DESIGN ANALYSIS AND DEVELOPMENT OF STAND ALONE POWER UNIT

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With Specialization in Power Apparatus and Electric Drives)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work that is being presented in this dissertation report entitled **"DESIGN ANALYSIS AND DEVELOPMENT OF STAND ALONE POWER UNIT"** submitted in partial fulfillment of the requirements for the award of the degree of **Master of Technology** with specialization in **Power Apparatus and Electric Drives,** to the **Department of Electrical Engineering, Indian Institute of Technology, Roorkee**, is an authentic record of my own work carried out, under the guidance of **Dr. S. P. Singh**, Professor, Department of Electrical Engineering.

The matter embodied in this dissertation report has not been submitted by me for the award of any other degree or diploma.

Date: 29/6/07
Place: Roorkee

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

June 29, 07

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(M. Raghavendra)

ABSTRACT

The fast depletion of fossil fuels has drawn attention towards the use of non conventional energy sources wind, tidal, biomass and small hydro energy. In remote areas which are rich in non conventional energy sources, stand alone systems are considered as promising option due to difficulty and costly to install grid systems for electrification. The squirrel cage induction generator is most suitable to convert the mechanical energy into electrical energy due to its inherent advantages.

It is well known that an externally driven induction machine can be successfully operated as an induction generator with sustained self excitation when an appropriate value of a capacitor bank is appropriately connected across the terminals of the induction machine. Such an induction machine is called a self-excited induction generator (SEIG). Self-Excitation process in induction generators is a complex physical phenomenon, which has been studied extensively in the past. The interest in this topic is sustained primarily due to its application in isolated power systems for power generation.

The terminal reactive power support in case of isolated generator is required to be adjustable so that the proper amount of reactive power can be supplied under different operating conditions. Consequently, a controllable terminal voltage for the self-excited generator can be obtained through an appropriate control scheme. To fulfill the objective of varying the equivalent capacitance connected to the generator terminal continuously; some power electronic circuits need to be introduced into such a system.

The self-excited induction generator is analyzed using the generalized-machine theory transient representation of the machine. Such an analysis produces instantaneous currents, which can be used to investigate the process of current and voltage build up during self-excitation and similarly perturbations due to load changes.

In this dissertation work the transient analysis of self-excited induction generator is carried out. The Dynamic model of three phase squirrel cage induction generator is developed on stationary d-q axes reference frame and the instantaneous values of direct and quadrature axis stator and rotor currents and voltages for different load currents are found by solving these differential equations representing the dynamic behavior of the machine. This includes the building up of voltage during the initiation stage of self-excitation and the perturbations of the terminal voltage and the stator current, which result from load changes.

The work is extended to chopper based ELC which tries to control the duty cycle of chopper so that generated power is divided between the dump load and consumer load and hence maintaining the generator output power constant. The fourth chapter includes the design of ELC and development of hard ware chopper control circuit. In the fifth chapter the design of full rating and reduced rating STATCOM for UPF loads and the Mathematical modeling of STATCOM for improvement of voltage regulation are discussed. Finally, the last chapter 6 includes the simulation results of transient behavior of SEIG and SEIG-STATCOM. This also includes the introduction to DSP for future work.

CONTENTS

LIST OF SYMBOLS

SEIG	Self excited induction generator
ELC	Electronic load controller
R_s	Per phase stator resistance
R_r	Per phase rotor resistance
C	No load Excitation capacitor
C_a, C_b, C_c	Excitation capacitors
L_m	Magnetizing Inductance
R_f	Filter Resistance
L_f	Filter Inductance
L_s	Per phase stator Leakage inductance
L_r	Per phase Rotor Leakage Inductance
T_e	Electro magnetic torque
P	No of Poles
J	Moment of inertia
F	Per Unit frequency
V_g	Air gap voltage
V_t	Terminal Voltage of SEIG
i_a, i_b, i_c	SEIG line currents
i_{cca}, i_{ccb}, i_{ccc}	Capacitor currents
i_{Da}, i_{Db}, i_{Dc}	AC currents of ELC
T_{shaft}	Shaft torque
R_L	Load resistance

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CHAPTER 1

INTRODUCTION

1.1 General

There is rapid development from the past few decades, in the use of renewable energy resources for electrical power generation which plays a key role in rural electrification and industrialization programs. In remote areas where a central grid connection is expensive or difficult to provide, small-scale autonomous power systems may be developed for supplying the local customers, thereby reducing the cost of the distribution lines. The system cost can further be reduced by using the cagetype, three-phase, self-excited induction generator (SEIG) as the electromechanical energy converter.

The excessive use of conventional sources of energy has increased the fast depletion of the fuel reserves. This has resulted in the subsequent increase in energy cost, the environmental pollution and above all the global warming. Many studies have been conducted to rationalize the use of the conventional sources of the energy and to explore the use of other forms of the energy. This has motivated the world wide interesting in reducing the pollution and conservation of the limited conventional fuels by encouraging more and more use of the energy available from the non-conventional/renewable sources such as the wind, the biogas, the tidal waves and the small hydro power stations on the running canals and rivulets etc. the potential of the energy available from the small hydro and the wind sources, seems to be quite promising to meet the future energy demands, especially in the remote and isolated areas. The objective of the harnessing of such non-conventional energy sources could be achieved in a big way by the development of the suitable low cost generating systems. The electric power generation from these sources will not only supply the energy to the remote and isolated areas, but can also supplement the power requirements of the inter connected systems. However these systems will become more viable if their cost is reduced to the minimum. Therefore, the squirrel cage rotor induction generators are receiving much attention for such applications due to its low cost and robust construction.

a) *AC–DC–AC Link:* In this, the ac output of the three-phase alternator is rectified by using a bridge rectifier and then converted back to ac using line-commutated inverters. Since the frequency is automatically fixed by the power line, they are also known as synchronous inverters.

b)Double Output Induction Generator (DOIG): The DOIG consists of a three-phase wound rotor induction machine that is mechanically coupled to either a wind or hydro turbine, whose stator terminals are connected to a constant voltage constant frequency utility grid. The variable frequency output is fed into the ac supply by an ac–dc–ac link converter consisting of either a full-wave diode bridge rectifier and thyristor inverter combination or current source inverter (CSI)-thyristor converter link.

One of the outstanding advantages of DOIG in wind energy conversion systems is that it is the only scheme in which the generated power is more than the rating of the machine. However, due to operational disadvantages, the DOIG scheme could not be used extensively. The maintenance requirements are high, the power factor is low, and reliability is poor under dusty and abnormal conditions because of the sliding mechanical contacts in the rotor. This scheme is not suitable for isolated power generations because it needs grid supply to maintain excitation.

(iii)Variable-Speed Variable Frequency: For variable speed corresponding to the changing derived speed, SEIG can be conveniently used for resistive heating loads, which are essentially frequency insensitive.

1.3 Advantages of SEIG [22]

- Lower capital cost.
- Simple and rugged construction.
- Self-excited induction generator do not require any sophisticated control and can provide reliable and relatively inexpensive means to generate electricity for loads, where small frequency variation is allowed up to certain extent.
- A separate dc source is eliminated in case of a SEIG, which is necessary for excitation in case of a synchronous generator. Maintenance problem like brush maintenance is removed.

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An induction machine can be used as an induction generator in two ways, namely, in the externally excited mode and in the self excited mode. The externally excited induction generator draws its excitation in terms of lagging magnetizing current from power source to which it is connected, to produce its rotating magnetic field. The frequency and voltage of the externally excited induction generator is governed by the frequency and voltage of the power source with which it is excited. However, if an appropriate capacitor bank is connected across the terminals of rotating induction machine, a voltage is developed across the machine terminals. The residual magnetism in the magnetic circuit of the machine sets up small voltage in its stator winding. This voltage is applied to the capacitor and causes the flow of lagging current in the stator winding which produces rotating flux in its air gap. This rotating field produces the voltage across the machine terminals. Such generators are called as the "Self Excited Induction Generators (SEIG)" and can be used to generate the power from constant as well as variable speed prime movers.

1.2 Classification of Induction Generators [32]

On the basis of rotor construction, induction generators are two types (i.e., the wound rotor induction generator and squirrel cage induction generator). Depending upon the prime movers used (constant speed or variable speed) and their locations (near to the power network or at isolated places), generating schemes are classified as :

i) constant-speed constant-frequency (CSCF)

ii) variable-speed constant-frequency (VSCF)

iii) variable-speed variable-frequency (VSVF)

(i) Constant-Speed Constant Frequency (CSCF): In this scheme, the prime mover speed is held constant by continuously adjusting the blade pitch and/or generator characteristics.

(ii) Variable-Speed Constant Frequency: The variable-speed operation of wind electric system yields higher output for both low and high wind speeds .This results in higher annual energy yields per rated installed capacity. Both horizontal and vertical axis wind turbines exhibit this gain under variable-speed operation. Popular schemes to obtain constant frequency output from variable speed are as shown.

a) AC–DC–AC Link: In this, the ac output of the three-phase alternator is rectified by using a bridge rectifier and then converted back to ac using line-commutated inverters. Since the frequency is automatically fixed by the power line, they are also known as synchronous inverters.

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- A separate dc source is eliminated in case of a SEIG, which is necessary for excitation in case of a synchronous generator. Maintenance problem like brush maintenance is removed.

- Main feature is the automatic protection against external short circuit, which causes the excitation to collapse and consequently no current flow.
- The variable speed prime mover need not be governed.
- SEIG can be operated in parallel with out any problem of synchronization i.e. they may operate at different speed and still share load.

1.4 Disadvantages of SEIG

- It has poor inherent frequency and voltage regulation.
- Its efficiency is comparatively less due to higher core and magnetizing current losses.
- More heating in rotor.
- The terminal voltage waveform is likely to be distorted because of the need to stabilize the excitation for saturated conditions.
- A high voltage is generated at the terminals if synchronous machine connected to induction generator through long transmission line is disconnected and the line capacitance excites the induction machine. This phenomenon is called as accidental self-excitation. But would be rare in actual practice since use is made to shorter lines.
- The most sever disadvantage of SEIG is its inherently low lagging power factor.

1.5 Applications of SEIG [3]

- In laboratories where a source of sine wave power is desired.
- In installations of small capacity where single or 3 phase power is required and where the cost of synchronous generator and auxiliaries is prohibitive.
- Promising stand-alone power supply in rural districts

1.6 Problems associated with SEIG:

- The main drawback with the SEIG is its poor inherent frequency and voltage regulation. The output voltage and frequency of these generators depend upon the prime mover speed, load impedance, and excitation capacitance.

- Its efficiency is comparatively less due to higher core and magnetizing current losses.
- More heating in rotor.

1.6.1 Voltage and frequency regulations

It is desired that the induction generator provide a constant terminal voltage under varying loads. In practice, a drop in both the terminal voltage and frequency occurs when load is increased. A constant terminal voltage alone implies an increasing value of air gap flux for the induction generator, which would result in a continuously varying magnetizing reactance. A constant 'air gap voltage to frequency ratio' ensures the operation of the induction generator at a constant air gap flux. Hence, in this analysis the criterion of maintaining a constant 'air gap voltage to frequency ratio' is considered.

The resulting effect of increasing the ac load active power in an IG terminal voltage reduction, due to the changes in magnetization characteristic and in the excitation bank capacitive reactance. It has been observed that the voltage drops at the stator and rotor resistance and leakage reactance are not the main cause of the poor voltage and frequency regulations in the isolated IG. The fundamental factor that effects the voltage regulation is the influence of the frequency on the generator magnetization characteristics. In case the inductive reactive power increases, the voltage reduction would be higher, due to the demand of capacitive reactive power from the excitation bank to compensate for reactive power.

1.6.2 Methods to improve voltage and frequency regulations

a) **Switched capacitor:** Regulates terminal voltage in discrete steps.

b) **Saturable core reactor:** The saturable core reactor in parallel to the fixed capacitors can maintain the terminal voltage constant. Absence of switching operation will provide smooth waveform of the terminal voltage of the induction generator. But it involves potentially large size and weight due to necessity of a large saturating inductor.

c) **Long shunt and short shunt compensation:** The terminal voltage can be improved by including an additional series capacitance to provide additional VAR with load. It gives better performance in terms of voltage regulation but the series capacitor causes the problem of sub synchronous resonance.

d) **Static VAR compensation:** The static VAR compensator consists of thyristor phase controlled reactor in parallel with thyristor switched capacitor and fixed excitation capacitor. It faces the problem of weight losses in the inductor.

e) **Current-controlled voltage source inverter:** Current-controlled voltage source inverter acts as a voltage regulator for maintaining constant terminal voltage.

f) **Electronic load controller/Induction generator controller:** Electronic load controller controls both voltage and frequency regulation.

1.7 Statement of problem

1. To model the mathematical model of induction machine in d-q stationary reference frame.
2. To study and simulate transient performance of SEIG during no-load and loading with different types of loads.
3. To design the ELC of SEIG and hardware implementation.
4. To design STATCOM and its mathematical modeling and simulation.
5. To analyze the simulation results of a given machine.

1.8 Organization of dissertation

Chapter 1: It contains the basic concept of self-excited induction generator. It notes advantages of SEIG in comparison to synchronous generator while highlighting the problems of voltage and frequency regulations.

Chapter 2: It briefly discusses the different work done in the field of self-excited induction generator by taking literatures available in journals, books and IEEE papers.

Chapter 3: In this chapter a brief study on steady state analysis and modeling and simulation eqns. of transient performance of SEIG under different loadings.

Chapter 4: In this chapter, the design procedure of ELC and rating of ELC for different machine ratings and its hardware implementation is discussed.

Chapter 5: This chapter includes the design of different STATCOM i.e. full rating and reduced rating and its ratings for different rating of machines and its mathematical modeling is discussed.

Chapter 6: In this chapter, simulation results of SEIG under different loadings, and STATCOM results are shown and conclusions are made based on the observations taken in chapters 2, 3, 4 and 5.

Finally references and appendix are included.

LITERATURE REVIEW

The increasing concern for the environment and resources has motivated the world towards rationalizing the use of conventional energy sources to meet the ever-increasing energy demand. Traditionally, Synchronous generators have been used for power generation but induction generators are increasingly being used these days because of their relative advantageous features over conventional synchronous generators. Over the years, the researchers have been engaged in investigation related to analysis, design and control aspects of SEIG with a view to evolve viable standby by/autonomous power generating units driven by oil engines, micro hydro turbines and wind turbines.

The concept of self-excitation of induction machine emerged for the first time in 1935, when Basset and Potter [1] reported that the induction machine can be operated as an induction generator in isolated mode by using external capacitor. They concluded that the induction machine with capacitive excitation would build up its voltage exactly as does a dc shunt generator, the final value being determined by the saturation curve of the machine and by the value of reactance of the excitation capacitance. The induction generator can be made to handle almost any type of load.

Barkle and Ferguson [3] have described the theory and application of an induction generator. They have given the equivalent circuit and phasor diagram of an induction generator and have reported that equivalent circuit contains two variables: the slip s which is a function of speed and magnetizing reactance X_m and is determined by saturation and is a function of the air-gap voltage E_a. After knowing the values of variables, performance characteristics of SEIG can be achieved. They have reported that behavior of induction generator depends on the terminal voltage to establish the magnetizing current hence under short circuit condition terminal voltage collapses. They have mentioned that generated frequency of SEIG increases with speed. Due to increase in frequency, VAR output of capacitor increases directly and consequently maximum voltage resulting from self-excitation is also increased.

Malik and Haque [4] have investigated the steady-state analysis of SEIG incorporating the core loss effect. The two simultaneous non-linear equations of fourth and fifth order are solved to predict the performance of voltage and frequency of the SEIG feeding a balanced R-L load. They have shown that besides voltage and frequency the analysis can be used to predict the minimum value of terminal capacitance required for excitation as well as for maintaining a constant terminal voltage.

Al Jabri and Alolah [5] have presented the limitation of the SEIG operation and have observed that there is an optimal choice for the speed, terminal capacitor and load values that gives maximum output power. For fixed load and terminal capacitor value there are upper and lower bounds on the speed beyond which the machine will not operate. On the other hand, for fixed speed and load impedance, there are upper and lower limits on the terminal capacitor values beyond which the machine will not operate. Al Jabri [5] has derived closed form expressions for both per unit frequency and magnetizing reactance based on approximate method.

It is well known that the reactive power requirement of SEIG increases with load to maintain the constant terminal voltage. Murthy [8] have dealt with steady state-analysis for finding out the reactive power requirement of SEIG with constant speed and variable speed prime mover. The analytical technique uses the standard equivalent circuit and two non-linear equations of first order obtained in terms of capacitance (X_c) and frequency (f) and these equations are solved by Newton-Raphson method. Malik and Mazi [10] have proposed the analytical method to compute minimum capacitance (C_{min}) for self-excitation under no load conditions. They have found that minimum capacitance requirement for the SEIG varies inversely proportional to the square of the speed and inversely proportional to the maximum saturated magnetizing reactance. They have concluded that the terminal capacitance required for a loaded machine is significantly higher than the corresponding no load value and it is affected by load impedance, its power factor (PF) and machine speed.

B.C. Doxey [11] in his paper concluded that the basic requirement for the induction motor to work as a SEIG is the leading current of correct magnitude. Sutanto [12] in their paper examined the transient behavior of a three phase SEIG supplying a symmetrical load. They presented an approach to model the saturation effect from the steady-state standpoint. Murthy [13] analyzed the steady-state performance of induction generators, maintaining constant terminal voltage under resistive and reactive loads. They explained a modified analytical method for determining the range of capacitive VAR requirements for maintaining a constant flux and for obtaining performance with a desired level of voltage regulation. The analysis uses the steady state equivalent circuit to predict the performance of the generator.

Faiz [14] published a paper regarding the design of a self-excited induction generator by minimizing the rotor resistance and increasing the flux density until the magnetic circuit of the generator saturates. They concluded that the best way to optimize the design of an induction generator is to design an induction machine, which can handle the saturated magnetizing current and high voltages.

Levi and Liao [15] provided a purely experimental treatment of the self-excitation process in induction generators. S. P. Singh [19] modeled a delta connected self-excited induction generator, which could handle symmetrical and unsymmetrical load and capacitor configuration. They also discussed the SEIG behavior under balanced and unbalanced fault condition considering the main and cross flux saturation for load perturbation, line-to-line short circuit, opening of one capacitor and opening of single phase load etc. The emphasis was placed on situations that led to voltage collapse and total demagnetization of the machine, and on variable speed operation of the machine with fixed capacitor bank. Kuo and Wang [20] discussed that it is convenient to simulate the power electronic circuits using circuit oriented simulators, while equation solvers are more appropriate to simulate the various electric machines and control systems. When electric machines and power electronic devices are combined and must be solved by an equation solver, the power electronic circuit is to be derived to properly combine with the machines dynamic equations.

Wamkeue [21] presented a generalized unified electromechanical state model in terms of current and flux of SEIG. A k-factor saturation method is used to account for magnetic saturation. Kuo and Wang [20] analyzed both voltage regulation and current harmonic suppression of a SEIG under unbalanced and non-linear load. They used a hybrid model based on the three phase a-b-c and d-q frames of reference to model the dynamic behavior of the machine.

The terminal voltage of the three phases SEIG with variable loads can be maintained constant by adjusting the value of the excitation capacitance or by controlling the prime mover speed. The adjustable excitation capacitor value can be achieved by many control strategies. Tarek Ahmed [23] in their paper has presented the simulation of three-phase SEIG with Static VAR compensator for its voltage regulation. The paper describes an effective algorithm for evaluating the steady state performance analysis of the SEIG driven by a VSPM (variable speed prime mover) as well as CSPM (constant speed prime mover) based on the equivalent circuit representation in the frequency domain. For this scheme the SVC composed of the fixed capacitors in parallel with the TSC (thyristorised switched capacitor) and TCR (thyristor controlled reactor).

Switched capacitors, static VAR compensator and static compensator may provide reactive power. Bhim Singh et al. [30] discussed the performance analysis of static compensator (STATCOM) based voltage regulator. They considered a three phase IGBT based voltage source inverter for harmonic elimination. Singh et al. [33] designed the optimum values of different components of STATCOM for different rating machines. Leidhold [21] propose a control strategy based on instantaneous reactive power theory. The principle is based on power Invariant Park's transformation.

Smith [17] discussed an approach to control induction generators on stand-alone micro-hydro systems. With this approach both voltage and frequency can be controlled by load controller, which senses voltage rather than frequency. Bhim Singh and Murthy [28] modeled an electronic load controller (ELC) for a self excited induction generator, used for load balancing at varying consumer loads as required for stand alone micro-hydel generators driven by uncontrolled turbines. They considered a chopper based ELC for the system. They designed the SEIG and ELC in such a way such that the SEIG sees two balanced three phase loads in parallel and that the total power is constant.

MODELLING AND ANALYSIS OF THREE-PHASE SELF-EXCITED INDUCTION GENERATOR

3.1 Basic concept

The induction machine can work as a generator in parallel to a large network, which will supply the necessary reactive power to magnetize the magnetic circuits of the induction machine. Regeneration is possible, if the rotor of the induction machine is made to rotate above synchronous speed decided by the supply frequency and the pole number of the machine. When operating on an isolated grid, the magnetizing current may be furnished by capacitors.

An autonomous induction machine is able to generate electric power only if self-excitation occurs and it can be sustained. It will generate useful amounts of electrical power if connected to an excitation system consisting of simple static components when it is driven at its normal operating speed by means of a prime mover. If an appropriate capacitor bank is connected across its terminals, the residual magnetism in rotor initiates voltage build up which is augmented by the capacitor current to cause a continuous rise in voltage. A steady state voltage results due to the magnetic saturation, which balances the capacitor and the machine voltage. The wave shape of the output voltage is sinusoidal and the frequency of the output is directly proportional to the rotor speed minus the slip speed.

3.2 Steady State Equivalent Circuit

The performance of an induction generator can be study by using its equivalent circuit. This steady state equivalent ckt is similar to that of an induction motor with the input voltage source substituted by a capacitance and load. The assumptions of per phase circuit model are:

- All the generator parameters are assumed to be constant.
- All the circuit parameters are independent of saturation.
- Magnetizing reactance is dependent on saturation
- Core losses and effects of harmonics in the machines are neglected

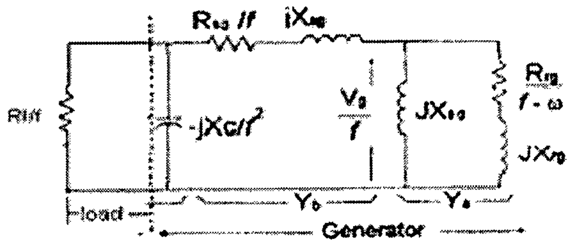


Fig3.1 equivalent circuit of SEIG

The Steady state performance of SEIG can be calculated by using Loop impedance and nodal admittance methods. The equivalent ckt parameters determined by no-load and blocked rotor tests for different machines are given in Table 3.1

Table 3.1 Equivalent Parameters of Different Machines

S. no	Power Rating (KW)	Connection	Line Voltg (V)	Line Ct (A)	Frq /pole	Rs (Ω)	Rr (Ω)	Xls =Xlr	Rm (Ω)	Xm (Ω)	Base impedance (Ω)
1.	3.7	Δ	415	7.6	50/4	5.53	5.86	9.60	4850.18	270.30	94.58
2.	5.5	Δ	415	11	50/4	3.43	3.54	5.91	1531.36	177.68	65.34
3.	7.5	Δ	230	26.2	50/4	0.76	1.03	1.50	255.40	43.66	15.20
4.	7.5	Δ	415	14	50/4	2.48	3.96	5.27	315.47	141.43	17.30
5.	15	Δ	415	30	50/4	0.69	0.74	3.49	658.57	65.16	23.96
6.	25	Δ	400	40	50/4	0.56	0.72	1.50	206.56	62.09	17.32

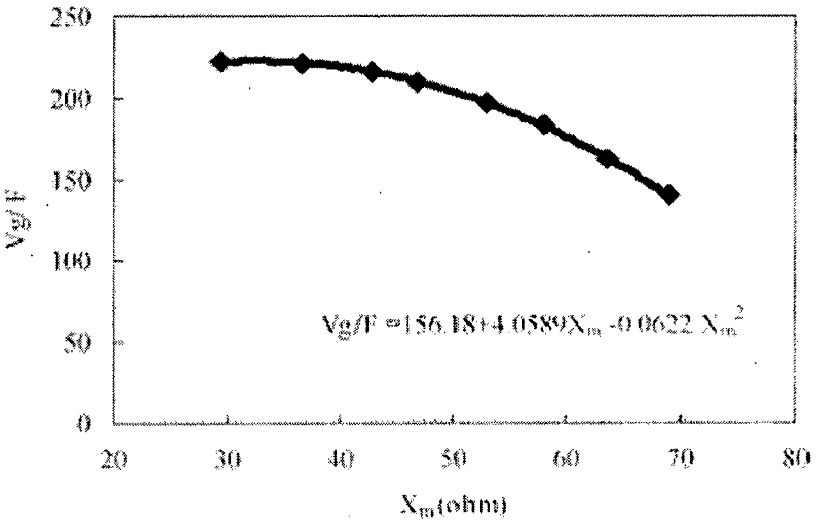


Fig3.2.V_g/F vs X_m characteristics of 7.5 KW machine

The magnetization characteristic depicted in the fig3.2 is the relation ship between the airgap voltage V_g and magnetizing reactance X_m is found by synchronous speed test. The machine is run at synchronous speed and ac voltage is supplied to the stator terminal at rated frequency.

