# MODELING AND SIMULATION OF SELF - EXCITED INDUCTION GENERATOR WITH VOLTAGE REGULATOR

## 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

**SHANTHI SWAROOP DONTHU**



DEPARTMENT OF ELECTRICAL ENGINEERING
DIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE -247 667 (INDIA)

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# CANDIDATE'S DECLARATION

I hereby declare that work which is being presented in this dissertation entitled **"Modeling and Simulation of Self-Excited Induction Generator with Voltage Regulator"** in partial fulfillment of the requirement for the award of degree of Master of Technology with specialization in **Power Apparatus and Electric Drives**, submitted in the department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my work under supervision of **Dr. S. P. Srivatava,** Associate Professor & **Dr. Pramod Agarwal,** Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee.

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

**Date: June**

29/06/06

**Place: Roorkee** **(SHANTHI SWAROOP DONTHU)**

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


**(Dr. S. P. SRIVATAVA)**
**Associate Professor**
Department of Electrical Engg.
Indian Institute of Technology
Roorkee, Roorkee-247667
(India)

**(Dr. PRAMOD AGARWAL)**
**Professor**
Department of Electrical Engg.
Indian Institute of Technology
Roorkee, Roorkee-247667
(India)

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**(D.SHANTHI SWAROOP)**

**Date:**

**Place:**

# ABSTRACT


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 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 indeed in 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.

This dissertation work proposes a static compensator based technique in order to provide balanced reactive power operation for the induction generator with the load connected at the stator terminal of the IG. The proposed controller by using current-controlled voltage source inverter (CC-VSI) regulates the IG terminal voltage against changing load conditions. The scheme doesn't require computations and information regarding rotor speed for calculating the excitation current, there by minimizing the cost of the controller. A simulation model is developed in MATLAB/SIMULINK simulator software to know the performance of the proposed system. This dissertation work carried out with the analysis and performance of SEIG with Current-Controlled Voltage Source Inverter.

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# LIST OF SYMBOLS

Symbols used in this text are defined at appropriate places. However for easy reference the principal symbols are listed here.

| | |
|---|---|
| SEIG | Self-Excited Induction Generator |
| MMF | Magneto Motive Force |
| $f_s$ | Synchronous Frequency |
| Vg | Air-gap Voltage |
| $V_{abcs}$ | Stator Voltages |
| $I_{abcs}$ | Stator Currents |
| $V_{abcr}$ | Rotor Voltages |
| $I_{abcr}$ | Rotor Currents |
| $R_s$ | Stator Resistance |
| $R_r$ | Rotor Resistance |
| $L_s$ | Stator Leakage Inductances |
| $L_r$ | Rotor Leakage Inductances |
| $X_{odqs}$ | Stator Variables |
| $X_{odqr}$ | Rotor Variables |
| X | Flux Linkages, Voltages or Currents |
| . | Angle Between d-axis and q-axis of Stator |
| $[K_s]$ | Constant For abc-axis to dqo-axis transformation for Stator Variables |
| $[K_r]$ | Constant For abc-axis to dqo-axis transformation for Rotor Variables |
| p | Derivative Operator |
| $._r$ | Rotor Speed |
| $L_m$ | Mutual Inductance |
| C | Excitation Capacitance per Phase |
| $R_f$ | Filter Resistance |
| $L_f$ | Filter Inductance |
| Te | Electromagnetic Torque |
| P | Number of Poles |
| Ic | Compensating Currents |
| \|Vs\| | Magnitude of Terminal Voltage |
| CC-VSI | Current Controlled Voltage Source Inverter |

| | |
|---|---|
| HCC | Hysteresis Current Controller |
| PWM | Pulse Width Modulation |
| $C_{dc}$ | DC side Capacitance of Inverter |
| $V_{dc}$ | DC side Capacitor Voltage |
| E | Counter EMF |

Chapter 1

# INTRODUCTION

## 1.1 INTRODUCTION

### BASIC CONCEPT

The Self-Excited Induction Generators (SEIGs) are receiving increased attention from the utilities over the world to obtain the energy from renewable/non-conventional sources for remote and isolated areas. The main problems in the use of induction machine as a generator are related to the varying voltage and frequency, the loss of self-excitation, the overloading of the machine, the transient over voltages due to the capacitance switching or the load loss. But, the robust construction of induction machine specially squirrel cage type rotor, offers maintenance free operation and the least cost of the generating system. This has motivated to facilitate the use of the induction generator in isolated mode with suitable low cost control which could ensure the reliable supply of good quality. Also, such system for power generation could be made efficient and cost effective to compete with the other conventional sources of energy.

