STATCOM BASED VOLTAGE REGULATOR FOR SELF-EXCITED INDUCTION GENERATOR

A DISSERTATION

Submitted in partial fulfilment 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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JUNE, 2005

I.D. No. MT-292/2005-23/RB-SP

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled "**STATCOM BASED VOLTAGE REGULATOR FOR SELF-EXCITED INDUCTION GENERATOR**" 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 Electrical Drives** (PAED) of the institute, is an authentic record of my own work carried out during the period from August 2004 to June 2005 under the supervision of **Dr. S.P. Singh,** Associate professor, Department of Electrical Engineering , Indian Institute of Technology, Roorkee, Roorkee.

I have not submitted the matter embodied in this dissertation work for the award of any other degree.

Dated: 29/06/05

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

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ACKNOWLEDGEMENT

I take this opportunity to express my sincere gratitude towards my guide Dr. S.P. SINGH, Associate professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee for his guidance, advice and encouragement, which were the constant source of inspiration for the completion of the research work. His painstaking support and exhaustive involvement in successful completion of this dissertation are greatly acknowledged. I humbly acknowledge a lifetime's gratitude to him. It has been excellent opportunity for me to learn and work under his esteemed supervision and guidance during the entire period of dissertation work.

I am grateful to all my teachers of PAED group for their suggestion and constant encouragement.

I am thankful to the staffs of the Drives lab, staff members of workshop and store for their kind co-operation .I sincerely acknowledge my indebtedness to Mr. Tularam Yadav, Lab in charge, senior machines lab for his help and co-operation in performing different experiments during my dissertation work.

I am thankful to my classmate Mr. P.Sivakrishna for his help in hardware work.

My gratitude and indebtedness are due to my family members for their constant encouragement and blessing.

RASHMILATA BEHERA

ABSTRACT

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 application of self-excited induction generators (SEIG) in isolated power systems. Owing to the changed emphasis on energy problems, the development of suitable low cost isolated power generators, driven by renewable energy sources such as wind, biogas, etc is indeed a promising alternative.

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 instantaneous values of direct and quadrature axis stator and rotor currents and voltages for different load currents are found by solving differential equations representing the dynamic behaviour 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 overcome the voltage regulation by using different techniques. In the fourth chapter the simulation for improvement of voltage regulation using STATCOM based voltage regulator is included. The same method is extended to consider a STATCOM along with an ELC to improve the terminal voltage. In the fifth chapter the control circuit for a chopper based ELC is developed which tries to control the duty cycle of chopper so that generated power is divided between the dump load and consumer load. The work also includes the results of experiments performed on a laboratory machine showing some basic steady state characteristic of self-excited induction generator.

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	Excitation capacitance per phase
L_m	Magnetising 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
F	Per Unit frequency
V_g	Air gap voltage
V_t	Terminal Voltage of SEIG
V_a	Phase voltage of Phase 'a'
I_a	Phase current of phase 'a'
R_l	Load resistance per phase

LIST OF FIGURES

CHAPTER-1

INTRODUCTION

1.1 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.

1.1.1 Self excitation

The basic requirement enabling an induction machine to function as an autonomous generator is the provision of a leading current of the correct magnitude. For the generation to occur when starting up from rest a residual magnetism must be present in the rotor and this induces small emf in the stator winding at a frequency proportional to the rotor speed. A leading current flows in the capacitor, the same current passing through the stator winding and producing an armature reaction flux assisting the original residual flux.

Due to self-excitation, the terminal voltage and the air gap voltage continue to increase. If the capacitor is of sufficient value the voltage continues to build up until it is limited by saturation of the magnetic circuit of the machine.

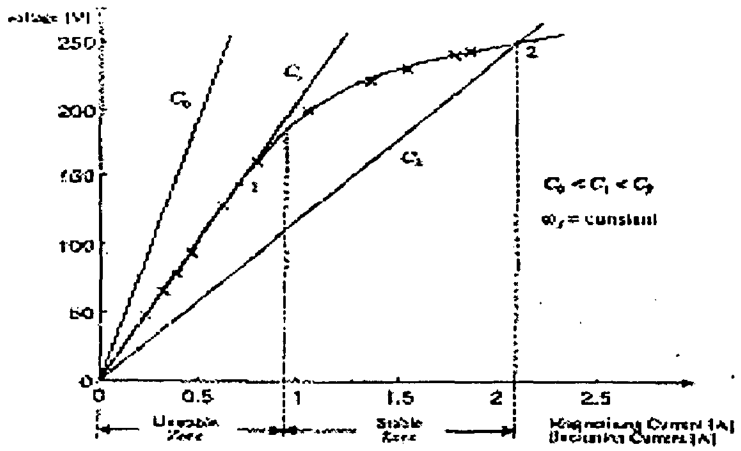


fig 1.1 magnetizing characteristic of SEIG

Let us consider that the machine has an initial residual flux (or some means are provided to inject an initial current into the stator winding), and the rotor is rotated by some external mechanical power source, such as a fuel engine, hydraulic turbine, etc. If external capacitors of adequate values are connected to the stator windings, self-excitation occurs. The magnitude of the generated voltage will depend among other things on the capacitance value, the load current, and the load power factor. Considering steady state operation it is possible to observe three regions clearly differentiated: (i) stable zone, corresponding to operation in the saturated region of the magnetic core, In this case, the linear I-V curve of the excitation capacitors intersects the core magnetizing curve at a well-defined point.(ii) an unstable zone, corresponding to operation on the linear region of the magnetic core; and (iii) a region of no-generation

The analysis of the SEIG is complicated because its operation depends on (i) Prime mover speed (ii) Capacitor (iii) Load.

1.2 Advantages of self excited induction generator

- 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.
- 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 without any problem of synchronization i.e. they may operate at different speed and still share load.

1.3 Applications of SEIG

- 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.

1.4 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.

1.4.1 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 is 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 reactances are not the main cause of the poor voltage and frequency regulation in the isolated IG. The fundamental factor that affects the voltage regulation is the influence of the frequency on the generator magnetization characteristic. 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.

1.4.2 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 subsynchronous 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:** Acts as a voltage regulator for maintaining constant terminal voltage.

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

1.5 Statement of problem

1. To model the induction machine in d-q stationary reference frame.
2. To study and simulate transient behaviour of SEIG during build up and loading.
3. To simulate STATCOM based voltage regulator for SEIG.
4. To simulate a regulator consisting of both STATCOM and ELC.
5. To analyze the experimental results of a given machine and to develop hardware of ELC for self excited induction generator.

1.6 Organisation of dissertation

1. 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.

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

3. Chapter-3 In this chapter a brief study on steady state analysis and modeling and simulation of transient behaviour is done.

4. Chapter–4: In this chapter the modeling and simulation of STATCOM based voltage regulator for SEIG is included. The work is extended to include modelling of simple STATCOM as a source of lagging and leading power. The

STATCOM with ELC is combined to form improved ELC for keeping the voltage and frequency constant.

5. Chapter-5: This chapter includes hardware implementation of control circuit of an ELC designed for the machine-II specified in appendix.

6. Chapter-6: In this chapter the conclusions are made in the light of different observations taken in earlier chapter

Finally references and appendix are included.

CHAPTER-2

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.

B.C. Doxey [2] 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 et al. [3] in their paper examined the transient behaviour of a three phase SEIG supplying a symmetrical load. They presented an approach to model the saturation effect from the steady-state standpoint. Murthy et al. [4] analysed 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. Grantham et al. [5]. considered the effect of main flux saturation. They took iron loss into account. However Hallenius et al. [8] emphasized the importance of cross saturation during self-excitation.

Al Jabri et al. [7] presented the performance of the induction generator under a wide range of varying conditions. They considered that the equivalent circuit resembles a negative resistance oscillator where the negative resistance is provided by the negative slip of the machine, while the magnetizing reactance X_m plays the role of a non-linear element. To have a negative slip F (per unit frequency) must be less than v (per unit speed) and greater than zero. This gives the bound $0<F<v$ on the range of generated frequency. They considered the effect of three external elements namely, (i) the speed (ii) the terminal capacitance and (iii) load impedance and controlling these three elements the performance was studied.

Faiz et al. [12] 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 [19] provided a purely experimental treatment of the self-excitation process in induction generators. S.P.Singh et al. [25] modelled a delta connected self-excited induction generator, which could handle symmetrical and unsymmetrical load and capacitor configuration. They also discussed the SEIG behaviour 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. S.C. Kuo and L. Wang [23] 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.

Sridhar et al. [11] analyzed the system consisting shunt and series capacitance and developed a method to choose appropriate set of values of capacitors for desired voltage regulation. Li wang and Jian-yi Su [15] presented a comparative study of steady-state performance of both Long-shunt and short-shunt configurations of an isolated self-excited induction generator under various loading condition.

Dependency of the output voltage and frequency of the isolated self-excited induction generator on the speed, load and terminal capacitance causes certain limitations on its performance. Marra and Pomilio [20] presented a PWM voltage-source inverter to improve the electrical characteristic of an isolated induction generator. In this analysis the electronic converter allows to achieve a better system behavior in many aspects: voltage regulation, frequency stabilization and reactive power compensation. Shadhu Khan and Chatterjee [17] designed single-input single-output control system for voltage control of a stand-alone self-excited induction generator employing inductively loaded current controlled solid state lead lag VAR compensator.

Wamkeue et al. [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 [22] 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 et al. [32] in their paper have 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. [29] 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 et al. [26] propose a control strategy based on instantaneous reactive power theory. The principle is based on power Invariant Park's transformation.

N.P.A. Smith [14] 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 S.S. Murthy [31] 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.

CHAPTER 3

ANALYSIS OF SEIG

3.1 Steady state analysis

In order to study the performance of an induction generator, its equivalent circuit must be used. This steady state equivalent circuit is similar to the equivalent circuit of an induction motor with the input voltage source substituted by a capacitance and load. Commonly used assumptions of per phase circuit model:

- In the per phase equivalent circuit:
- 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

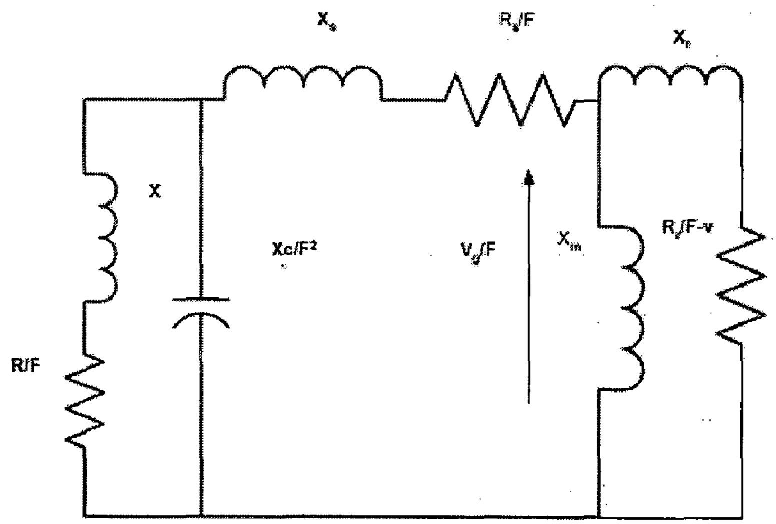


Fig3.1 equivalent circuit of SEIG

In Steady state analysis two nonlinear simultaneous equations in terms of F and X_m are obtained and the equivalent circuit is solved for a given load and speed using loop impedance method [10]. For the dissertation work relevant experimentation was carried out on a 3 phase, 440V, 15.6 amp, 7.5 KW delta connected induction machine driven by a DC motor. It is clearly observed in Fig. 3.2 the terminal voltage of a SEIG decreases with the increase in resistive load under fixed value of capacitance.

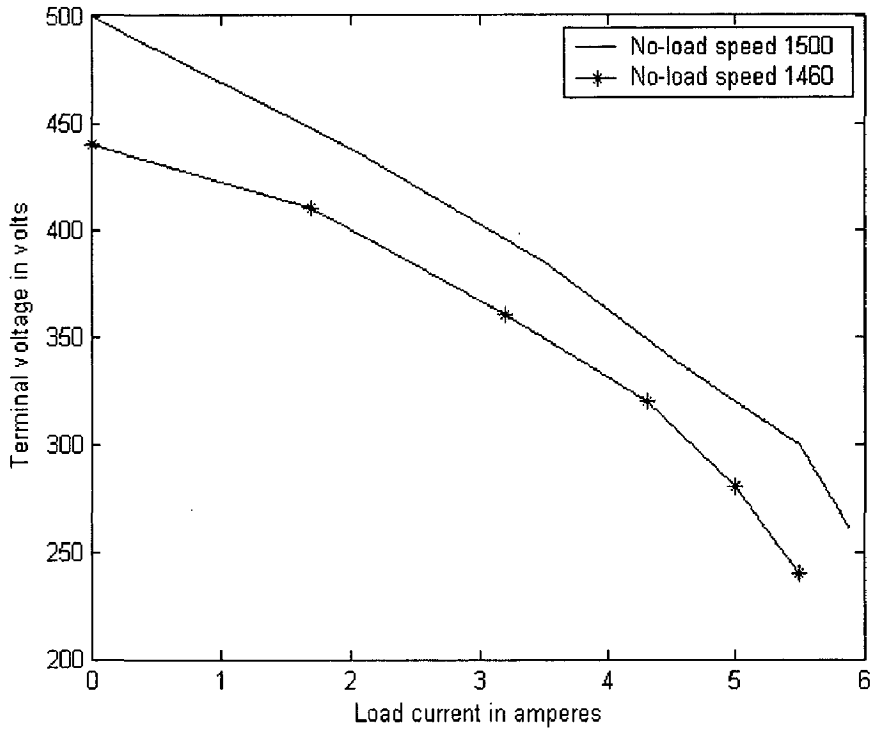


Fig3.2 Steady state characteristic showing change in terminal voltage due to change in load for two different no-load speeds.

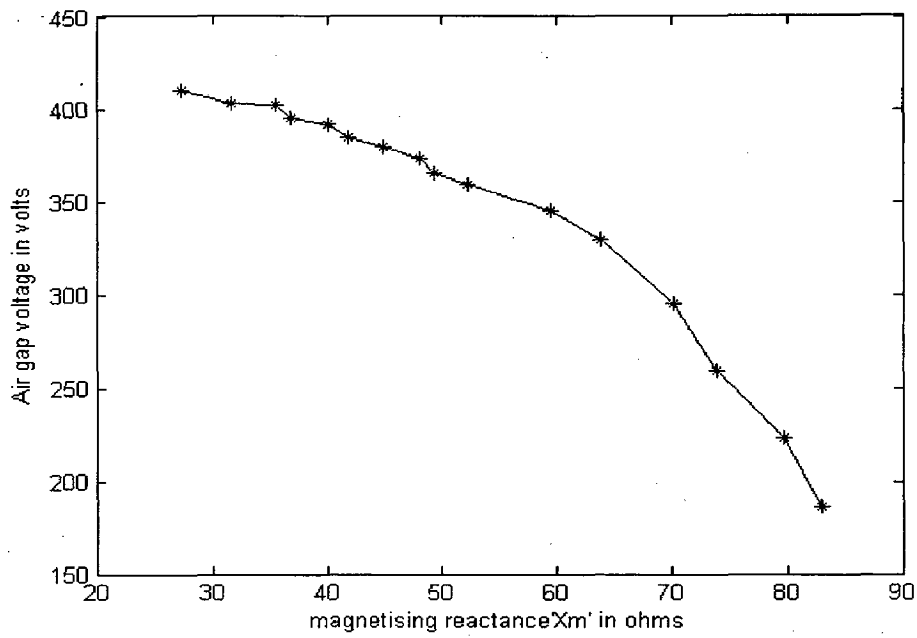


Fig3.3 magnetization characteristic

The magnetization characteristic depicted in Fig.3.3 is the relation ship between the airgap voltage and 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. Since the slip is equal to zero the rotor branch in Fig. 3.1 is open and the magnetizing reactance is given by:

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

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

Where V_s and I_s are per phase supply voltage and Supply current.

3.2 Transient analysis of seig

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.

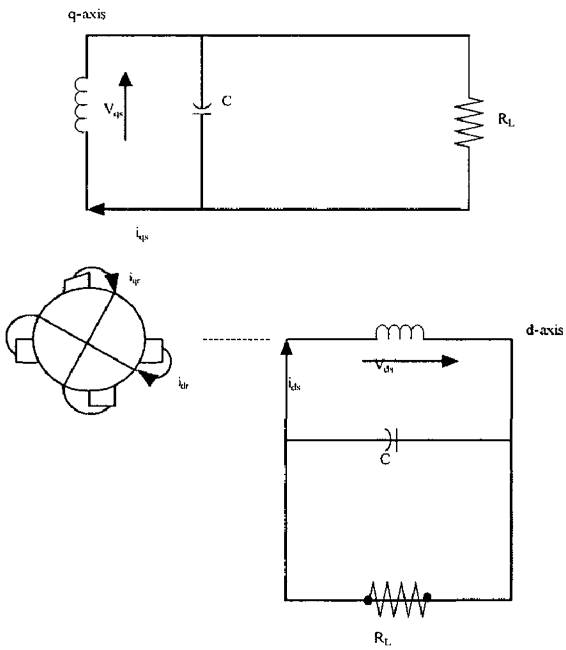


Fig3.4 SEIG in d-q axes stationary reference frame

This model is based on the assumption that it is possible to decompose the total flux linking each winding into leakage and magnetization components, and that it is possible to consider a privileged direction of magnetization.

The voltage and current relationship in a self-excited induction generator [31]

$$[v] = [R][i] + [L]p[i] + \omega_r [G][i] \tag{3.1}$$

where ω_r is the speed of induction machine.

$$[v] = \begin{bmatrix} v_{ds} & v_{qs} & v_{dr} & v_{qr} \end{bmatrix}^T$$

$$[R] = diag\begin{bmatrix} R_s & R_s & R_r & R_r \end{bmatrix}$$

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

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

Thus, The current derivative can be expressed as:

$$p[i] = [L]^{-1}\{[v] - [R][i] - \omega_r[G][i]\} \tag{3.2}$$

The developed electromagnetic torque of the SEIG is:

$$T_{shaft} = T_e + J(2/P)p\omega_r \tag{3.3}$$

Here T_{shaft} is the input torque to the SEIG from the turbine, J=moment of inertia and P=number of poles.