The magnetizing reactance is given by:

$$X_m = \sqrt{\left((V_s/I)^2 - R_s^2\right)} - X_s$$

By employing a curve-fitting technique, the magnetizing characteristic can be mathematically expressed as

$$V_g/F = K_1 + K_2X_m + K_3X_m^3$$

where V_g is the air-gap voltage, F is per unit (p.u.) frequency and X_m is the magnetizing reactance.

The unsaturated values of the magnetizing reactance of different machines obtained experimentally are also given Table 3.1. Values of coefficients K_1, K_2, K_3, and are given in Table 3.2 for different machines. To keep the terminal voltage of the SEIG constant at varying loads, the required capacitance values are given in Table 3.3.

Air-gap voltage Vg is calculated as: $V_g = X_m I_s$

where I_s is the per phase current.

Table 3.2 Coefficients of magnetizing characteristics of Different electrical machines

$$(V_g/F = K_1 + K_2 X_m + K_3 X_m^3)$$

Power Rating (kW)	K_1	K_2	K_3
3.7	348.35	2.0024	-0.0091
5.5	88.128	7.9262	-0.0425
7.5	156.18	4.0589	-0.0622
15	203.37	14.082	-0.2185
22	274.66	9.8999	-0.1741

Table 3.3 Capacitance Requirements of Different machines

Power Rating (kW)	Capacitance at No-Load (C_0) (μF)	Capacitance (C_R).at Full-Load (UPF) (μF)	Capacitance (C_L) at Full-Load (LPF) (μF)
3.7	15.5	24.96	38.18
5.5	23.09	33.84	56.8
7.5	85.56	181.61	295
15	57.77	91.10	146.90
22	62.238	103.24	206.97

Determination of stable operation of SEIG [33]

From the magnetizing curve (fig 3.3),

On no load, the capacitor current $I_c=V_1/X_c$ must be equal to the magnetizing current $I_m=V_1/X_m$. The voltage V_1 is a function of I_m, linearly rising until the saturation point of the magnetic core is reached.

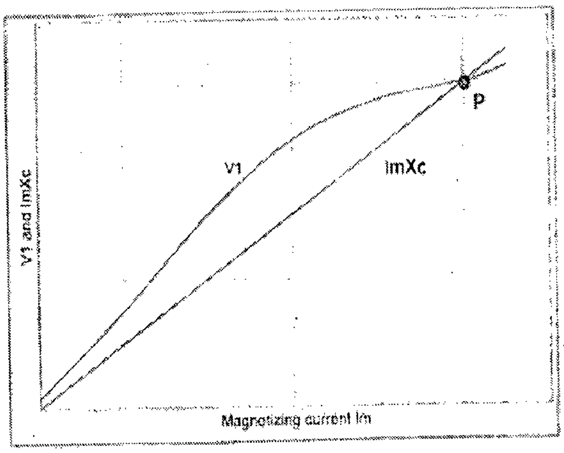


Fig 3.3 Magnetizing curve

The stable operation requires the line I_mX_c to intersect the V_1 vs I_m curve. The operating point is fixed when V_1/X_C equal to V_1/X_m.

i.e. $1/X_c=1/X_m$

i.e. $C=1/(2\pi f)^2 L_m$

3.3 Transient analysis of SEIG [22]

The initiation of self-excitation process is a transient phenomenon and is better understood if analyzed using instantaneous values of current and voltage. A number of dynamic models are available for simulating induction machine performance; but the d-q variable model has proved reliable and accurate. The d-q model with currents as state variables in a stationary reference frame is used for the transient analysis of a SEIG because the effect of frequency variation with time and the effect of saturation can be explicitly observed.

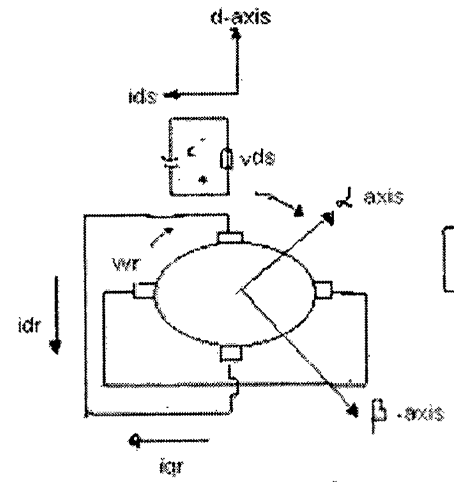


Fig 3.4 circuit model of three phase SEIG in the d-q axis stationary reference frame

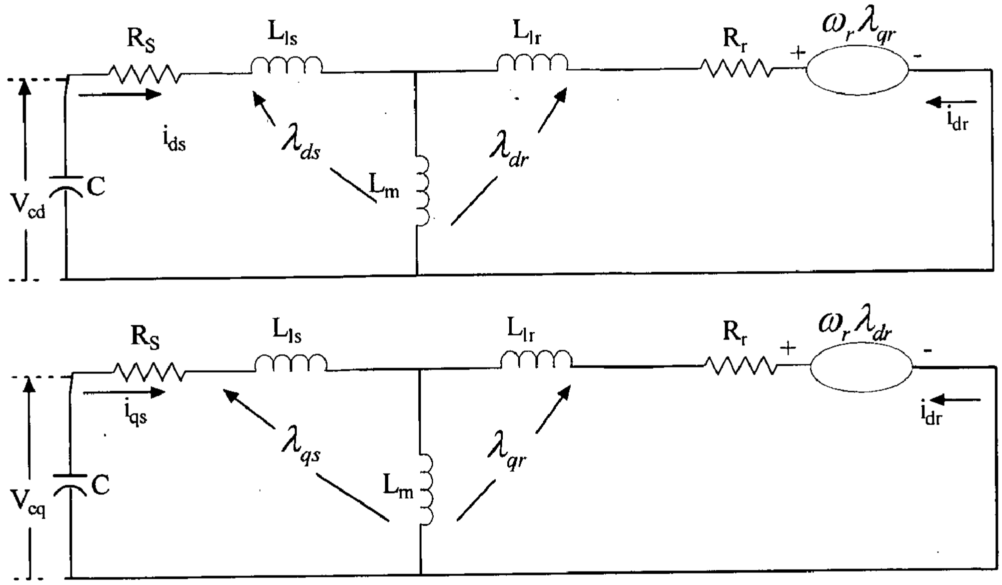


Fig 3.5 Equivalent ckt of IG in d-q axis reference frame

3.4 Modeling of Self Excited Induction Generator [28]

The circuit model of three phase capacitor excited induction generator in stationary d-q reference frame is shown in fig. 3.1. The Voltage-current equations of SEIG in d-q reference frame are described as:

$$[v]=[R][i]+[L]p[i]+w_r[G][i]$$

Where p represents the derivative w. r. t. time, [v] and [i] represents 4 × 1 column matrices of voltage and which is given as:

$$[v]=\begin{bmatrix} v_{ds} & v_{qs} & v_{dr} & v_{qr}\end{bmatrix}^T \quad [i]=\begin{bmatrix} i_{ds} & i_{qs} & i_{dr} & i_{qr}\end{bmatrix}^T \qquad [R]=diag\begin{bmatrix} R_s & R_s & \mathrm{R}_r & R_r\end{bmatrix}$$

and [L] , [G] represents the transformer and rotational inductance matrices defined as:

$$[L]=\begin{bmatrix} L_s+L_m & 0 & L_m & 0 \\ 0 & L_s+L_m & 0 & L_m \\ L_m & 0 & L_r+L_m & 0 \\ 0 & L_m & 0 & L_r+L_m \end{bmatrix} \qquad [G]=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_m & 0 & L_r+L_m \\ L_m & 0 & L_r+L_m & 0 \end{bmatrix}$$

Substituting the above matrices i.e. [v], i], [R], [L], [G] in the above voltage-current relation,

$$v_{ds}=R_si_{ds}+L_spi_{ds}+L_mpi_{dr} \qquad \text{(i)}$$

$$v_{qs}=R_si_{qs}+L_spi_{qs}+L_mpi_{qr} \qquad \text{(ii)}$$

$$0=R_ri_{dr}+L_mpi_{ds}+L_rpi_{dr}+w_rL_mi_{qs}+L_ri_{qr} \qquad \text{(iii)}$$

$$0=R_ri_{qr}+L_mpi_{qs}+L_rpi_{qr}-w_rL_mi_{qs}-w_rL_ri_{dr} \qquad \text{(iv)}$$

From equations (iii) and (iv) we can write,

$$pi_{dr}=-(R_r/L_r)i_{dr}-(L_m/L_r)pi_{ds}-w_r\left({}^{L_m}\!/\!_{L_r}\right)i_{qs}-i_{qr}w_r \qquad \text{(v)}$$

$$pi_{qr}=-(R_r/L_r)i_{qr}-(L_m/L_r)pi_{qs}+w_r\left({}^{L_m}\!/\!_{L_r}\right)i_{ds}+i_{dr}w_r \qquad \text{(vi)}$$

Substituting $p\,i_{dr}$, $p\,i_{qr}$ i.e. (v), (vi) in (i) and (ii),

$$p i_{ds} = \left(\frac{1}{L_s - \frac{L_m^2}{L_r}} \right) \left[v_{ds} - R_s i_{ds} + \left(\frac{L_m}{L_r} \right) R_r i_{dr} + w_r \left(\frac{L_m^2}{L_r} \right) i_{qs} + w_r L_m i_{qr} \right] \quad (3.1)$$

$$p i_{qs} = \left(\frac{1}{L_s - \frac{L_m^2}{L_r}} \right) \left[v_{qs} - R_s i_{qs} + \left(\frac{L_m}{L_r} \right) R_r i_{qr} - w_r \left(\frac{L_m^2}{L_r} \right) i_{ds} - w_r L_m i_{dr} \right] \quad (3.2)$$

Substituting pi_{ds} , pi_{qs} i.e. (2.1), (2.2) in (v) and (vi),

$$pi_{dr} = \left(\frac{1}{1 - \frac{L_m^2}{L_s L_r}} \right) \left[-(R_r/L_r) i_{dr} - \left(\frac{L_m}{L_s L_r} \right) v_{ds} + \left(\frac{L_m}{L_s L_r} \right) R_s i_{ds} - w_r \left(\frac{L_m}{L_r} \right) i_{qs} - w_r i_{qr} \right] \quad (3.3)$$

$$pi_{qr} = \left(\frac{1}{1 - \frac{L_m^2}{L_s L_r}} \right) \left[-(R_r/L_r) i_{qr} - \left(\frac{L_m}{L_s L_r} \right) v_{qs} + \left(\frac{L_m}{L_s L_r} \right) R_s i_{qs} + w_r \left(\frac{L_m}{L_r} \right) i_{ds} + w_r i_{dr} \right] \quad (3.4)$$

The electromagnetic torque developed by the generator is given by

$$Te = (3P/4) L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right) \quad (3.5)$$

Torque balance equation is as

$$(P/2J)\left(T_{shaft} - Te\right) = \frac{d\omega_r}{dt} \quad (3.6)$$

Where T_{shaft} is the torque transmitted to the shaft of induction generator from prime mover (Appendix I). T_e is the developed electromagnetic torque acting against the prime mover and J is the moment of inertia of the shaft. P is the number of poles.

The derivative of the rotor speed from eqn. (2.6) is

$$pw_r = (P/2J)\left(T_{shaft} - T_e\right) \quad (3.7)$$

The SEIG operates in the saturation region and its magnetizing characteristic is non linear in nature. The magnitude of magnetizing current is calculated as:

$$I_m = \sqrt{(ids + idr)^2 + (iqs + iqr)^2} \tag{3.8}$$

The magnetizing inductance (Lm) is function of Im and is given as

$$L_m = A_1 + A_2 I_m + A_3 I_m^2 + A_4 I_m^3 \tag{3.9}$$

where the coefficients A_1, A_2, A_3, A_4 is given in Appendix.

From d-q axis to abc transformation SEIG three phase voltages and currents are calculated as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} \quad \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{0s} \end{bmatrix} \tag{3.10}$$

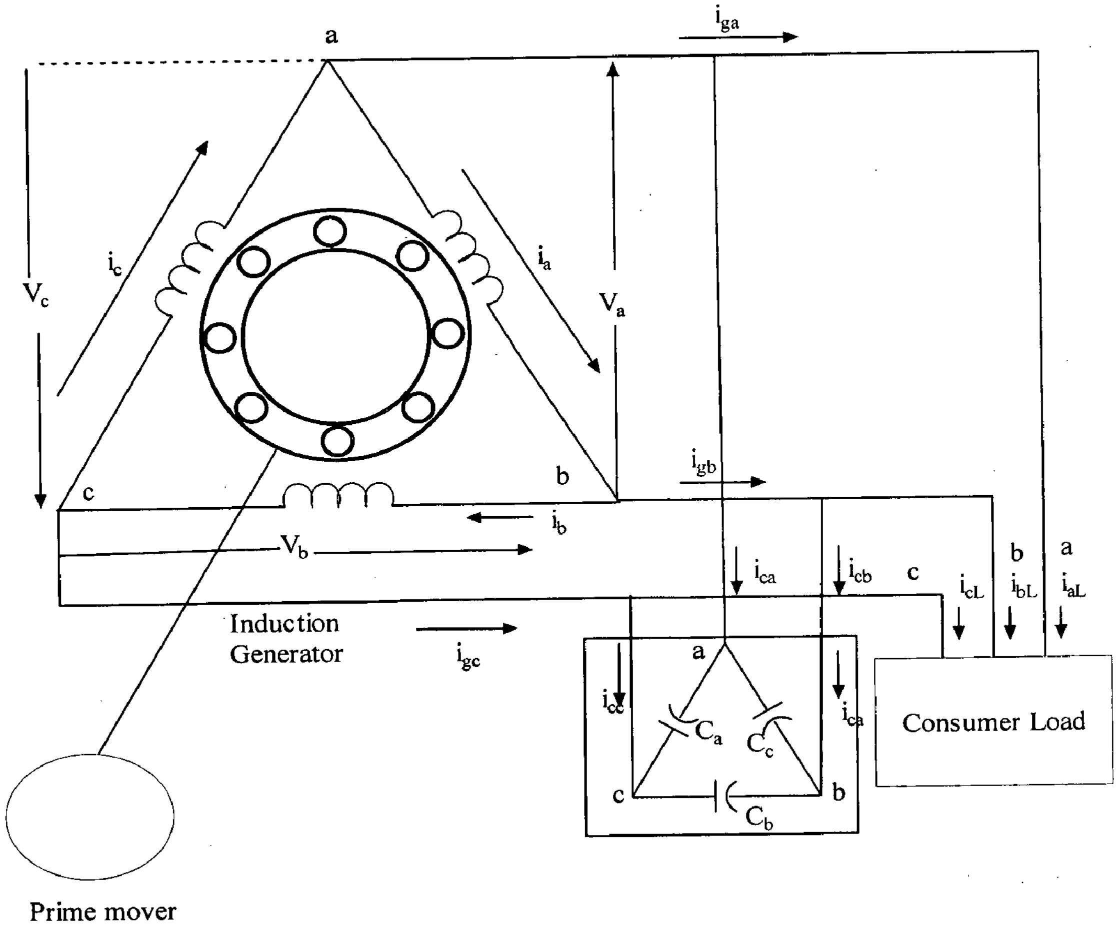


Fig 3.6 SEIG with Consumer Load

From KCL to the ckt comprising Excitation capacitor and consumer load, the node ct eqns are as:

$$C_b pv_b - C_a pv_a = i_{cca} = i_a - i_{aL} \tag{3.11}$$

$$C_c pv_c - C_b pv_b = i_{ccb} = i_b - i_{bL} \tag{3.12}$$

$$C_a pv_a - C_c pv_c = i_{ccc} = i_c - i_{cL} \tag{3.13}$$

where, i_{aL} , i_{bL} , i_{cL} are line currents of load.

Generator line currents are given by

$$i_a = i_{ga} - i_{gb} \tag{3.14}$$

$$i_b = i_{gb} - i_{gc} \tag{3.15}$$

$$i_c = i_{gc} - i_{ga} \tag{3.16}$$

For delta connection sum of three voltages is zero

$$v_a + v_b + v_c = 0 \tag{3.17}$$

From eqns.(3.11),(3.12) and (3.17)

$$(C_a + C_b)\, pv_a + C_a pv_b = i_{cca} = i_{ga} - i_{gb} - i_{aL} \tag{3.18}$$

$$-C_b pv_a + C_c pv_b = i_{ccb} = i_{gb} - i_{gc} - i_{bL} \tag{3.19}$$

From eqns. (3.18) and (3.19)

$$pv_a = (C_c i_{cca} - C_a i_{ccb}) / K_{eq} \tag{3.20}$$

$$pv_b = (\{C_a + C_b\} i_{cca} + C_b i_{ccb}) / K_{eq} \tag{3.21}$$

where, $K_{eq} = C_a C_b + C_b C_c + C_c C_a$ (3.22)

for balanced excitation,

$$C_a = C_b = C_c = C_x$$

$$K_{eq} = 3C_x^2$$

therefore,

$$pv_a = \frac{(i_{ca} - i_{cb})}{3C_x} = \frac{\{i_{ga} - i_{al}\} - \{i_{gb} - i_{bl}\}}{3C_x} \tag{3.23}$$

$$pv_b = \frac{(i_{ca} + 2i_{cb})}{3C_x} = \frac{\{(i_{ga} - (i_{al} + i_{Da})\} - 2\{(i_{gb} - (i_{bl} + i_{Db})\}}{3C_x} \tag{3.24}$$

$$v_c = -(v_a + v_b) \tag{3.25}$$

3.5 Modeling of Self-Exciting Capacitor Bank [19]

Here capacitors are used for self-excitation of induction generator. The equations governing the voltage across the capacitors are as:

$$P[Qc] = [Is]-[I_L]-[Ic]$$

Where [Qc] are the charges on the capacitor bank, [Is} are stator currents, $[I_L]$ are load currents and [Ic] are the compensating currents supplied by the inverter.

$$[Qc]=\begin{bmatrix} Q_{dc} \\ Q_{qc} \end{bmatrix} \quad [Is]=\begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix} \quad [Ic]=\begin{bmatrix} I_{dc} \\ I_{qc} \end{bmatrix} \quad \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix}=(1/C)\begin{bmatrix} Q_{dc} \\ Q_{qc} \end{bmatrix}$$

3.6 Modeling of consumer Loads

3.6.1 Resistive Load

The resistive load line currents i_{aL}, i_{bL}, i_{cL} are given by:

$$i_{aL} = (v_a - v_c)/R_{La} \tag{3.26}$$
$$i_{bL} = (v_b - v_c)/R_{Lb} \tag{3.27}$$
$$i_{cL} = (v_c - v_a)/R_{Lc} \tag{3.28}$$

Where,

R_{La}, R_{Lb}, R_{Lc} are three phase resistances of the delta connected resistive loads.

3.6.2 Inductive Load

The derivatives of load currents are given by:

$$pi_{pa} = (v_a - R_{La} i_{pa})/L_{la} \tag{3.29}$$
$$pi_{pb} = (v_b - R_{Lb} i_{pb})/L_{lb} \tag{3.30}$$
$$pi_{pc} = (v_c - R_{Lc} i_{pc})/L_{lc} \tag{3.31}$$

Therefore, the line currents of load are:

$$i_{la} = i_{pa} - i_{pb} \qquad i_{lb} = i_{pb} - i_{pc} \qquad i_{lc} = i_{pc} - i_{pa} \tag{3.32}$$

Thus, by using the eqns. from 3.1 to 3.22 we can design the three phase SEIG mathematical modeling in SIMULINK / MATLAB software and the Flow-chart is shown in fig 3.7.

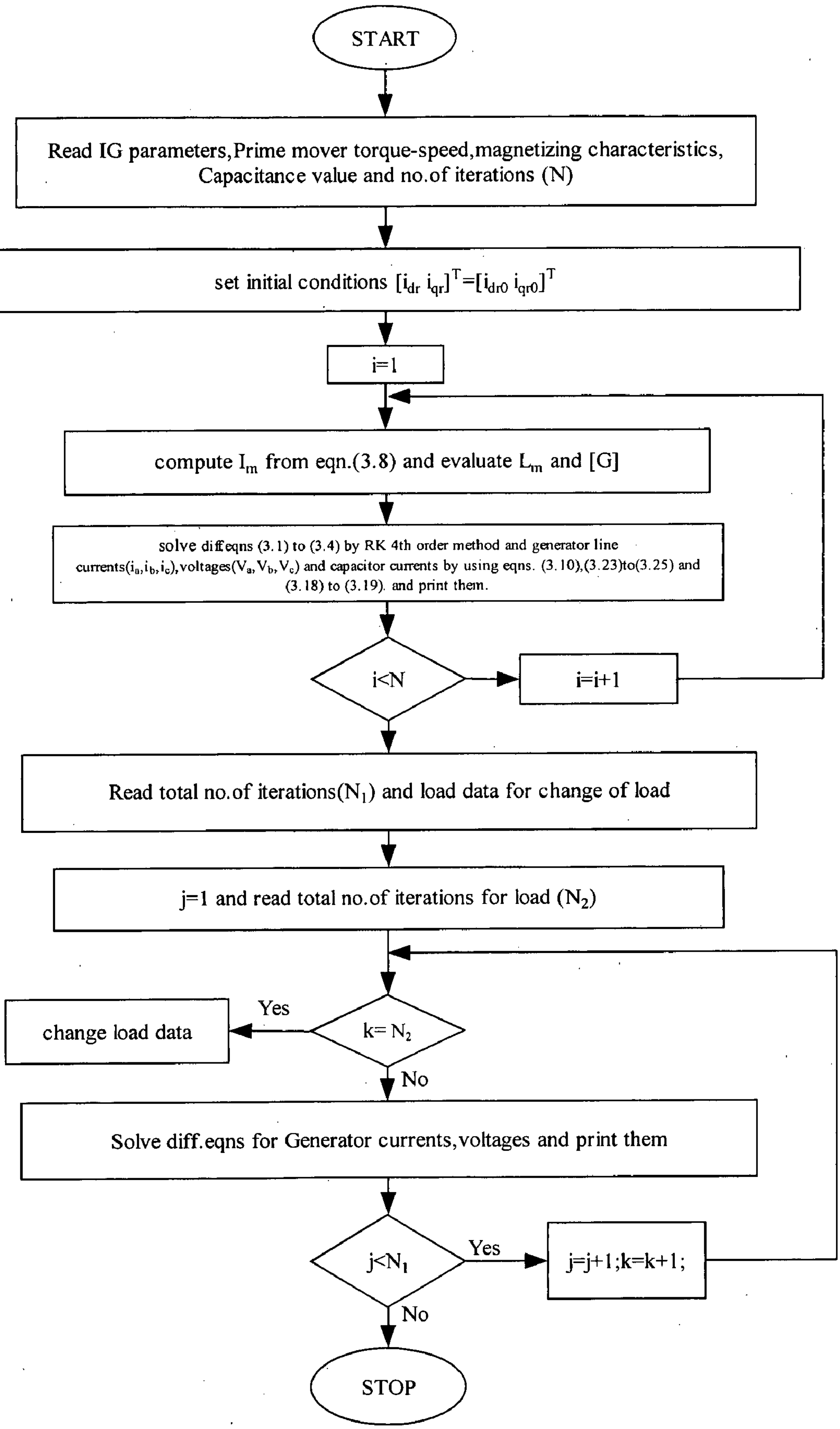


Fig 3.7 Flow chrart of SEIG

CHAPTER 4

DESIGN OF ELECTRONIC LOAD CONTROLLER

4.1 Electronic Load Controller

4.1.1 Description

The proposed ELC is the combination of an uncontrolled rectifier, a filtering capacitor, chopper, and a series dump load (resistor). The schematic diagrams of ELC–SEIG systems are shown in Figs.4.1 for supplying three-phase loads.