### GENERAL

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.

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 windings 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 and can be used to generate the power from constant as well as variable speed prime movers. In case of the short circuit or the over loading, the induction generator may loose its voltage and the residual magnetism of the machine may be lost. This will prevent the machine from again building up of the voltage. The residual magnetism in the machine has to be restored for the voltage buildup. The few methods for the revival of the residual magnetism are, by running the machine as a motor with the existing supply, discharging a charged capacitor through the stator windings while the machine is under operating and connecting a 12 volt battery across the machine terminals for few minutes.

In case of the small power plants the cost of the electromechanical equipment can be reduced drastically by the use of such generators as they are expensive and the use of the governors and the emergency shutdown devices could be dispensed with. The voltage and the frequency of such generators very with the load, speed and the capacitor connected across the machine terminals. Such generators could be used in practice only if they are able to generate the supply of constant voltage and constant frequency under varying loads. With the recent development in the area of power and digital electronics it is quite possible to obtain the output supply from the SEIGs of the desired quality with the suitable control.

An induction generation is ideally suited for use in small and medium power plants to hardness the locally available resources in order to feed the power to isolated areas or the areas connected to common grid. The induction generator can be driven by the hydro turbines like the water wheels or small hydro turbines operated by the velocity heads in the rivers and canals, the ultra low heads on the canal falls, small hydro heads on these streams in the hills and the head created by the tidal waves. Also, the induction generator can be used to generate the power from other different types prime movers like petrol run and petrol start and kerosene run engines, the diesel engines, the wind mills, the gas turbine driven by the bio, the industrial waste, the LPG gases and the steam turbines operated by the low grade coal and the waste heat released from the chemical industries.

An induction generator can be used as an isolated source of supply and may be used as a stand by supply in hospital, the libraries, cinema hall, auditorium etc. Also the induction generators can be used as a source of the power generation in the remote and the isolated places for the lighting and heating loads etc.

In most of the applications, the supply with constant voltage is required. To cope with the situation of a varying load and speed, the terminal voltage of the SEIG could be maintained at the desired level with a controlled reactive power source. The static VAR compensator can provide a continuously varying reactive power under the varying load and speed on the generator..

In addition to above applications, the induction generator can also be operated in parallel with a synchronous generator or a synchronous condenser of a comparable capacity. During parallel operation, synchronism is not required and the generator need not be operated at a common synchronous speed. Moreover, due to the absence of the synchronous torque the problem of hunting could also be avoided. Normally both the cage and the wound rotor induction generators could be used with the variable speed prime movers to feed the generated power to the grid or isolated loads using different control schemes depending upon cost, simplicity, reliability and ratings. However, the wound rotor induction generator could be operated to generate the power at a speed above and below the synchronous speed.

The squirrel cage induction generators have been preferred in comparison with the synchronous generators for small scale power generation due to their low cost, robust construction and ease of maintenance. The induction generators do not require separate dc exciter and its related equipment like field breaker, automatic voltage regulator etc. therefore, such generators need minimal maintenance. The cage induction generators can be driven at a run away speed relatively for a longer duration than the other type of generators (such as the synchronous or the dc generator) because of the absence of the field windings on the rotor and its cage construction. In case of the short circuit across the machine terminals, the sustained transients are not generated due to the absence of field. The other advantage of the cage induction generators such as the absence of the slip ring, the commutator brushes, the battery packs and the inverter are well known.

However, in spite of the several advantages, the conventional induction motor used as the induction generator has various disadvantages such as poor inherent voltage and frequency regulation and moderate efficiency. To overcome poor voltage regulation of SEIG a number of schemes have been proposed. The scheme based on switched capacitor [1] finds limited application because it regulates the terminal voltage in discrete steps. In recent years, the inverter based reactive power sources have been used for regulating the AC output voltage profile of a SEIG under balanced three-phase loading conditions.

**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 with out any problem of synchronization i.e. they may operate at different speed and still share load.

**Disadvantages of self-excited induction generator:**

- 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.