The derivative of rotor speed of the SEIG from above equation is:

$$p\omega_r = \{(p/2J)\}(T_{shaft} - T_e) \tag{3.4}$$

The developed electromagnetic torque of the self-excited induction generator is expressed as:

$$T_e = (3P/4)L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) \tag{3.5}$$

The induction machine is assumed to be driven by a constant head micro-hydro turbine whose characteristic is assumed linear just like that of a separately excited dc motor. In the laboratory the field current and armature voltage of the dc machine are kept constant and the torque speed characteristic is given by:

$$Tshaft = a - b\omega_r \tag{3.6}$$

In Micro-hydel system, prime mover has drooping characteristic and may be expressed for the simulation purpose as:

$$T_{shaft} = (3370 - 10\omega_r)$$

The self-excited induction generator operates in the saturation region and its magnetization characteristics are non-linear in nature. Thus the magnetizing current should be calculated at every step of integration in terms of stator and rotor currents as:

$$I_m = \sqrt{(ids + idr)^2 + (iqs + iqr)^2} \qquad (3.7)$$

Three-phase voltages are obtained by converting d-q axes components into a,b,c phase voltage as: $\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{os} \end{bmatrix}$

Fourth order Runge-Kutta method

A method of numerically integrating ordinary differential equations by using a trial step at the mid point of an interval to cancel out low order terms. The fourth order Runge-Kutta method is most commonly used for solution of differential equations and is synonymous with Rung-kutta method. The working method is that for finding the increment 'k' of 'y' corresponding to an increment 'h' of 'x' is as:

K_1=h*f(x_0,y_0)

K_2= h*f(x_0+1/2*h,y_0+1/2*k_1)

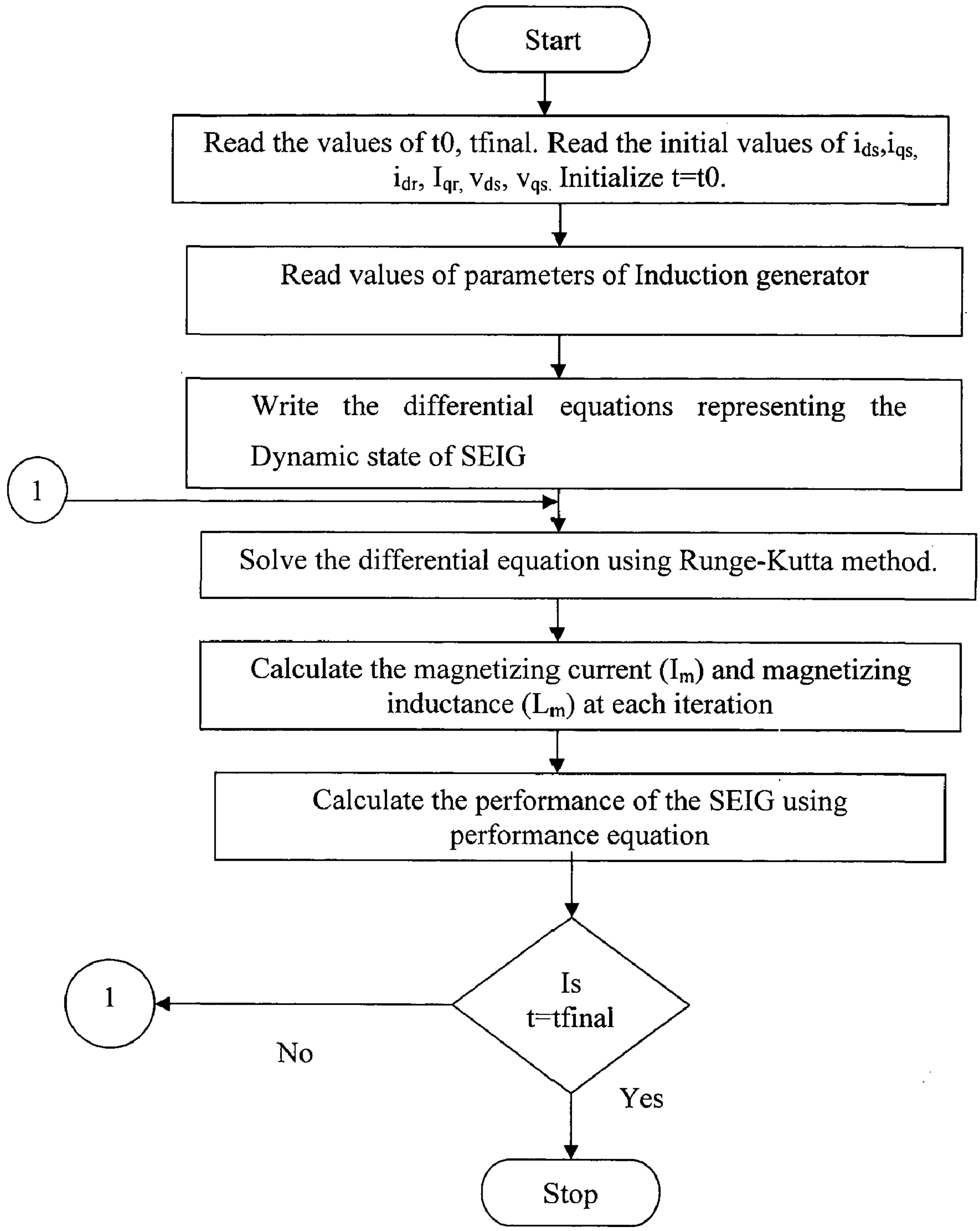
K3= h*f(x_0+1/2*h,y_0+1/2*k_2)

K4= h*f(x_0+h,y_0+k_3)

K=1/6(k_1+2k_2+2k_3+k_4)

This method is reasonably simple and robust and is a good general candidate for numerical solution of differential equations when combined with an intelligent adaptive step size routine. This method is used in simulations for solving the dynamic equations.

3.2.1 Flow chart for analysis of self excited induction generator



3.3 Results for transient analysis

For the simulation purpose two different machines are considered the rating of which are given in appendix. The variation of magnetizing reactance with magnetizing current of machine-I is taken as:

$$L_m = 0.1407 + 0.0014 I_m - 0.0012 I_m{}^2 + 0.000048 I_m{}^3$$

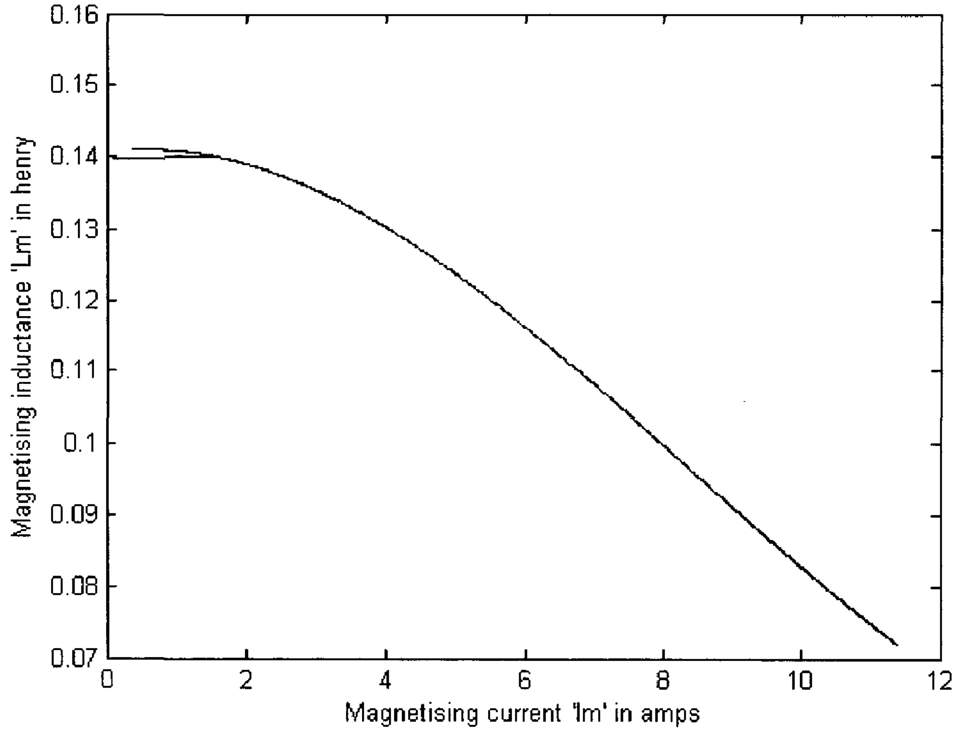


Fig 3.5(a) Variation of magnetizing inductance with magnetizing Current (Machine-I)

For the machine-II when the dynamic analysis simulation is carried out the variation of magnetizing inductance is found to be as Fig. 3.5(b):

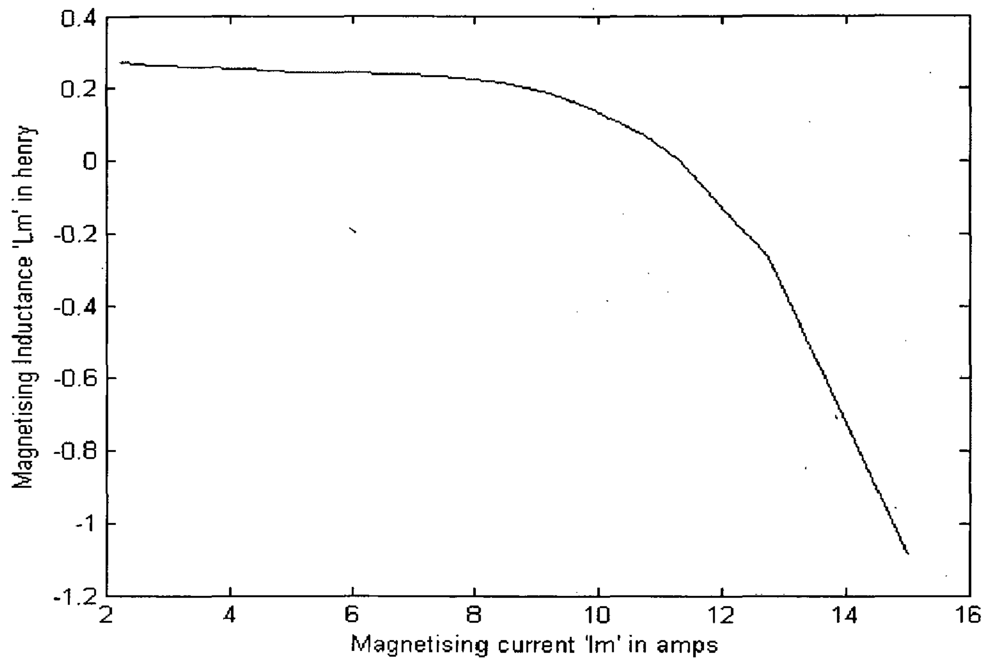


Fig 3.5(b) Variation of magnetizing inductance with magnetizing Current (Machine-II)

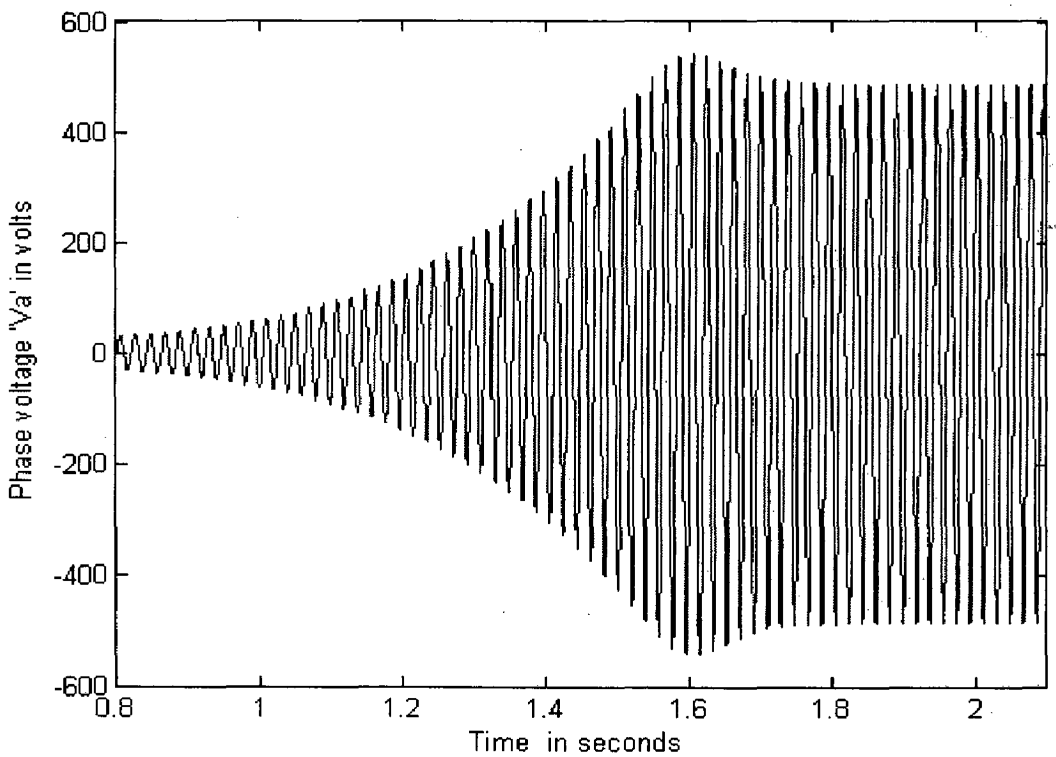


Fig 3.6 Voltage build up of machine-II

3.3.1 Results of simulations showing dynamic performance of machine-I

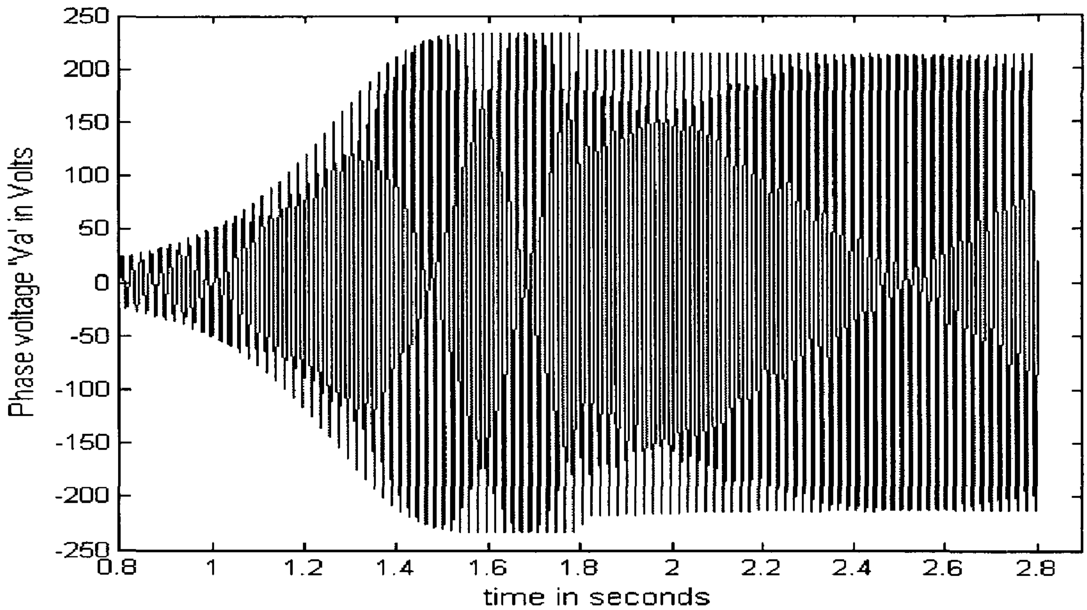


Fig3.7 Voltage build up and change in voltage due to application of resistive load

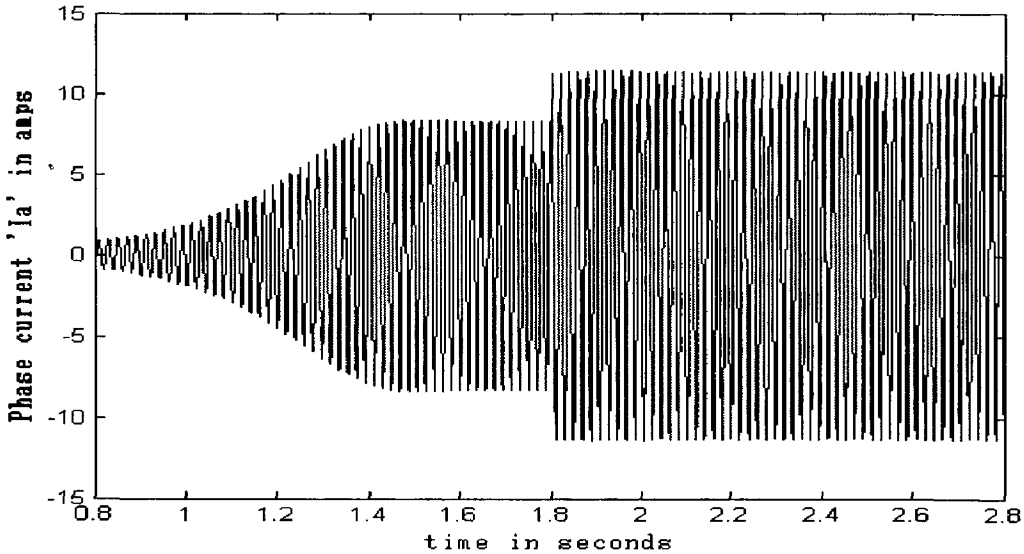


Fig3.8 Change in current due to application of resistive load

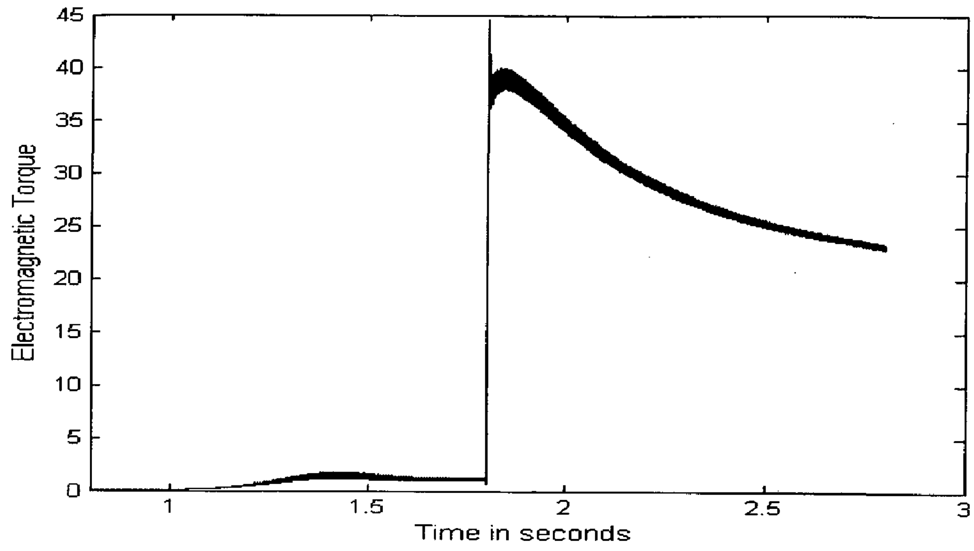


Fig3.9 Electromagnetic Torque

Simulation was carried out to observe the dynamic process of SEIG including building up process, load perturbation and de-excitation due to short circuit. The Machine whose data is given in appendix was simulated for building up of voltage for excitation capacitance of 120 micro-farad. For no-load condition a high resistance of 100 K Ohm was taken as load resistance. As observed at time t=1.8 sec resistive load is applied which is simulated as Rl=25 Ohm and it is seen in Fig 3.7 that there is a drop in voltage. For the same condition the current wave form and the instantaneous torque are shown in Fig. 3.8 and Fig. 3.9 respectively The R-L load is simulated by adding an extra differential equation and taking L=0.01 H. and the voltage waveform is shown in Fig 3.10. The current for rectifier load is shown in Fig 3.11.

Other conditions like change in excitation capacitance was observed in Fig. 3.12 The machine has a change in capacitance at 1.9 sec from 120 microfarad to 60 microfarad and it is observed that there is decrease in terminal voltage proving the fact that the terminal voltage is a function of excitation capacitance.

For observing the de-excitation the load resistance at 1.8 sec is simulated to be 5 ohms and it is observed in Fig. 3.13 that the terminal voltage drops to zero after some cycles and confirms the fact that SEIG takes protection against external short circuit by de-excitation.