The uncontrolled rectifier converts the SEIG ac terminal voltage to dc. The uncontrolled rectifier output has the ripples, which should be filtered and, therefore, a filtering capacitor (C) is used to smoothen the dc voltage. An IGBT is used as a chopper switch. A suitable gate driver circuit has been developed that turns on the chopper switch when the consumer load on SEIG is less than the rated load and turns off the chopper switch when consumer load on the SEIG is at a rated value. When the chopper switch is switched on, the current flows through the dump load and consumes the difference power (generated power-consumed power) which results in a constant load on the SEIG and, hence, constant voltage and frequency at the load.

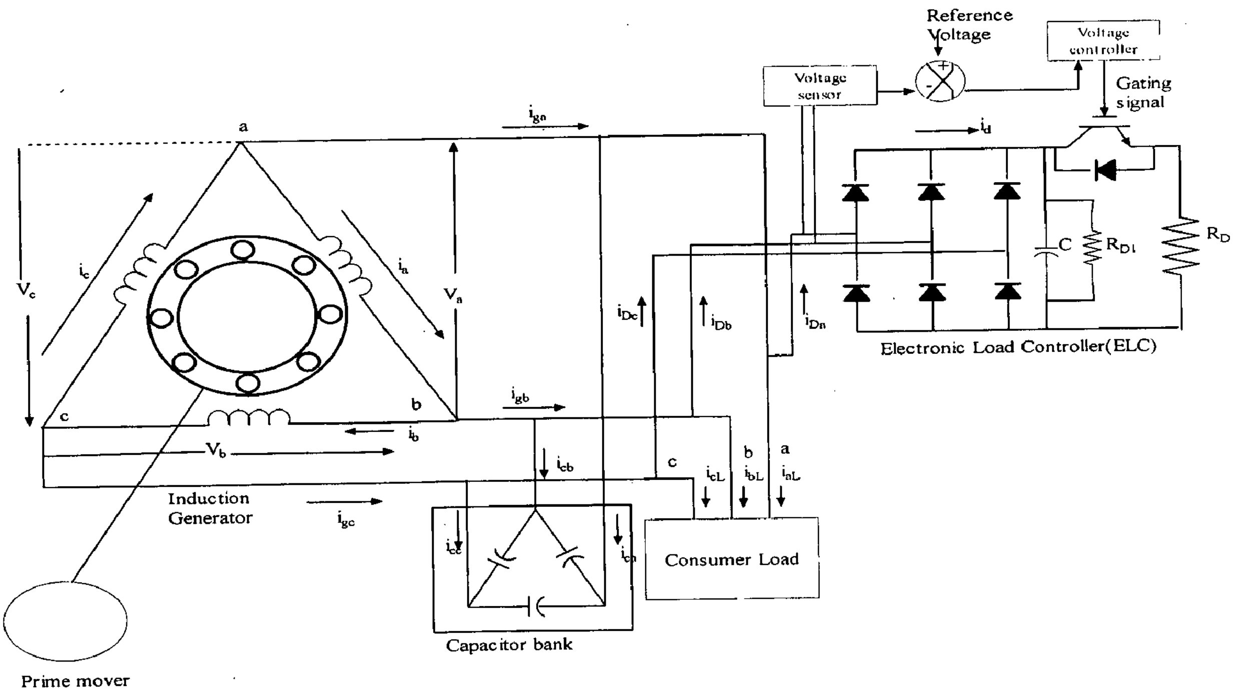


Fig 4.1 Schematic diagram of thee phase SEIG with an ELC

PRINCIPLE

The SEIG–ELC system consists of a three-phase delta-connected induction generator driven by an uncontrolled hydro-turbine and an ELC. Suitable valued capacitors are connected across the SEIG such that it generates rated terminal voltage at full load. Since the input power is nearly constant, the output power of the SEIG is held constant at varying consumer loads. The power in surplus of the consumer load is dumped in a resistance through the ELC. Thus, SEIG feeds two loads in parallel such that the total power is constant, that is where is the generated power of the generator (which should be kept constant), is consumer load power, and is the dump load power.

$$P_{out} = P_d + P_c$$

FLOWCHART OF ELC OPERATION

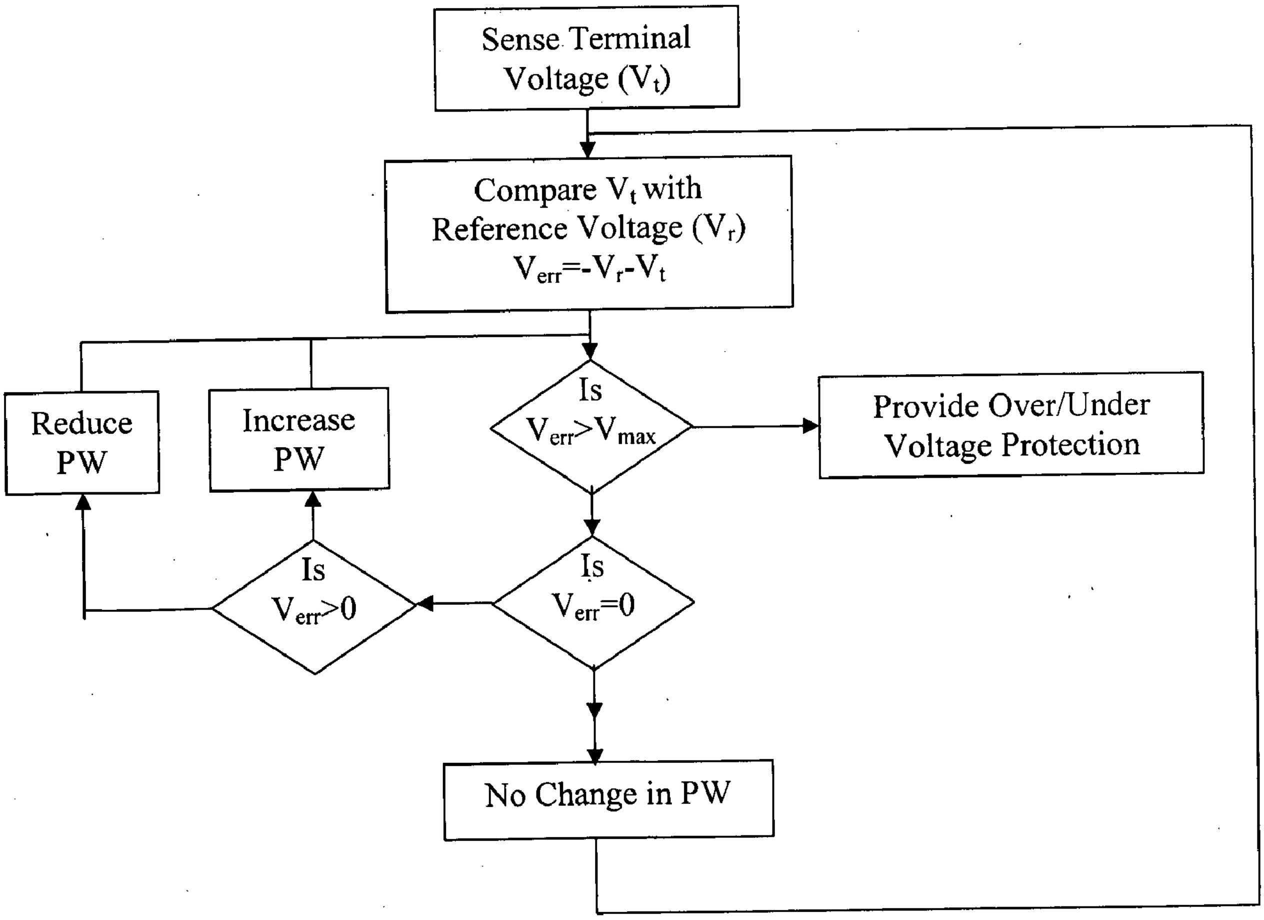


Fig 4.2 Flow chart of ELC operation

4.1.2 Design of Three Phase ELC [33]

The voltage and current rating of the SEIG decides the component rating of ELC because in the constant power operation, SEIG always operates at the rated power. Per-phase capacitance required for generating rated power at rated speed and voltage for a balanced condition is given in Table 4.1.

Table 4.1 Capacitance Requirement of three phase SEIG with three phase and single phase loads

Power rating (kW)	capacitance requirement of three phase SEIG for three phase loads (μF)		Capacitance requirement of three phase SEIG for single phase load (μF)			
			C_a(μF)		C_b(μF)	
	No-load	Rated load	No-load	Rated load	No-load	Rated load
3.7	15.5	24.96	17.8	85	35.6	170
5.5	23.09	33.84	25.25	110	50.5	220
7.5	86.56	181.61	70	250	140	500
15	57.77	91.10	64	250	128	500
22	62.23	103.24	68.2	300	136.2	600

The voltage rating: of the uncontrolled rectifier and chopper switch will be the same and dependent on the rms ac input voltage and average value of the output dc voltage.

$$V_{DC} = 1.35 * V_{LL} = 1.35 * 400 = 540 \text{ (v)}$$

For 10% over voltage: $V_{peak} = 1.414 * V_{LL} = 1.414 * 440 = 622.25$ (v)

Current rating: $I_{ac} = \frac{P}{\sqrt{3}V_{LL}}$ =3.73kW/(400* $\sqrt{3}$)=5.39 (A)

$I_{Dac} = I_{ac}/0.955 = 5.39/0.955 = 5.644$ (A)

$I_{peak} = 2*I_{Dac} = 2*5.644 = 11.288$ (A)

Rating of Dump load Resistance: $R_D = V_{dc}^2/P = 540^2/3.73 = 78.18\Omega$

Dc link capacitance: RF = 0.05

$$C = \left\{\frac{1}{12fR_d}\right\}\left\{1 + \frac{1}{\sqrt{2}RF}\right\} = 322.85\mu f$$

Standard Ratings: Rating of rectifier & chopper: 900 V, 15 A

Dump load: 84 Ω

Dc filtering capacitance: 380 μf

In this way we can design the Three phase ELC for 3.7 kW, 400 V, 7.5 A, Δ-connection, 1440 rpm Laboratory machine and ELC parameters for different ratings of m/cs are given in Table 4.2.

Table: 4.2 Three phase ELC parameters for different machines

m/c Power rating (kW)	Rectifier ratings		Chopper ratings		Rating of dump load (Ω)	Rating of Dc filtering capacitor (μF)
	Voltage (V)	Current (A)	Voltage (V)	Current (A)		
3.7	900	15	900	15	84	380
5.5	900	25	900	25	57	560
7.5	600	50	600	50	12	2000
15	900	50	900	50	23	1500
22	900	75	900	75	13	2000

Applications: it is assumed that power diverted to dump loads is wasted. But this power can be used in various ways:

- Ironing
- Cooking
- Heating water
- Battery charging
- Street lighting using incandescent lamps

4.2 Hard ware Design

4.2.1 Power Supplying Circuits

DC regulated power supplies (+12v, -12v, +5v) are required for providing biasing to various transistors, IC's etc. The circuit diagram for various dc regulated power supplies are shown in *fig 4.3*; in it the single phase ac voltage is stepped down to 12V and then rectified using a diode bridge rectifier. A capacitor of 1000µf, 50volts is connected at the output of the bridge rectifier for smoothening out the ripples in the rectified DC regulated voltages. IC voltage regulators are used for regulating the voltages on load also. Different IC voltage regulator that are used are; 7812 for +12V, 7912 for -12V and 7805 for +5V. A capacitor of 100µf, 25V capacitor is connected at the output of the IC voltage regulator of each supply for obtaining the constant and ripple free DC voltage.

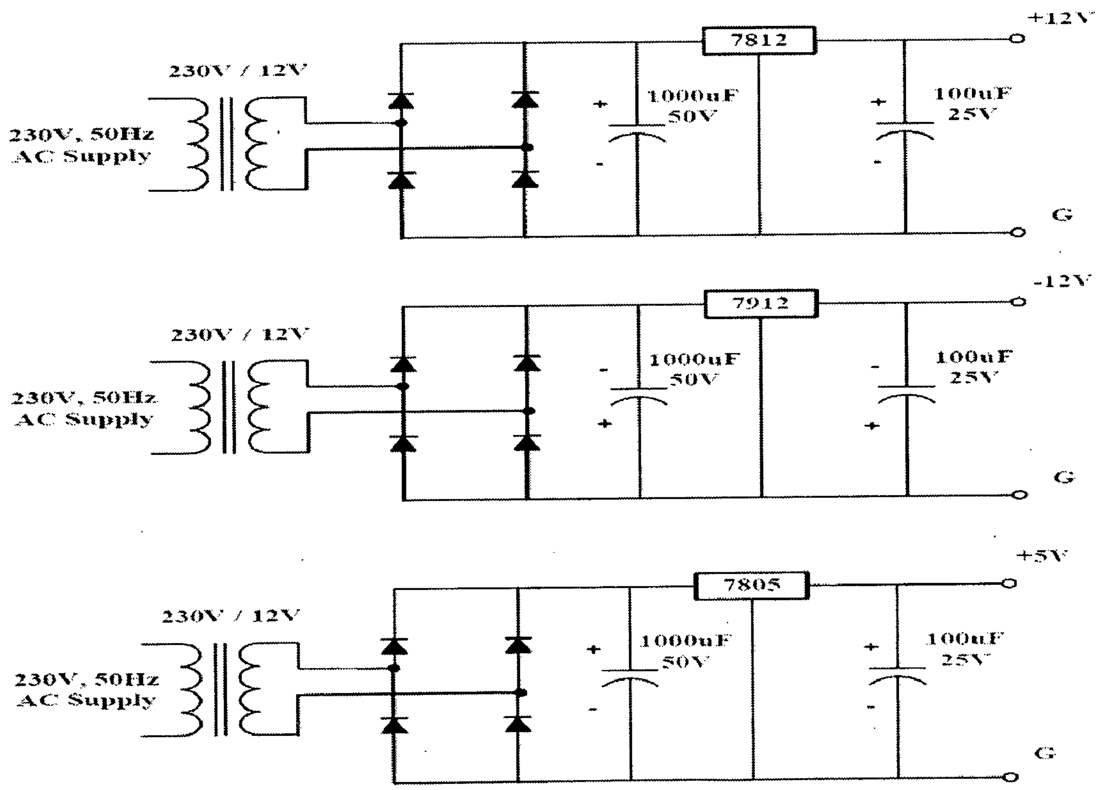


Figure 4.3 Circuit Diagrams for IC regulated Power Supplies

DC VOLTAGE	IC REGULATOR
+5V	7805
+12V	7812
±12V	7812, 7912

4.2.2 Power Circuit of ELC

The power circuit consists of a diode bridge rectifier connected to dump load through an IGBT chopper. The output of the rectifier is filtered through two capacitors of rating 450V, 2200 micro-farad connected in series to support the high voltage.

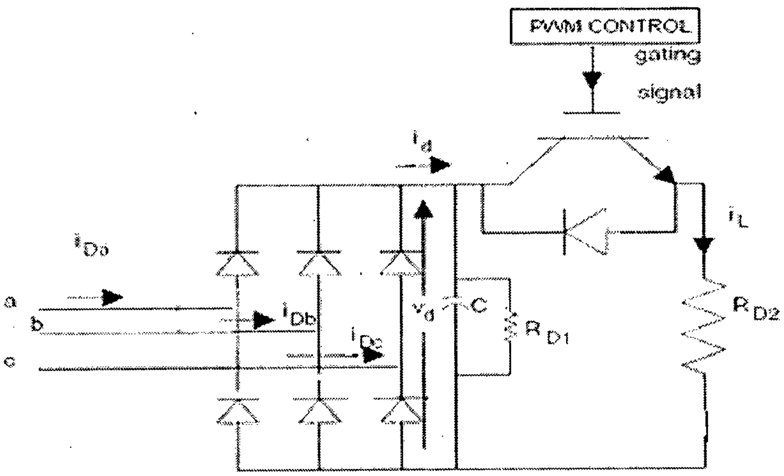


Fig 4.4 Power circuit of ELC

4.2.3 Voltage Sensing Circuit

The SEIG voltage is sensed using a step down transformer and rectified through a single-phase rectifier circuit for a feedback signal. A calibration circuit and a buffer is connected at the output of the capacitor to calibrate the sensed voltage.

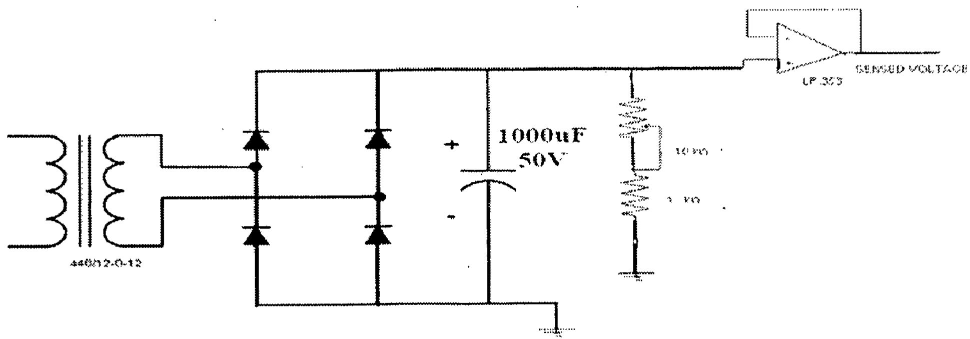


Fig 4.5 Voltage sensing circuit

4.2.4 PWM Circuit

This uses the TL084, a 14-pin DIL IC containing four individual op-amps. The saw tooth waveform is generated with two of them (U1A and U1B), configured as a Schmitt Trigger and Miller Integrator, and a third (U1C) is used as a comparator to compare the saw tooth with the reference voltage and switch the power transistor. Fourth op-amp is used as a voltage follower to buffer the reference potential divider. The high input and low output impedance of this draws very little current from the Potential divider network.

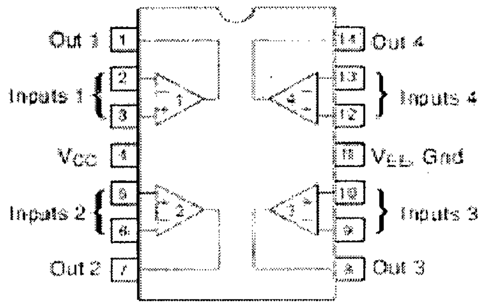


Fig 4.6 TL084 pin connections

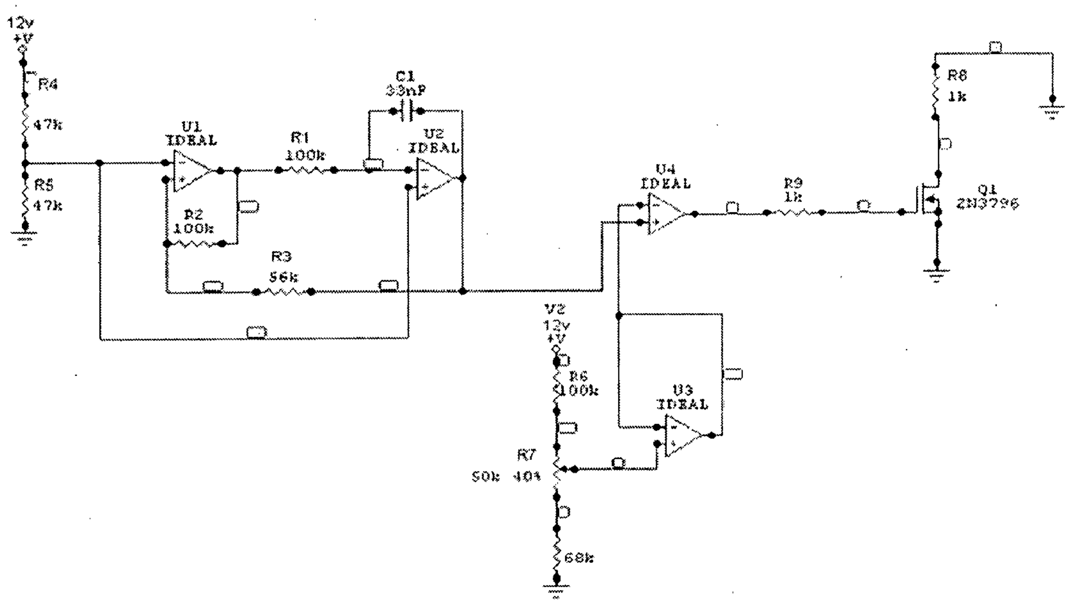


Fig 4.7 Simulation of PWM Circuit

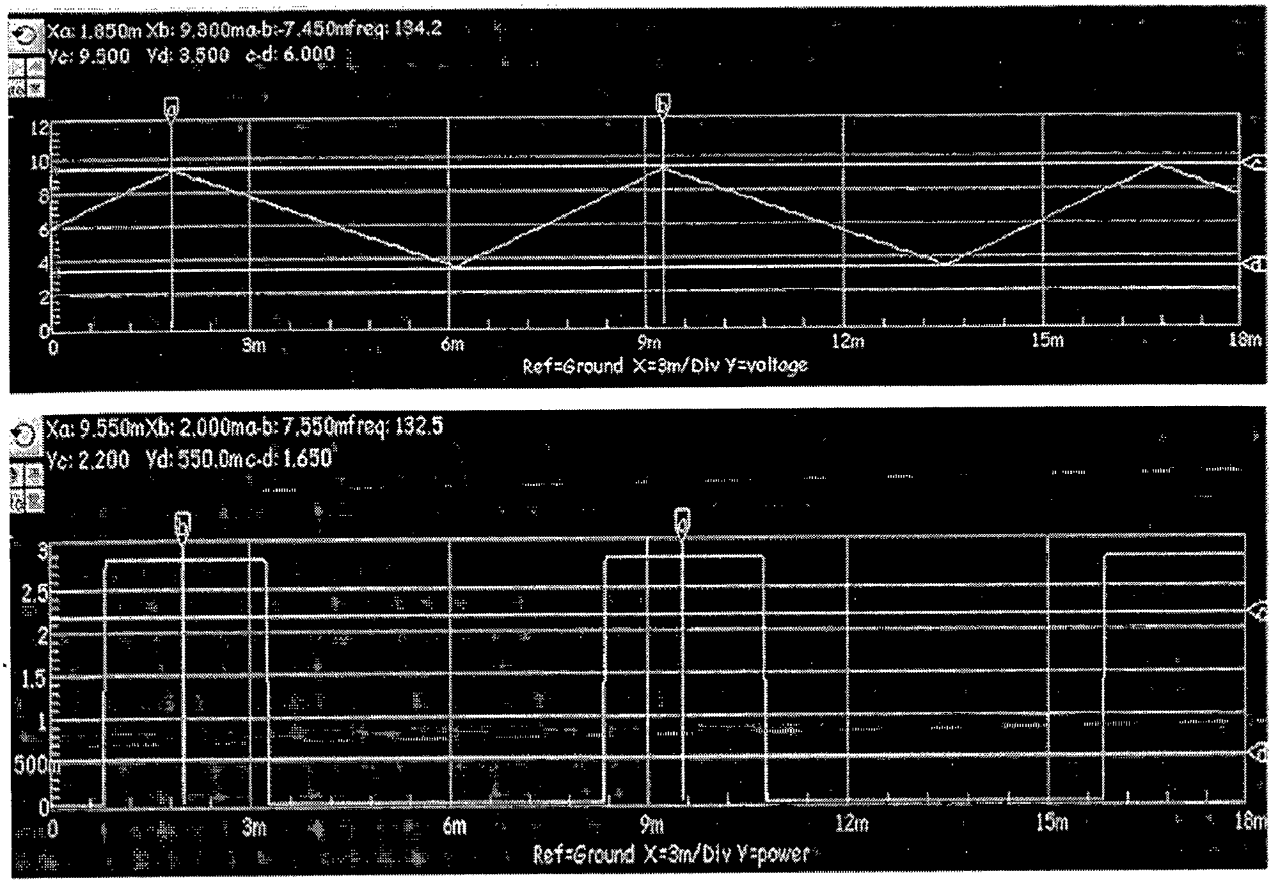


Fig 4.8 Waveforms

4.2.5 Saw Tooth Wave Generator

(A) Saw Tooth Wave form:

A saw tooth signal is a signal that increases gradually with a constant slope, then drops sharply when it is `reset', after which the cycle is repeated. See the above figure. A saw tooth oscillator is needed for PWM (Pulse Width Modulation) control of the output voltage. The output of the PI controller is compared with the saw tooth oscillator to generate the control signal for the active switch, in this case the IGBT.

$$f_{osc} = R_2 / 4R_1R_3C_1$$

This assumes that the op-amp integrator is ideal. In practice, f_{osc} will be lower because of reduced integrator gain at high differential input voltages. We need *R3*>R4 for oscillations to occur, and the ratio of the rise time to the fall time of the resulting waveform is set by R_2/R_1.

