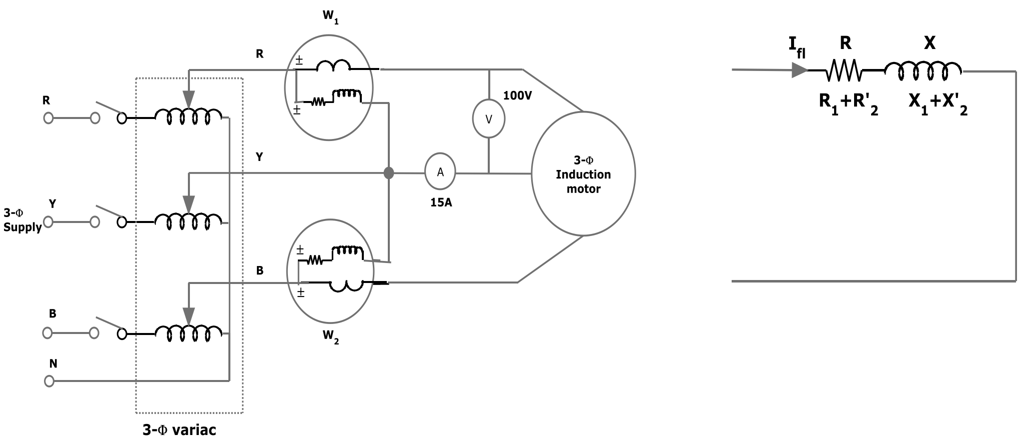


Fig. 3.2circuit connection diagram and equivalent circuit during short circuit test

Total input resistance under short-circuit condition $R_{sc} = \frac{P_{sc}}{3I_{sc}^2}$ (3.5)

Total input impedance under short-circuit condition $Z_{sc} = \frac{V_{sc}}{I_{sc}}$ $Z_{sc} = \frac{V_{sc}}{I_{sc}}$ (3.6)

Total input reactance under short-circuit condition $X_{sh} = \sqrt{Z_{sh}^2 - R_{sh}^2}$ (3.7)

From the fig. 3.2 $X_o = x_1 + x_2$ (3.8)

$$R_{sc} = r_1 + r_2\left(\frac{X_m}{x_2 + X_m}\right)^2 \quad (3.9)$$

For a wound rotor induction motors, x_1 is assumed to be equal to x_2

$$x_1 = x_2 = \frac{X_{sc}}{2} \quad (3.10)$$

By using the eq. (3.4, 3.9, 3.10) we can determined the equivalent circuit parameter of induction machine.

Where r_1, r_2, x_1, x_2 and X_m are stator referred leakage resistances and inductances of stator and rotor respectively.

3.3 Determination of Magnetization Characteristics of IM

Synchronous speed test:

1. The stator is connected to supply through auto- transformer. Rotor is coupled to external prime mover. This experiment is conducted at synchronous speed of rotor. It is similar to open circuit test because slip is zero.
2. A separately excited DC motor act as prime mover.
3. Then the terminal voltage, per phase current drawn by machine and power taken from supply were obtained by varying the stator voltage of the induction machine in steps, while varying adjust dc machine supply to retain the rotor speed equal to synchronous speed.
4. From the series of data taken, relationship between air gar voltage and magnetizing current can be determined from curve fitting method.

The relationship between V_g and I_m follow a standard form of nonlinear equation

$$V_g = FI_m\left(K_1 e^{K_2 I_m^2} + K_3\right) \tag{3.11}$$

Where K_1, K_2 and K_3 are constants

V_g is the air gap voltage

F is the frequency in p.u, defined as $F = \dfrac{f}{f_{base}}$

Where f is the rotor frequency.

f_{base} is the reference frequency used in the test to obtained the excitation curve.

The magnetizing reactance can be obtained directly from equation (3.11) as

$$X_m = \omega L_m = \frac{V_g}{I_m} F\left(K_1 e^{K_2 I_m^2} + K_3\right) \quad (3.12)$$