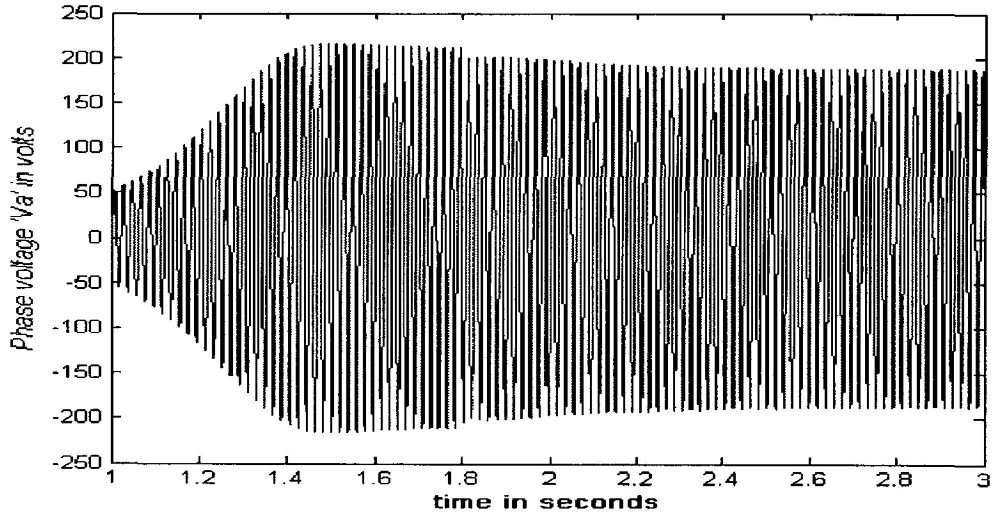


Fig3.10 Voltage build up and change in voltage due to application of inductive load

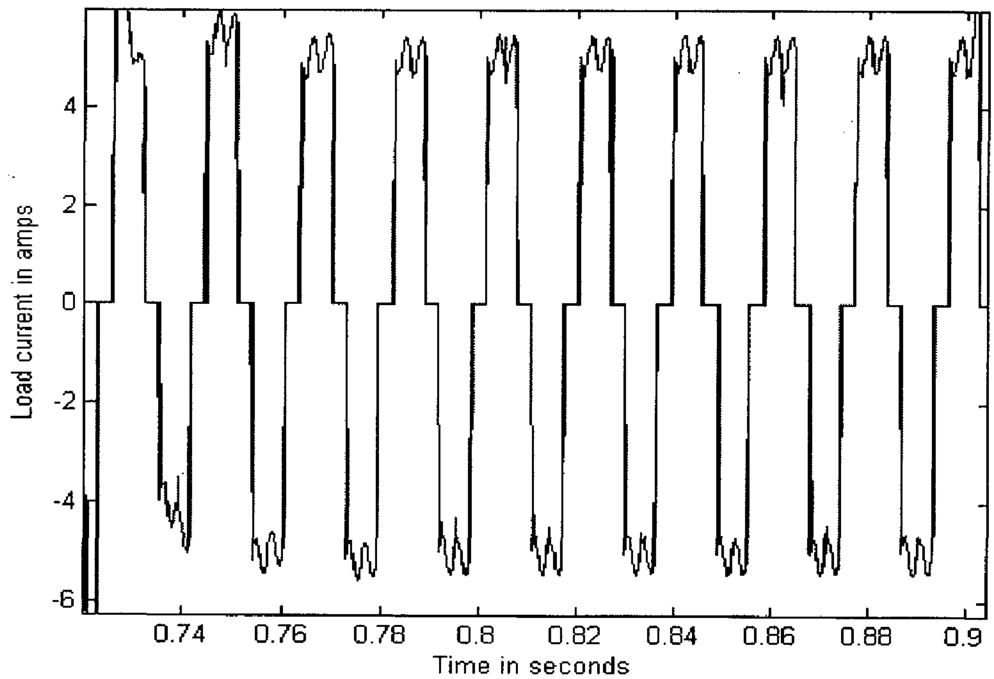


Fig3.11 Load current due to application of rectifier load

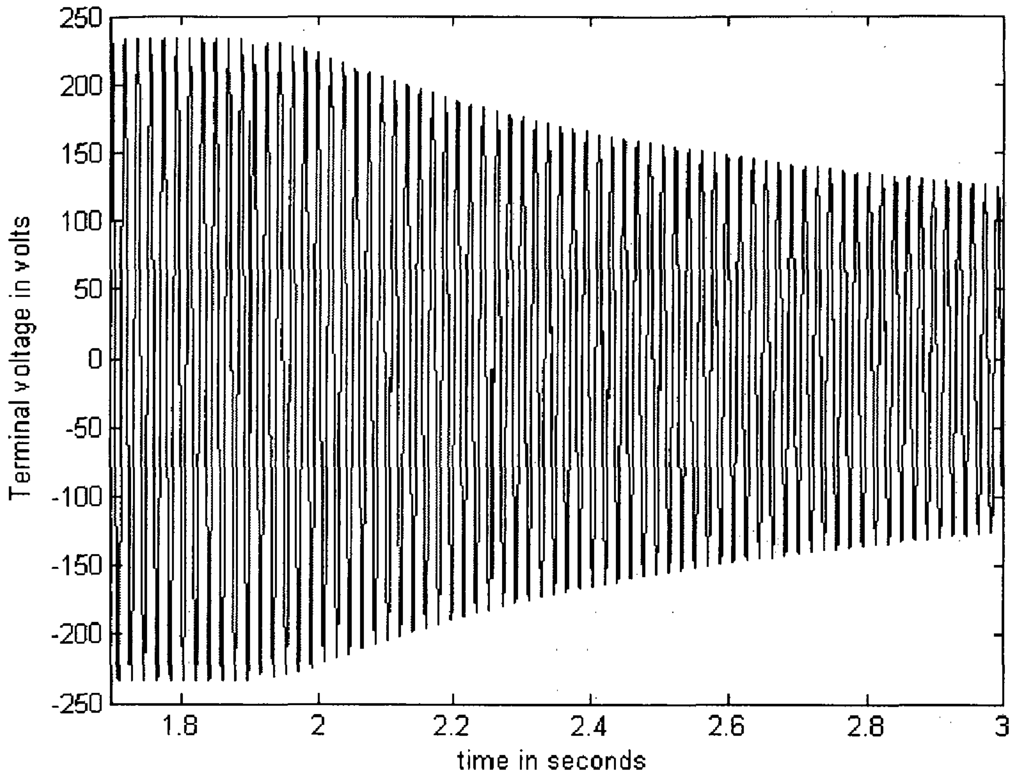


Fig3.12 Change in terminal voltage due to change in excitation capacitance

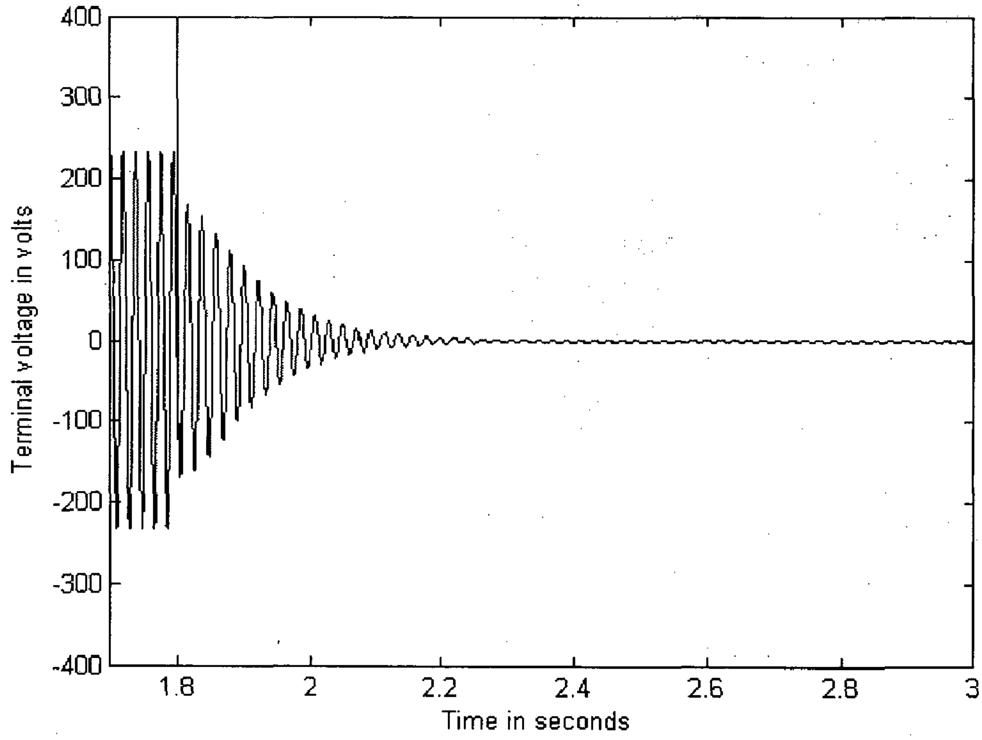


Fig3.13 Change in terminal voltage due to short circuit

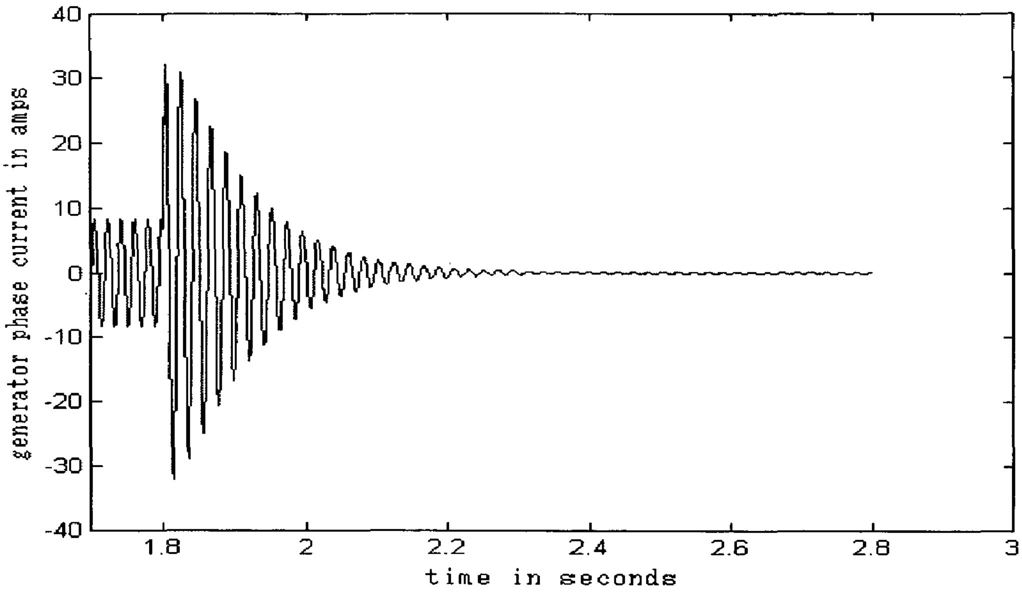


Fig3.14 Change in phase current due to short circuit

3.4 Electronic load controller

3.4.1Theory

An Electronic load controller or Induction generator controller is used for a micro hydro system fitted with a stand-alone generator. Together with dump load connected to it, an ELC serves as an automatic, electrical brake that controls voltage produced by generator.

Two types of ElCs are usually used.

- AC Controller with back-to-back thyristors feeding a fixed resistive fixed resistive dump load. Firing angle control varies power in the dump load. .
- A rectifier-chopper feeding a fixed resistance on the DC side. Varying the duty cycle of the chopper controls dump power.

The AC controller introduces higher current harmonics and VAR demand so nowadays rectifier-chopper system is used.

In chopper based ELC scheme a three-phase delta connected induction generator is driven by an uncontrolled micro hydel turbine. The generator is operated as an SEIG by connecting a fixed terminal capacitor of such a value as to result in rated terminal voltage at full load. As the input power is nearly constant, the output power of the SEIG must be held constant at all consumer loads. Any decrease in consumer load may accelerate the machine and raise the voltage and frequency levels to prohibitively high values, resulting in large stresses on other connected loads. The power in surplus of the consumer load is dumped in a resistance through an ELC. Thus the SEIG sees two balanced three-phase loads in parallel such that the total power is constant, thus: $P_{out}=P_d+P_c$

Where P_{out} is the generated power of the generator, P_c is the consumer power and P_d is the dump load power. This dump power may be used for space heating, water heating, battery charging, cooking baking.

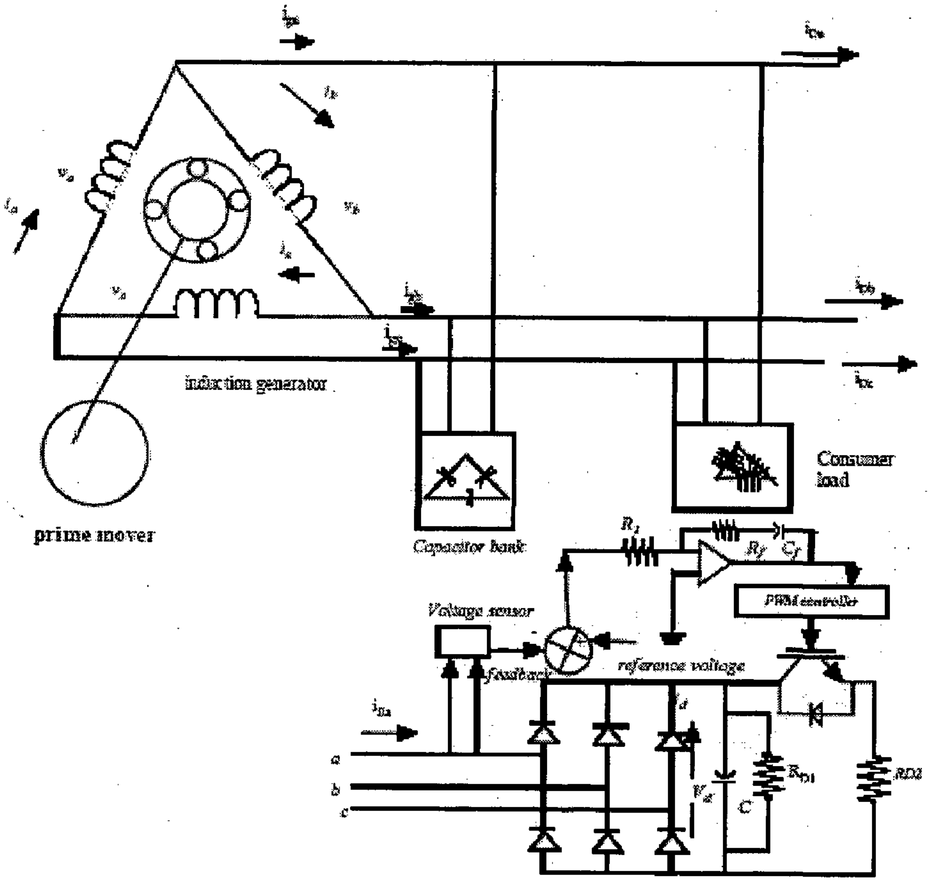


Fig3.15 Variation of Dump load current at the application of consumer load

3.4.2Modelling of SEIG with ELC

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{os} \end{bmatrix}$$

In the given circuit line voltage v_{ab} v_{bc} and v_{ca} are obtained as follows:

$v_{ab} = -v_b$; $v_{bc} = -v_c$; And $v_{ca} = -v_a$; $v_{ab} + v_{bc} + v_{ca} = 0$

$$i_{aL} = (v_{ab} - v_{ca})/R_L$$
$$i_{bL} = (v_{bc} - v_{ab})/R_l$$
$$i_{cL} = (v_{ca} - v_{bc})/R_l$$

$$pv_{ab} = (i_{ca} - i_{cb})/3C$$
$$pv_{bc} = (i_{ca} + 2i_{cb})/3C$$

Where i_{ca}, i_{cb}, i_{cc} are current through excitation capacitor and i_{al}, i_{bl}, i_{cl} are load currents of phase a, phase b, phase crespectively.

The ELC comprises of an uncontrolled rectifier bridge, control circuit and an IGBT chopper switch. The stator voltage is fed to the rectifier through small source inductance and resistance. A filter capacitance C_{dc} is connected across the rectifier output to filter out the ripples.

$pi_d = (v_{max} - v_d - 2R_f i_d)/(2L_f)$, i_d,v_d are the charging current and capacitor voltage respectively, L_f,R_f are filter inductance and resistance.

$pv_d = (i_d - i_L)/C_{dc}$ where i_L=(vd/Rd1) +S((vd/Rd2) .

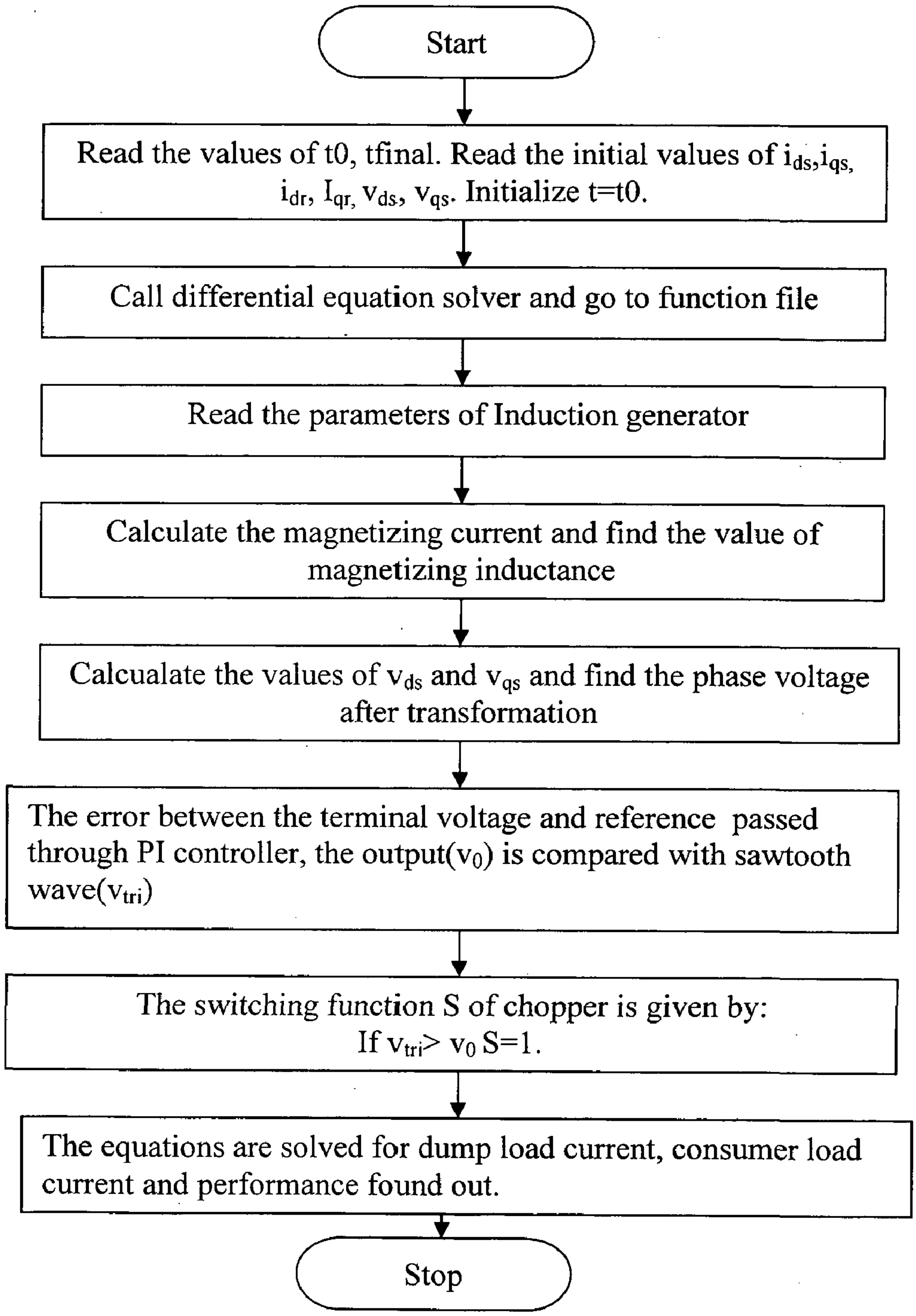
R_{d2} is resistance of dump load and R_{d1} is discharging resistane.