(B)Circuit Explanation:

+12V D. C. Supply is applied at terminal 4 and terminal 11 is grounded. Thus all the four op amps of TL084 are biased in this way.

Saw tooth waveform frequency depends upon the values of R_1 and C_1. Resistors R_4 and R_5 determine the dc voltage that is applied to the inverting terminal of operational amplifier A and the noninverting terminal of operational amplifier B. We will refer to the dc voltage as V_{dc}. The presence of feedback at the inverting terminal of B ensures that its voltage is nearly equal to V_{dc}. The voltage at the noninverting terminal of A determines whether the output voltage of A is high at its maximum value of V_{dc} or zero.

We begin our analysis assuming that the voltage at the noninverting terminal of A is less than V_{dc} so that the output voltage of A is zero. That is $V_{oa}(t=0) = 0$The current through R can now be computed as

$$i(t)=V_{dc}/R$$

The constant (dc) current through R maintains its continuity through the capacitor C and charges the capacitor. The voltage across C, with the polarity as marked, is

$$V(t) = (V_{dc}/RC)*t + V_{c,min}$$

Where $V_{C,min}$ is the voltage across C from the prior operation. The charging process will continue until the voltage at the noninverting terminal is just above the voltage at its inverting terminal (V_{dc}). At that instant, the voltage across the capacitor will be at its maximum and so will be the output voltage of B. Let us assume that the time taken for the voltage across the capacitor to reach its maximum value is T_C , where the subscript C stands for the charging time.

Setting $V_a(t) = V_{dc}$, we can write the following equation in terms of the maximum value of the output voltage of B as

$$V_{dc} = V_{ob.max} \frac{R_2}{R_1 + R_2}$$

The maximum output voltage of B is

$$V_{ob.max} = V_{dc}\left(1 + \frac{R_1}{R_2}\right)$$

Thus, the maximum voltage across the capacitor is

$$V_{C,max} = V_{ob,max} - V_{dc} = V_{dc}\left(\frac{R_1}{R_2}\right)$$

The maximum voltage across the capacitor depends upon the circuit elements R_1 and R_2 once the dc reference level for V_{dc} is chosen.

The change in the voltage can be expressed as

$$V_{C,max} - V_{C,min} = \frac{V_{dc}}{RC} T_C$$

The expression for the minimum voltage of B can be written as

$$V_{dc} = V_{ob,min}\left(\frac{R_2}{R_1 + R_2}\right) + V_{oa,max}\left(\frac{R_1}{R_1 + R_2}\right)$$

This equation yields the minimum value of the output voltage of B as

$$V_{ob,min} = V_{dc}\left(1 + \frac{R_1}{R_2}\right) - V_{oa,max}\left(\frac{R_1}{R_2}\right)$$

Therefore, the minimum value of the capacitor voltage is,

$$V_{C,min} = V_{ob,min} - V_{dc} = (V_{dc} - V_{oa,max})\left(\frac{R_1}{R_2}\right)$$

The saw tooth output voltage is applied at the noninverting terminal of comparator C where it is compared with the variable reference voltage V_{ref}, which is expected to be greater than minimum output voltage of B, $V_{ob,min}$. The output of the comparator is a rectangular pulse whose duration depends upon the reference voltage V_{ref} as shown below. The lower the reference voltage, the wider the pulse width of the output voltage of comparator C.

This circuit uses two ICs of OP-amp μA741.

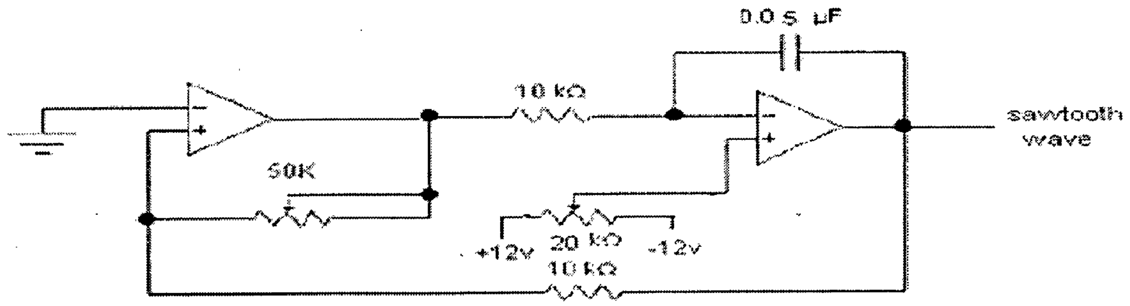


Fig 4.10 Saw tooth wave generator

The triangular waves can be generated using a bi-stable comparator circuit together with an integrator. The output (triangular form) of the integrator circuit serves as input to the bistable comparator and similarly the output (square form) serves as input to the integrator circuit. The integrator causes linear charging and discharging of the capacitor and therefore producing a triangular waveform. If capacitance is varied in the integrator circuit, the periods of both output and input also changes. When the capacitance is increased the period increases and when the capacitance is decreased the period decreases.

For 12 V power supply, range of output voltage of saw tooth waveform is 2.64V to 9.36V(2kz,7V observed) (calculated based on above analysis).

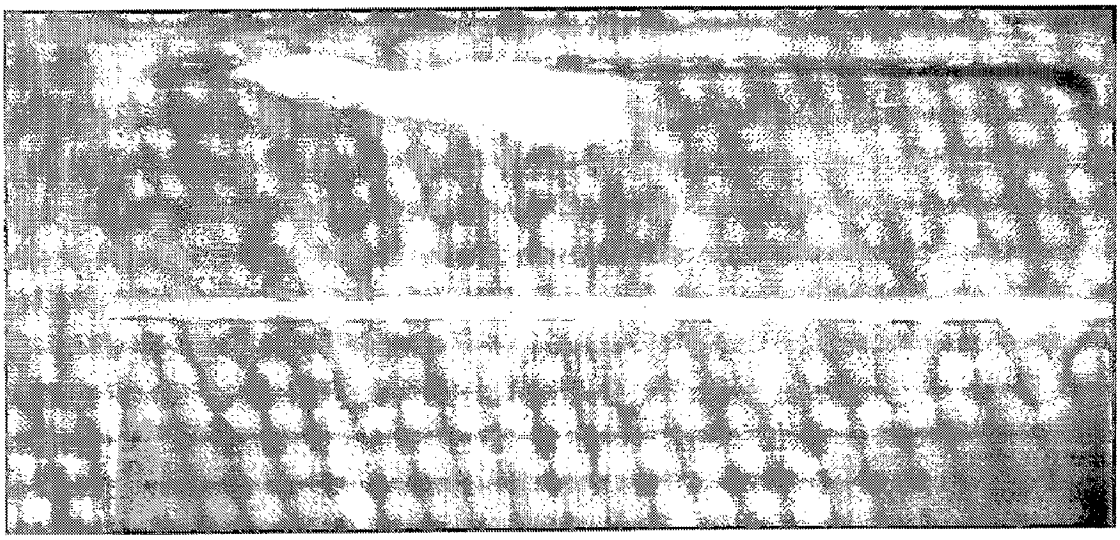


Fig 4.11 Saw tooth waveform recorded on CRO in Laboratory

4.2.6 PI Controller

This is fabricated on PCB. The design and analysis of PI controller to generate the peak value of reference is done which is shown in *fig 4.12.*·The transfer function of the circuit in the linear region of its operation is given;

$$G_C(s) = \frac{K_C(1+sT_C)}{s}$$

$$where, T_C = C_f R_f and$$

$$K_C = \frac{1}{R_1 C_f}$$

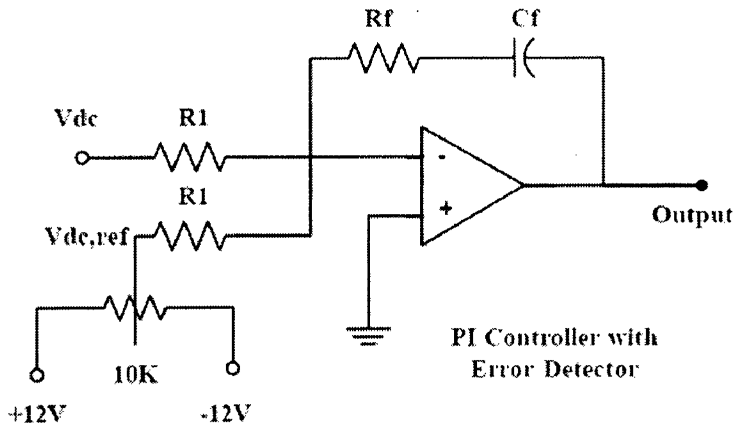


Figure 4.12: PI controller

ASSUMPTIONS:

K1=R_f/R_1=34.55

R_fC_f=0.1935 let C_f=0.1□f implies R1=56kohm, R_f=2 Mohm

4.2.7 Gate pulse generation circuit

The triangular output of PI controller is compared with saw tooth wave and gate of varying pulse width is generated.

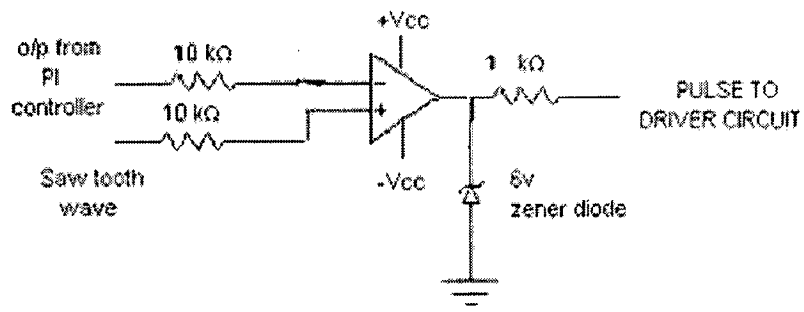


Fig 4.13 Gate pulse generation circuit

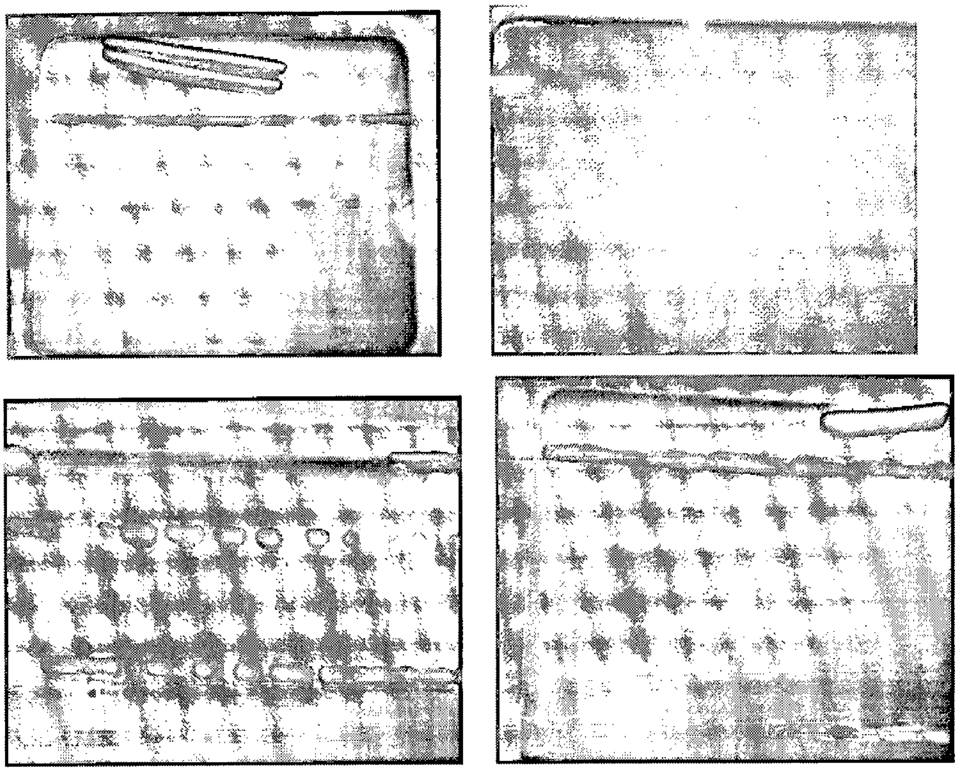


Fig 4.14 Pulse generation at various duty cycles

4.2.8 Pulse Amplification and Isolation Circuit

The pulse amplification and isolation circuit for IGBT is shown in *figure 4.15*. The opto-coupler (MCT-2E) provides the necessary isolation between the low voltage isolation circuit and high voltage power circuit .The pulse amplification is provided by the output amplifier transistor 2N222.

When the input gating pulse is at +5V level, the transistor saturates, the LED conducts and the light emitted by it falls on the base of phototransistor, thus forming its base drive. The output transistor thus receive no base drive and, therefore remains in cut-off state and a +12 v pulse (amplified) appears across it's collector terminal (w.r.t.ground). When the input gating pulse reaches the ground level (0V), the input switching transistor goes into the cut-off state and LED remains off, thus emitting no light and therefore a photo transistor of the opto-coupler receives no base drive and, therefore remains in cut-off state .A sufficient base drive now applies across the base of the output amplifier transistor .it goes into the saturation state and hence the output falls to ground level. Therefore circuit provides proper amplification and isolation. Further, since slightest spike above 20v can damage the IGBT, a 12 V zener diode is connected across the output of isolation circuit. It clamps the triggering voltage at 12.

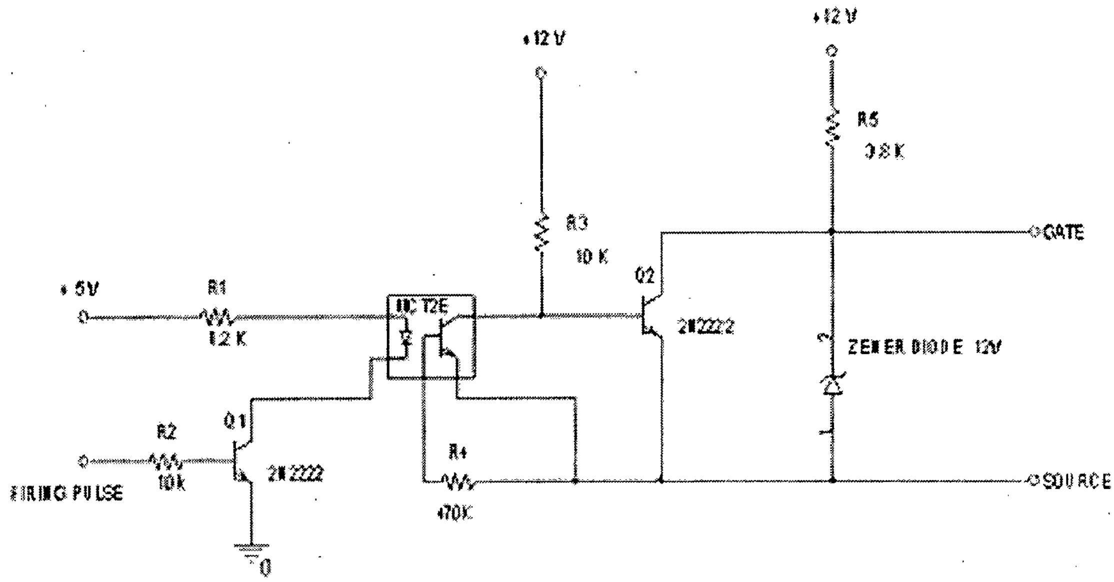


Figure 4.15: Pulse amplification and isolation circuit

4.2.9 Circuit Protection

(A) **Snubber Circuit for IGBT protection:**

IGBTs are used in power electronics application, because of hard switching applications and lower conduction losses. Most of the IGBTs are used in hard switching applications up to 20 kHz, beyond that switching losses in IGBTs becomes very significant.

Switching such high currents in short time gives rise to voltage transients that could exceed the rating of IGBT especially if the bus voltage is close to the IGBT's rating. Snubbers are therefore needed to protect the switch from transients. Snubber circuit for IGBT as shown in Figure 4.16.

Snubbers are employed to:

- Limit di/dt or dv/dt.
- Transfer power dissipation from the switch to a resistor.
- Reduce total switched losses.

RCD snubbers are typically used in high current application. The operation of RCD snubber is as fallows: The turn-off makes the voltage zero at the instant the IGBT turn-off. At turn-off, the device current is transfer through the diode D_s and the voltage across the device builds up. At the turn-on, the capacitor C_s discharges through the resistor R_S. The capacitor energy is dissipated in the resistor R_S at turn-on.

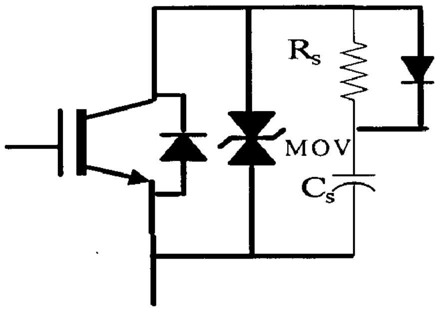


Fig 4.16. Snubber circuit of IGBT

***(B)* Over voltage protection:**

An additional protective device Metal-oxide-varistor (MOV) is used across each device to provide protection against the over voltages. MOV acts as a back-to-back zener and bypass the transient over voltage across the device. In general the voltage rating of MOV is kept equal are below the rating of IGBT to protect it from the over voltages.

***(C)* Over heating protection:**

Due to the ohmic resistance of IGBT and anti - parallel diode, I^2 R loss takes place as a result of the current conduction, which results the heat generation, thus raising the device temperature, this may be large enough to destroy the device. To keep device temperature within the permissible limits, all IGBTs are mounted on aluminum heat sink and is then dissipated to the atmosphere.

(D) Short circuit protection:

The thermal capacity of semiconductor device is small. A surge current due to a short circuit may rise device temperature much above its permissible temperature rise limit which may instantaneously damage the device. Hence, the short circuit protection is provided by fast acting fuses in series with each supply line.

CHAPTER 5

DESIGN AND MATHEMATICAL MODELLING OF SEIG STATCOM

5.1 Theory

Capacitor self-excited induction generator suffers from it's inherent poor voltage regulation. A number of methods have been proposed for regulating the voltage profile of the SEIG. The long shunt and short shunt connections of stator windings and the series/parallel capacitors of a SEIG provides a simple method but the series capacitors used in these configurations could result in sub synchronous resonance when the generator is connected to inductive or dynamic load.

An effective capacitive VAR controller has become central to the success of SEIG system for stand-alone applications. Reactive power may be provided by switched capacitors, static VAR compensator (SVC) and static compensator (STATCOM). A switched capacitor scheme is cheaper, but it regulates the terminal voltage in discrete steps. Electromechanical switches are found to cause unstable chattering and solid state switching needs correct timing.

The development and advances in the technology of power semiconductor devices have revolutionized the concept of power control. Application of these devices in industrial applications has increased tremendously out of which the control of electric machines is predominant. Due to the fast development of high-capacity power semiconductor and power electronic application techniques, the available solid-state switches such as MOSFETs, IGBTs, GTOs are being used as fast power switches in the field of solid-state synchronous voltage source (SVS). The function of solid-state SVS is similar to that of a rotating synchronous condenser (STAT-CON) or a static compensator (STATCOM). STATCOM employs a voltage source inverter that internally generates capacitive/inductive reactive power.

STATCOM is connected in parallel with a fixed capacitor and load. STATCOM consists of a three-phase current controlled voltage source inverter (CC-VSI) and an electrolytic capacitor and its DC bus. The DC bus capacitor is used to self-support a DC bus of STATCOM and takes very small active power from SEIG for charging and gives sufficient reactive power as per requirement. Thus, STATCOM is a source of leading or lagging currents and acts in such a way as to maintain constant voltage across the SEIG terminals at varying loads. AC output terminals of STATCOM are connected through filter reactance to the ac mains created by SEIG.

5.2 SEIG STATCOM

5.2.1 System Description

The schematic diagrams of SEIG with excitation capacitor, STATCOM, load, and control scheme are shown in Fig.5.1. Excitation capacitors are selected to generate the rated voltage of SEIG at no load. The additional demand of reactive power is fulfilled using the STATCOM under varying loads. The STATCOM acts as a source of lagging or leading current to maintain a constant terminal voltage with varying loads. The STATCOM consists of a three-phase IGBT-based current controlled VSI, dc bus capacitor, and ac inductors. The output of the inverter is connected through the ac filtering inductors to the SEIG terminals. The dc bus capacitor is used as energy storage device and provides self-supporting dc bus.

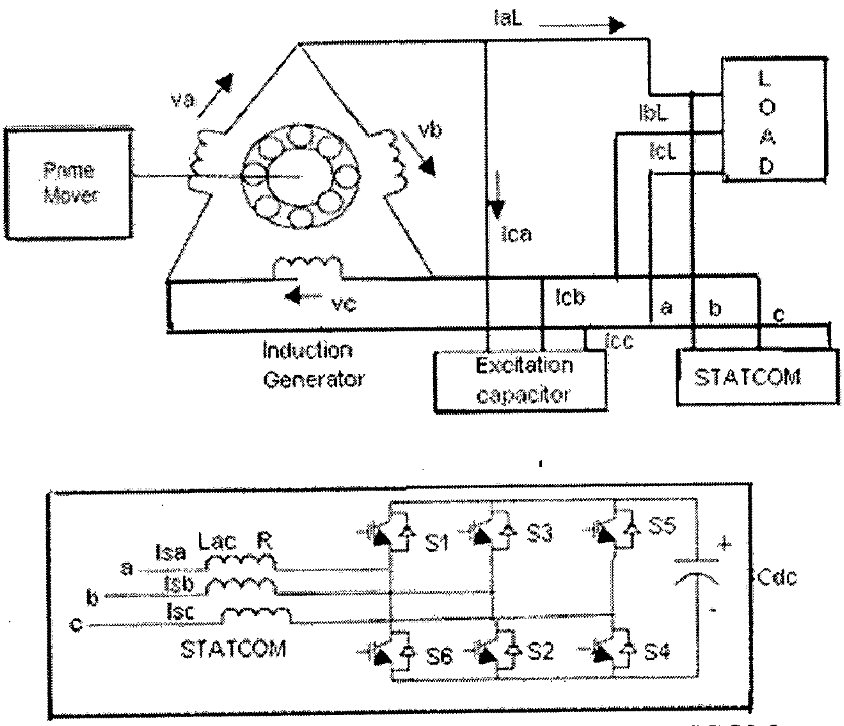


Fig 5.1 Schematic diagram of three phase SEIG-STATCOM system

PRINCIPLE OF OPERATION:

Generated voltage of the SEIG system depends on the prime mover speed, connected terminal capacitance, and load. Prime mover may be a micro hydel/wind turbine, biomass, or oil driven engine. The speed of these prime movers may not be constant as it varies depending on the energy source and the characteristics of the energy converter employed. The controlled reactive power is responsible for keeping the terminal voltage constant with change in load.

The dc bus capacitor is used to self-support a dc bus of STATCOM and takes very small active power from SEIG for charging and gives sufficient reactive power as per requirement. Thus, STATCOM is a source of leading or lagging currents and acts in such a way as to maintain constant voltage across the SEIG terminals at varying loads. Ac output terminals of STATCOM are connected through filter reactance to the ac mains created by SEIG.

5.2.2 Design of STATCOM

In this, STATCOM is designed for 7.5 kW,3-phase,230V,26.2A,Δ-connected squirrel cage induction machine. When terminal voltage of the SEIG is higher than the reference voltage, STATCOM operates as an inductor and maintains constant terminal voltage. When the terminal voltage is less than the reference voltage, STATCOM provides the capacitive VAR to SEIG.

Types of STATCOM:

There are two types of STATCOM.(i).Full Rating STATCOM (ii).Reduced Rating STATCOM.

In Full Rating STATCOM, the differential reactive power (full load kVAR-no load kVAR) is supplied by STATCOM .In the latter half the value of differential reactive power (full load kVAR-no load kVAR) is supplied by STATCOM and the remaining half by an ac capacitor bank.

(A) Design of Full Rating STATCOM:

Table 5.1 shows the capacitance, Excitation Requirements, Rating of STATCOM to maintain Rated voltage for unity power factor Loads is shown for Different m/c Power Ratings[30].