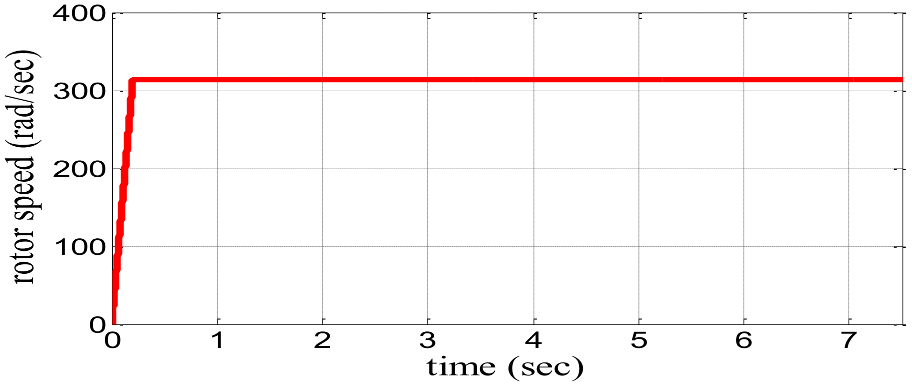
The variation magnetizing inductance L_m with I_m, is highly nonlinear function. The Lm verses I_m curve for the laboratory prototype induction machine is shown in fig.3.3.

3.4 Results and Discussions

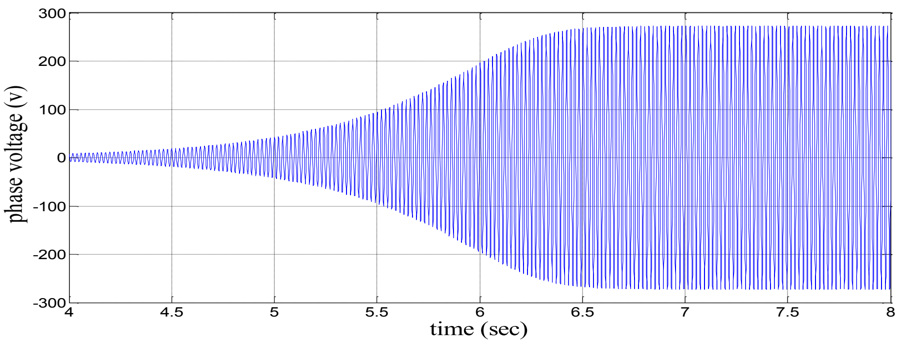
The rating of laboratory induction machine is given in table 3 of Appendix A. DC motor of separately excited configuration is taken as prime mover of induction generator. Mutual inductance as a function of magnetizing current is also experimentally determined and shown in Fig.3.3. Operating point should be chosen in the negative slope zone known as stable operating region. The prime mover speed is set at 3000 rpm and per phase value of delta connected excitation capacitors taken as 17μF. The stator terminal voltage is taken through a 100:1 probe. Oscilloscope setting are 13.6 V/div and 20 ms/div.

3.4.1 SEIG under no load

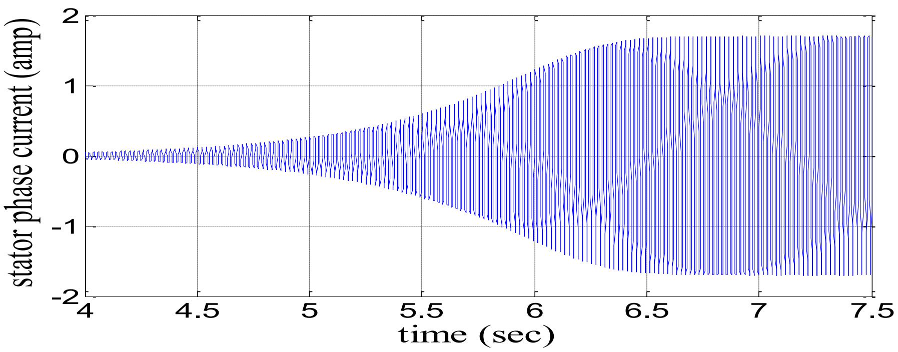
With excitation capacitance of 17 μf, rotor speed increased to 314 rad/sec, the generated phase voltage and phase current attains their steady state peak value of 274 v (rms 193.4v) and 1.65A (rms 1.16 A) in 6.5 sec. The simulated and experimental outcomes are shown in Fig.3.3. Fig.3.3 (b) shows the simulated stator terminal voltage and Fig.3.3 (d) shows the experimental one. Each experimental figure shown below is obtained from laboratory oscilloscope. Fig.3.3 (e) shows the variation of magnetizing inductance during voltage build up process. It is found out that the value of L_m varies from o.6 H to o.5 H with a variation of magnetizing current from 0 A to 1.7A.