Here 'S' is the switching function of IGBT chopper switch.

Modelling of control scheme of ELC

The SEIG output voltage is sensed using step down transformer and rectified through single-phase rectifier circuit for feed back signal and is compared with reference voltage. The error voltage is fed to a PI controller and the output of PI controller is compared with saw tooth carrier wave form to result in PWM signal to alter the duty cycle of chopper.

Flow chart for simulation of ELC



3.4.3Results showing SEIG with ELC for machine-I

The terminal voltage control using an ELC is simulated for the same machine. At 0.5 sec after steady state has been reached the dump load is connected to the terminals of SEIG through a chopper. At 0.7 second, consumer load is connected which is simulated by Rl=50 ohms. The terminal voltage, Phase current and dump load current are shown in fig3.16 to 3.18.

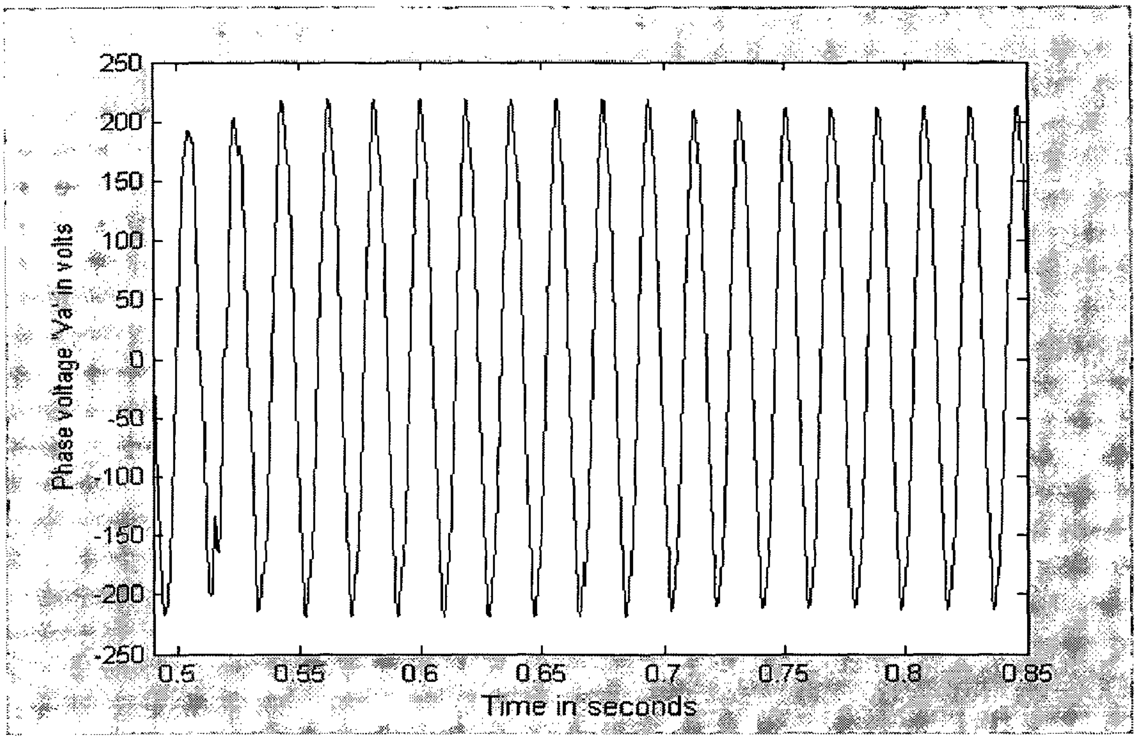


Fig3.16 Phase voltage "V_a"

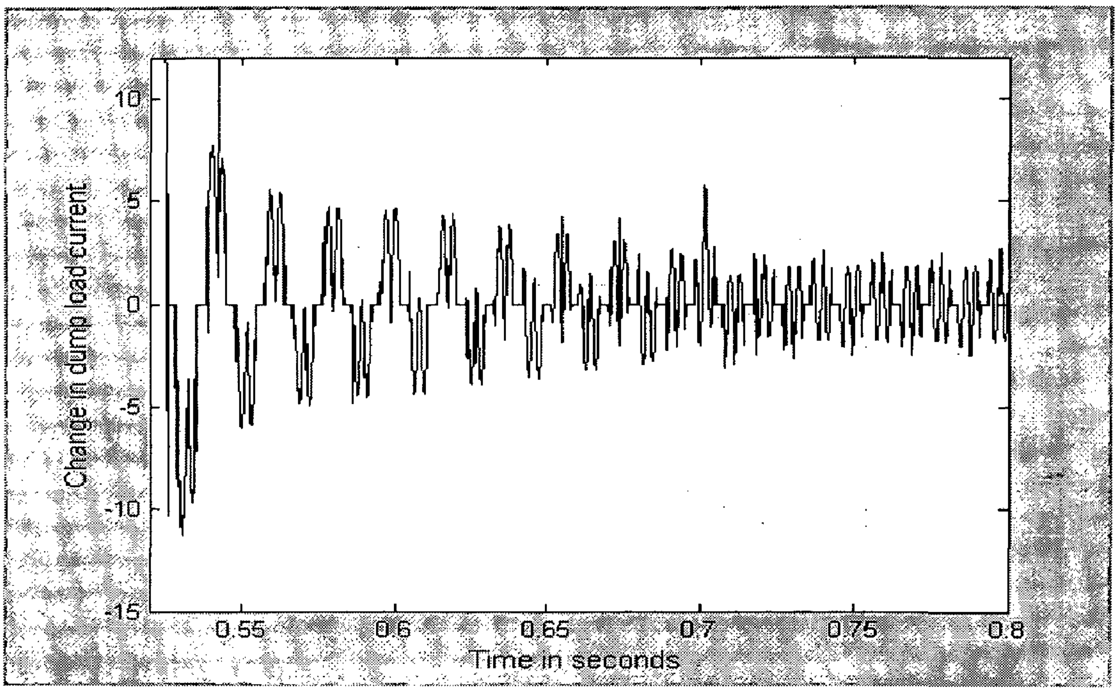


Fig3.17 dump load current "I_{da}"

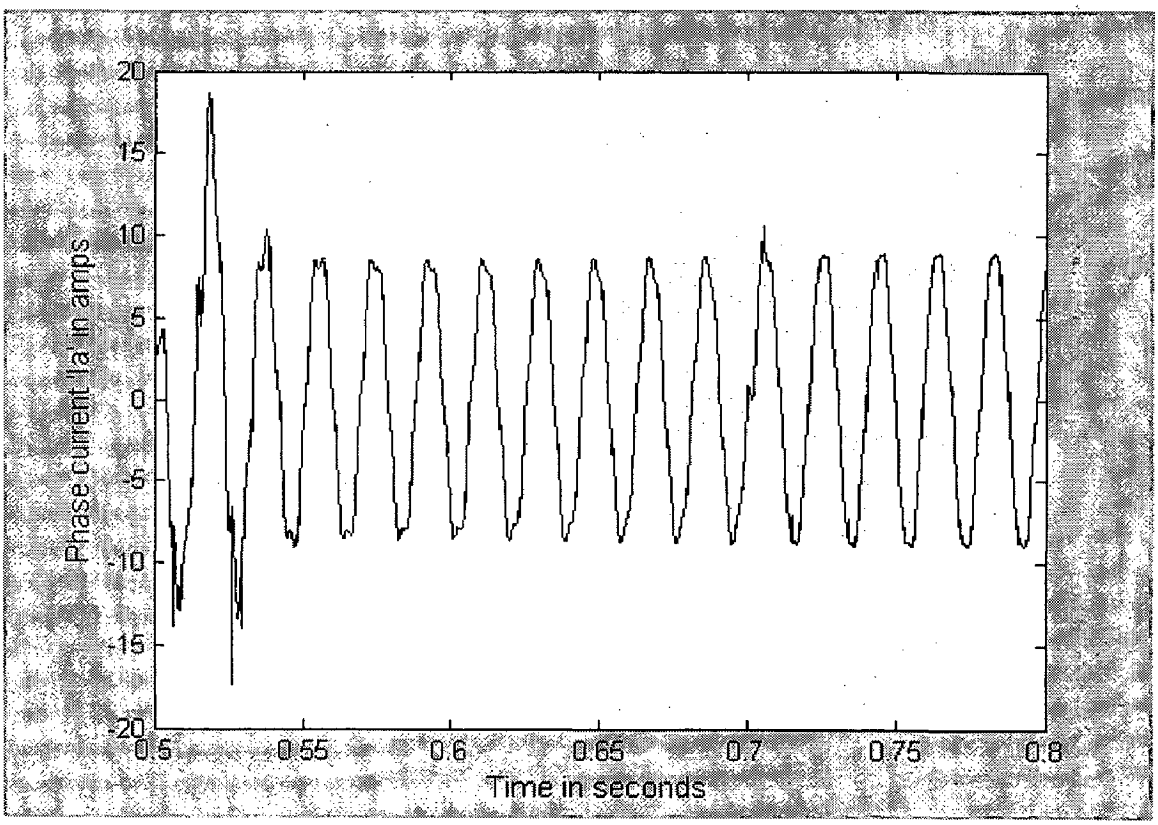


Fig3.18 phase current "I_a"

CHAPTER-4

STATCOM BASED VOLTAGE REGULATOR

4.1 Theory

Capacitor self-excited induction generator suffers from its' 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 subsynchronous 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.

4.2 Control strategy of STATCOM

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

$$V_t=\{(2/3)(v_a^2+v_b^2+v_c^2)\}^{1/2} \quad (4.1)$$

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

$$u_a=v_a/V_t; u_b=v_b/V_t; u_c=v_c/V_t \quad (4.2)$$

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 :

$$w_a=-u_b/\sqrt{3}+u_c/\sqrt{3} \quad (4.3)$$

$$w_b=\sqrt{3}u_a/2+(u_b-u_c)/2\sqrt{3} \quad (4.4)$$

$$w_c=-\sqrt{3}u_a/2+(u_b-u_c)/2\sqrt{3} \quad (4.5)$$

(1) **Quadrature component of source reference current**:

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

$$V_{er(n)}=V_{tref(n)}-V_{t(n)} \quad (4.6)$$

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 :

$$I^*_{smq(n)}=I^*_{smq(n-1)}+K_{pa}\{V_{er(n)}-V_{er(n-1)}\}+K_{is}V_{er(n)} \quad (4.7)$$

Where K_{pa} and K_{is} 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

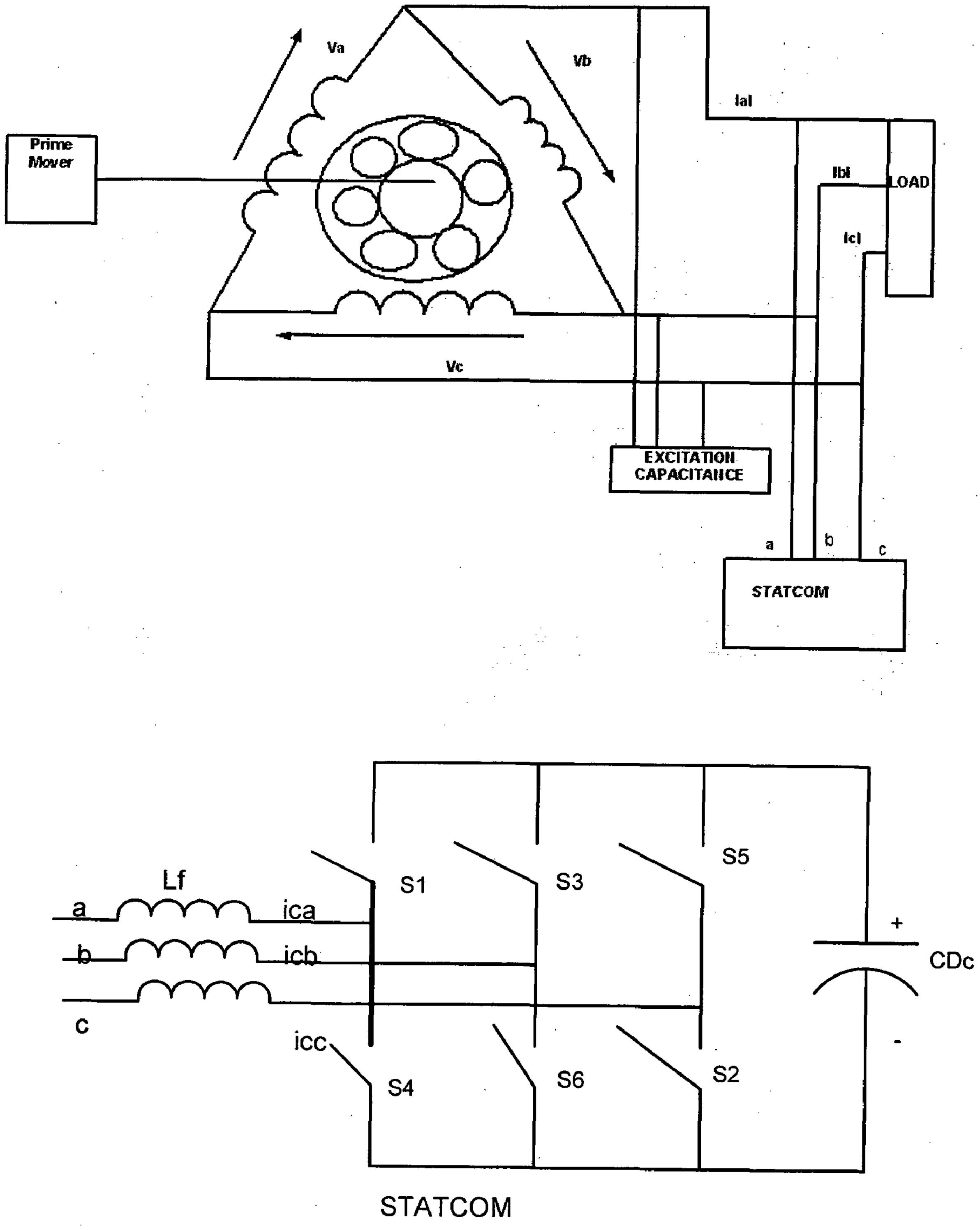


Fig4.1 SEIG with STATCOM

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

$$i^*_{saq}=I^*_{smq}w_a; i^*_{sbq}=I^*_{smq}w_b; i^*_{scq}=I^*_{smq}w_c \quad (4.8)$$

(2) In phase component of source reference current

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

$$V_{dcer(n)}=V_{dcref}-V_{dc(n)} \quad (4.9)$$

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:

$$i^*_{smd(n)}=I^*_{smd(n-1)}+K_{pi}\{V_{dcer(n)}-V_{dcer(n-1)}\}+K_{id}V_{dcer(n)} \quad (4.10)$$

$i^*_{smd(n)}$ 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:

$$i^*_{sad}=I^*_{smd}u_a; {}^*_{sbd}=I^*_{smd}u_b; i^*_{scd}=I^*_{smd}u_c \quad (4.11)$$

(3) **Total source reference currents**:

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

$$i^*_{sa}=i^*_{saq}+i^*_{sad} \quad (4.12)$$

$$i^*_{sb}=i^*_{sbq}+i^*_{sbd} \quad (4.13)$$

$$i^*_{sc}=i^*_{scq}+i^*_{scd} \quad (4.14)$$

(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:

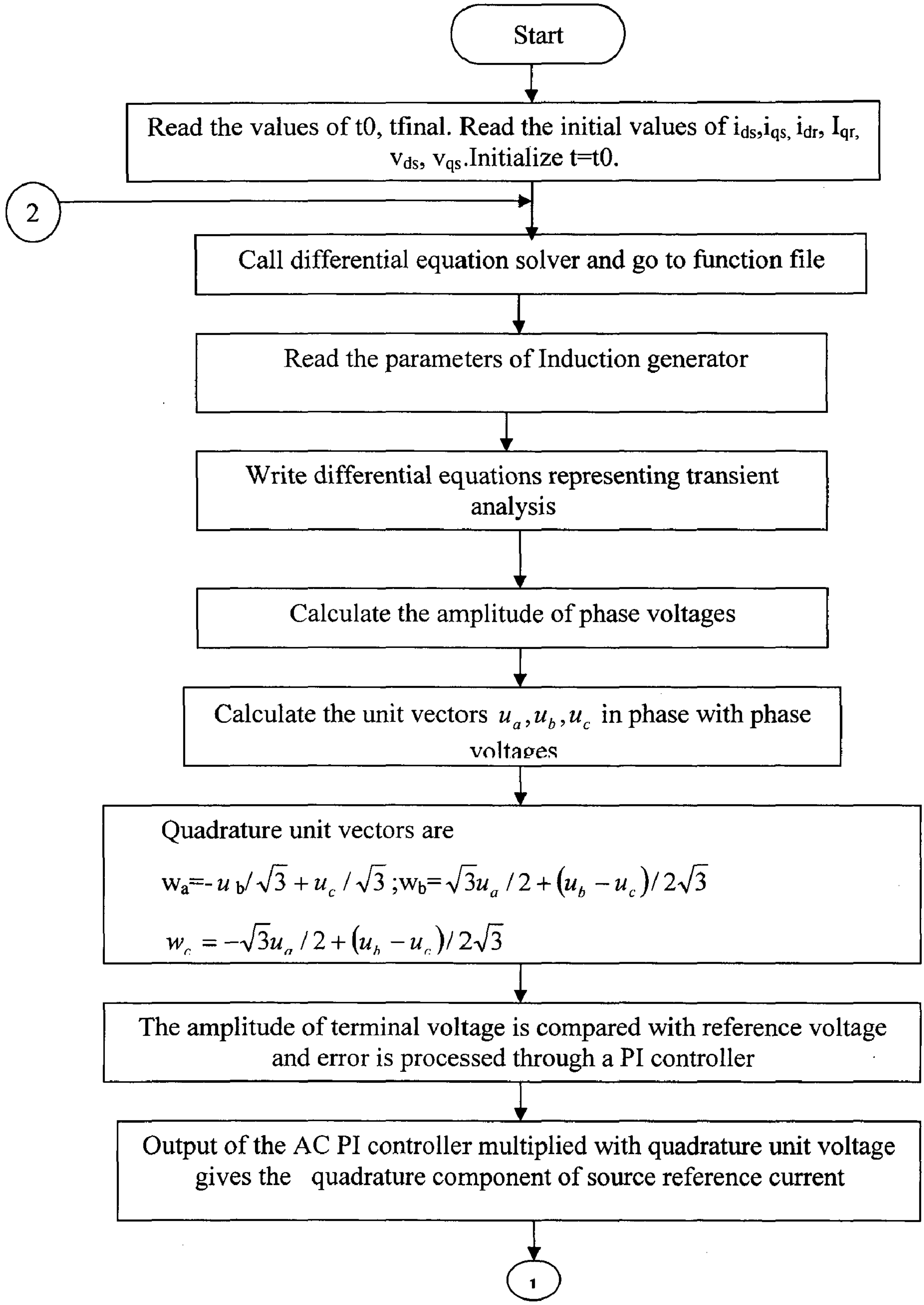
$$i_{saerr}=i^*_{sa}-i_{sa} \quad (4.15)$$