**Application of Self-Excited Induction Generator:**

Main application of SEIG is in the remote areas where non conventional energy sources as wind, small water falls etc. are available to fulfill the power requirement for agriculture and domestic purpose as heating and lighting requirements economically.

SEIGs can be used for battery charging even if the input torque to induction machine is of varying nature by connecting chopper circuit through an un-controlled rectifier. It has been seen that constant DC output voltage is achieved by using above system and so can be used for the purpose in remote zones.

**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.

**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.

**STATEMENT OF PROBLEM**

1. To model the induction machine in generating mode.
2. To study the behavior of SEIG during voltage buildup and load changing.
3. To simulate Current-controlled voltage source inverter based voltage regulator for SEIG.
4. To analyze the experimental results of a given induction generator and to develop hardware of current-controlled voltage source inverter for self-excited induction generator.

## 1.2 LITERATURE SURVEY

### 1.2.1 HISTORICAL DEVELOPMENT OF SEIG

It is well known that if an induction machine is rotating at super-synchronous speed and its magnetizing current is supplied from the line or any other source of ac power, the machine behaves as an asynchronous generator. It could also be shown that the active component of current reverses the direction as the machine change it's mode of operation from motoring to generating or vice-versa. But, the magnetizing current component of the machine maintains its direction from the external source. However, such generators didn't find much application earlier as it requires to draw lagging current for its magnetizing either from grid or synchronous generator or synchronous condenser of comparable capacity.

It was realized in back twenties that a rotating induction machine may remains excited even if line voltage was removed and sufficient amount of capacitance was connected at the machine terminals while the rotation of the machine was maintained by an external mechanical prime mover. This phenomenon of the voltage buildup with capacitance is also known as self-excitation. The generated voltage was dependent on the speed and magnitude and power factor of the load. At the time the phenomenon of self-excitation was considered to be undesirable as it caused severe over voltages and could be dangerous to the machine windings and the capacitors. The major drawback of the SEIG was that its frequency and voltage drops with load and has moderate efficiency in addition to poor voltage and frequency regulation. Therefore due to above problems much attention was not given by the utilities for the use of SEIGs.

In the recent years, due to increasing cost of conventional energy, the research in the field of the non-conventional energy has been intensified. This situation has lead to revaluation of known sources of energy for commercial exploitation. As a result, the induction generator is getting much attention for its use with non-conventional sources of energy. Moreover, with the enormous development in the field of power and digital electronics, it is possible to design a low cost static VAR source which could make the SEIG as low cost stand alone generating system as a viable concept of providing electric supply of prescribed specification. Therefore the SEIG has become possible source of low cost power generation from renewable or non-conventional energy systems comprising of small hydro, wind, biogas and tidal waves, waste energy released from process industries for co-generation and others. In the recent past a considerable number of investigations have been made on the analysis, operation and control of the SEIG for its suitability in different applications.

### 1.2.2 LITERATURE REVIEW ON THE SEIG

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 generator 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/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 1953, 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 conclude that the induction machine with capacitive excitation would buildup its voltage exactly as does a dc shunt generator, the final valve being determined by the saturation curve of the machine and by the valve 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 behavior of a three phase SEIG supplying a symmetrical load. They presented an approach to model the saturation effect from the steady-state stand point. 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 requirement 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. [6] emphasized the importance of cross saturation during 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 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. [8] published a paper regarding the design of 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 [9] provided a purely experimental treatment of the self-excitation process in induction generators. S.P.Singh et al [10] 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. S.C.Kuo and L.Wang [11] discussed that it is convenient to simulate the power electronics 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 electronics devices are combined and must be solved by an equation solver, the power electronic circuit is to be derived to properly combined with the machines dynamic equations.

Sridher et al [12] analyzed the system consisting shunt and series capacitance and developed a method to choose appropriate set of valves of capacitors of desired voltage regulation. Li wang and Jian-yi su [13] 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 conditions.

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 [14] presented a PWM voltage source inverter to improve the electrical characteristics 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 Chatarjee [15] 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. [16] 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 [17] analysed 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 of the three phase SEIG with variable loads can be maintained constant by adjusting the valve 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. [18] 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 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. [19] 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. [20] designed the optimum values of different components of STATCOM for different rating machines. Leidhold et al. [21] proposed a control strategy based on instantaneous reactive power theory. The principle is based on power invariant Park's transformation.