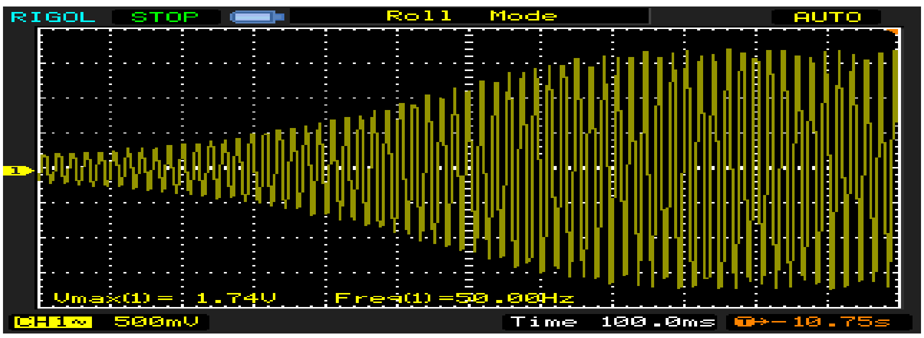
(a) Rotor speed



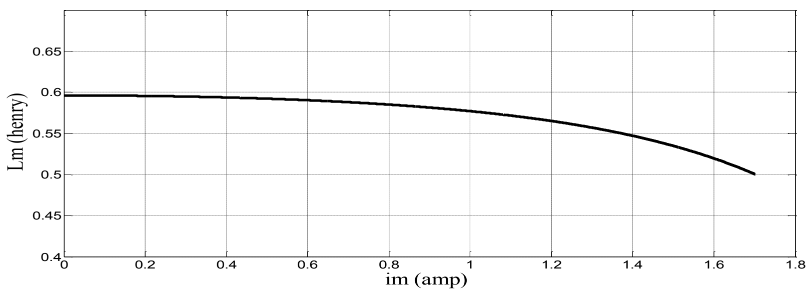
(b) Stator terminal voltage



(c) Machine line current



(d) Stator terminal voltage (experiment)

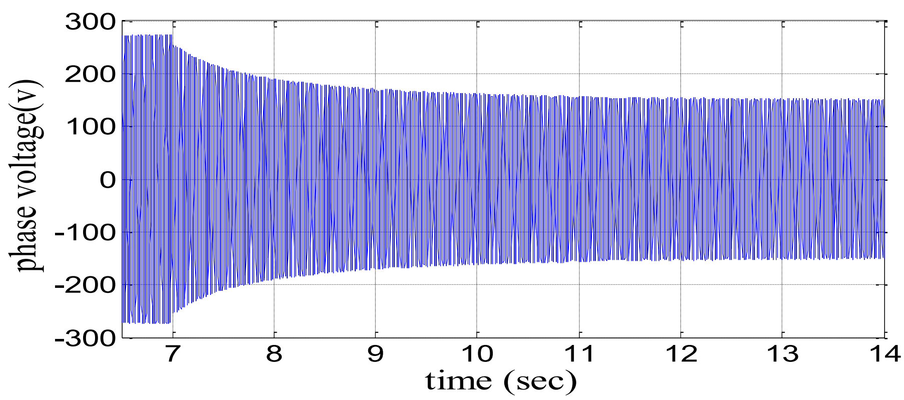


(e) Magnetizing characteristic

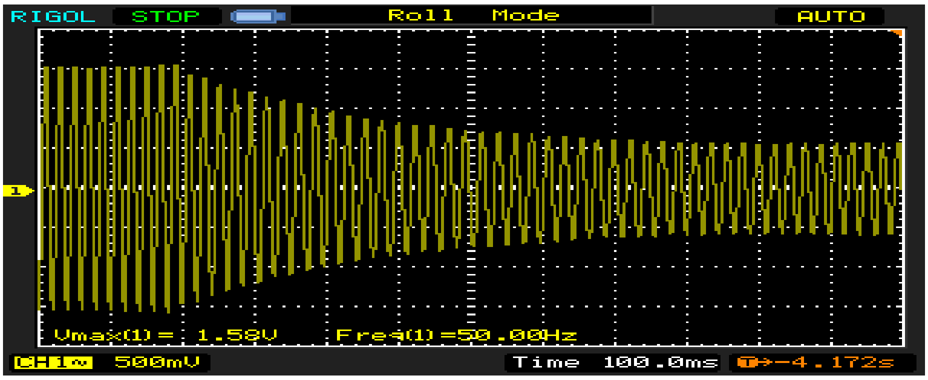
Fig. 3.3

3.4.2 SEIG under upf load

Here a load of 0.5 KW, *upf* brought to machine at 7 sec with excitation capacitance of 17µf. It is observed from Fig.3.4 the influence of load caused a steady state voltage of peak value 156v (rms 220v) and load current of 1.13A (rms). The simulated, experimental results of phase voltage are shown in Fig.3.4. Fig. 3.4(a) is simulated stator terminal phase voltage, (b) shows the experimental one.