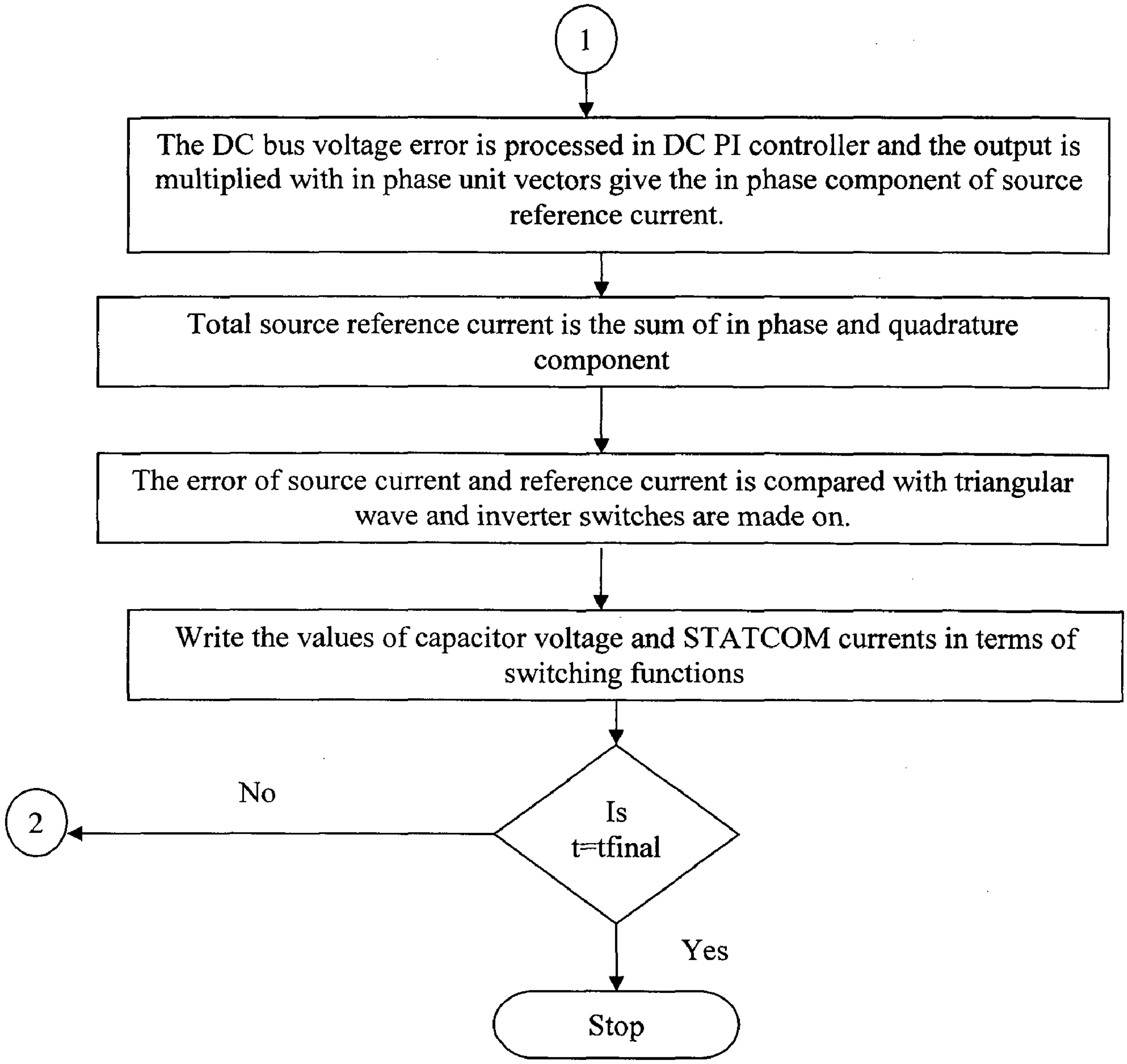
$$i_{sberr}=i^*_{sb}-i_{sb} \quad (4.16)$$

$$i_{scerr}=i^*_{sc}-i_{sc} \quad (4.17)$$

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.

Flow chart for STATCOM based regulator




1
The DC bus voltage error is processed in DC PI controller and the output is multiplied with in phase unit vectors give the in phase component of source reference current.
Total source reference current is the sum of in phase and quadrature component
The error of source current and reference current is compared with triangular wave and inverter switches are made on.
Write the values of capacitor voltage and STATCOM currents in terms of switching functions
Is t=tfinal
No
2
Yes
Stop

4.3Results

The fixed capacitance required to excite the generator to a peak voltage of 250 V is 120 micro-farad. The system is allowed to attain steady state and at 0.9 sec a resistive load is applied which is simulated by Rl=25 ohm. It is observed in Fig.4.3 that there is a drop in terminal voltage. At 1.2 sec giving firing pulses to the switches of inverter makes STATCOM on. The STATCOM tries to increase the terminal voltage. The control is simple PWM control where the reference currents are produced by the control strategy discussed earlier.

4.3.1 RESULTS OF STATCOM BASED REGULATOR

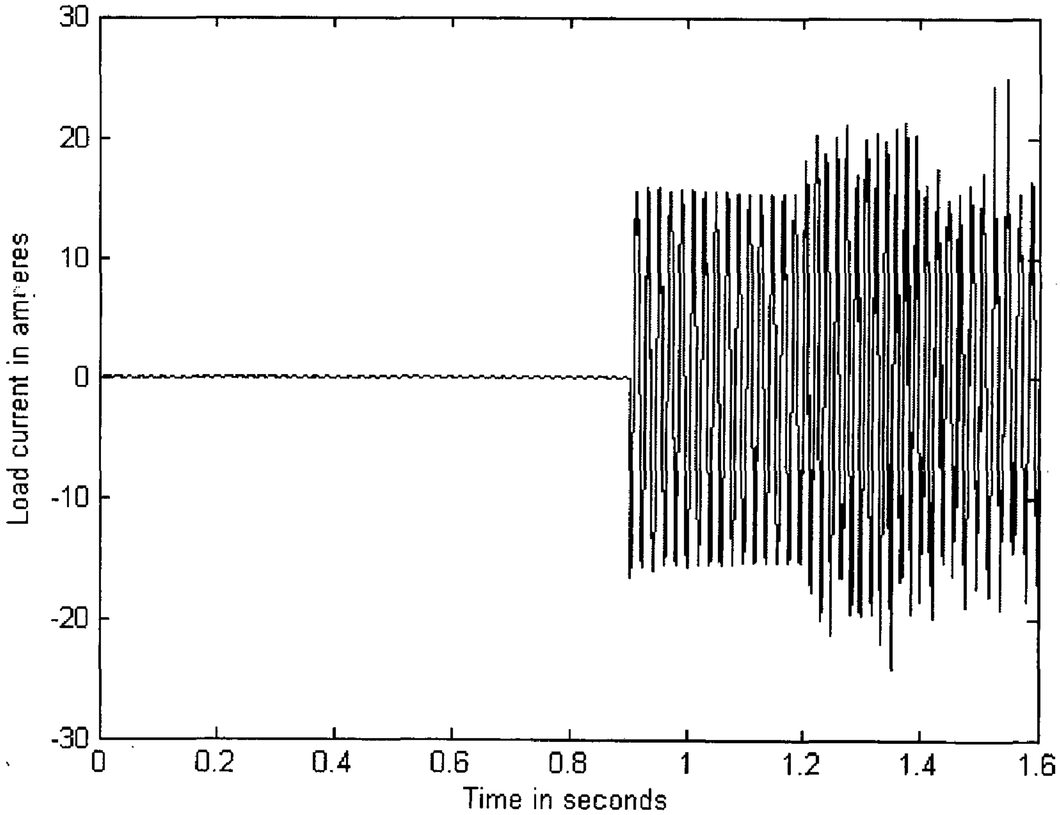


Fig 4.2(a) Load current

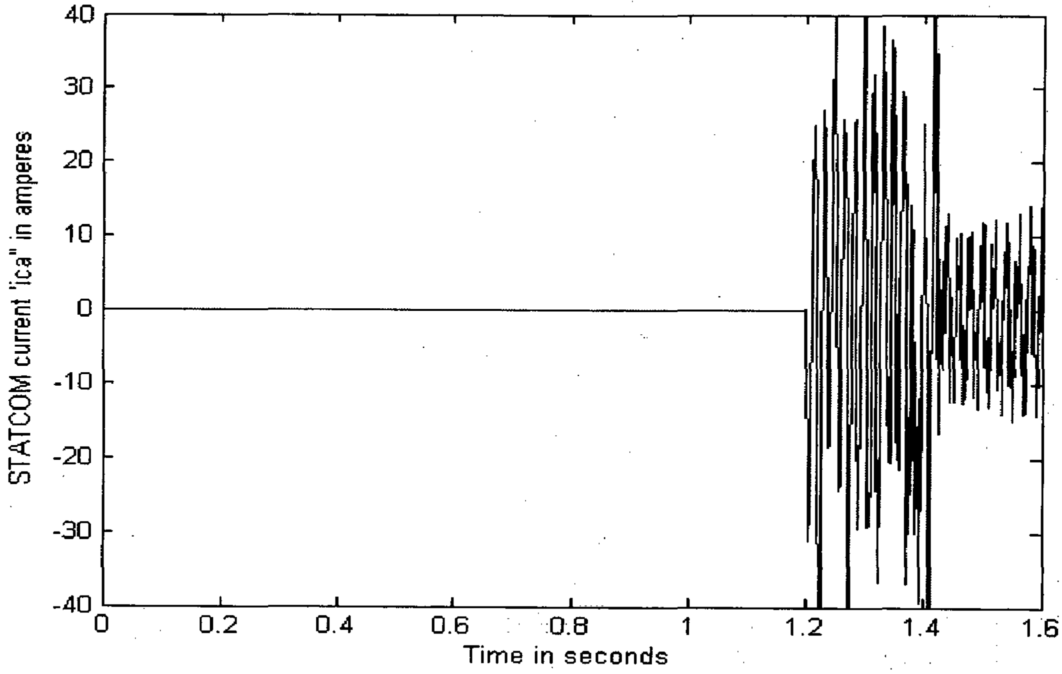


Fig4.2(b) STATCOM current

Fig. 4.2(b) 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=1.2 seconds. There is small oscillation at the switching in inverter but damps out within a few cycle.

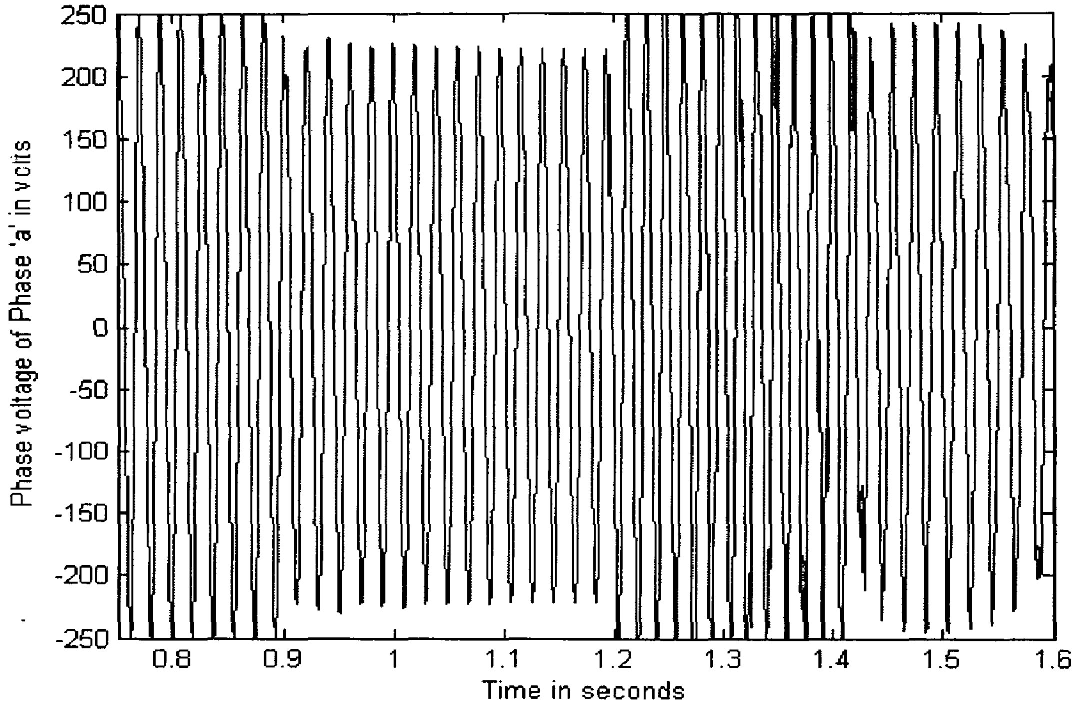


Fig 4.3(a) Phase voltage after application of load and STATCOM

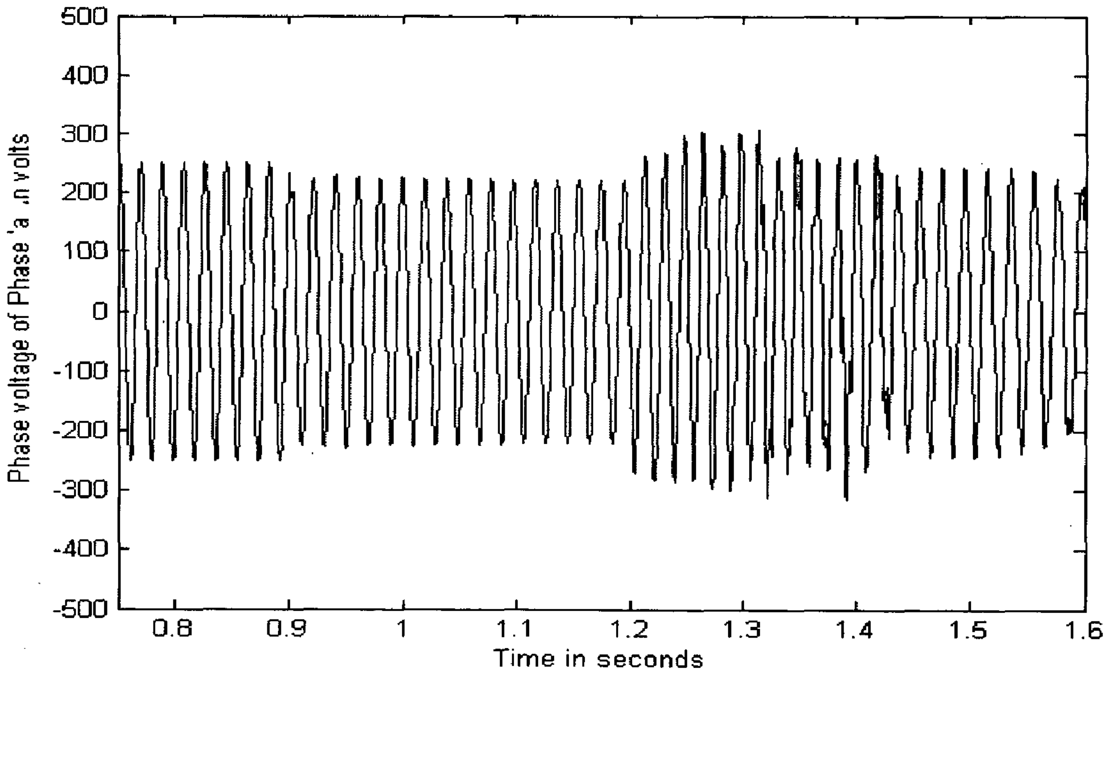


Fig 4.3(b) Phase voltage after application of load and STATCOM in enlarged axes

4.4 Modelling of STATCOM combined with ELC

In this combination we take a current controlled Voltage source inverter, which acts as a STATCOM with a DC chopper. The STATCOM acts as a voltage regulator and the DC chopper keeps the rated power on the SEIG. So the combination of STATCOM and ELC acts as a voltage and frequency regulator.

4.4.1 Modelling of DC bus chopper

The generated power of the SEIG is calculated by transforming three-phase quantity into two-phase quantity:

$$v_\alpha = \sqrt{2}/3(v_a - v_b/2 - v_c/2) \tag{4.18}$$

$$v_\beta = \sqrt{2}/3(\sqrt{3}/2v_b - \sqrt{3}/2v_c)$$

$$i_\alpha = \sqrt{2}/3(i_a - i_b/2 - i_c/2) \tag{4.19}$$

$$i_\beta = \sqrt{2}/3(\sqrt{3}/2i_b - \sqrt{3}/2i_c)$$

The instantaneous generated power is given by:

$$P_{gen} = v_\alpha i_\alpha + v_\beta i_\beta \tag{4.20}$$

Generated power is compared with reference power

$$P_{er(n)} = P_{ref} - P_{gen(n)} \tag{4.21}$$

The power error is processed in a PI controller to maintain the constant generated power. The output of is compared with a triangular wave and the gate pulse for IGBT chopper is produced.

4.4.2 Modelling of voltage source inverter

The instantaneous value of DC bus voltage is given by

$$pV_{dc}=(SAi_{ca}+SBi_{cb}+SCi_{cc}-SDV_{dc}/R_d)/C_{dc} \tag{4.22}$$

SA, SB, SC are switching functions of voltage source inverter switches S1-S6. SD is switching function of chopper.