Table 5.1: Capacitance, Excitation Requirements & Rating of STATCOM to maintain Rated voltage

Machine rating (kW/V)	Capacitance at no load (μF)	Capacitance at full load (μF)	Excitation requirements		Rating of STATCOM to maintain rated vtg(Q_{AR})	
			at No-load KVAR(Q_0)	at Full load KVAR(Q_R)	Full rating (Q_{AR})	Reduced rating (Q_{AR})
3.7/415	15.5	24.96	2.51	4.05	1.53	0.76
5.5/415	23.09	33.84	3.75	5.49	1.74	0.87
7.5/220	85.56	181.6	4.31	9.05	4.74	2.37
7.5/415	29.3	48.00	4.76	7.79	3.03	1.51
15/381	57.77	91.10	9.37	14.98	5.41	2.70
22/400	62.238	103.24	9.38	15.568	6.19	3.10

From Table 5.1,

The additional Reactive Power (QA) required at full load to maintain constant voltage of SEIG at UPF load is obtained for 7.5kW m/c as

$$Q_{AR} = (Q_R - Q_o) \tag{5.1}$$

$$= (9.05-4.31) = 4.74 \text{ KVAR}$$

The current rating of the STATCOM corresponds to additional reactive power required from no load to full load at UPF and it is calculated as

Additional VAR$(Q_{AR}) = \sqrt{3}VI_S$ where, V is the SEIG line voltage and I_S is the STATCOM line current.

$$I_S = Q_{AR}/(1.732*V) \tag{5.2}$$

$$= 4.74/(1.732*230) = 11.89 \text{ (A)}$$

For satisfactory PWM control, the DC voltage must be more than peak of line Voltage (i.e. rated voltage of SEIG 230 V).

$$V_{DC} = \frac{2\sqrt{2}\left(V/\sqrt{3}\right)}{ma} \tag{5.3}$$

$$= 375.58 \approx 400 \text{ V}$$

The inductance can be calculated as

$$L_f = \frac{\left(\sqrt{3}/2\right) ma V_{DC}}{6 a f_s i_{cr(PP)}} \tag{5.4}$$

where, m is the modulation index

fs is the Switching frequency(10kHZ)

icr(pp) is the current ripple through inductor

a=1.2(during transients, the current rating is likely to vary from 120% to 180% of the steady-state value. In inductance calculation current rating of 120% of steady-state current is taken during transients.)

After substituting the above values, inductance value $L_f = 2.85$mH.

Voltage drop across inductor = $2 \pi f L_f I_s = 12.8$ V

The rating of the dc bus capacitor of STATCOM is a very important factor as it should provide the instantaneous energy at sudden loading of SEIG. It also provides energy instantaneously to SEIG under transient operation. The response time of STATCOM is around 200 to 350(μs) [18].

By considering 8% dip in the dc link voltage, during transients, energy transfer from capacitor to the SEIG to provide reactive power is calculated as:

$$E = 1/2 \ C (\Delta V)^2 = 3 \ V_{ph} I_s t \tag{5.5}$$

$C_{DC} = 396\mu F$

Voltage and current Ratings of IGBTs:

Voltage and current ratings of the solid-state devices (IGBTs) are decided based on maximum voltage across the devices and current through the devices. Under dynamic condition, change in terminal voltage of the SEIG is considered to be 10%. The Max.AC voltage is calculated as:

$$\sqrt{2}\left(V + V_L + V_d\right) \approx 375 \text{ V}$$

Where, V_L is Voltage drop across inductor

V_d is 10% of Vph for dynamic condition

Max. line current by considering the safety factor of 1.25 is:

$= 1.25(I_{cr(pp)}+I_{s(peak)}) \approx 23.11$

Standard Ratings: Rating of inductor Lf: 2.85mH

Rating of IGBT switches: 375 V, 23.11 A

Rating of DC capacitor: 470μF

(B) Design of Reduced Rating STATCOM:

In this, half the value of differential reactive power (full load kVAR-no load kVAR) is supplied by STATCOM and the remaining half by an ac capacitor bank.

The required reactive power for SEIG at no load and rated UPF load is same as in full-rating STATCOM. Hence, the additional VAR (Q_{AR}) requirement is same, i.e., 4739 VAR, out of which half is supplied by STATCOM and remaining half is supplied by additional ac capacitors.

$Q_{AR} = (Q_R-Q_o)/2 = 4739/2 \approx 2370$ VAR

The statcom line current is

$I_S=Q_{AR}/(1.732*V)$

$= 2.37/(1.732*230) = 5.94$ (A)

The dc bus voltage from eqn. 5.3 is 400 V.

The inductance value from eqn.5.4 is:

$$L_f = \frac{\left(\sqrt{3}/2\right) maV_{DC}}{6af_s i_{cr(PP)}} = 5.7 \text{ mH}$$

Voltage drop across the ac inductor = 2 п f Lf Is = 12.82 V

The DC link capacitance from eqn.(5.5) is : 198 μF

The voltage rating of the devices is the same in reduced STATCOM as in full-rating STATCOM. But, the current rating reduces because STATCOM should supply only half the value of reactive power.

Max. Line current by considering the safety factor of 1.25 is:

$= 1.25(Icr\ (pp) + Is\ (peak)) \approx 11.55$ (A)

Standard Ratings:

Rating of inductor L_f: 5.7mH

Rating of IGBT switches: 600 V, 15 A

Rating of DC capacitor: 220μF

The STATCOM Ratings for Different Rating of electrical machines for UPF loads is given in the following Tables 5.2, 5.3.

Table 5.2 Full-Rating STATCOM parameters for different m/cs at UPF Load

Power Rating (kW)	SEIG terminal voltage (V)	DC bus Voltage (V)	Current Ratings (A)	AC Inductance (mH)	Dc bus capacitance (μF)
3.7	415	700	2.14	27.82	100
5.5	415	700	2.42	24.53	100
7.5	230	400	11.90	2.85	470
15	415	700	7.52	7.90	220
22	400	700	8.92	6.67	220

Table 5.3 Reduced-Rating STATCOM parameters for different m/cs at UPF load

Power Rating (kW)	SEIG terminal voltage (V)	DC bus Voltage (V)	Current Ratings (A)	AC Inductance (mH)	Dc bus capacitance (μF)
3.7	415	700	1.07	55.64	68
5.5	415	700	1.21	49.06	68
7.5	230	400	6.00	5.71	220
15	415	700	3.76	15.81	100
22	400	700	4.46	13.34	100

OBSERVATIONS:

The voltage rating of the SEIG decides DC bus voltage of the STATCOM. Therefore DC bus voltage is same for all machines. Current rating of STATCOM increases with machine rating because reactive power requirement increases with machine power rating. The AC inductance value decreases and DC bus capacitance value increases with increase in rating of electrical machines. The value of Ac capacitance increases because of higher reactive power required in higher rating of machines.

The value of DC capacitor is half in reduced rating STATCOM than full rating STATCOM and AC inductor values are doubled in reduced rating STATCOM compared to full rating STATCOM. Device ratings are considerably reduced in case of reduced rating STATCOM. Therefore, the cost of devices and capacitors reduces resulting in overall reduction in the cost of STATCOM.

5.3 Mathematical Modeling of SEIG-STATCOM System [30]

The schematic diagram of system and control scheme is shown in Fig 5.1 and Fig 5.2 which consists of the SEIG, controller and its control scheme. The mathematical modeling of each component is as follows.

5.3.1 Modeling of Control strategy of STATCOM:

The control scheme of the controller is the heart of the system and generates gating pulses for VSI and chopper switches. It consists of two PI controllers, each for maintaining constant Dc voltage of "voltage and frequency controller (VFC)"and constant SEIG terminal voltage.

Three-phase voltages at the SEIG terminals (v_a,v_b,v_c) are considered sinusoidal and hence their amplitude is computed as:

$$v_t = \sqrt{2/3(v_a^2 + v_b^2 + v_c^2)} \qquad (5.6)$$

The unit vector in phase with v_a,v_b, and v_c are :

$$u_a=v_a/v_t;u_b=v_b/v_t;u_c=v_c/v_t \qquad (5.7)$$

The unit vectors in quadrature with v_a, v_b, v_c may be derived using a quadrature transformation of the in-phase unit vectors u_a,u_b and u_c as :

$$w_a = \frac{(-u_b + u_c)}{\sqrt{3}} \qquad (5.8)$$

$$w_b = \frac{\sqrt{3}}{2}\left(u_a + \frac{1}{3}(u_b - u_c)\right) \qquad (5.9)$$

$$w_c = \frac{\sqrt{3}}{2}\left(-u_a + \frac{1}{3}(u_b - u_c)\right) \qquad (5.10)$$

(1) Quadrature component of source reference current:

The AC voltage error V_{er} at the n^{th} sampling instant is:

$$V_{er(n)}=V_{tref(n)}-V_{t(n)} \qquad (5.11)$$

Where $V_{tref(n)}$ is the amplitude of reference AC terminal voltage and $V_{t(n)}$ is the amplitude of the sensed three-phase AC voltage at the SEIG terminals at n^{th} instant. The output of the PI controller ($I^*_{smq(n)}$) for maintaining AC terminal voltage constant at the n^{th} sampling instant is expressed as :

$$I^*_{smq(n)}=I^*_{smq(n-1)}+K_{pa}\{V_{er(n)}-V_{er(n-1)}\}+K_{ia}V_{er(n)} \qquad (5.12)$$

Where K_{pa} and K_{ia} are the proportional and integral gain constants of the proportional integral (PI) controller, $V_{er(n)}$ and $V_{er(n-1)}$ are the voltage errors in the n^{th} and $(n-1)^{th}$ instant and $I^*_{smq(n-1)}$ is the amplitude of the quadrature component of the quadrature component of the source reference current.

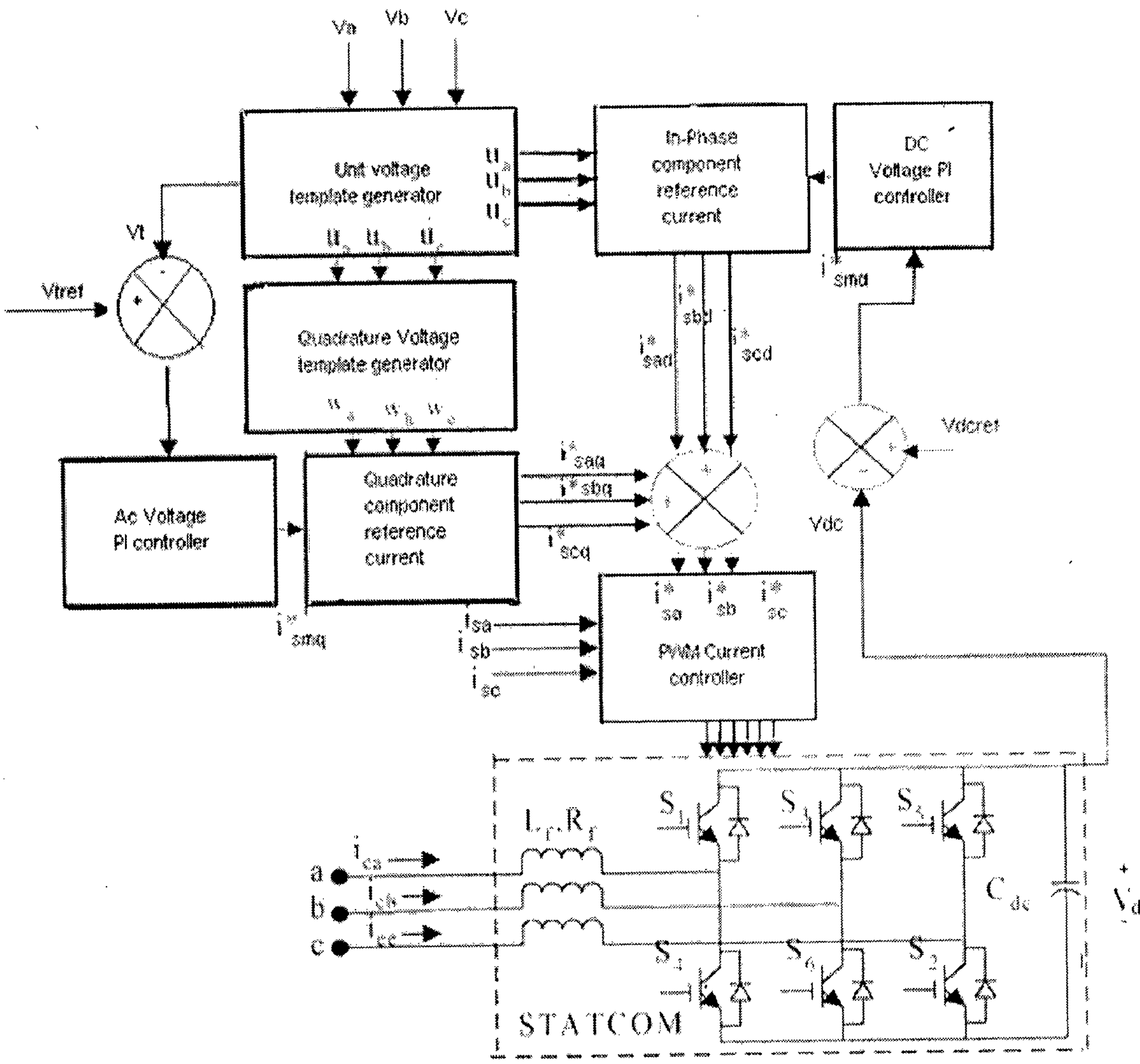


Fig 5.2 SEIG-STATCOM Control Scheme

at $(n-1)^{th}$ instant. The quadrature components of the source reference currents are estimated as:

$$i^*_{saq}=I^*_{smq}w_a; i^*_{sbq}=I^*_{smq}w_b; i^*_{scq}=I^*_{smq}w_c \quad (5.13)$$

(2) In phase component of source reference current:

The DC bus voltage error V_{dcer} at n^{th} sampling instant is:

$$V_{dcer(n)}=V_{dcref}-V_{dc(n)} \quad (5.14)$$

Where V_{dcref} is the reference DC voltage and $V_{dc(n)}$ is the the sensed DC link voltage of the CC-VSI. The output of the PI controller for maintaining DC bus voltage of the CC-VSI at the n^{th} sampling instant is expressed as:

$$i^*_{smd(n)}=I^*_{smd(n-1)}+K_{pi}\{V_{dcer(n)}-V_{dcer(n-1)}\}+K_{id}V_{dcer(n)} \quad (5.15)$$

$i^*_{smd(n)}$ is considered as the amplitude of active source current. K_{pi} and K_{id} are the proportional and integral gain constants of the DC bus PI voltage controller. In-phase components of source reference currents are estimated as:

$$i^*_{sad}=I^*_{smd}u_a; i^*_{sbd}=I^*_{smd}u_b; i^*_{scd}=I^*_{smd}u_c \quad (5.16)$$

(3) Total source reference currents:

Total source reference currents are sum of in-phase and quadrature components of the source reference currents as:

$$i^*_{sa}=i^*_{saq}+i^*_{sad} \quad (5.17)$$

$$i^*_{sb}=i^*_{sbq}+i^*_{sbd} \quad (5.18)$$

$$i^*_{sc}=i^*_{scq}+i^*_{scd} \quad (5.19)$$

(4) PWM current controller:

The total reference currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are compared with the sensed source currents (i_{sa}, i_{sb}, i_{sc}). The ON/OFF switching patterns of the gate drive signals to the IGBT are generated from the PWM current controller. The current errors are computed as:

$$i_{saerr}=i^*_{sa}-i_{sa} \quad (5.20)$$

$$i_{sberr}=i^*_{sb}-i_{sb} \quad (5.21)$$

$$i_{scerr}=i^*_{sc}-i_{sc} \quad (5.22)$$

These current error signals are amplified and then compared with the triangular carrier wave. If the amplified current error signal corresponding to phase a

(i_{saerr}) is greater than the triangular wave signal switch S_4 (lower device) is ON and switch S_1 is OFF and the value of switching function SA is set to zero. If the amplified current error signal corresponding to i_{saerr} is less than the triangular wave signal switch S_1 is ON and switch S_4 is OFF, and the value of SA is set to 1.

5.3.2 Modeling of STATCOM:

The STATCOM is a current controlled voltage source inverter and modeled as follows: The derivative of its DC bus voltage is defined as:

$$pv_{dc} = \left(i_{ca}SA + i_{cb}SB + i_{cc}SC\right)/C_{dc} \tag{5.23}$$

Where SA, SB and SC are switching functions for the ON/OFF positions of voltage source inverter switches S1-S6.

The PWM AC line line voltages are:

$$\begin{aligned} e_{ab} &= e_a - e_b = v_{dc}(SA - SB) \\ e_{bc} &= e_b - e_c = v_{dc}(SB - SC) \\ e_{ca} &= e_c - e_a = v_{dc}(SC - SA) \end{aligned} \tag{5.24}$$

The volt-current equations of the output of voltage source inverter are:

$$\begin{aligned} v_a &= R_f i_{ca} + L_f p i_{ca} + e_{ab} - R_f i_{cb} - L_f p i_{cb} \\ v_b &= R_f i_{cb} + L_f p i_{cb} + e_{bc} - R_f i_{cc} - L_f p i_{cc} \\ i_{ca} &+ i_{cb} + i_{cc} = 0 \end{aligned} \tag{5.25}$$

By solving eqn.(4.20),STATCOM current derivatives are obtained as:

$$\begin{aligned} pi_{ca} &= \{(v_b - e_{bc}) + 2(v_a - e_{ab}) - 3R_f i_{ca}\}/3L_f \\ pi_{cb} &= \{(v_b - e_{bc}) - (v_a - e_{ab}) - 3R_f i_{ca}\}/3L_f \end{aligned} \tag{5.26}$$

The AC line voltages at the common point of coupling are given as:

$$\begin{aligned} pv_a &= \frac{\{(i_a - (i_{al} + i_{ca})\} - \{(i_b - (i_{lb} + i_{cb})\}}{3C_x} \\ pv_b &= \frac{\{(i_a - (i_{al} + i_{ca})\} + 2\{(i_b - (i_{lb} + i_{Db})\}}{3C_x} \\ V_a &+ V_b + V_c = 0 \end{aligned} \tag{5.27}$$

Thus, by using SEIG eqns.from (3.1) to (3.22) and by using STATCOM eqns. from (5.6) to (5.27) the “SEIG STATCOM” can be modeled and the Flow chart is shown in Fig. 5.3.

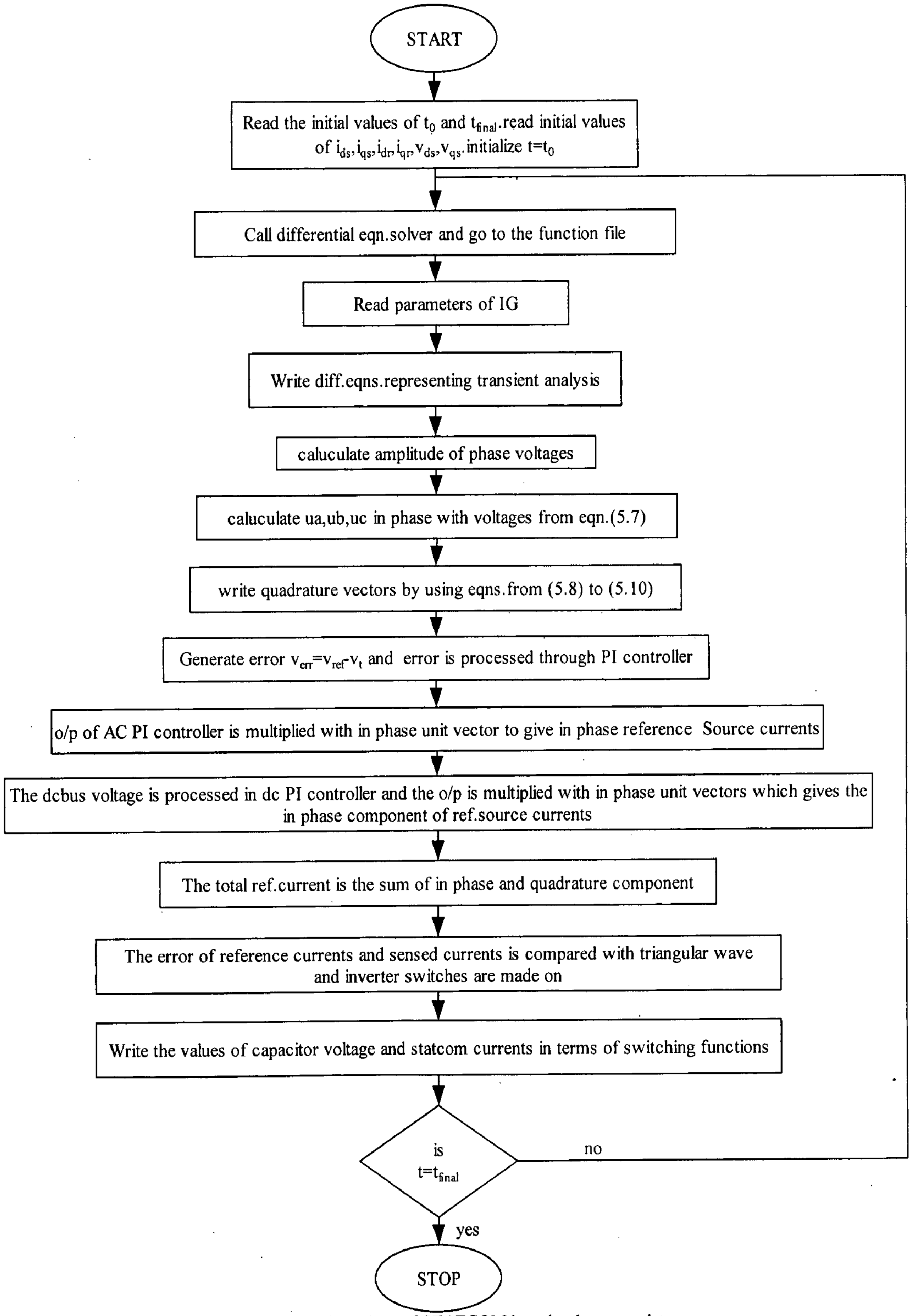


fig 5.3 Flow chart of STATCOM based voltage regulator

CHAPTER 6

SIMULINK BLOCK DIAGRAMS AND SIMULATION RESULTS

6.1 SIMULINK BLOCK DIAGRAMS

6.1.1 SEIG Model

By using the equations from (3.1) to (3.22) from chapter 3 we can model the Self-Excited induction generator (SEIG) with resistive and inductive loads. The block diagram of "SEIG" is shown in fig 6.1 and 6.2.

The parameters of machine are shown in APPENDIX-I.