N.P.A.Smith [22] 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 [23] 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 SEIG sees two balanced three phase loads in parallel and that the total power is constant.

In induction generators unbalanced reactive power operation results in voltage variations. This work proposes a static compensator based technique in order to balance the reactive power operation intern for maintaining constant voltage from no load to full load. CC-VSI balances the reactive power requirements of induction generator. The proposed control scheme regulates the IG terminal voltage against changing load conditions. The scheme does not require computations and information regarding rotor speed for calculating the excitation current, thereby minimizing the cost of the controller.

## 1.3 ORGANISATION OF THESIS

This consists of several chapters. These are

1. **Chapter-1:** First chapter contains the introductory part of the SEIG with the advantages and disadvantages of SEIG with its applications.
2. **Chapter-2:** This chapter contains the modeling and analysis of SEIG. In this basically the SEIG is simulated in different conditions of excitation capacitors and loads and the performances are observed.
3. **Chapter-3:** In this chapter the Current Controlled Voltage Source Inverter (CC-VSI) is modeled and simulated in two conditions of reference signals. In first condition the reference signals are balanced while in the second case unbalanced reference signals are used.
4. **Chapter-4:** The proposed voltage regulation technique for SEIG by using current controlled voltage source inverter is discussed and the performances are observed.
5. **Chapter-5:** In this final chapter the conclusions are made depending upon the various observations taken in chapter-2, 3 and 4.

Finally the references and appendixes are made.

# SELF-EXCITED INDUCTION GENERATOR MODELLING & ANALYSYS

The Self-Excited Induction Generators (SEIGs) are receiving increased attention from the utilities over the world to obtain the energy from renewable/non-conventional sources for remote and isolated areas. The main problems in the use of induction machine as a generator are related to the varying voltage and frequency, the loss of self-excitation, the overloading of the machine, the transient over voltages due to the capacitance switching or the load loss. But, the robust construction of induction machine specially squirrel cage type rotor, offers maintenance free operation and the least cost of the generating system. This has motivated to facilitate the use of the induction generator in isolated mode with suitable low cost control which could ensure the reliable supply of good quality. Also, such system for power generation could be made efficient and cost effective to compete with the other conventional sources of energy.

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.

## 2.1 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.

## 2.2 Voltage Control of SEIG Using CC-VSI

This technique proposes a static compensator based technique in order to provide excitation for the induction generator with the load connected at the stator terminals of the IG. CC-VSI inverter provides the excitation current. The proposed controller regulates the induction generator terminal voltage against varying rotor speed and changing load conditions. This scheme doesn't require computation and information regarding rotor speed for calculating the excitation current, there by minimizing the cost of the controller. The schematic of the system is shown in Fig 2.1.