(a) Stator terminal voltage



(b) Stator terminal voltage (experiment)

Fig.3.4

3.5 Summary

In this chapter, experiments performed on an induction generator are reported. First open circuit test and short circuit test have performed and equivalent circuit parameters are determined. The exact magnetizing characteristic is determined by rotating the induction machine at synchronous speed by prime mover. From the experimental data magnetization characteristics, L_m verses I_m curve has determined through accurate curve fitting technique. Mutual inductance is plotted as a function of magnetizing current and its value in the stable operating zone is determined from the graph. Finally the voltage build up process of SEIG was experimentally studied.

CHAPTER 4

A DYNAMIC VOLTAGE CONTROLLER FOR SEIG

4.1 Introduction

The main drawback of using induction generators excited by capacitor bank are their inherently poor voltage regulation and uncontrollable frequency of operation. The output voltage of a SEIG can be controlled by introducing an appropriate voltage regulation scheme. The number of schemes of voltage control have been recommended by many authors. The voltage control method using switched capacitor does not allow smooth control, it either increases or decreases voltage in steps. Voltage regulation with the help of saturating reactor is not economically considerable because it involves a potentially large size and weight. The series capacitor in long shunt configuration has better performance than shunt capacitance but there is a possibility of occurrence of series resonance when load is particularly inductive. An isolated induction generator connected to current controlled VSI with a single capacitor on the DC link side draws lagging or leading current to regulate the terminal voltage.

4.2 Close Loop Voltage Controller of SEIG

Variable voltage and frequency output of a SEIG is its major drawback which can be overcome by a large extent by using power converter with a DC- side capacitor. Reactive power exchange between generator and controller is adjusted by controlling switching pattern of converter. Due to switching the DC side capacitor of converter act like a three phase capacitor. The reactive current or VAR requirement by the induction generator comes from the converter through adjustment of magnitude and phase of current drawn by it.

The voltage regulator for the SEIG system consist of IGBT based current controlled voltage source inverter (VSI) with a electrolytic capacitor at dc link and control circuit to generate switching pulses is shown in Fig.4.1. The rating and parameter of the generator for which voltage regulator is developed is given in Appendix A, the prime mover of which could be constant speed variable power in nature. The voltage regulator connected to SEIG terminal through filter impedance. The control principle involves to regulate the terminal voltage of SEIG based on controlling the output current of the voltage source inverter. The converter can draw active and reactive current from the AC main of SEIG, decided by control circuit in order to regulate voltage level of induction generator. It is worth discussing to analysis the working principle of converter, how it exchange active and reactive power with AC supply. On DC side of converter an electrolytic capacitor is present which initially excited by AC bus through rectifier action or it is charged initially. We cannot expect reactive power at DC bus since reactive power is not produce at zero frequency.