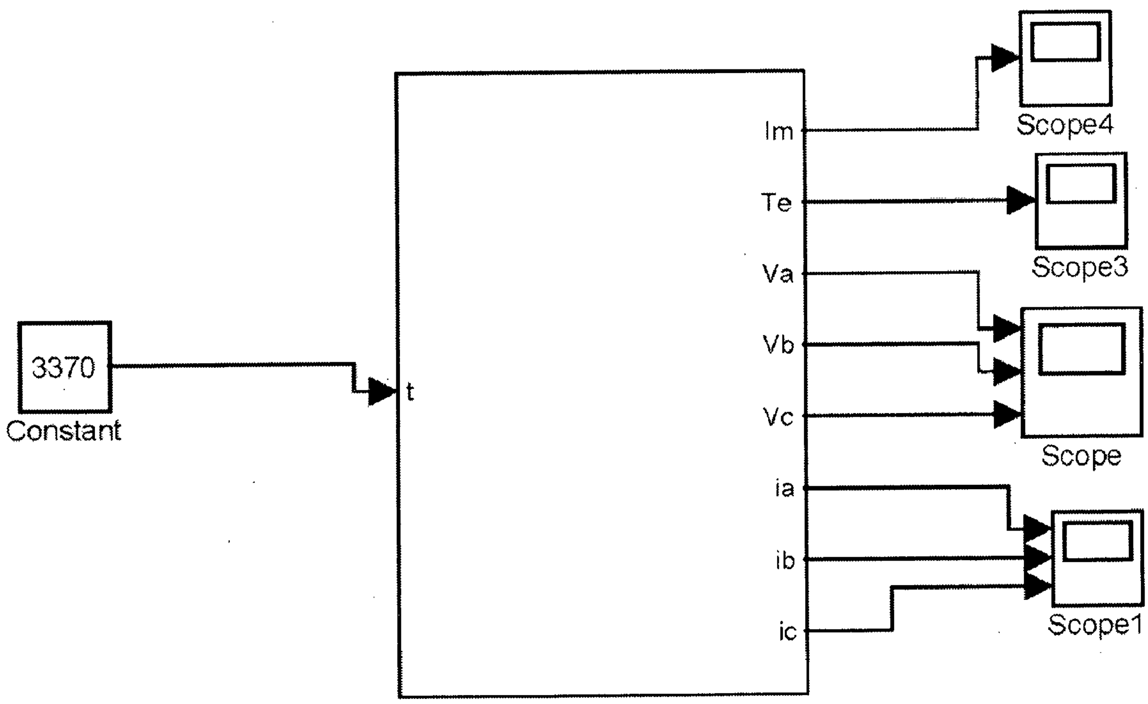


Fig 6.1 SEIG block diagram

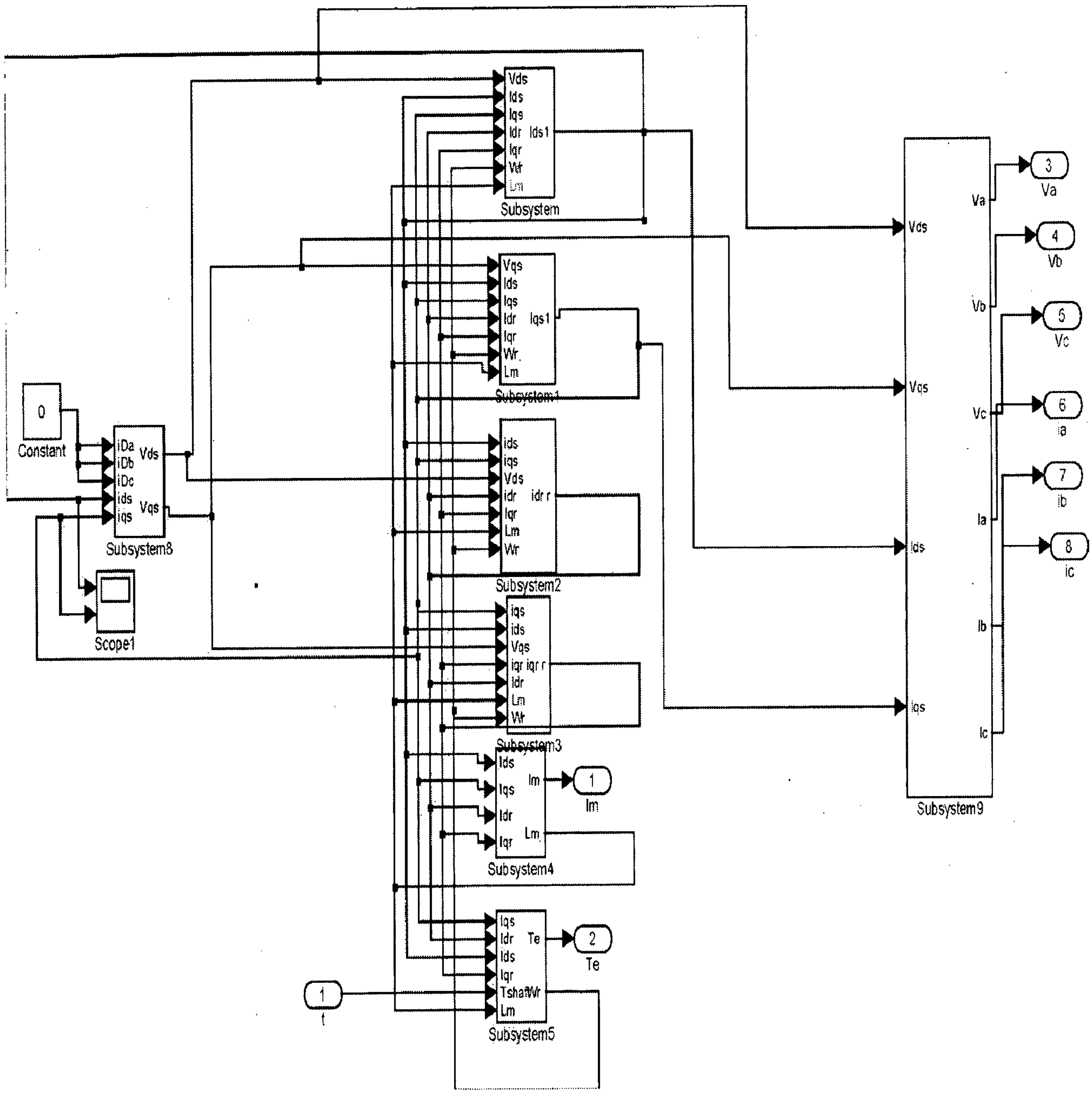


Fig 6.2 SEIG subsystem

6.1.2 SEIG-STATCOM Model

By using the equations from (5.1) to (5.22) from chapter 5 and equations from (3.1) to (3.22) from chapter 3, we can model the Self-Excited induction generator (SEIG) with STATCOM. The block diagram of "SEIG-STATCOM" is shown in fig 6.3 and 6.4. The parameters of STATCOM are shown in APPENDIX-I.

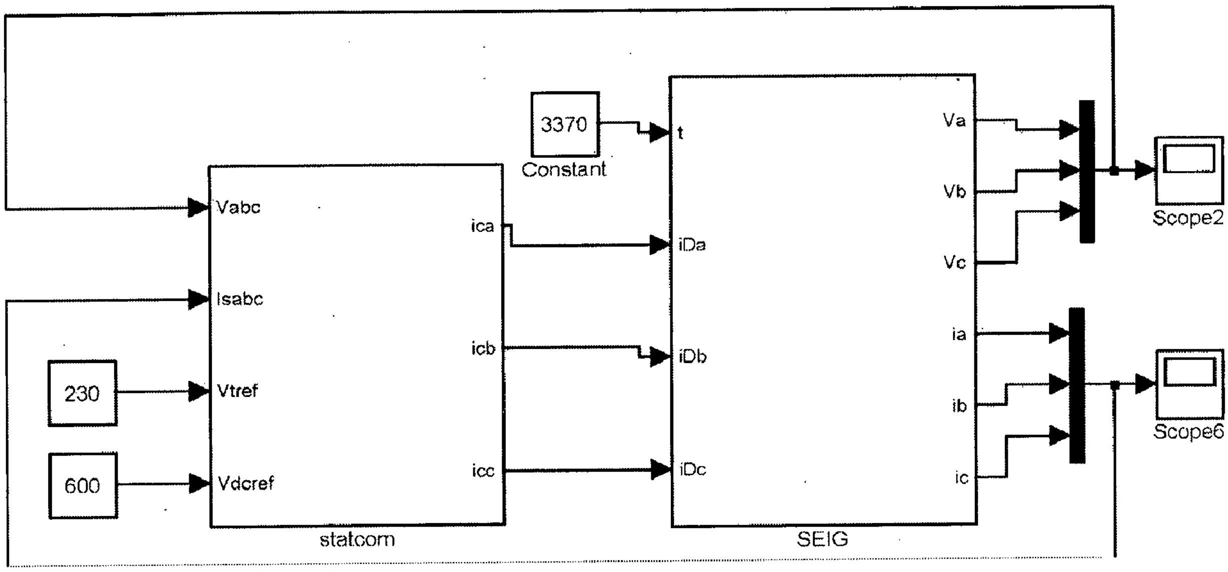


Fig 6.3 SEIG-STATCOM block diagram

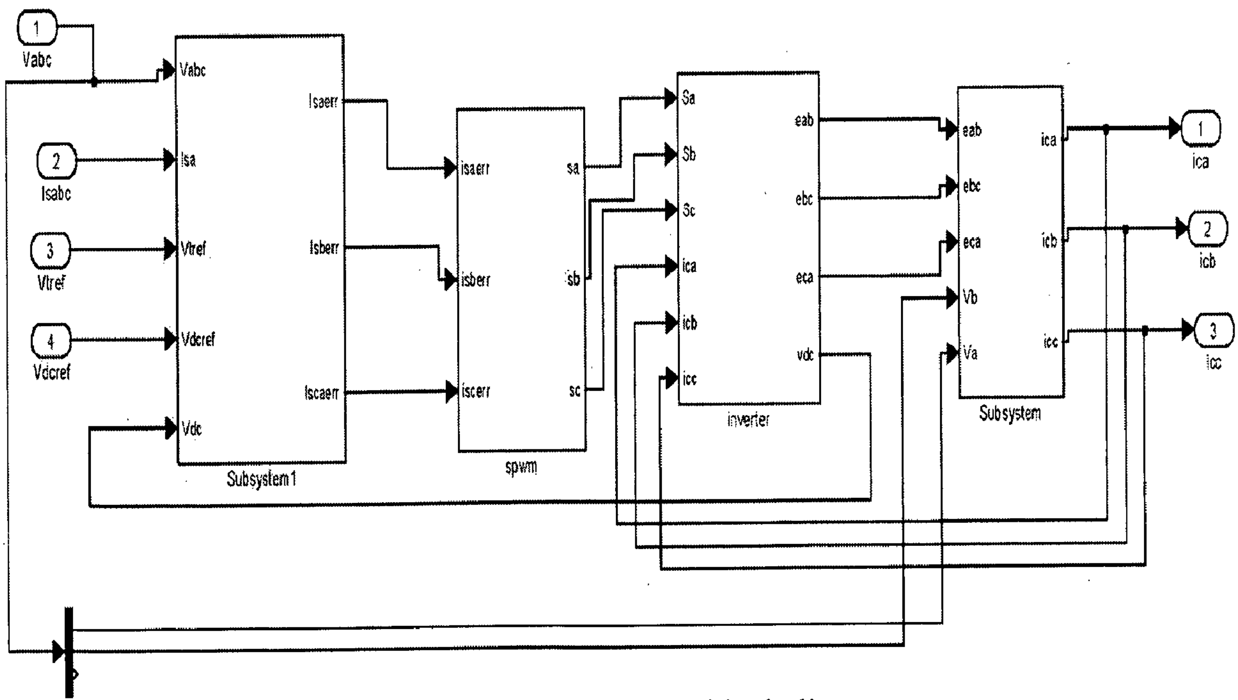


Fig 6.4 SEIG-STATCOM block diagram

6.2 SIMULATION RESULTS

6.2.1 SEIG: By using the equations from (3.1) to (3.22) from chapter 3 we can model the Self-Excited induction generator (SEIG) with resistive and inductive loads.

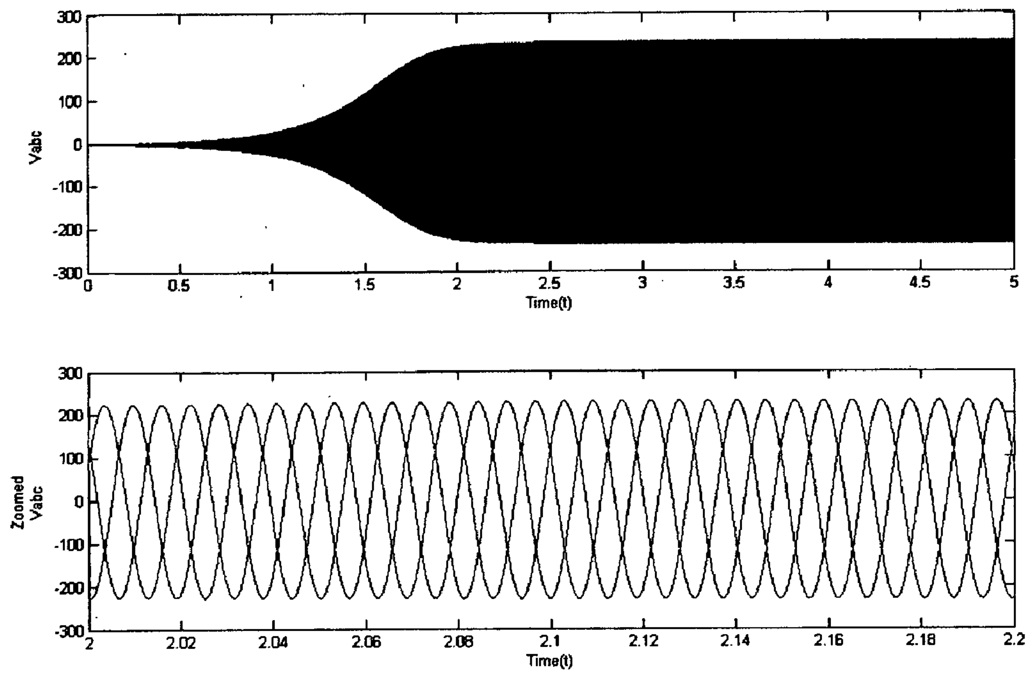


Fig 6.5 Three phase Voltages

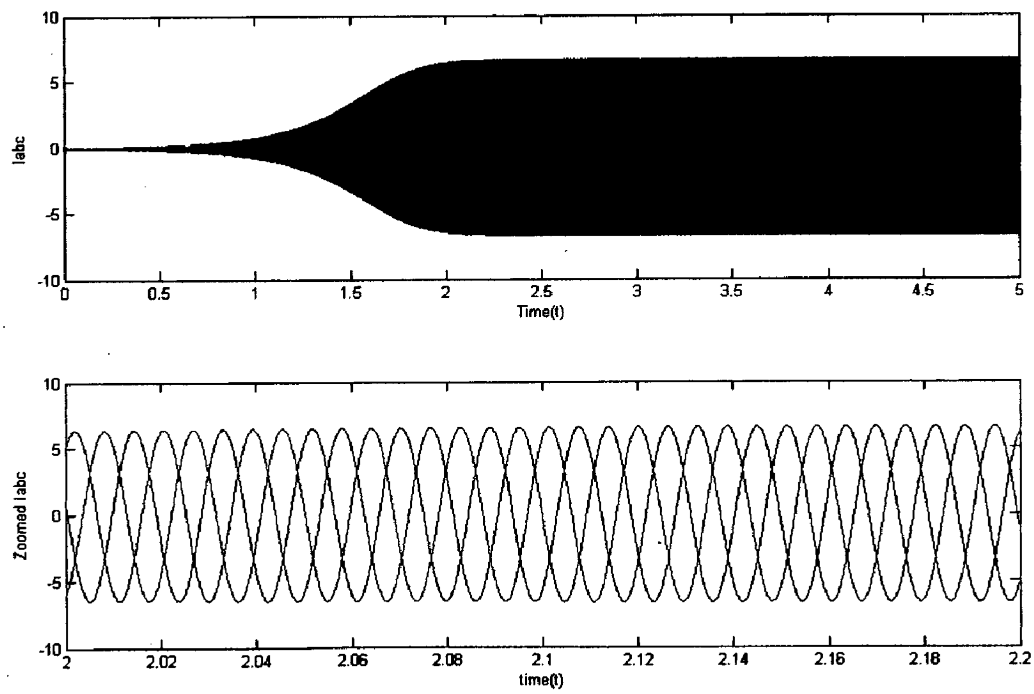


Fig 6.6 Three phase currents

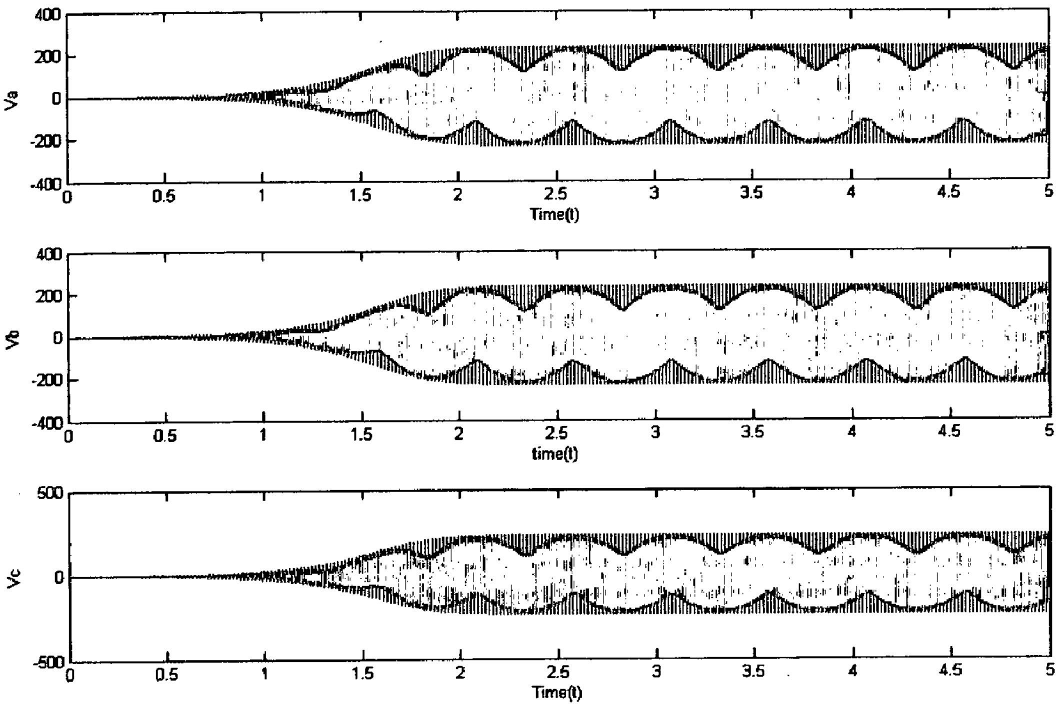


Fig 6.7 Three-phase Voltages under no load

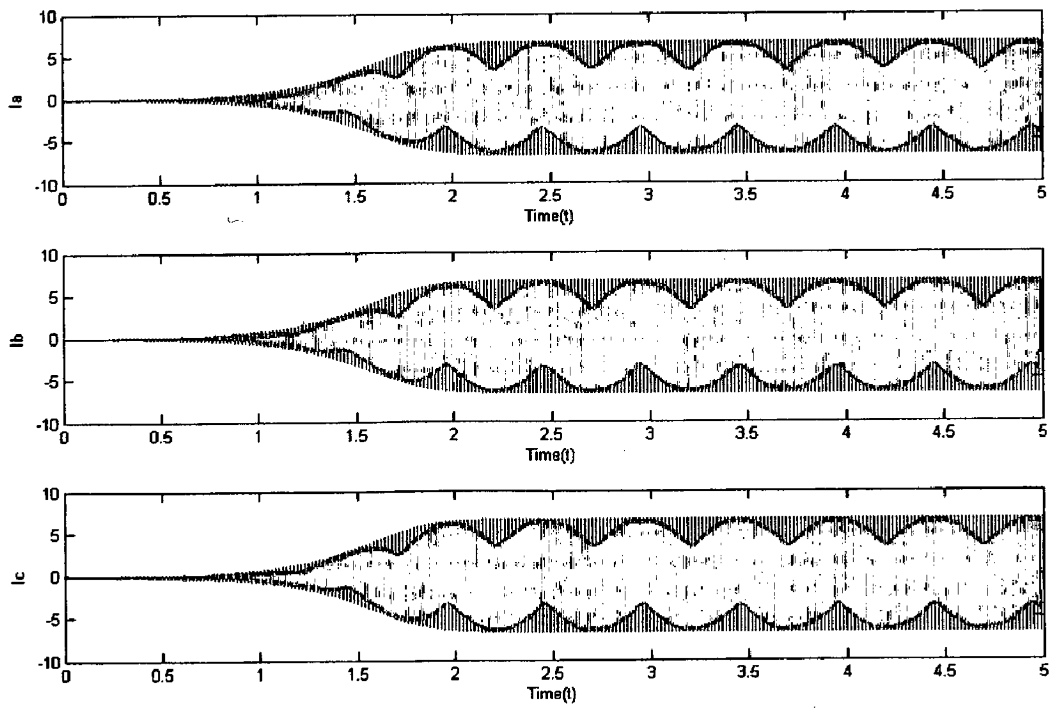


Fig 6.8 Three-phase currents under no load

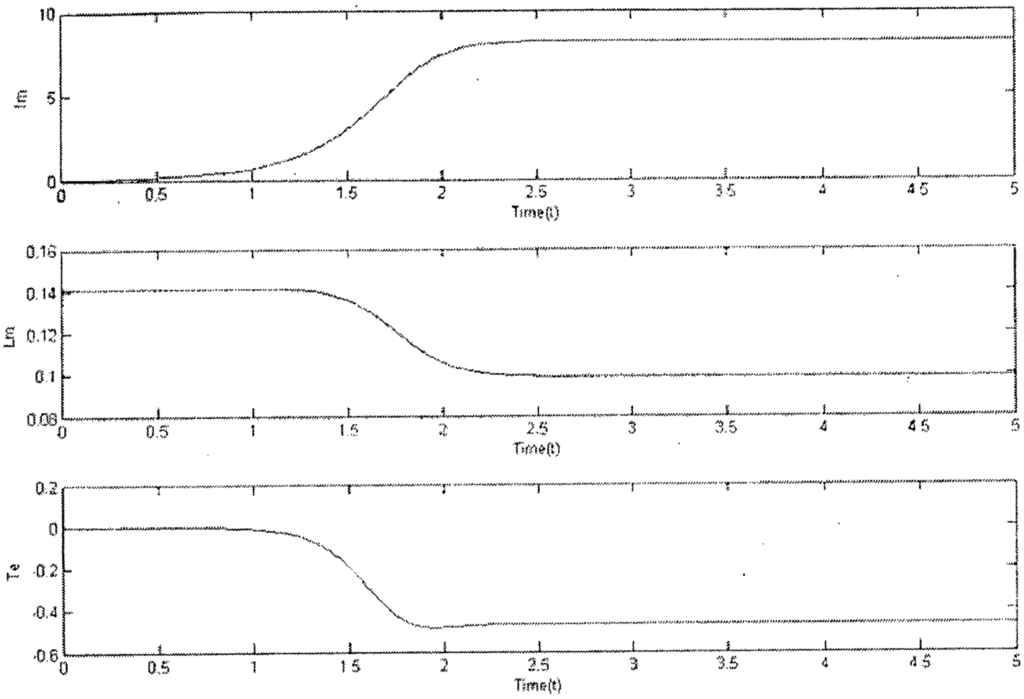


Fig 6.9 Magnetizing current, Magnetizing inductance, Electro magnetic torque

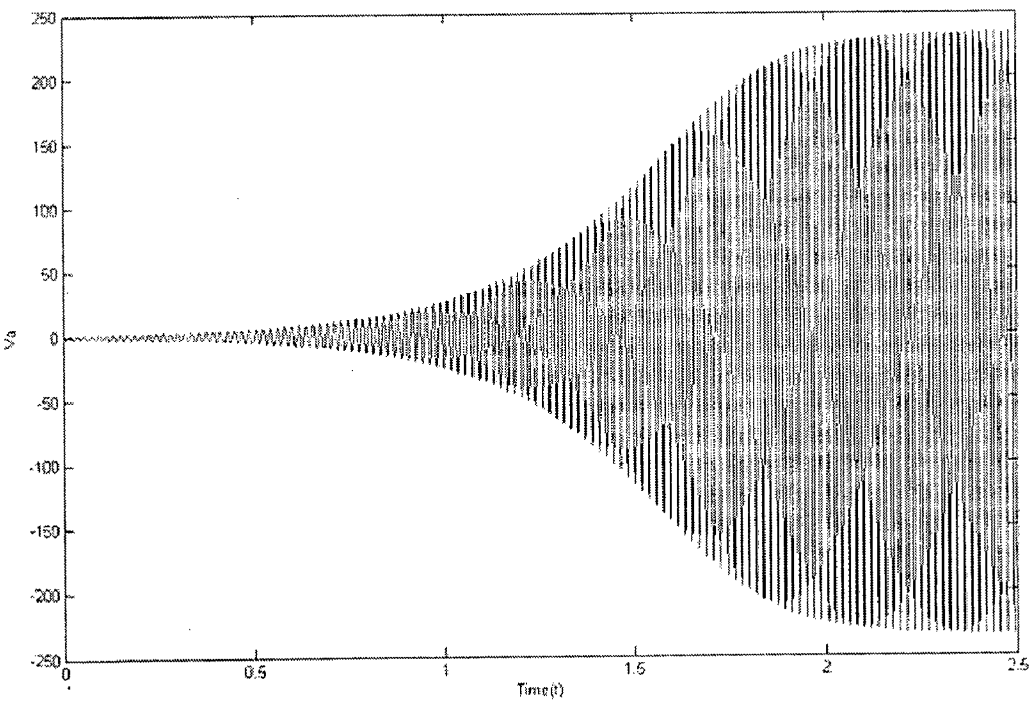


Fig 6.10 Voltage builds up under no-load

(A) Voltage builds up process under No-load condition:

To generate the rated voltage (230 V) at rated speed (1500 rpm), 85μF capacitance per phase is connected across the stator winding of the self-excited induction generator.