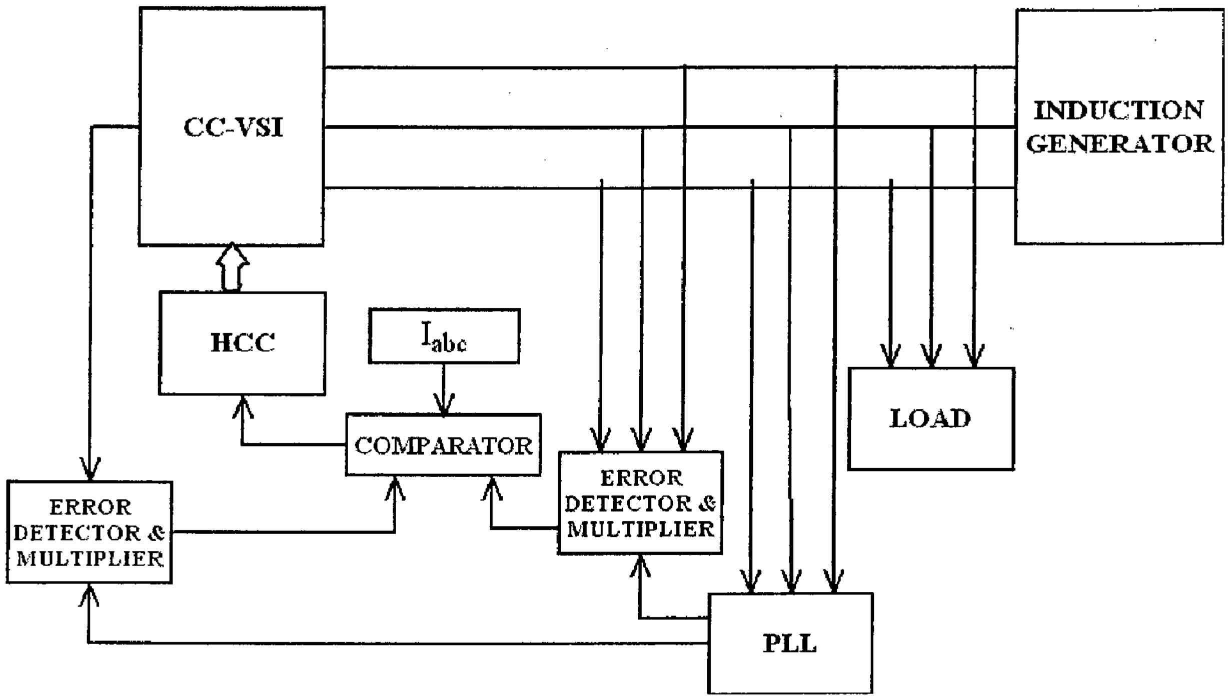



**Figure 2.1 Overall System Block Diagram**

## 2.3 Modeling of SEIG

In the analysis of SEIG, the following assumptions are made [25]:

- Only magnetizing reactance is assumed to be affected by magnetic saturation, all other parameters of the machine are assumed to be constant.
- Leakage reactance of stator and rotor, are taken to be equal.
- MMF space harmonics and time harmonics in the induced voltage and current waves are ignored.
- Core losses in the machine are neglected.

With these assumptions the induction machine can be modeled in stationary d-q axis reference frame, whose voltage and flux equations are given by [25]

$$[V_{abcs}] = [R_s][I_{abcs}] + p[F_{abcs}] \tag{1}$$

$$[V_{abcr}] = [R_r][I_{abcr}] + p[F_{abcr}] \tag{2}$$

$$[F_{abcs}] = [L_s][I_{abcs}] + [L_{sr}][I_{abcr}] \tag{3}$$

$$[F_{abcr}] = [L_{sr}]^T [I_{abcs}] + [L_r][I_{abcr}] \tag{4}$$

Where-

$[V_{abcs}] = [V_{as} \quad V_{bs} \quad V_{cs}]^T$ (Stator Voltages)

$[I_{abcs}] = [I_{as} \quad I_{bs} \quad I_{cs}]^T$ (Stator currents)

$[F_{abcs}] = [F_{as} \quad F_{bs} \quad F_{cs}]^T$ (Stator Flux Linkages)

$[V_{abcr}] = [V_{ar} \quad V_{br} \quad V_{cr}]^T$ (Rotor Voltages)

$[I_{abcr}] = [I_{ar} \quad I_{br} \quad I_{cr}]^T$ (Rotor Currents)

$[F_{abcr}] = [F_{ar} \quad F_{br} \quad F_{cr}]^T$ (Rotor Flux Linkages)

$$[Rs] \equiv \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0\ 0 \\ 0 & 0 & Rs \end{bmatrix} \qquad [Rr] \equiv \begin{bmatrix} Rr & 0 & 0 \\ 0 & Rr & 0\ 0 \\ 0 & 0 & Rr \end{bmatrix}$$

$$[L_s] \equiv \begin{bmatrix} (L_{ls} + L_{ms}) & -L_{ms}/2 & -L_{ms}/2 \\ -L_{ms}/2 & (L_{ls} + L_{ms}) & -L_{ms}/2 \\ -L_{ms}/2 & -L_{ms}/2 & (L_{ls} + L_{ms}) \end{bmatrix}$$

$$[L_r] \equiv \begin{bmatrix} (L_{lr}+L_{mr}) & -L_{mr}/2 & -L_{mr}/2 \\ -L_{mr}/2 & (L_{lr}+L_{mr}) & -L_{mr}/2 \\ -L_{mr}/2 & -L_{mr}/2 & (L_{lr}+L_{mr}) \end{bmatrix}$$

$$[L_{sr}] \equiv L_{sr}\begin{bmatrix} \cos\theta r & \cos(\theta r+120) & \cos(\theta r-120) \\ \cos(\theta r-120) & \cos\theta r & \cos(\theta r+120) \\ \cos(\theta r+120) & \cos(\theta r-120) & \cos\theta r \end{bmatrix}$$