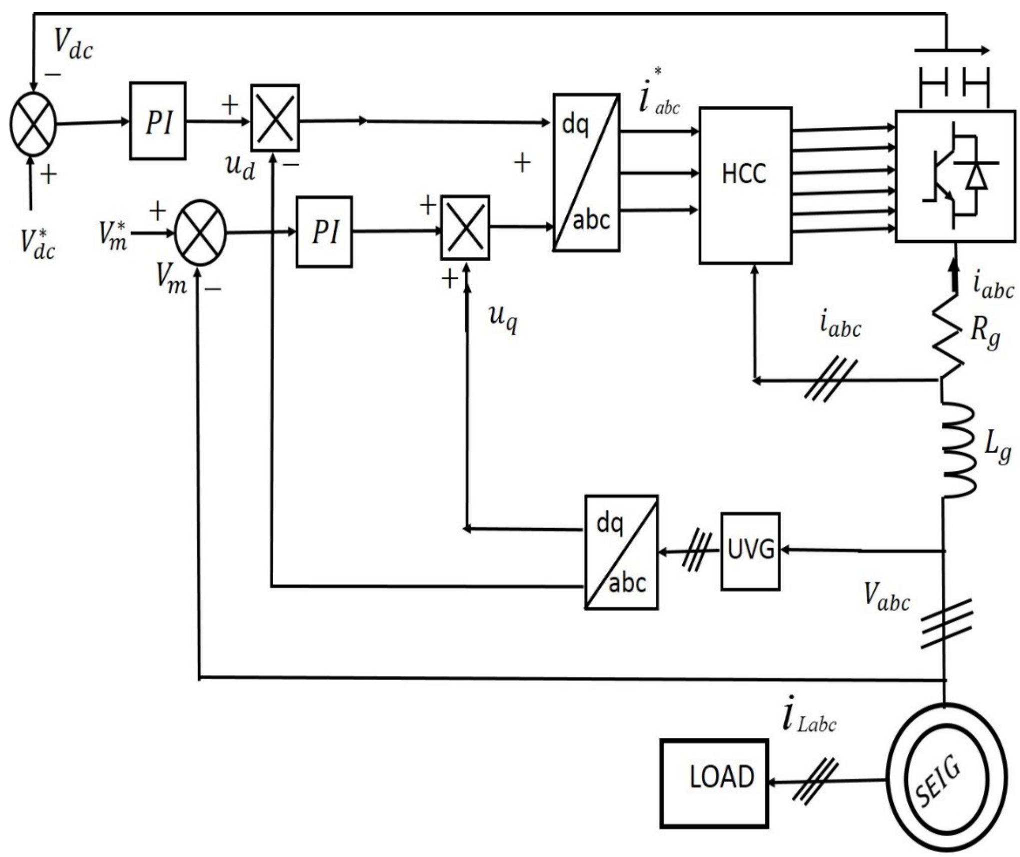


Fig 4.1. Control scheme voltage regulator for three phase SEIG

The DC capacitor play no role in reactive power generation. The converter simply interconnects the three terminals in such a way that the reactive current can flow in AC main lines. The converter produces a circulating current among the phases with zero average power exchange. Semiconductor switches are not lossless, they dissipate some amount of active power during switching and conduction time. The active power loss during switching is supplied by the DC bus by reducing capacitor voltage. However this loss can provided from AC source instead from DC bus to keep the DC voltage at constant level. The active power drawn from AC source depends on magnitude of in phase current. Hence the magnitude of in phase current drawn from AC source depends on DC voltage level. The reactive power supplied by the converter which regulates voltage level of SEIG, depend on the quadrature component of current drawn by converter. Hence the magnitude of quadrature component of current decided by the AC voltage level.

The voltage error signal generated from the difference between maximum value of SEIG terminal voltage and the reference maximum voltage, the voltage error signal processed through PI controller, the output of PI controller adjust the magnitude of reference reactive current that would be drawn by converter. The voltage error signal generated from the difference between actual DC capacitor voltage sensed at the DC bus and the reference DC bus voltage. The voltage error signal processed through PI controller, the output of PI controller adjust the magnitude of active current that would be drawn by converter.

4.3 Modelling of Controller Circuit

4.3.1 Modelling of Voltage Source Inverter

The VSI is operating in current controlled mode and modelled by following differential equation

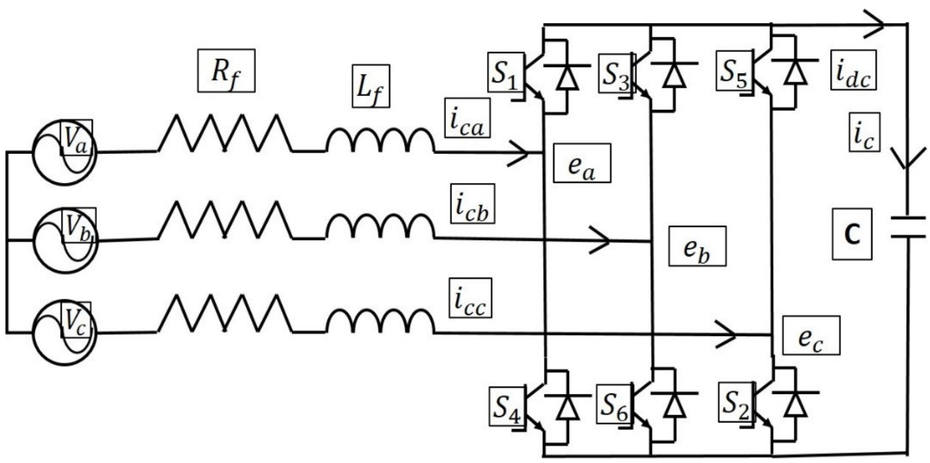


Fig 4.2. Voltage source inverter with DC link capacitor

$$pi_{ca} = -\frac{R_f}{L_f} i_{ca} + \frac{1}{L_f}\left(v_a - e_a\right) \tag{4.1}$$

$$pi_{cb} = -\frac{R_f}{L_f} i_{cb} + \frac{1}{L_f}\left(v_b - e_b\right) \tag{4.2}$$

$$pi_{cc} = -\frac{R_f}{L_f} i_{cc} + \frac{1}{L_f}\left(v_c - e_c\right) \tag{4.3}$$

$$pv_{dc} = \frac{i_{ca}S_A + i_{cb}S_B + i_{cc}S_C}{C_{dc}} \tag{4.4}$$

Where S_A, S_B, and S_C are switching functions. V_a, V_b and V_c are three phase sinusoidal AC terminal voltages of SEIG. V_{dc} is the DC bus voltage. L_f and R_f are the filter inductance and resistance respectively.