The balanced three phase voltages and three phase currents of SEIG are shown in fig 6.5 and 6.6.Fig 6.7, 6.8,and 6.9 shows the waveforms of SEIG Voltages (Va,Vb,Vc) , line currents (ia,ib,ic),magnetizing current(Im)and developed electromagnetic torque(Te).

(B) Three phase SEIG with Balanced Resistive Load:

The different characteristics of SEIG under resistive load change are shown from Fig 6.11 to 6.17. Here first the machine is running under no-load. The value of terminal voltage is 234 V. Suddenly a load 60Ω/phase is applied at time t=3 sec, then the terminal voltage drops to 213V.this phenomenon is due to the shifting of magnetizing inductance (Lm)(from fig.6.15)(and hence magnetizing current (Im) from fig.6.15 ,into unsaturated region from saturated region. The load currents are shown in fig 6.16 and 6.17.

(C)Three phase SEIG with Balanced Inductive Load:

The characteristics of SEIG under inductive load change are shown in Fig 6.18. At time t=3sec, an inductive load of (60+j250) Ω is applied and terminal voltage is again reduced to 225V.

(D) Sudden disconnection of self-excited capacitor:

The response of induction generator due to sudden disconnection of self-excited capacitor at t=4 sec is shown in fig 6.19.due to which the voltage will fall to zero.

(E) Loss of Excitation due to step change of load:

This response is shown in fig 6.20.the step load change from 60Ω to 10Ω is takes place at t=4 sec, the voltage becomes zero due to pulling of magnetizing inductance into unsaturated region.

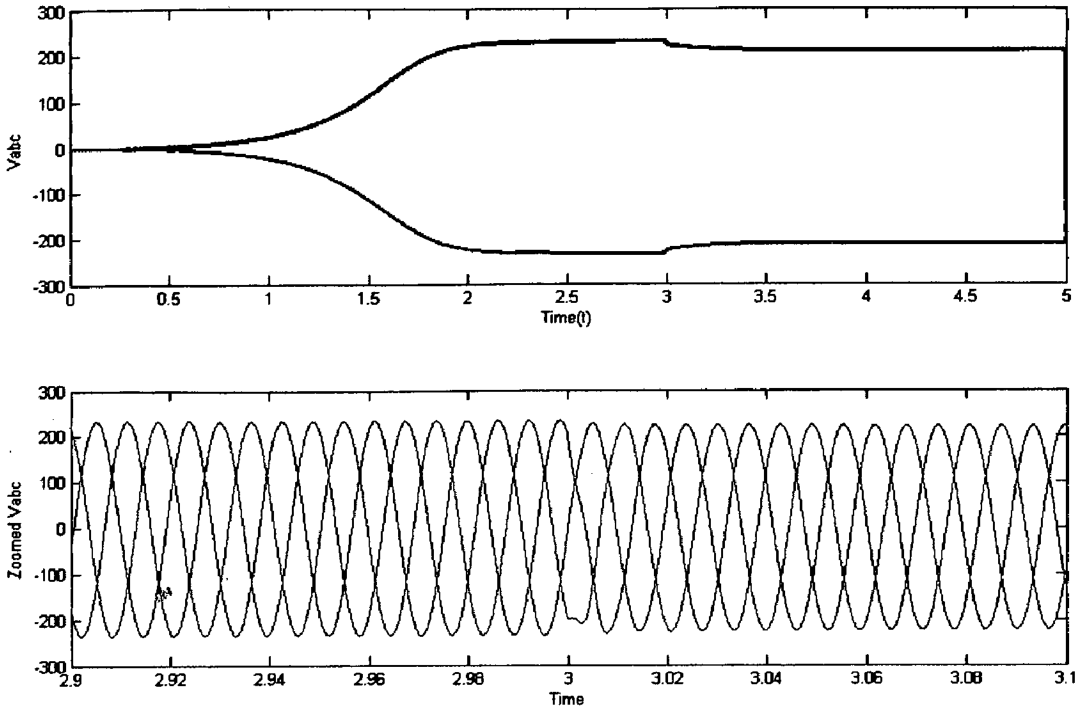


Fig 6.11.Three phase Voltages with R-load (60Ω)

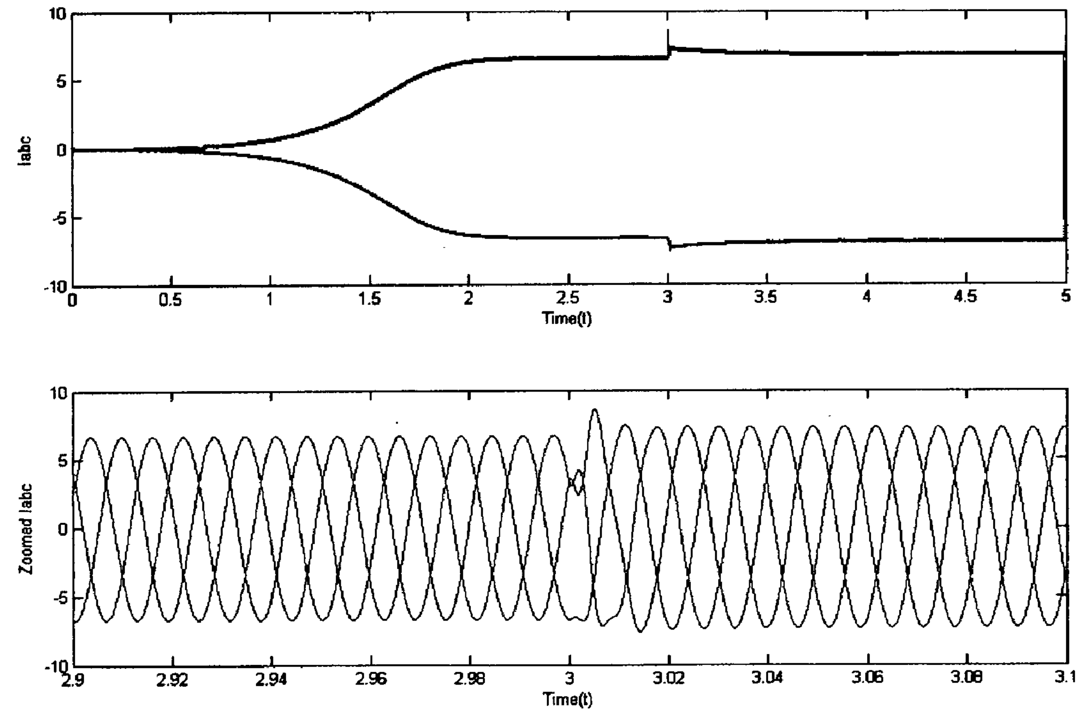


Fig 6.12.Three phase currents with R-load (60Ω)

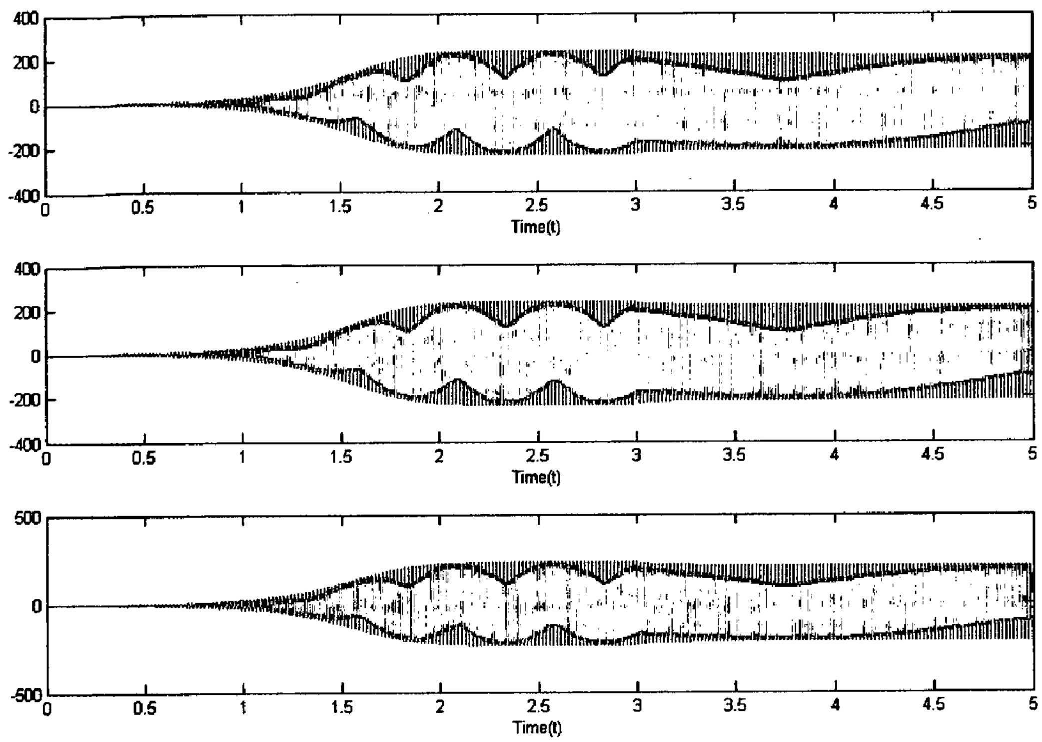


Fig 6.13 Line Voltages due to application of R- load (60Ω)

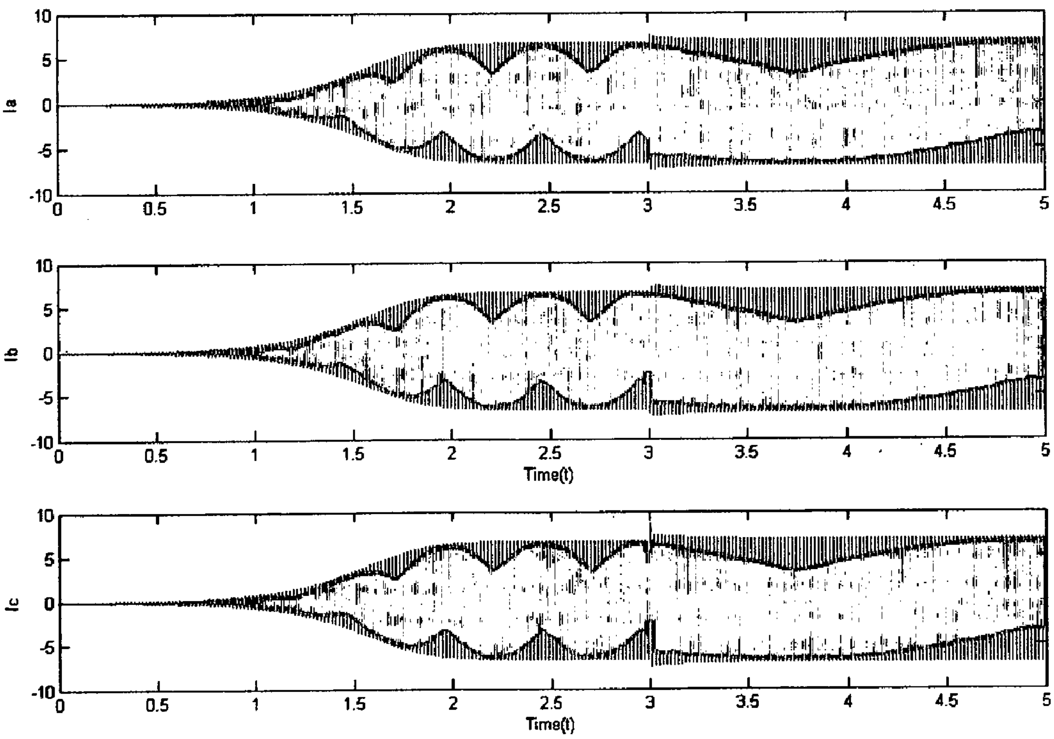


Fig 6.14 Line currents due to application of R-load (60Ω)

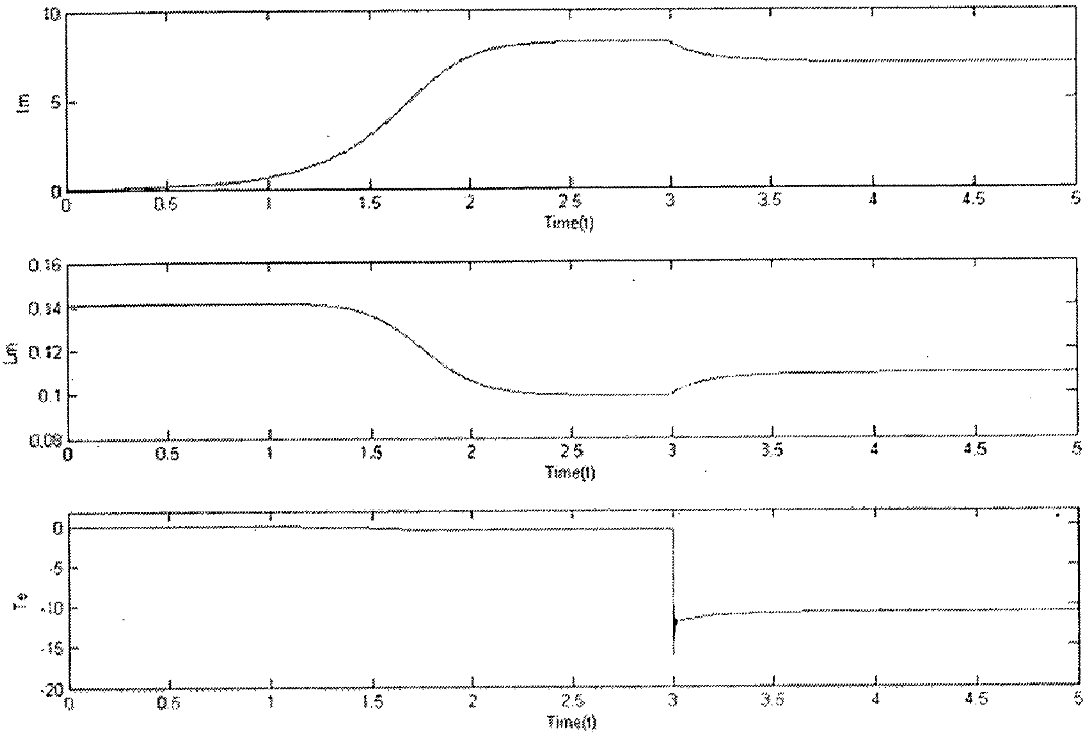


Fig 6.15 Magnetizing current, Magnetizing inductance, Electromagnetic torque

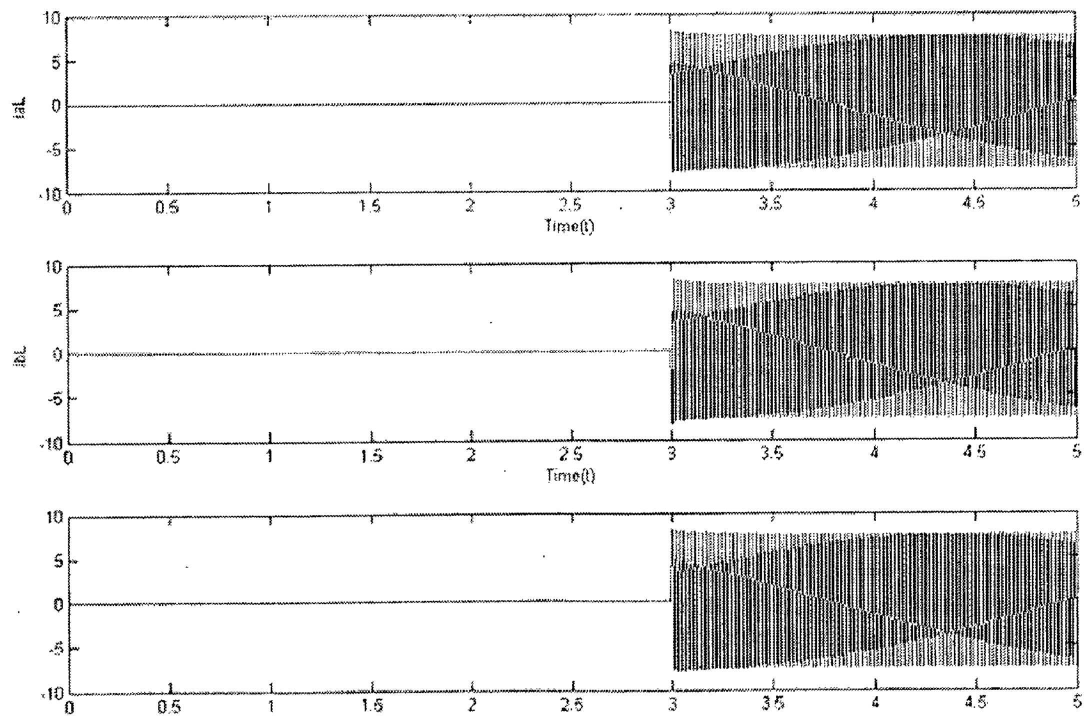


Fig 6.16 Load currents due to application of R-load (60Ω)

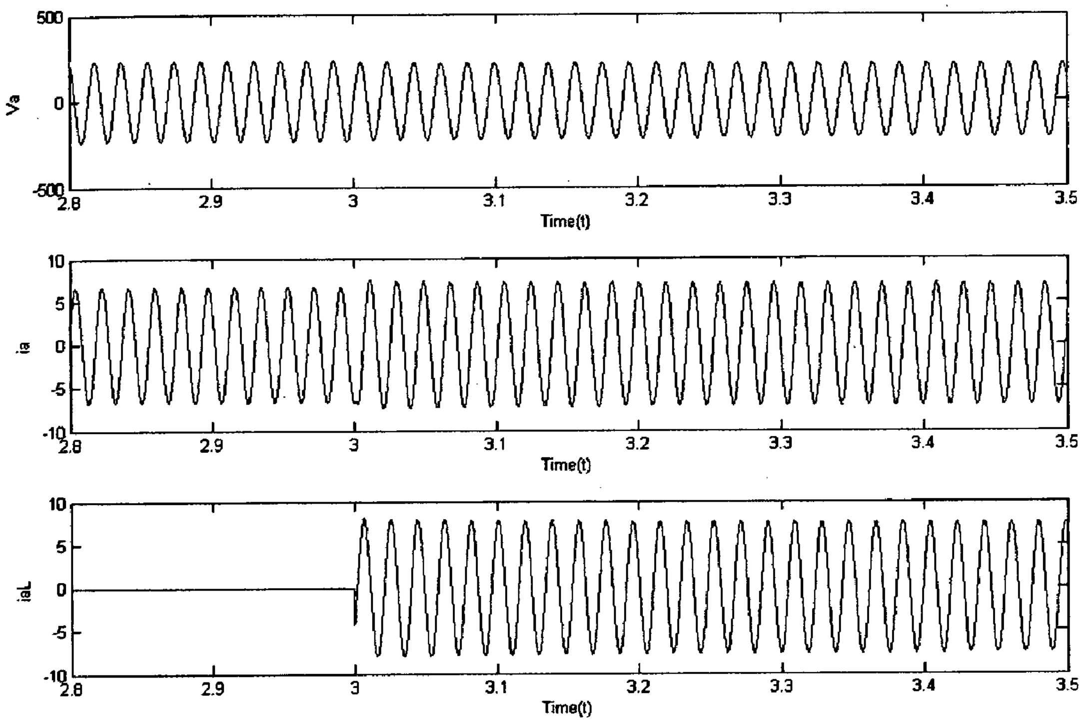


Fig 6.17 Generator line voltage, current, load current on Zoomed axis

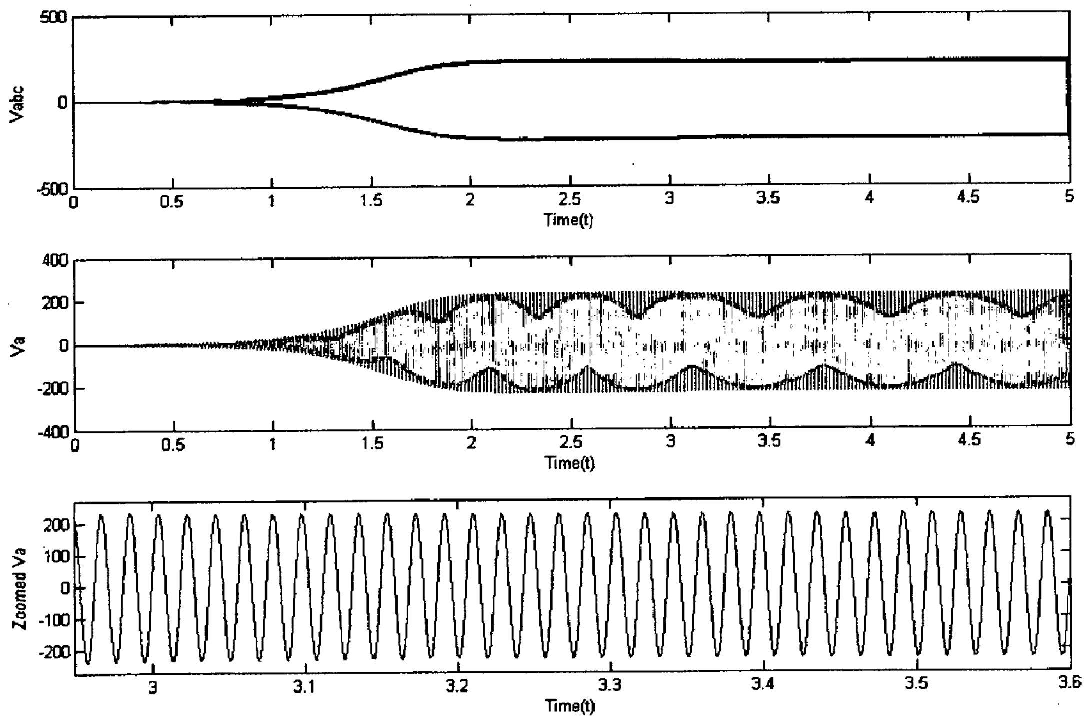


Fig 6.18 line voltage due to inductive Load (60+j250) Ω

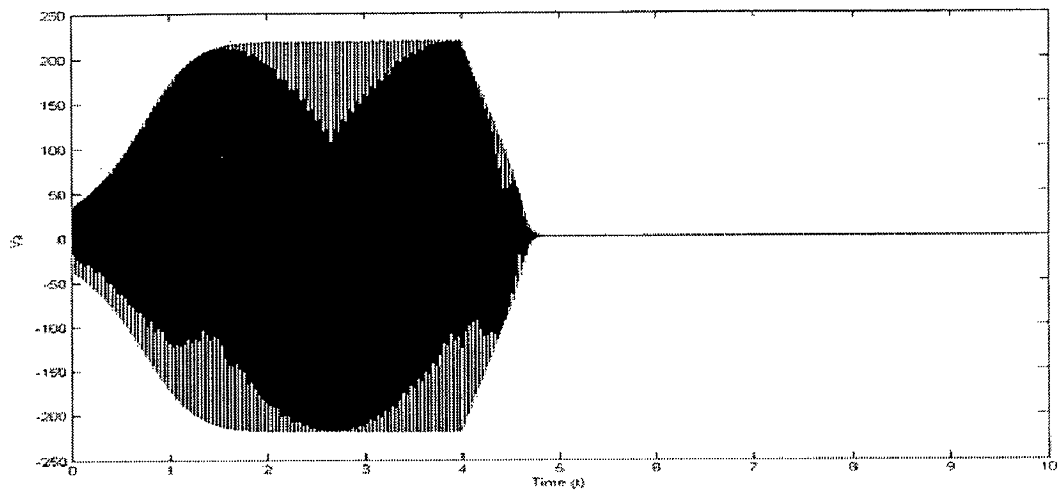


Fig 6.19 Response due to sudden disconnection of capacitor

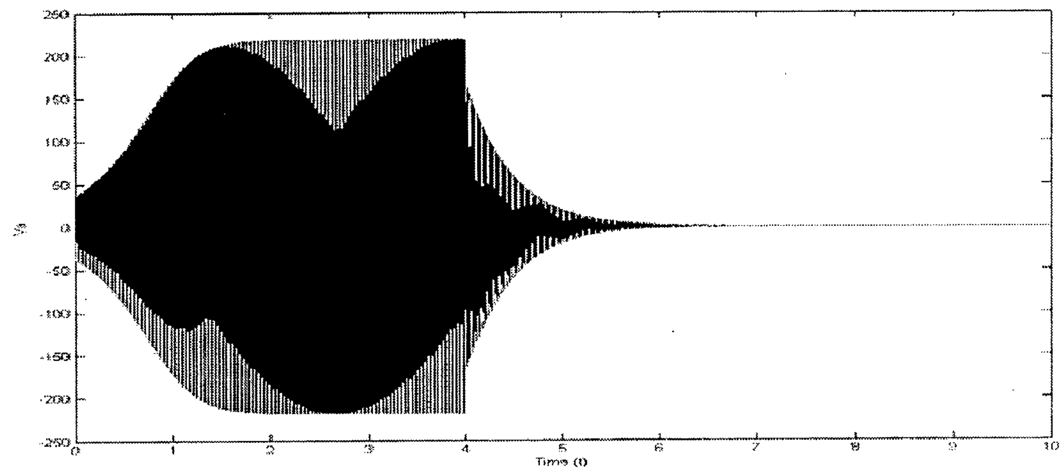


Fig 6.20 Loss of excitation due to step change of load

(F) Three phase SEIG with unbalanced Resistive Load:

The transient response of SEIG with unbalance loading (R_{aL}=2.5kΩ, R_{bL}=50Ω, R_{cL}=40Ω) is shown in fig.6.21. Fixed capacitance is required to excite the generator to a voltage of 230 V is ≈ 85μF. The system is allowed to attain steady state and at t = 3se c, a resistive load is applied which is unbalance in nature. Due to this one of the phase current increases and remaining becomes more or less constant.