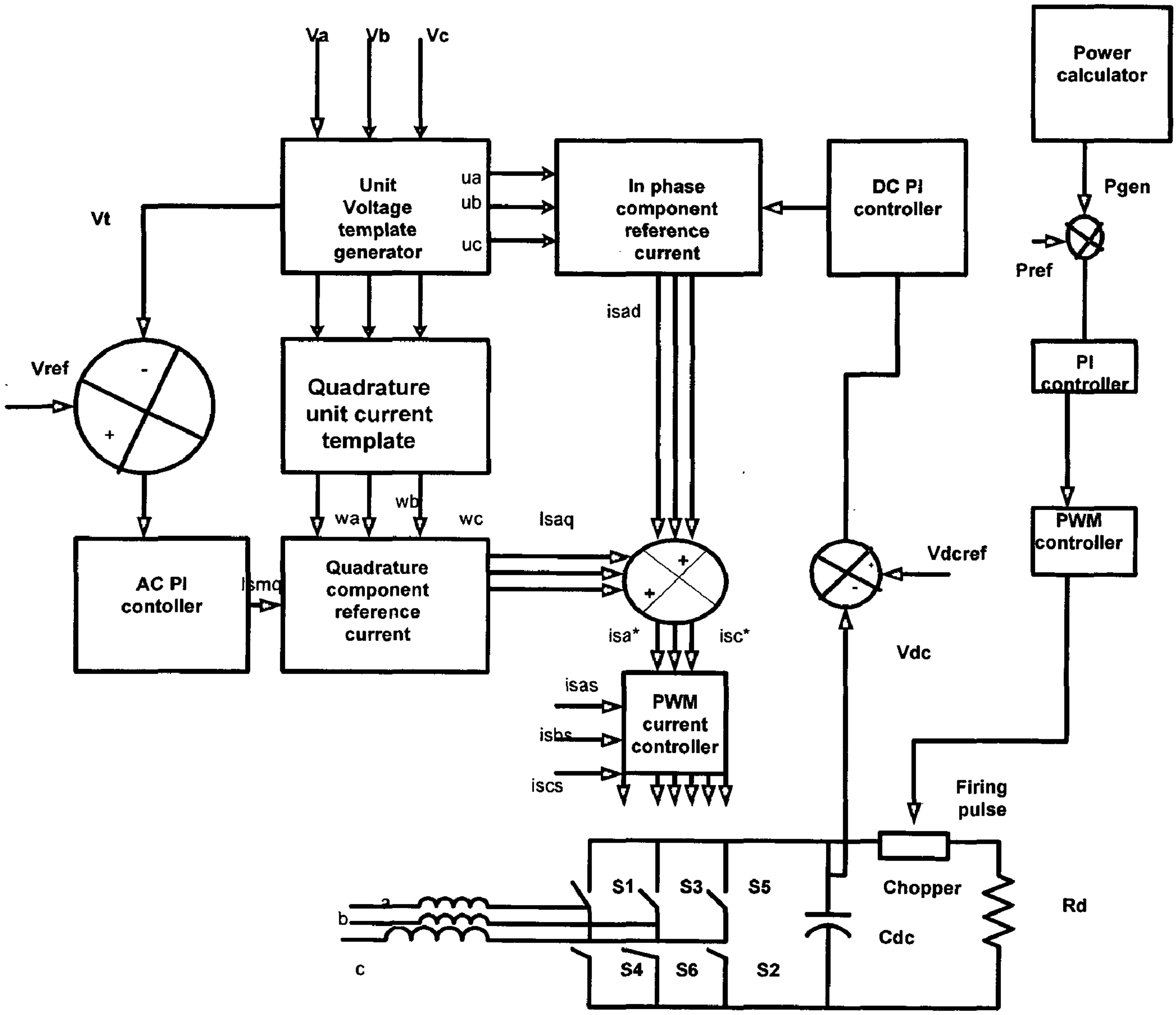


Fig. 4.4 Schematic of control strategy STATCOM with ELC

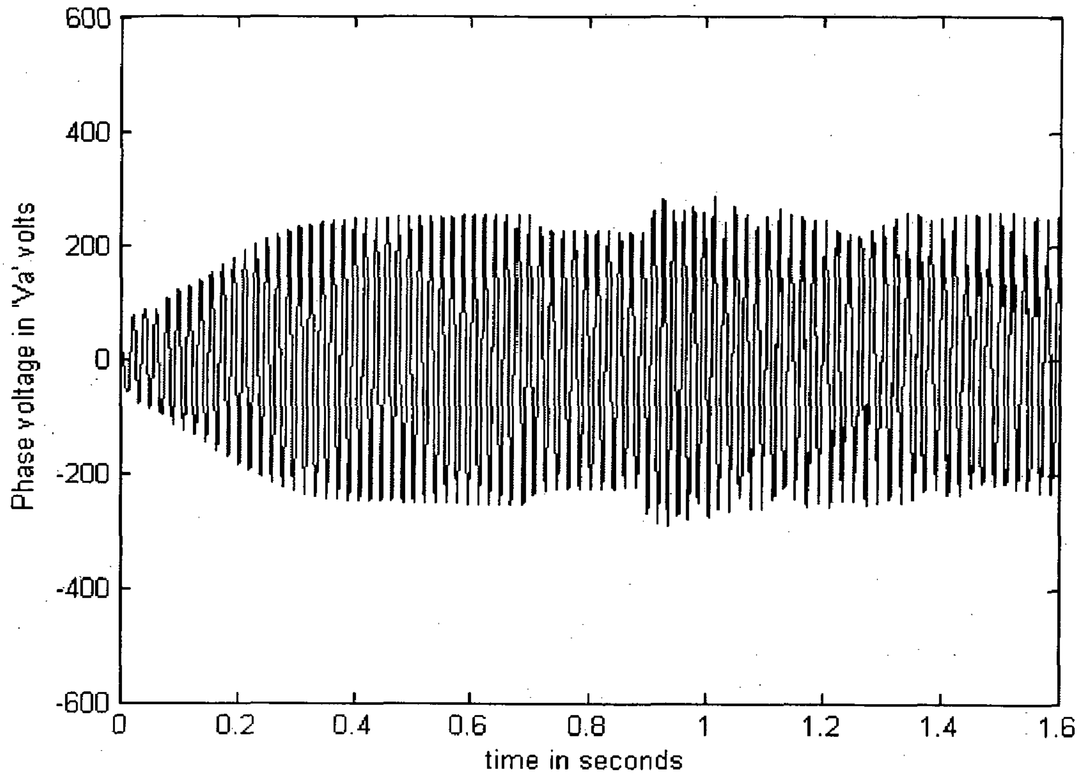


Fig 4.5 Phase Voltage

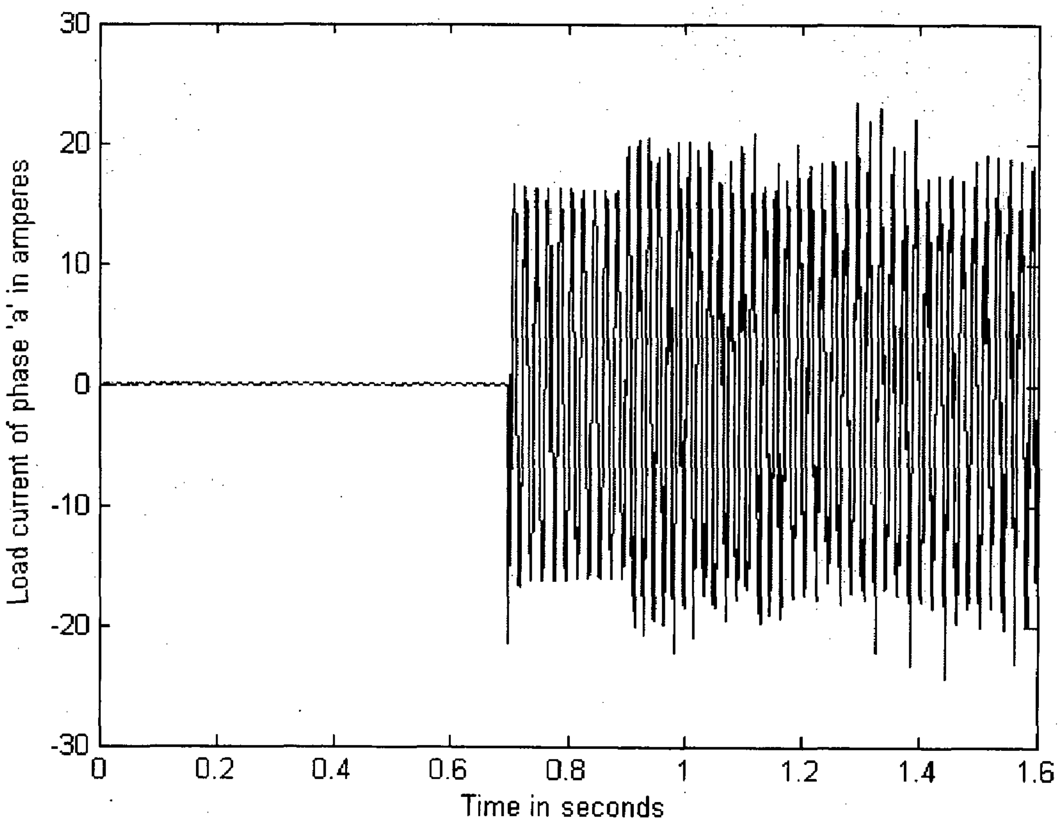


Fig4.6 Load current

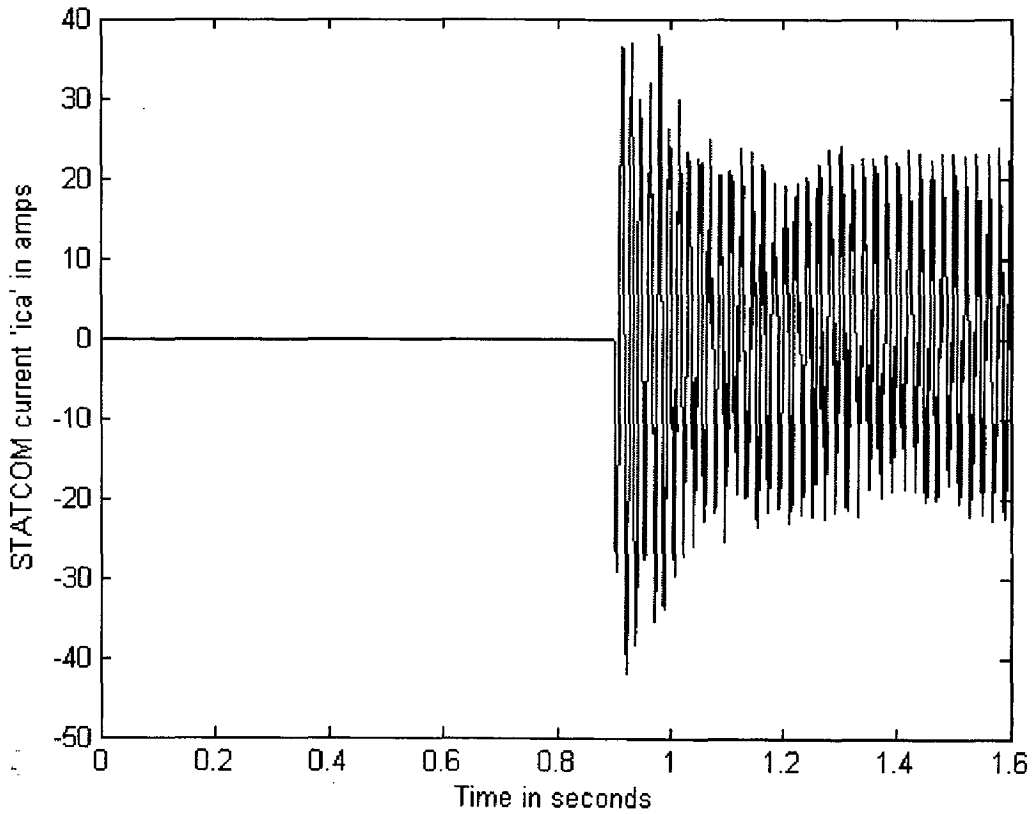


Fig4.7The STATCOM current

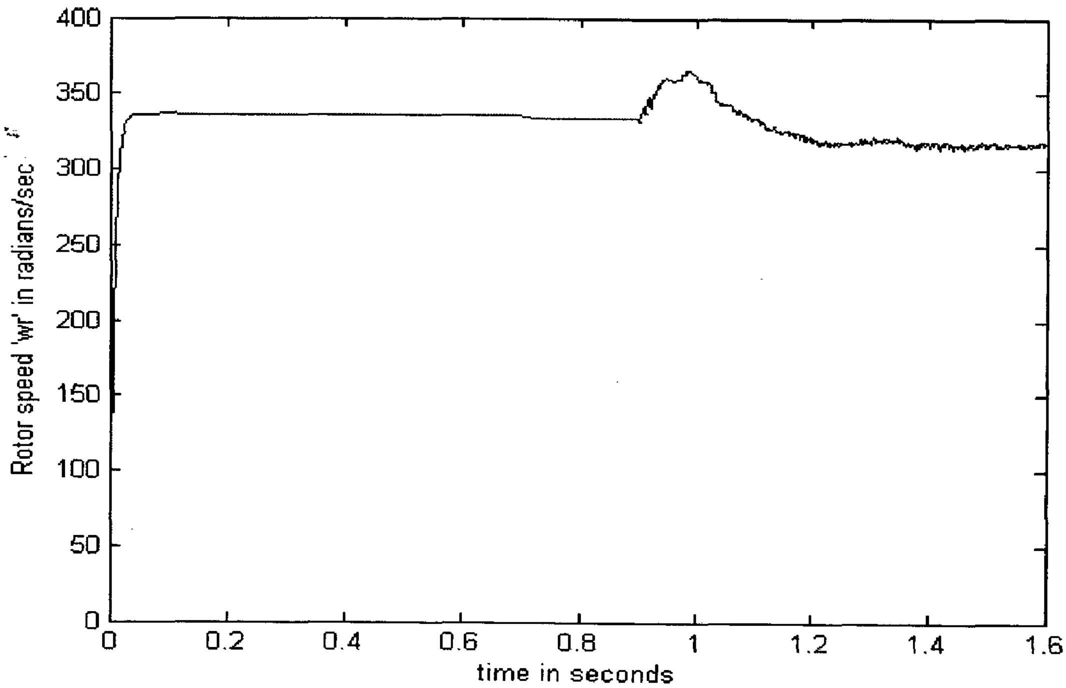


Fig 4.8 The rotor speed

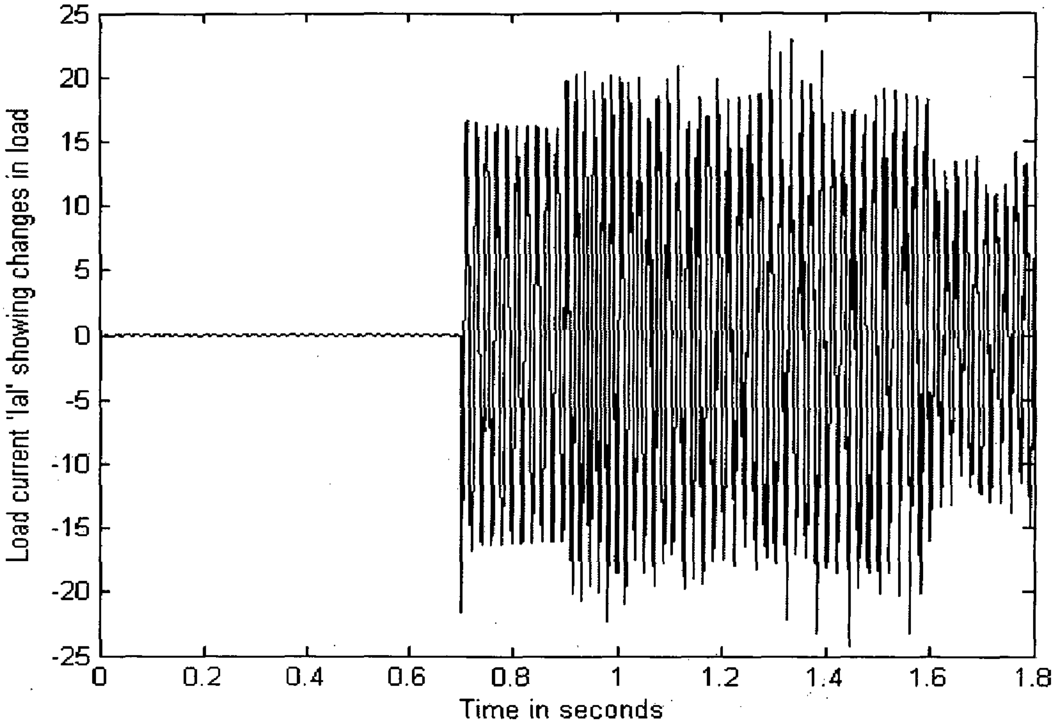


Fig 4.9 Load current showing change in load

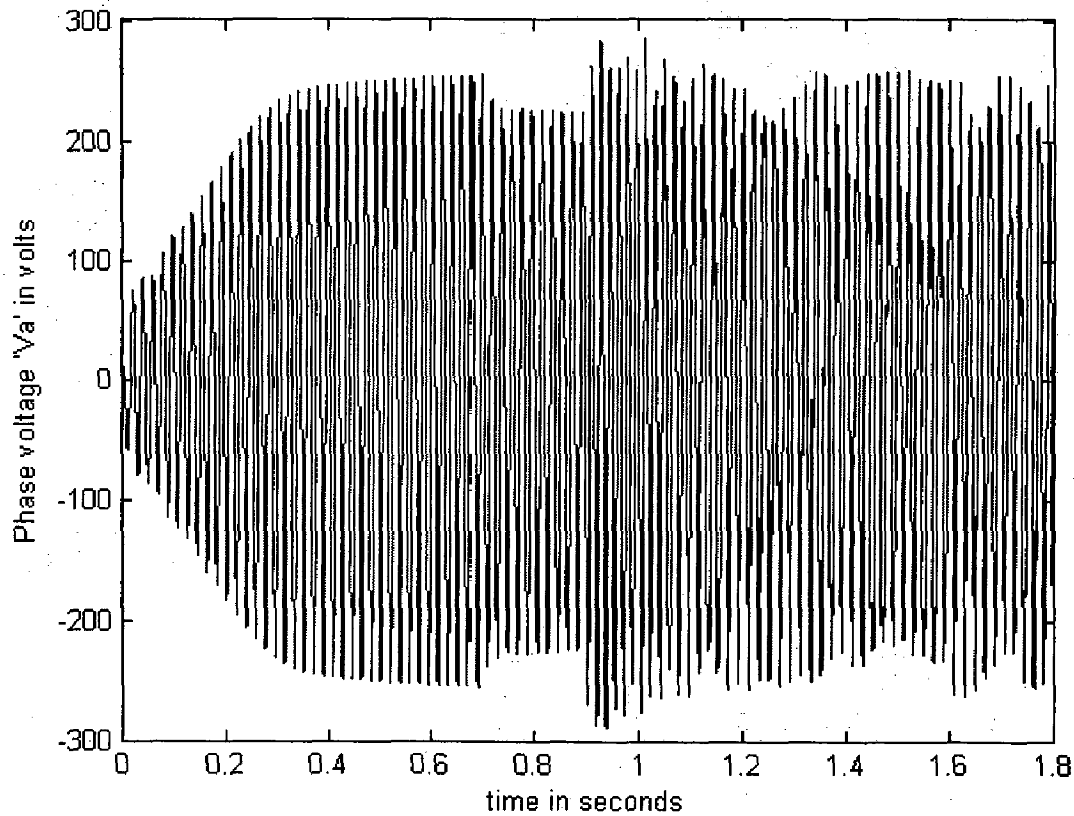


Fig 4.10Terminal voltage showing change in load

4.5 Results of STATCOM with ELC

Fig. 4.5 shows transient waveform of Phase voltage of SEIG. It is observed that that voltage gradually builds up and after some time the steady state is reached. It is observed in Fig 4.5, at time t=0.7 sec a resistive load is applied and the terminal voltage drops. At 0.9 sec STATCOM is made on and the terminal voltage improves. The load current is shown in Fig. 4.6. The STATCOM current, which initially oscillates at a higher value damps out within a few cycles as shown in Fig.4.7. Fig 4.8 shows the rotor speed and it is observed that there is a small change in speed after the STATCOM is made on. Fig. 4.9 and Fig.4.10 show the load current and terminal voltage when there is change in load from Rl=25 Ohm to Rl=35 Ohm at time t=1.6 sec and it is observed that the terminal voltage of SEIG is approximately maintained.

CHAPTER-5

DEVELOPMENT OF HARDWARE FOR ELC

5.1 Hardware implementation

An Electronic load controller was designed for a given laboratory machine, the data of which is listed in Appendix as machine-II. For this dissertation purpose the electronic load controller consists of an uncontrolled diode bridge rectifier in series with a chopper and dump load (resistors). Duty cycle of the chopper is adjusted so that the output power of the generator remains constant. Duty cycle of the chopper is decided through closed loop control of SEIG output voltage. The SEIG voltage is sensed through the voltage sensor and rectified through the single-phase rectifier for feed back signal. The rectified signal is compared with reference signal and error signal is fed to PI controller. The output of PI controller is compared with PWM sawtooth waveform to decide the duty cycle of the chopper to generate a gating signal to the IGBT.

5.1.1 Power supplies

D.C. regulated power supplies (+12V, -12V and +5V) are required for providing the biasing to various transistors, integrated circuits etc. The system development has inbuilt power supplies for this purpose. The circuit diagram for various power supplies are shown in fig. The single-phase ac voltage is stepped down and then rectified by using diode bridge rectifier. A capacitor of 1000 μF, 50 V is connected at the output of the bridge rectifier for smoothing out the ripples in the rectified dc voltage of each supply. IC voltage regulated chips 7812,7912 and 7805 are used for obtaining the dc regulated power supplies. A capacitor of 100 μF, 25 V is connected at the output of the IC voltage IC voltage regulator of each supply for obtaining the constant, ripple free dc voltage.