e_a, e_b and e_c are the three phase AC output voltage of inverter. These voltages may be expressed as

$$e_a = V_{dc}\frac{\left(2S_A - S_B - S_c\right)}{3} \tag{4.5}$$

$$e_b = V_{dc}\frac{\left(-S_A + 2S_B - S_c\right)}{3} \tag{4.6}$$

$$e_c = V_{dc}\frac{\left(-S_A - S_B + 2S_c\right)}{3} \tag{4.7}$$

The switching function S_A assumes the values of 1 and 0. S_A is 1 if upper switch of leg A is on and 0 for lower switch if on.

4.3.2 Estimation of VSI Reference Current

The maximum amplitude of phase voltage

$$V_m = \sqrt{\frac{2}{3}\left(v_a^2 + v_b^2 + v_c^2\right)} \tag{4.8}$$

The unit vectors voltages can be defined as

$$u_a = \frac{v_a}{V_m} \tag{4.9}$$

$$u_b = \frac{v_b}{V_m} \tag{4.10}$$

$$u_c = \frac{v_c}{V_m} \tag{4.11}$$

Quadrature axis and direct axis component is derived as

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{4.12}$$

The quadrature component of VSI reference current is derived from the voltage error between amplitude V_m of the AC voltage at the SEIG terminal and set reference current V_m^* is given by

$$\varepsilon(t) = V_m^* - V_m \tag{4.13}$$

The output of PI controller is given as

$$I_q = K_p(\varepsilon(t)) + K_I \int_0^t \varepsilon(t)dt \tag{4.14}$$

The quadrature component of VSI reference current reference currents ere estimated as

$$I_d^* = u_d * I_d \tag{4.14}$$

The quadrature axis component of VSI reference current is derived from the voltage error between DC bus bar voltage V_{DC} and set reference current V_{DC}^* is given by

$$\varepsilon(t) = V_{DC}^* - V_{DC} \tag{4.15}$$

The output of PI controller is given as

$$I_d = K_p(\varepsilon(t)) + K_I \int_0^t \varepsilon(t)dt \tag{4.16}$$

The direct axis component of VSI reference current reference currents ere estimated as

$$I_q^* = u_q * I_q \tag{4.17}$$

Three phase VSI reference current is given by

$$\begin{bmatrix} I_{ca}^* \\ I_{cb}^* \\ I_{cc}^* \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \end{bmatrix} \begin{bmatrix} I_q^* \\ I_d^* \\ I_0^* \end{bmatrix} \tag{4.18}$$

4.3.3 Hysteresis Current Controller

The ON/ OFF switching pattern of the gate driving signal to IGBTs, generated from hysteresis comparator, is represented mathematically as

If $i_a < (i_a^* - hb)$ switch S_1 off and switch S_4 on, S_A=0

If $i_a > (i_a^* + hb)$ switch S_1 on and switch S_4 off, S_A=1

If $i_b < (i_b^* - hb)$ switch S_3 off and switch S_6 on, S_B=0

If $i_b > (i_b^* + hb)$ switch S_3 on and switch S_6 off, S_B=1

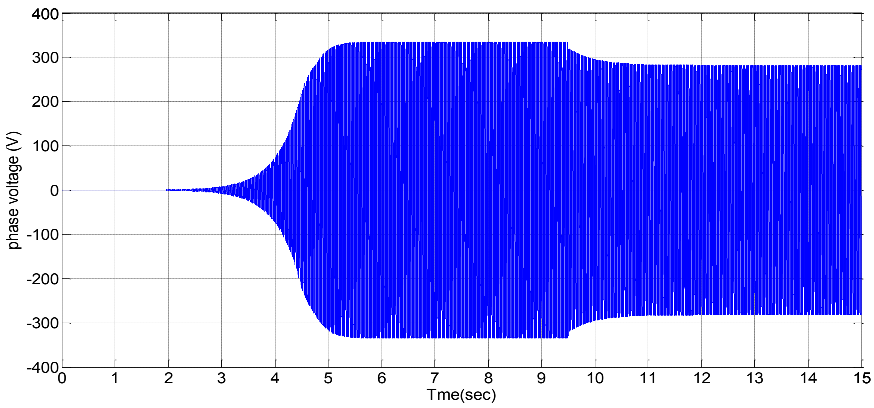
If $i_c < (i_c^* - hb)$ switch S_5 off and switch S_2 on, S_C=0