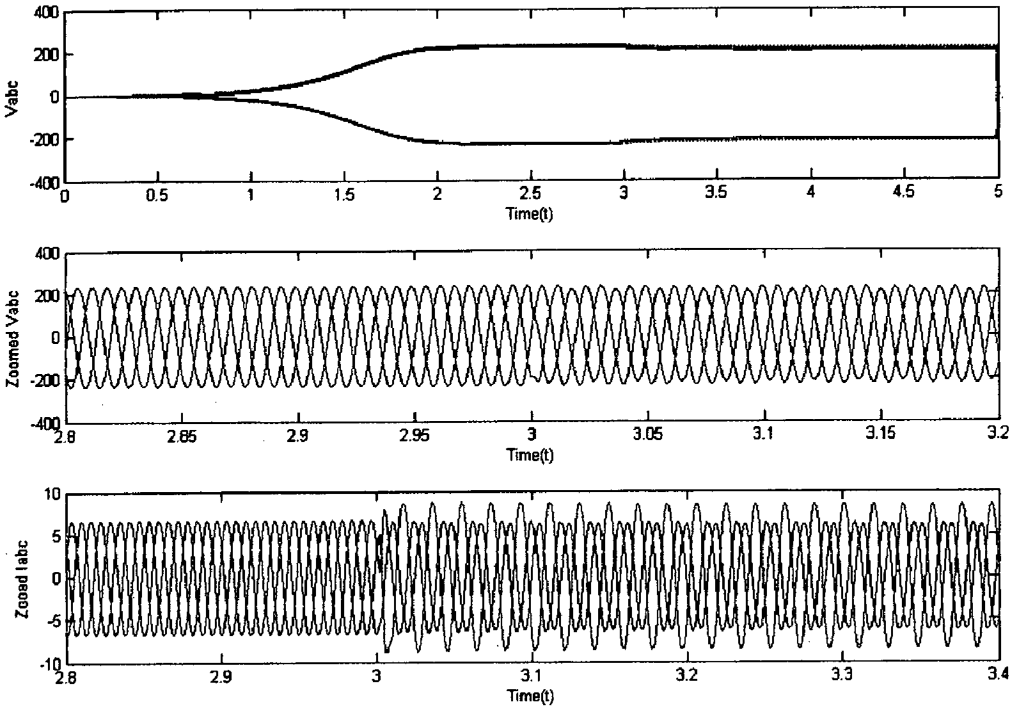


Fig 6.21 Three phase voltages and currents and load currents due to unbalanced loading (R_{aL}=2.5kΩ.R_{bL}=50Ω,R_{cL}=40Ω)

6.2.2 SEIG-STATCOM

The fixed capacitance required to excite the generator to a voltage of 230 V is ≈ 85μF. The system is allowed to attain steady state and at t=4sec, a resistive load is applied which is simulated by R_l=60Ω. It is observed that there is a drop in terminal voltage. At t=5sec, by giving firing pulses to the switches of inverter makes STATCOM on. The STATCOM tries to increase the terminal voltage and the line current after application of STATCOM as shown in fig 6.22. The control is simple PWM control where the reference currents are produced by the control strategy discussed earlier.

Fig. 6.22 also shows the STATCOM current for phase 'a'. The current was initially zero until the firing pulses are given to the inverter switches at time t=5 seconds. There is small oscillation at the switching in inverter but damps out within a few cycles.

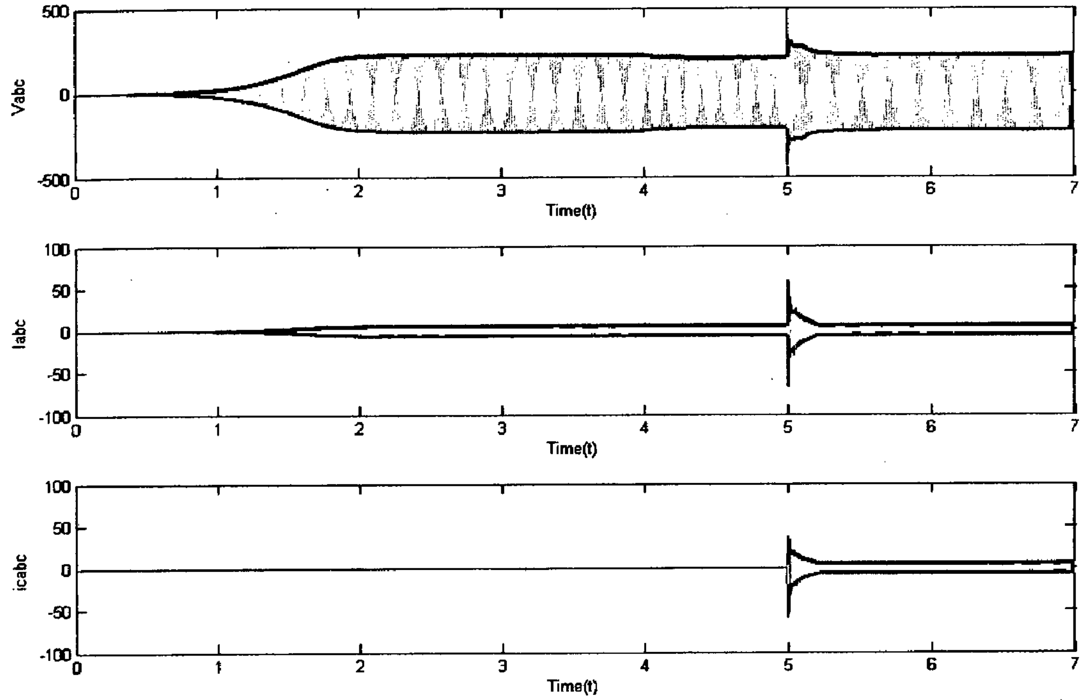


Fig 6.22 line voltage after application of STATCOM at t=5sec

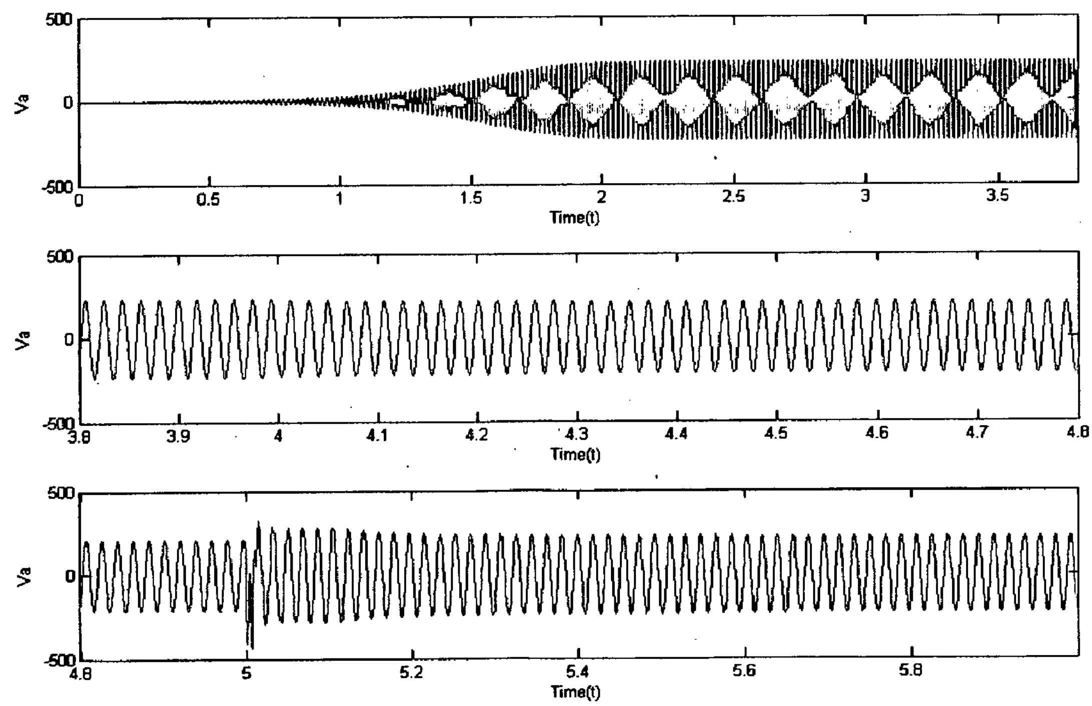


Fig 6.23 Zoomed Line voltage of Phase-A

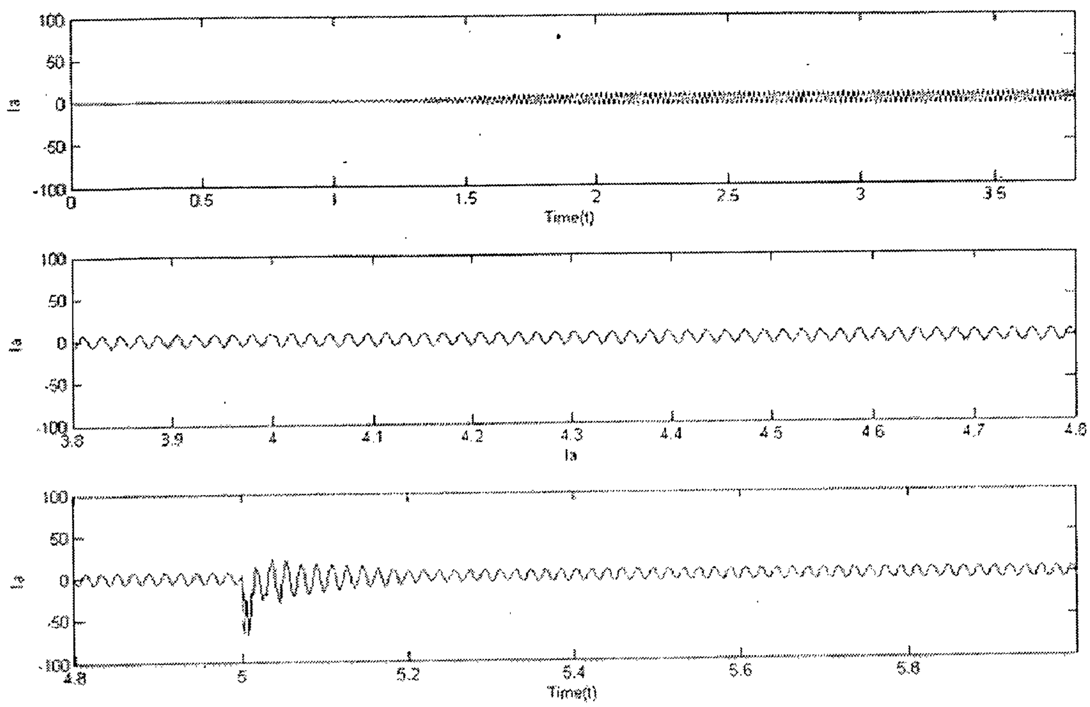


Fig 6.24 Line current after application of STATCOM at t=5sec

6.3 INTRODUCTION TO DSP

6.3.1 Advantages of DSP:

(i) New generations of motor control digital signal processors (DSPs) lower their supply voltages from 5V to 3.3V to offer higher performance at lower cost.

(ii) The entire logic portion of the m/c control circuitry is able to run atmost {(3.3/5) + (15)} V supply due to availability of compatible components and ICs in the market.

(iii) The Work with DSP is simple and inexpensive.

6.3.2 DSP Interfacing Peripheral circuits and Components:

There are usually only a few types of peripheral circuits and components that interface to the DSP.

The following are the most common examples:

- Communication interface for SCI (serial communication interface) and CAN (control area network) controller such as RS-232 and CAN transceiver.

- Serial components connected to SPI (serial peripheral interface) such as serial DAC, serial EEPROM, and serial LED driver
- Power device (IGBT or MOSFET) drivers for the PWM outputs
- Voltage and current sensing and conditioning circuits that interface to the on-chip ADC.
- Speed and position sensing sensors that interface to the capture and quadrature encoded pulse (QEP) decoding logic such as hall-effect sensors and optical encoders.

These peripherals, except for the driver circuits that are typically 15V, are mostly available in 3.3V or 3.3V compatible forms and have no issue interfacing directly to a 3.3V DSP.

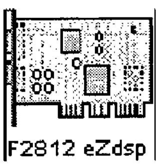
The Embedded Target for the TI TMS320C2000 DSP Platform integrates Simulink and MATLAB with Texas Instruments express DSP tools.

(1). Steps in building up the Model:

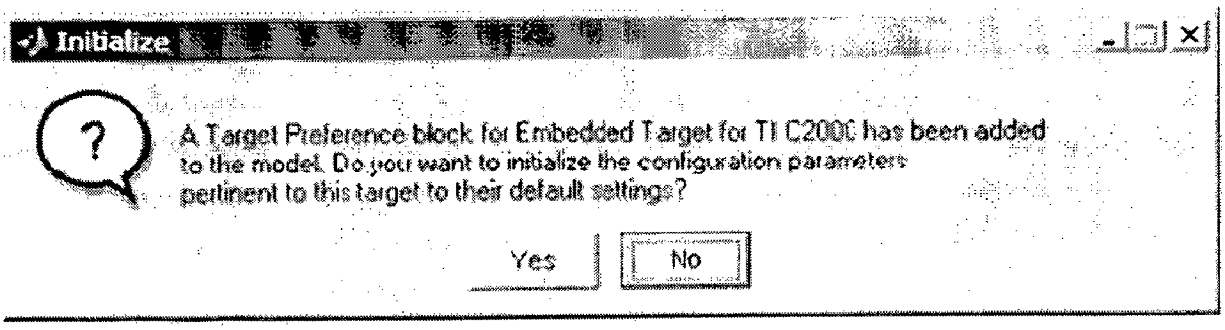
Step 1: In the Library: c2000lib window, select **File > New > Model** to create a new Simulink model.

Step 2: In the Library: c2000lib window, double-click the C2000 Target Preferences library block.

Step 3: From the Target Preferences Library window, drag the F2812 eZdsp block into the model.



The following query asks to set preferences automatically.



Step 4: Click **Yes** to allow automatic setup. The following settings are made, referenced in the table below by their locations in the

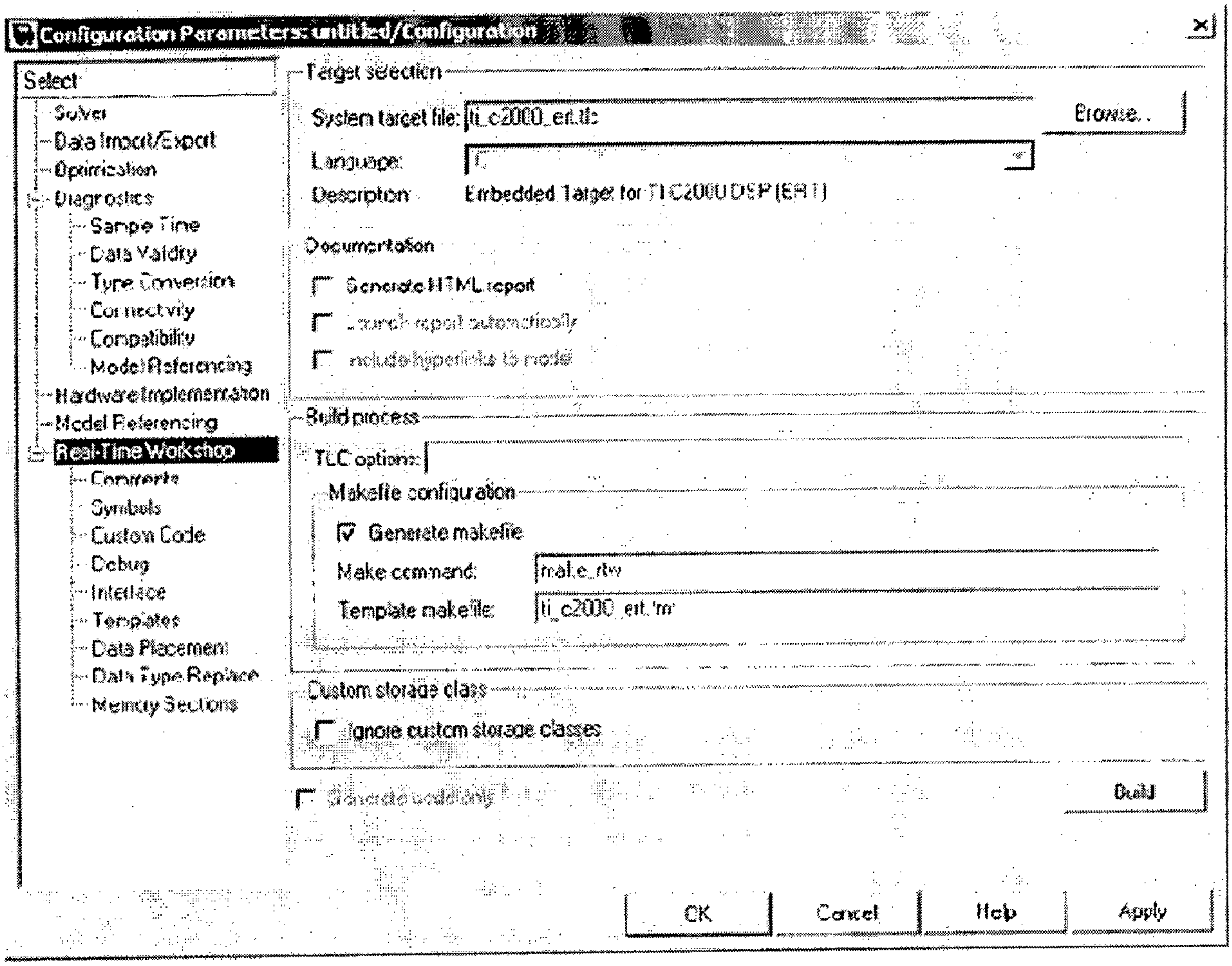
Simulation > Configuration Parameters dialog box:

Pane	Field	Setting
Solver	Stop time	inf
Solver	Type	Fixed-step
Data Import/Export	Save to workspace - Time	Off (cleared)
Data Import/Export	Save to workspace - Output	Off (cleared)
Hardware Implementation	Device type	TI C2000

Pane	Field	Setting
Real-Time Workshop	Target configuration - System target file	ti_c2000_grt.tlc
Real-Time Workshop	Target configuration - Template makefile	ti_c2000_grt.tmf

Step 5: Select **Simulation > Configuration Parameters** from model main menu, to Verify and set the simulation parameters. These Parameters for this model are saved and stored in the model file.

Step 6: Set options for the real-time model in **Real-Time Workshop** pane and the Real time Workshop pane options are as shown below.



- **System target file**. Clicking **Browse** opens the **System target file browser** containing ti_c2000_grt.tlc or ti_c2000_ert.tlc options and select ti_c2000_grt.tlc.
- **Make command**. To generate code from DSP application, use the standard command make_rtw. Enter make_rtw for the **Make command**.
- **Template makefile**. Depending on the System target file Real-Time Workshop automatically selects the appropriate template makefile:

  ti_c2000_grt.tmf or ti_c2000_ert.tmf.
- **To generate source code**: without building and executing the code,we can generate C-code only by double clicking the "Build"option.

Step 7: Set the Target Preferences by double-clicking the F2812 eZdsp block and adjust these parameters.

Build Options:

Subfield	Field	Setting
Compiler Options	CompilerVerbosity	Verbose
	KeepASMFiles	False
	OptimizationLevel	Function(-o2)
	SymbolicDebugging	Yes
Linker Options	CreateMAPFile	True
	KeepOBJFiles	True
	LinkerCMDFile	Full_memory_map
RunTime Options	BuildAction	Build_and_execute
	OverrunAction	Continue

CCS Link Options:

Field	Setting
CCSHandleName	CCS_Obj
ExportCCSHandle	True

(2).Generating code from the model:

Step 1: Double-click the C281x DSP Chip Support Library to open it.

Step 2: Build the model by using the C281x DSP Library block sets and place F2812 eZdsp block on the top of main model.

Step 3: We can automatically generate the code from the Simulink model window by clicking build in the **Real-Time Workshop** pane of the Configuration. Parameters dialog or by clicking **Build all** button on the toolbar or by pressing the keyboard shortcut, **Ctrl+B.**

(3).Creating Code Composer Studio Projects Without Loading:

Step1: In the **Real-Time Workshop** pane in the Simulation Parameters dialog box, select ti_c2000.tlc as the system target file.

Step 2: Select Create_CCS_Project for the **BuildAction** in the Target Preferences block.

Step 3: Set the other Target Preferences options, including those for **CCSLink** and the click **Build** to build the new CCS project.

We can generate varying duty cycle gate pulse to fire IGBT of ELC ckt by using C28xADC for conversion of analogue sensed voltage to digital signal and comparing it with carrier wave.

CONCLUSION

Conclusions

In this dissertation work, the capacitance calculation for self excitation was discussed. The SEIG is modeled in stationary d-q axis reference frame and the voltage build up phenomenon under no-load condition and its transient behavior with different types of balanced loads and loss of excitation due to step loading are simulated.

The design of two different types of full rating and reduced rating STATCOM based voltage regulator for three-phase SEIG are done. STATCOM is modeled and simulated for resistive load which is connected in parallel with the fixed capacitor and provides additional VAR required at the given load and power factor and this developed mathematical model for SEIG-STATCOM system is able to improve the terminal voltage.

The design of three phase ELC was discussed and its control circuit for Electronic Load Controller designed for given machine is developed.. The control circuit senses the terminal voltage and accordingly produces the firing pulse for ELC chopper so that the total generated power is divided between consumer load and dump load and duty cycle variation of pulse is due to the variation in sensed voltage due to varying power consumption in main load is observed.

Scope for future work:

- This work can be extended for non linear load such as rectifier loads.
- The control circuit of ELC can be simplified by using SG3525 PWM chip. It has two o/p pins 11 and 14 and at each pin we obtain the pulses of 50% duty cycle. By connecting the two o/p's in parallel we can improve the duty cycle to 100%.
- The analogue gate control circuit of ELC can be replaced by using TMS320F2812 DSP kit.

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APPENDIX-I

Coefficients of prime mover characteristic:

$T_{shaft} = K_1 - K_2\ \omega_r$; $K_1 = 3370$, $K_2 = 10$;

Specifications of machine I: For the simulation the machine used is 7.5 KW, 230 V, 26.2 amps, Δ-connection, 50Hz, 4-pole, $R_s = 0.76\ \Omega$, $R_r = 1.03\ \Omega$, $X_{ls} = X_{lr} = 1.5\ \Omega$; J=0.1384;

Magnetizing characteristic coefficients:

$A_1 = 0.1407$, $A_2 = 0.0014$, $A_3 = -0.0012$, $A_4 = 0.00005$.

Specifications of machine II: 3.7 KW, 415V, 7.6 A, Δ-connection, 50Hz, 4-pole

$R_s = 5.525\Omega$, $R_r = 5.86\ \Omega$, $X_{ls} = X_{lr} = 9.60\ \Omega$, $J = 0.0842$;

STATCOM Control parameters:

L_f=3.5mH, Rf = 0.15Ω, C_{dc} = 4000μF.

AC voltage PI controller: K_{pa} = 0.0.0956; K_{ia} = 0.0045;

DC voltage controller K_{pd} = 0.85; K_{id} = 0.17;