Power circuit for ELC

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

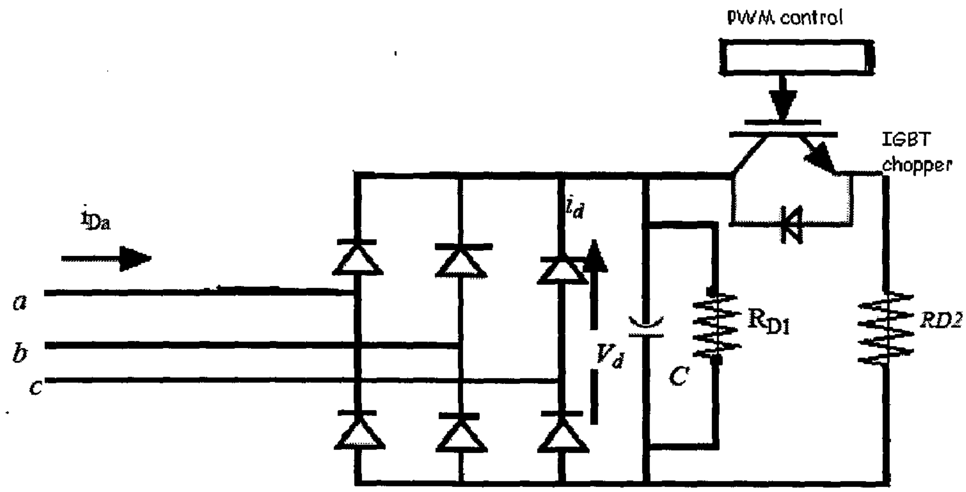


Fig5.1 Power circuit for Chopper based Electronic load controller

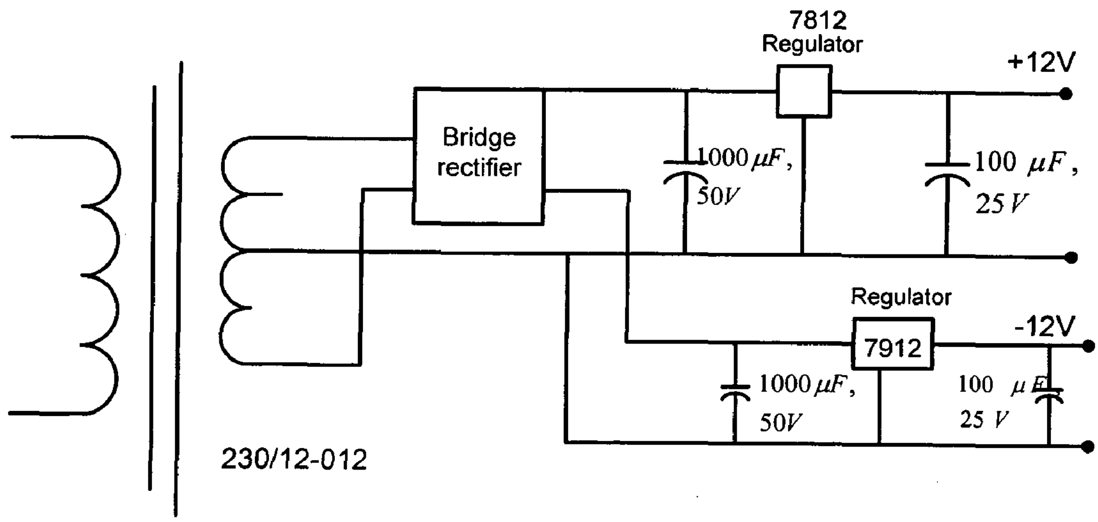


Fig5.2 circuit diagram for power supplies +12 V and –12 V

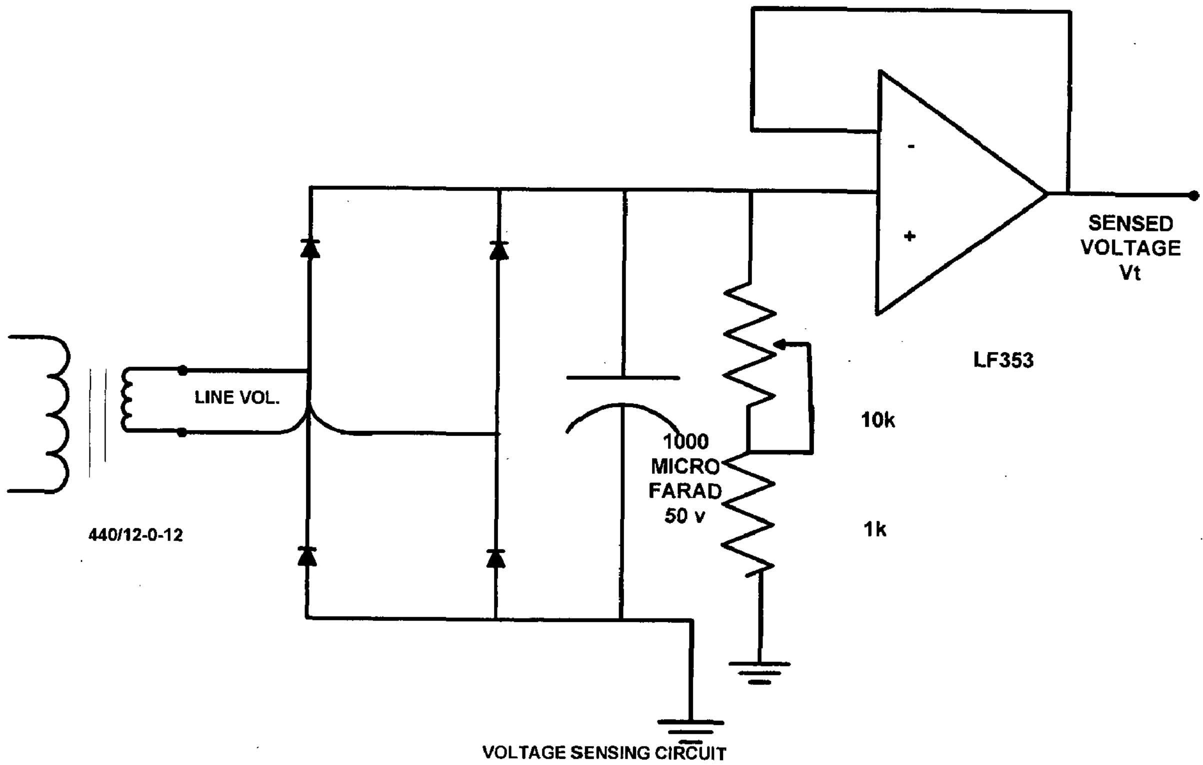


Fig5.3 Voltage sensing circuit

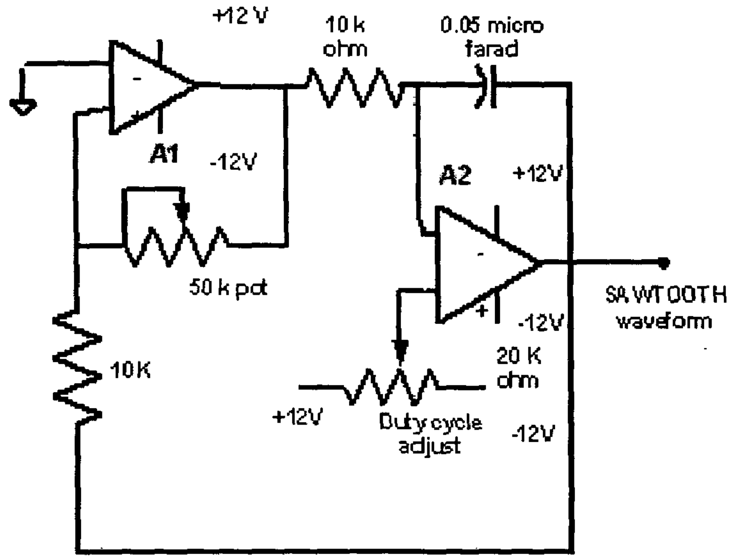


Fig5.4 Diagram showing sawtooth wave generator

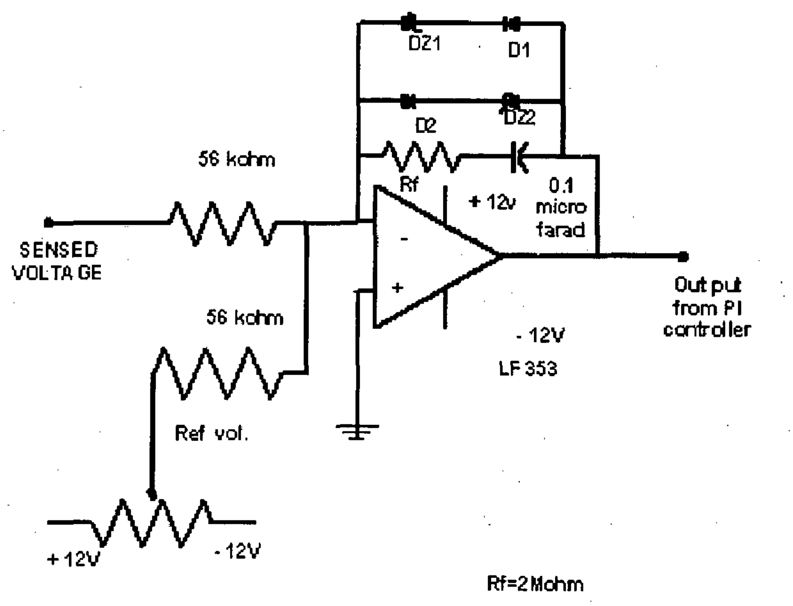


Fig5.5 PI controller

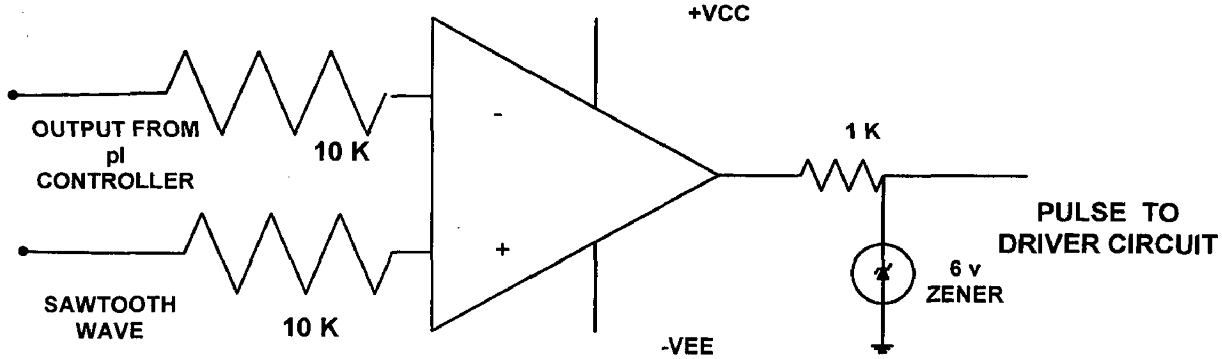


fig5.6 gate pulse generation circuit

5.1.2 Voltage sensing circuit

The SEIG output voltage is sensed using a step down transformer and rectified through a single-phase rectifier circuit for a feed back signal. A small capacitor is used to filter the ripples from the rectified voltage used as the feed back signal. A calibration circuit and a buffer is connected at the output of the capacitor to calibrate the sensed voltage.

5.1.3 PI controller

The error detector, PI controller and limiter are combined in a single circuit. The sensed voltage is compared with the reference voltage and the error is processed through the PI controller. Diode D1, and zener diode DZ1 provide limitations on the maximum positive voltage and diode D2 and zener diode DZ2 provide limitation on the maximum negative voltage.

For the design of PI controller the following assumptions are taken.

$K1=R_f/R_1=34.55$

$R_fC_f=0.1935$

Taking C_f value to be 0.1 micro-farad

R1=56 kohm

Rf=2 Mohm

Pulse generation circuit:

The output of PI controller is compared with sawtooth wave and gate pulses are generated. A Zener is connected at the output of pulse generation circuit to clip off the negative half of the pulse.

5.1.4 Pulse Amplification and Isolation circuit

The Optocoupler(MCT2E) provides the necessary isolation between the low voltage control circuit and high voltage power circuit. The pulse amplification is provided by the output amplifier transistor 2N2222. The 0-5V gating pulses form the base drive for the input 2N2222 switching transistor. When the input gating pulse is +5 V level, the transistor saturates, the LED conducts and light emitted by it falls on the base of photo transistor, thus forming it's base drive. The output transistor thus receives no base drive and therefore remains in cutoff state and +15 V pulse appears across its collector terminal (with respect to ground). Now when the input gating pulse reaches the ground level (0V), the input switching transistor goes into the cutoff state and the LED remains off, thus emitting no light and therefore the photo transistor of Optocoupler receives no base drive and therefore remains in cutoff state. A sufficient base drive now applies across the base of the output amplifier transistor. It goes into saturation state and hence the output pulse falls to ground level. The circuit provides so proper amplification and isolation. Further since slightest spike above 20 V can damage the silicon layer of the device a 15 V zener is connected across the output of the isolation circuit. It clamps the triggering voltage at 15V and hence avoids the danger of damaging the silicon layer.

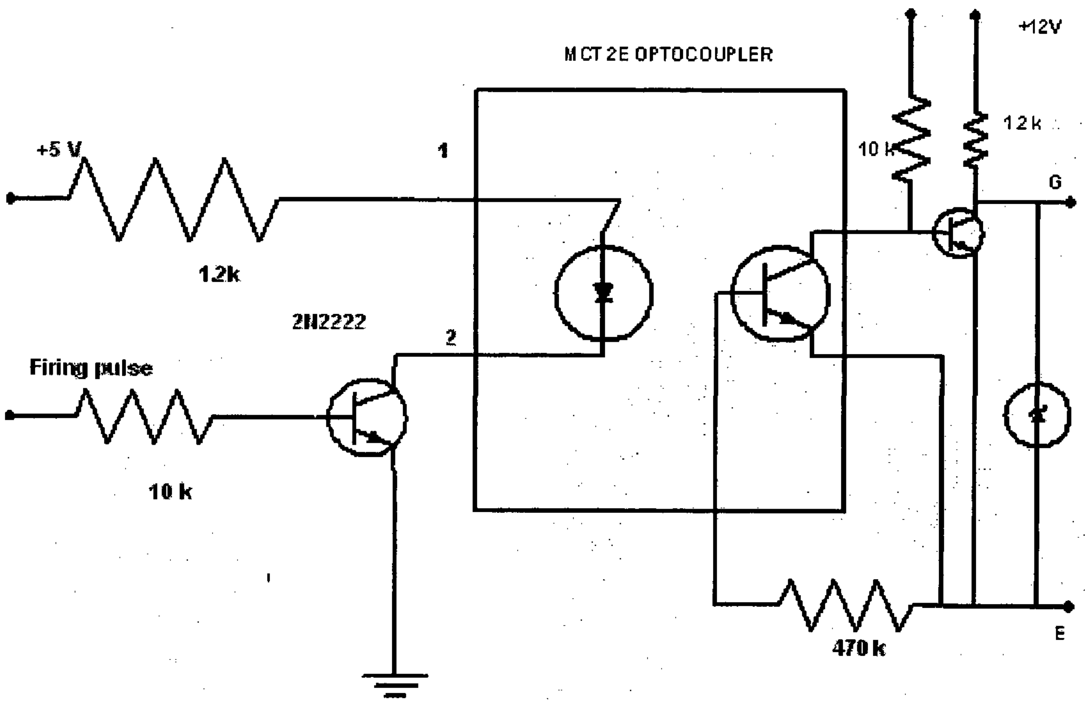


Fig5.7 Pulse Amplification and Isolation circuit

5.2 Results and discussions.

The waveform at the output terminal of Gate pulse generation circuit as shown in Fig. 5.6 was recorded and by changing the reference voltage the pulses were observed. It was found that the control circuit is able to respond to the change in sensed voltage as well as the reference voltage.

The power circuit for the ELC was connected to the given machine terminal and experimentation was performed. The shortcoming of the power circuit was the IGBT (25Q101), which was used as a chopper was able to withstand the high voltage for a short time period.

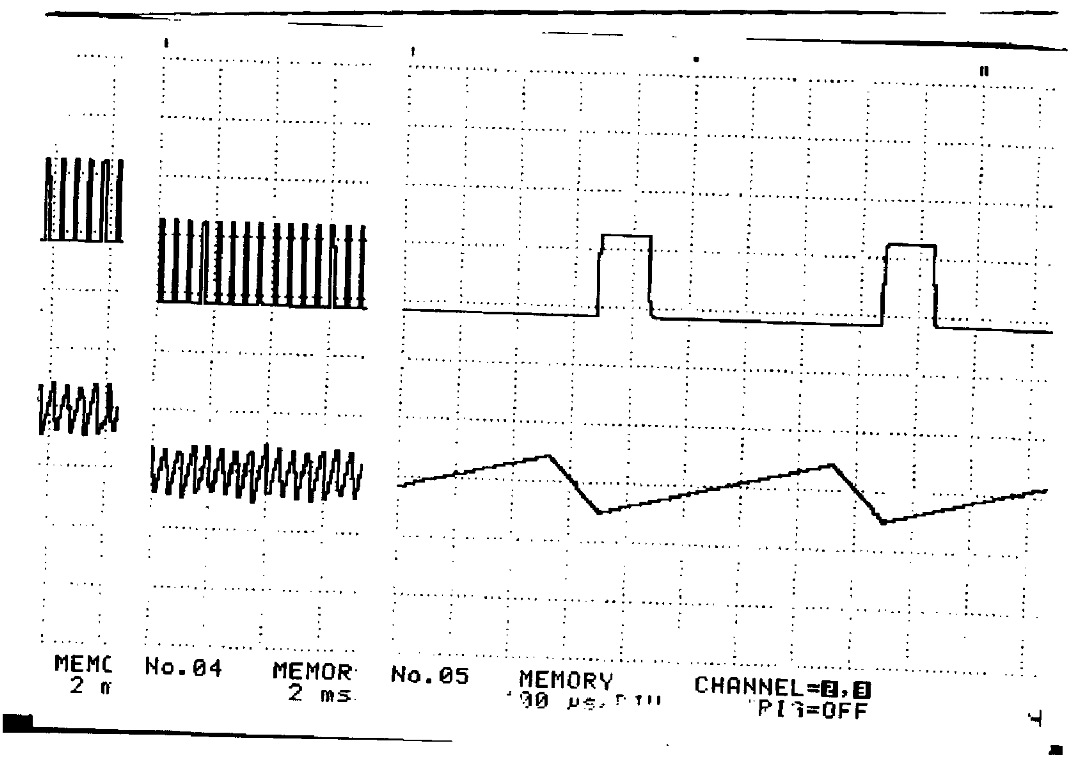


Fig5.8 Sawtooth wave and gate pulse

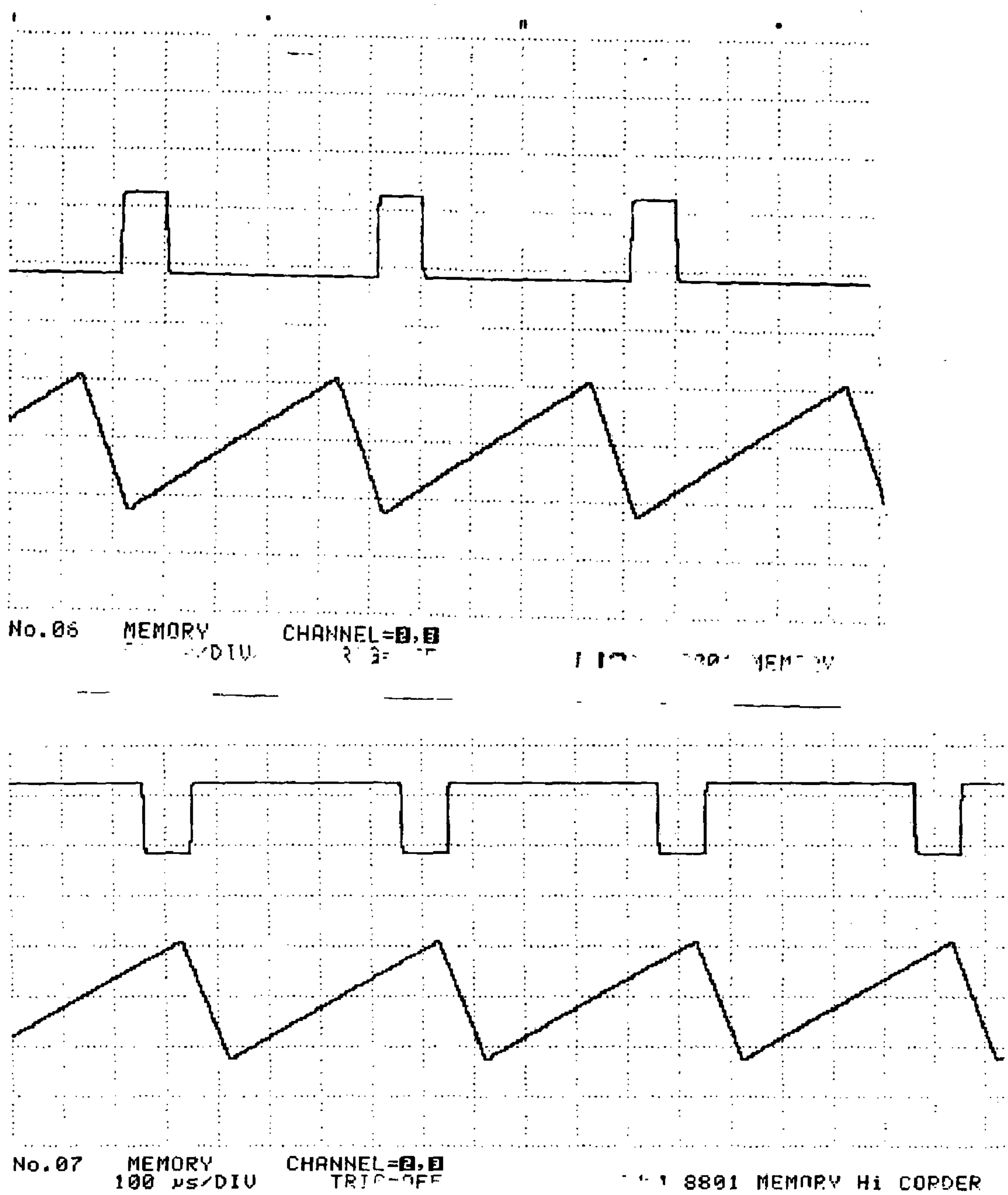


Fig5.9 The gate pulses due to change in reference voltage

5.3Circuit protection

5.3.1 Over voltage protection

A protective device called metal Oxide Varistor(MOV) is used across the device. It acts as aback-to-back zener and bypasses the transient over voltage across the device.