Now by transforming a-b-c variables into d-q variables:

$[X_{odqs}] = [K_s][X_{abcs}]$ ( For stator variables)

$[X_{odqr}] = [K_r][X_{abcr}]$ ( For rotor variables)

Where 'X' may be voltage, current or flux

$[X_{odqs}] = [X_{os}\ X_{ds}\ X_{qs}]^T$ and $[X_{abcs}] = [X_{as}\ X_{bs}\ X_{cs}]^T$

$$[K_s] = (2/3)\begin{bmatrix} 1/2 & 1/2 & 1/2 \\ \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \end{bmatrix}$$

$$[K_r] = (2/3)\begin{bmatrix} 1/2 & 1/2 & 1/2 \\ \cos\partial & \cos(\partial-120) & \cos(\partial+120) \\ \sin\partial & \sin(\partial-120) & \sin(\partial+120) \end{bmatrix}$$

Where 'θ' and '$\partial$' are the angles between d-axis and q-axis of stator and rotor respectively.

$$[K_s]^{-1} = \begin{bmatrix} 1 & \cos\theta & \sin\theta \\ 1 & \cos(\theta-120) & \sin(\theta-120) \\ 1 & \cos(\theta+120) & \sin(\theta+120) \end{bmatrix}$$

$$[K_r]^{-1} = \begin{bmatrix} 1 & \cos\partial & \sin\partial \\ 1 & \cos(\partial-120) & \sin(\partial-120) \\ 1 & \cos(\partial+120) & \sin(\partial+120) \end{bmatrix}$$

Now changing the a-b-c voltages into d-q voltages:

$[K_s][V_{odqs}] = [R_s][K_s][I_{odqs}]+p\{[K_s][F_{odqs}]\}$

$[K_r][V_{odqr}] = [R_r][K_r][I_{odqr}]+p\{[Kr][F_{odqr}]\}$

OR

$[V_{odqs}] = [R_s][I_{odqs}]+p[F_{odqs}]+[F_{odqs}]p[K_s][K_s]^{-1}$

$[V_{odqr}] = [R_r][I_{odqr}]+p[F_{odqr}]+[F_{odqr}]p[Kr][K_r]^{-1}$

By calculation we get that:

$$p[K_s][K_s]^{-1} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & p\theta \\ 0 & -p\theta & 0 \end{bmatrix}$$

$$p[K_r][K_r]^{-1} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & p\partial \\ 0 & -p\partial & 0 \end{bmatrix}$$

$$[K_s]^{-1}[L_s][K_s] = \begin{bmatrix} L_{ls} & 0 & 0 \\ 0 & L_{ls}+L_{lm} & 0 \\ 0 & 0 & L_{ls}+L_{lm} \end{bmatrix}$$

$$[K_s]^{-1}[L_{sr}][K_r] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & L_m \end{bmatrix}$$

$$[K_r]^{-1}[L_{sr}][K_s] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & L_m \end{bmatrix}$$

$$[K_r]^{-1}[L_r][K_r] = \begin{bmatrix} L_{lr} & 0 & 0 \\ 0 & L_{lr}+L_m & 0 \\ 0 & 0 & L_{lr}+L_m \end{bmatrix}$$

Where $L_m = (3/2)L_{ms}$

Putting the values:

$$\begin{bmatrix} F_{os} \\ F_{ds} \\ F_{qs} \end{bmatrix} = \begin{bmatrix} L_{ls} & 0 & 0 \\ 0 & L_{ls}+L_m & 0 \\ 0 & 0 & L_{ls}+L_m \end{bmatrix} \begin{bmatrix} I_{os} \\ I_{ds} \\ I_{qs} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & L_m \end{bmatrix} \begin{bmatrix} I_{or} \\ I_{dr} \\ I_{qr} \end{bmatrix}$$

$$\begin{bmatrix} F_{or} \\ F_{dr} \\ F_{qr} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & L_m \end{bmatrix} \begin{bmatrix} I_{os} \\ I_{ds} \\ I_{qs} \end{bmatrix} + \begin{bmatrix} L_{lr} & 0 & 0 \\ 0 & L_{lr}+L_{lm} & 0 \\ 0 & 0 & L_{lr}+L_m \end{bmatrix} \begin{bmatrix} I_{or} \\ I_{dr} \\ I_{qr} \end{bmatrix}$$

i.e.