If $i_c > (i_c^* + hb)$ switch S_5 on and switch S_2 off, S_C=1

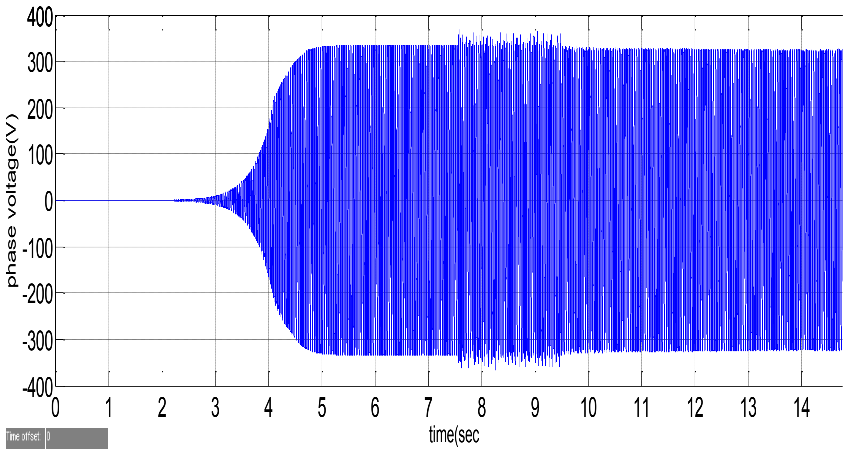
Where hb is the current band of the hysteresis current controller, value of which is given in the Appendix.

4.4 Results and Discussion

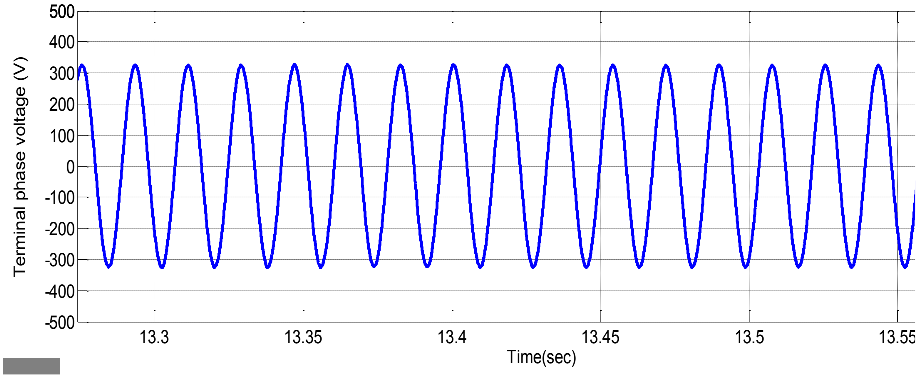
The effectiveness of the proposed voltage regulator in controlling terminal voltage of a three phase SEIG is verified by application of a 7 KW upf load. The self-excited induction generator terminal voltage with load before and after the application of controller and dc ink voltage are shown in fig.4.2. Uncontrolled terminal voltage shown in 4.2(a), a controlled output voltages with load shown in fig.4.2(b) and fig4.2(c). The line current of VSI shown in the figure 4.2(e).