5.3.2 Overload protection

Due to the ohmic resistance of MOSFET and diode, I^2R losses occur when they conduct the load current. This results in heat generation, which raises the temperature of the power device. To keep the device temperature within the permissible limits, the devices are mounted on heat sinks. So the heat is conducted from device to the heat sink and then dissipated to the atmosphere. Heat sinks are made from metal with high thermal conductivity. Aluminum is the most commonly used metal.

5.3.3 Short circuit protection

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

5.3.4 Snubber circuit

IGBTs are increasingly used in power electronic application, because of lower conduction losses. Snubbers are needed to protect the switch from transients. Snubbers are circuits, which are placed across semiconductor devices for protection and to improve performance.

- It can reduce or eliminate voltage or current spikes.
- Limit high dV/dt.
- Shape the load line to keep it within the safe operating area.
- Reduce total losses due to switching.
- Reduce EMI by damping voltage and current ringing.

CONCLUSIONS AND SCOPE FOR FUTURE WORK

Conclusions

In this dissertation work the concept of self-excitation in induction machine is discussed. The dynamic state analysis of self-excited induction generator is done using d-q axis in stationary reference frame. The dynamic model can handle any capacitor and load combination while maintaining generalized nature of model. It is observed that for a fixed value of capacitance, the terminal voltage of the self-excited induction generator drops with its loading. In this work some of voltage regulation techniques are discussed in brief.

The STATCOM based voltage regulator for three-phase SEIG is modeled and simulated for resistive load. The STATCOM is connected in parallel with the fixed capacitor and provides additional VAR required at the given load and power factor. The developed mathematical model for SEIG-STATCOM system is able to improve the terminal voltage. The ELC with STATCOM is regulating the terminal voltage by trying to maintain the generated power.

A control circuit for Electronic Load Controller designed for Laboratory machine is developed and experiments were performed on the given machine-II. 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. In the power circuit, the IGBT switch, which is used as a chopper, could withstand the high voltage for a short period that was shortcoming for the experimentation.

Scope for future work

- The work can be extended to non-linear load like controlled rectifier type load.
- The work can be extended to study the load unbalancing.
- The hardware for STATCOM based voltage regulator can be developed.

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APPENDIX-A

Specifications of machine I: For the simulation the machine used is 7.5 KW, 230 V, 15.6 amps. No of poles =4, R_s=1;R_r=0.81;L_s=0.0031;L_r=L_s; J=0.1385;

Specifications of machine II : 7.5 KW, 440V , Delta connected, 15.6 Amp, R_s =2.1935,

R_r=2.159, L_s=0.01896242, L_s=L_r .

STATCOM Control parameters:

Lf=0.022H, Rf=0.5 Ohm, Cdc=2200 μ F

AC voltage PI controller: Kpa=0.2;Kis=0.2;

DC bus voltage PI controller Kpi=0.0990;Kid=0.025;

Power PI controller Kpp=0.2;Kip=0.041;

APPENDIX-B

B.1 PROGRAM FOR TRANSIENT ANALYSIS

```
*************SCRIPT FILE*************
clear all;
clc;
global count Tc Va Vb Vc Tc1 Ia Ib Ic Wr Te
count=1;
global Lmstore;
global Imstore;
global v;
% To model the SEIG
%Lm=0.1407+0.0014.*Im-0.0012.*Im.^2+0.00005.*Im.^3;
t0=0;tfinal=3.5;tspan=[t0 tfinal];y0=[0.8 0.6 0.5 0.31 0.02 0 0]';
 [t,y]=ode45('difereq',tspan,y0);
```

```
****************FUNCTION FILE***************
function yprime=difer(t,y);
global count Tc Va Vb Vc Tc1 Ia Ib Ic Wr Te
global Lmstore;
global Imstore;
Rs=1;Rr=0.81;Ls=0.0031;Lr=Ls;J=0.1385;P=4;
C=0.000120;
 if t==0,
    V=[2;2;2];
 end
 if t>0,
 V=0.816*[1 0;-0.5 0.86;-0.5 -0.86]*[y(5,:);y(6,:)];
end
if t==0,
    I=[0.1;0.1;0.1];
 end
 if t>0,
 I=0.816*[1 0;-0.5 0.86;-0.5 -0.86]*[y(1,:);y(2,:)];
end
if t<=4,
  Rl=100000;
end
if t>=4,
    Rl=25;
 end
 if t>=1.8,
    Rl=5;
 end
 if t>=2.9,
  C=0.000050;
 end
 if t>=3.8,
   Rl=50;
```

```
 end
 if t==0,
    Lm=.140;
    Im=0.1;
 end
 if t>0,
    Im=sqrt((y(1,:)+y(3,:))^2+(y(2,:)+y(4,:))^2);
  Lm=0.1407+0.0014*Im-0.0012*Im^2+0.000048*Im.^3;
end
Va(count)=V(1,:);
Vb(count)=V(2,:);
Vc(count)=V(3,:);
Tc(count)=t;
Ia(count)=I(1,:);
Ib(count)=I(2,:);
Ic(count)=I(3,:);
Tc1(count)=t;
Imstore(count)=Im;
Lmstore(count)=Lm;
Wr(count)=y(7,:);
Te(count)=(3*P/4)*(Lm)*((y(2,:)*y(3,:))-y(1,:)*y(4,:));
t
count=count+1;
R=[Rs 0 0 0;0 Rs 0 0;0 0 Rr 0;0 0 0 Rr];
G=[0 0 0 0;0 0 0 0;0 -Lm 0 -Lm-Lr;Lm 0 Lm+Lr 0];
L=[Ls+Lm 0 Lm 0;0 Ls+Lm 0 Lm;Lm 0 Lr+Lm 0;0 Lm 0 Lr+Lm];
yprime=[inv(L)*([y(5,:);y(6,:);0;0]-([R]*[y(1,:);y(2,:);y(3,:);y(4,:)])-
(y(7,:)*[G]*[y(1,:);y(2,:);y(3,:);y(4,:)]));...
        (-y(1,:)-(y(5,:)/Rl))/C;...
        (-y(2,:)-(y(6,:)/Rl))/C;...
        (P/2*J)*((3370-10*y(7,:))-((3*P/4)*(Lm)*((y(2,:)*y(3,:))-
y(1,:)*y(4,:))))];
```

B.2 PROGRAMME FOR STATCOM BASED ELC

```
*************SCRIPT FILE*************
clear all;
clc;
global count Tc1 Ia tda Ida tdb tri tri1 Idb Vp Iref Ia1 Pgen Vp ta1 Id Iq vdc Ids
Iqs Idr Iqr wr Va Vb Vern Ismq Ismd Vdcern Imstore Lmstore Vdcstore
count=1;
Ismq(count)=.1;Ismd(count)=0.3;
 t0=0;tfinal=1.8;
 tspan=[t0 tfinal];y0=[0.8 0.8 0.9 0.2 0.835 0.5 0.5 0 0 0 0]';
 [t,y]=ode45('ielcdifernew',tspan,y0);
```

****************FUNCTION FILE***************

```
function yprime=difer(t,y);
% Machine parameters
global count Tc1 Ia Ida tda tdb Idb tri tri1 Ial Id Iq Vp tal Iref vdc Ids Iqs Idr Iqr Pgen
wr Va Vb Vern Ismq Vp Ismd Vdcern Imstore Lmstore Vdcstore
Rs=1;Rr=0.81;Ls=0.0031;Lr=Ls;J=0.1385;P=4;Kpa=0.2;Kis=0.2;Kpi=0.0990;Kid=0.
025;Kpp=0.2;Kip=0.041;
%parameter of statcom
Lf=0.0220;Cdc=0.002200;
C=0.000125;Rd1=57000;Rd=40;
Vtref=250;Vdcref=310;HB=1.50;Pref=6010;
if t<=0.7,
   Rl=90000;
end
if t>0.7,
   Rl=24;
end
if t>=1.6,
   Rl=50;
end
if t<=0.05,
Rf=8.9;
end
if t>0.05 & t<0.07,
   Rf=0.4;
end
if t>=0.07,
   Rf=0.5;
end
%t
%data for calculation;
if t==0,
   I=[0.6;0.1;0.7];
end
if t>0,
I=0.81649*[1 0;-0.5 0.866;-0.5 -0.866]*[y(1,:);y(2,:)];
end
```

```
Ia(count)=I(1,:);
Ib(count)=I(2,:);
Ic(count)=I(3,:);
Tc1(count)=t;
ia=I(1,:);
ib=I(2,:);
ic=I(3,:);
if t==0,
   Lm=0.1409;
   Im=0.1;
 end
 if t>0,
   Im=sqrt((y(1,:)+y(3,:))^2+(y(2,:)+y(4,:))^2);
  Lm=0.1407+0.0015*Im-0.00126*(Im^2)+0.000055*(Im^3);
  % Lm=0.1347+0.0015*Im-0.00016*(Im^2)+0.000048*(Im^3);
end
Id(count)=y(1,:)+y(3,:);
Iq(count)=y(2,:)+y(4,:);
Lmstore(count)=Lm;
Imstore(count)=Im;
if t==0,
  Vab=.1;
  Vbc=.1;
  Vca=.1;
Vba=-Vab;Vcb=-Vbc;Vac=-Vca;
  Vds=0.1;
  Vqs=0.1;
end
 if t>=0,
Va=y(5,:);
Vb=y(6,:);
Vc=-Va-Vb;
Vds=1.22*Va;
Vqs=((0.5*Va)+Vb)*1.4142;
Vca=y(5,:);
Vab=y(6,:);
Vbc=-Vab-Vca;
```

```
Vba=-Vab;Vcb=-Vbc;Vac=-Vca;
% Power calculation
Valpha=0.816*(Va-Vb/2-Vc/2);
Vbita=0.816*(0.8660*Vb-1.732*Vc);
Ialpha=0.816*(ia-ib/2-ic/2);
Ibita=0.816*(0.8660*ib-1.732*ic);
Pg=Valpha*Ialpha+Vbita*Ibita;
end
if t==0,
   Vm=0;
   ida=0;
   idc=0;
end
if t>0 & t<=0.9
   Vl=[Vab Vbc Vca Vba Vcb Vac];
   Vm=max(Vl);
end
if t>0 & t<=0.9
if Vm==Vac,
  ida=y(8,:);
  idc=-y(8,:);
end
if Vm==Vbc,
   ida=0;
  idc=-y(8,:);
end
if Vm==Vca,
  ida=-y(8,:);
 idc=y(8,:);
end
if Vm==Vba,
  idc=0;
   ida=-y(8,:);
end
if Vm==Vcb,
   idc=y(8,:);
   ida=0;
```

```
end
if Vm==Vab,
  ida=y(8,:);
  idc=0;
end
end
Ial(count)=(Vab-Vca)/Rl;
tal(count)=t;
R=[Rs 0 0 0;0 Rs 0 0;0 0 Rr 0;0 0 0 Rr];
G=[0 0 0 0;0 0 0 0;0 -Lm 0 -Lm-Lr;Lm 0 Lm+Lr 0];
L=[Ls+Lm 0 Lm 0;0 Ls+Lm 0 Lm;Lm 0 Lr+Lm 0;0 Lm 0 Lr+Lm];
if t==0,
   Vt=0.8;ua=0;ub=0;uc=0;
end
if t>0,
Vt=(2/3*(Va^2+Vb^2+Vc^2))^0.5;
ua=Va/Vt;ub=Vb/Vt;uc=Vc/Vt;
end
Pgen(count)=Pg;
Vt(count)=Vt;
Vern(count)=Vtref-Vt(count);
Vdc=y(9,:);
Vdcs(count)=Vdc;
Vdcern(count)=Vdcref-Vdcs(count);
Per(count)=Pref-Pgen(count);
wa=-ub/1.732+uc/1.732;
wb=0.866*ua+(ub-uc)/(2*1.732);
wc=-0.866*ua+(ub-uc)/(2*1.732);
if t<=0.9,
  Ismq(count)=0;Ismd(count)=0;Vp(count)=0;
end
if t>=0.9,
    Ismq(count)=Ismq(count-1)+Kpa*(Vern(count)-Vern(count-1))+Kis*Vern(count);
    Vp(count)=Vp(count-1)+Kpp*(Per(count)-Per(count-1))+Kip*Per(count);
end
if Ismq(count)<-16,
  Ismq(count)=-16;
```

```
end
if Ismq(count)>16,
  Ismq(count)=15;
end
if Vp(count)>16,
 Vp(count)=16;
end
if Vp(count)<-16,
 Vp(count)=-16;
end
Isaq=Ismq*wa;Isbq=Ismq*wb;Iscq=Ismq*wc;
 if t>=0.9,
Ismd(count)=Ismd(count-1)+Kpi*(Vdcern(count)-Vdcern(count-
1))+Kid*Vdcern(count);
end

if Ismd(count)>16,
  Ismd(count)=16;
end
if Ismd(count)<-16,
  Ismd(count)=-16;
end
% for triangular wave
pi=3.141;
w=2*pi*200;
vst=(8*15/(pi*pi))*(sin(w*(t-0.9))-1/9*sin(3*w*(t-0.9))+1/25*sin(5*w*(t-0.9))-
1/49*sin(7*w*(t-0.9)));
tri(count)=vst;
% for triangular wave1
pi=3.141;
w1=2*pi*200;
vst1=(8*1/(pi*pi))*(sin(w1*(t-0.9))-1/9*sin(3*w1*(t-0.9))+1/25*sin(5*w1*(t-0.9))-
1/49*sin(7*w1*(t-0.9)));
tri1(count)=vst1;
Isad=Ismd*ua;Isbd=Ismd*ub;Iscd=Ismd*uc;
Isas=I(1,:)-I(2,:);
Isbs=I(2,:)-I(3,:);
```

```
Iscs=I(3,:)-I(1,:);
Isa=Isaq+Isad;
Isb=Isbq+Isbd;Isc=Iscq+Iscd;
Isaerr=(Isa(count)-Isas);
Iref(count)=Isaerr;
Isberr=(Isb(count)-Isbs);
Iscerr=(Isc(count)-Iscs);

if t>=0,
   if Vp(count)/18>vst1,
      SD=0;
   else SD=1;
   end
if Isaerr/2.5>vst,
   SA=0;
else SA=1;
end
if Isberr/2.5>vst,
  SB=0;
else SB=1;
end
if Iscerr/2.5>vst,
  SC=0;
else SC=1;
end
end
count=count+1;
t
if t<=0.9,
yprime=[inv(L)*([Vds;Vqs;0;0]-([R]*[y(1,:);y(2,:);y(3,:);y(4,:)])-
(y(7,:)*[G]*[y(1,:);y(2,:);y(3,:);y(4,:)]));...
      ((ic-ia-(((Vca-(-Vab-Vca))/Rl)+idc)-(ia-ib-(((Vab-Vca)/Rl)+ida))))/(3*C);...
     ((ic-ia-(((Vca-(-Vab-Vca))/Rl)+idc))+(2*(ia-ib-(((Vab-Vca)/Rl)+ida))))/(3*C);...
      (P/(2*J))*((3370-10*y(7,:))-((3*P/4)*Lm*(y(2,:)*y(3,:)-y(1,:)*y(4,:))));....
     (Vm-y(9,:)-2*Rf*y(8,:))/(2*Lf);...
     (y(8,:)-(y(9,:)/Rd1))/Cdc;...
     0;...
```

```
    0];

end
if t>=0.9,
 Va=y(5,:);
Vb=y(6,:);
Vc=-Va-Vb;
Vds=1.22*Va;
Vqs=((0.5*Va)+Vb)*1.4142;
if t>=0.9,
Vt=(2/3*(Va^2+Vb^2+Vc^2))^0.5;
ua=Va/Vt;ub=Vb/Vt;uc=Vc/Vt;
end
Vdcstore(count)=Vdc;
Tc(count)=t;
%t
 yprime=[inv(L)*([Vds;Vqs;0;0]-([R]*[y(1,:);y(2,:);y(3,:);y(4,:)])-
(y(7,:)*[G]*[y(1,:);y(2,:); y(3,:);y(4,:)]));...
    ((ic-ia-(((Vca-(-Vab-Vca))/Rl)+(-y(10,:)-y(11,:)))-(ia-ib-(((Vab-
Vca)/Rl)+y(10,:))))) /(3*C);...
   ((ic-ia-(((Vca-(-Vab-Vca))/Rl)+(-y(10,:)-y(11,:))))+(2*(ia-ib-(((Vab-
Vca)/Rl)+y(10,:))))) /(3*C);...
    (P/2)*((3370-10*y(7,:))-((3*P/4)*(Lm)*(y(2,:)*y(3,:))-y(1,:)*y(4,:))/J);...
0;...
    (SA*y(10,:)+SB*y(11,:)+SC*(-y(10,:)-y(11,:))-SD*y(9,:)/Rd)/Cdc;...
   ((y(6,:)-(SB-SC)*y(9,:))+2*(y(5,:)-(SA-SB)*y(9,:))-3*Rf*y(10,:))/(3*Lf);...
   ((y(6,:)-(SB-SC)*y(9,:))-(y(5,:)-(SA-SB)*y(9,:))-3*Rf*y(10,:))/(3*Lf)];
end
```