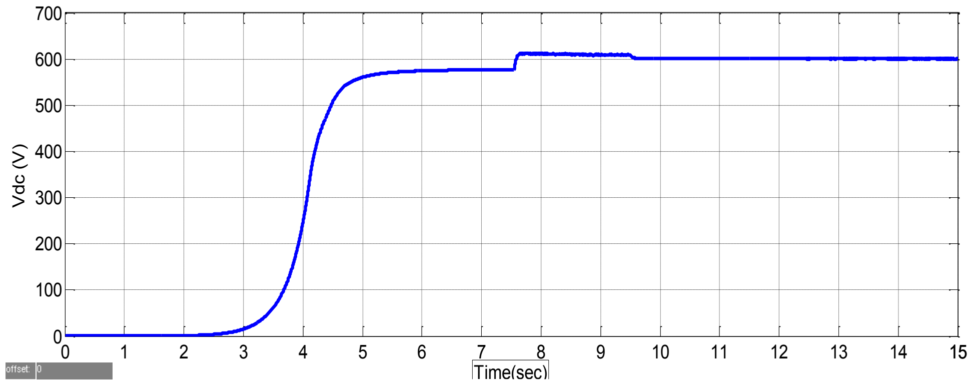
(a) Uncontrol stator terminal voltage



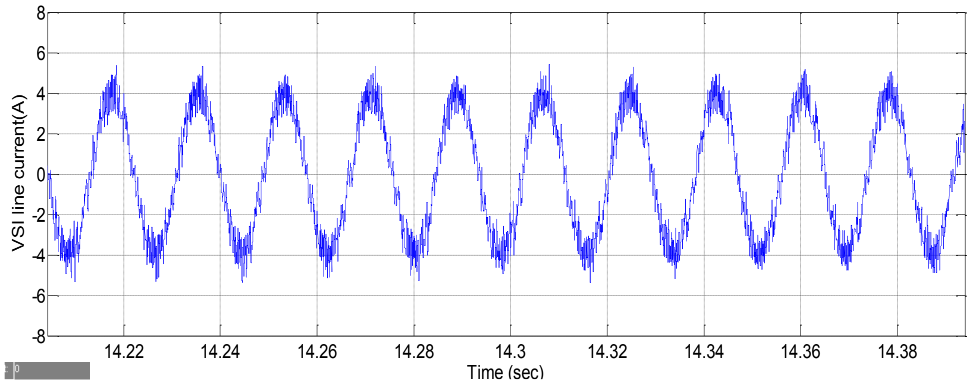
(b) Control stator terminal voltage



(c) Control stator terminal voltage



(d) Dc-link voltage



(e) VSI line current

Fig.4.2 Controlled and uncontrolled terminal voltage

4.5 Summary

In this chapter dynamics of voltage controller is presented, which controls the terminal voltage of SEIG under variation of step change load. The mathematical modelling of voltage regulator has been derived by a differential equation, presented in state space model. The derived model has been simulated through Matlab/Simulink environment. It is found that the proposed regulator is capable of providing reactive power demanded by SEIG and load to regulate the terminal voltage of SEIG.

CHAPTER 5

CONCLUSIONS

The operation of induction machine as a self-excited induction generator in isolated mode is explored both by experimentally and through simulation. The drawbacks of a SEIG without any control is its varying terminal voltage and frequency making it unfriendly with many applications. The modelling of induction machine in stationary reference frame is done to have dynamic analysis. Magnetizing inductance is the main parameter governing the voltage build up process. The drawback of varying terminal voltage is overcome using scalar voltage control method. Control scheme utilises current control voltage source inverter with dc link capacitor and two PI controllers. Under varying load conditions, PI controllers prove out to be good tracker of the reference making the terminal voltage constant in the given conditions. The impedance angle created between the generated output and inverter output is utilised for active power and reactive power transfer thus acting as voltage controller. Experiment is undertaken on 1.1 kw induction machine. Major contributions of this thesis are dq axes modelling of induction generator, mathematical analysis of SEIG, analysis of effect of speed, excitation capacitance and mutual inductance on self-excitation process of induction generator. Design and analysis of closed loop voltage control scheme for SEIG and Experiments on open loop voltage build-up process of SEIG are studied.

Suggestion for Future Work

The analysis and explanations presented in this thesis provide a good foundation for further research in the area of isolated induction generators. Some of the topics recommended for future work are:

- Development of a induction generator model that takes into account of core loss component for dynamic analysis of self-excited induction generator.
- Instead of current control technique SPWM and SVPWM based voltage controller can be implemented for SEIG.

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APPENDIX A

TABLE A.1

22KW, 4pole induction Machine Parameter

Power	22 KW
Voltage	415 V
Current	40 A
R_s (Ω)	0.2511
R_s (Ω)	0.2489
X_{ls} (Ω)	0.439
X_{lr} (Ω)	0.439
J (kg m2)	0.305

TABLE A.2

(L_m vs I_m characteristics) of 22KW induction machine

I_M (A)	L_M (H)
$I_M < 8$	0.075
$8 < I_M < 13$	$0.075 - 0.003(i_m-8)$
$13 < I_M < 23$	$0.06 - 0.002(i_m-13)$
$I_M > 23$	0.041

TABLE A.3

1.1KW, 3 phase, 2pole induction Machine Parameter

POWER	1.1 KW
VOLTAGE	380 V
CURRENT	2.6 A
R_S (Ω)	5.5068
R_S (Ω)	5.538
L_{LS} (H)	0.01125
L_{LR} (H)	0.01125