$F_{os} = L_{ls}I_{os}$

$F_{ds} = (L_{ls}+L_m)\ I_{ds}+L_mI_{dr}$

$F_{qs} = (L_{ls}+L_m)\ I_{qs}+L_mI_{qr}$

And

$F_{or} = L_{lr}I_{or}$

$F_{dr} = L_mI_{ds} + (L_{lr}+L_m)\ I_{dr}$

$F_{qr} = L_mI_{qs} + (L_{lr}+L_m)\ I_{qr}$

$[V] = [R][I]+[L]p[I]+\omega_r[G][I]$

$$[V] = \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} \qquad [I] = \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix}$$

$$[R_s] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & R_s \end{bmatrix}$$

$$[L] = \begin{bmatrix} (L_{ls}+L_m) & 0 & L_m & 0 \\ 0 & (L_{ls}+L_m) & 0 & L_m \\ L_m & 0 & (L_{lr}+L_m) & 0 \\ 0 & L_m & 0 & (L_{lr}+L_m) \end{bmatrix}$$

$$[G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_m & 0 & -(L_{lr}+L_m) \\ L_m & 0 & (L_{lr}+L_m) & 0 \end{bmatrix}$$

These equations need some modifications so as to make it suitable for the analysis of saturated induction machine incorporating cross saturation effect, since the saturation affects the magnetization characteristics. For this

$I_{md} = I_{ds}+I_{dr}$ and $I_{mq} = I_{qs}+I_{qr}$

$L_{md} = L_m+L_{dq}(I_{md}/I_{mq})$ and $I_{mq} = L_m+L_{dq}(I_{mq}/I_{md})$

The self inductances of stator and rotor in d-q axis are-

$L_{ds} = L_{ls}+L_{md}$ and $L_{qs} = L_{ls}+L_{mq}$

$L_{dr} = L_{lr}+L_{md}$ and $L_{qr} = L_{lr}+L_{mq}$

Duo to saturation-

$L_{ds} \neq L_{qs}$ and $L_{dr} \neq L_{qr}$

The electromagnetic torque in N-m is

$T_e = (P/2)[I_{abcs}]^T(d/d\theta r)[L_{sr}][I_{abcr}]$

Where P is the number of poles.

OR

$T_e = (3P/4)L_m(I_{dr}I_{qs}-I_{qr}I_{ds})$

## 2.4 Modeling of Self-Exciting Capacitor Bank

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.

$$[Qc] = \begin{bmatrix} Q_{dc} \\ Q_{qc} \end{bmatrix}$$

$$[Is] = \begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix}$$

$$[I_L] = \begin{bmatrix} I_{dl} \\ I_{ql} \end{bmatrix}$$

$$[Ic] = \begin{bmatrix} I_{dc} \\ I_{qc} \end{bmatrix}$$

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = (1/C)\begin{bmatrix} Q_{dc} \\ Q_{qc} \end{bmatrix}$$

## 2.5 Simulation of Self-Excited Induction Generator

Self-excited induction generator is simulated in MATLAB/SIMULINK simulator software, which is show in Fig 2.2, whose specifications are given in Appendix-A. Since here the torque of the prime mover is assumed to be constant throughout, hence the load torque is taken from the constant block of SIMULINK. For capacitor bank 100µF/phase of capacitors are used. For calculating |Vs|, first Vabc is transformed into stationary d-q reference frame and then calculated by

$$|Vs| = \sqrt{(V_{ds}^2+V_{qs}^2)}$$

The whole system consists of:

- Induction Machine
- Voltage and Current Measurement
- Scopes
- 3-φ Load

All subsystems are shown in Appendix-B.

Now Self-Excited Induction Generator is simulated in different modes, such as:

1. At no load
   - With C = 100µf/phase
   - With C = 120µf/phase
2. Load change
   - Resistive load change (from no-load to 200w/phase)
   - Inductive load change (from no-load to (200+j12)VA per phase)

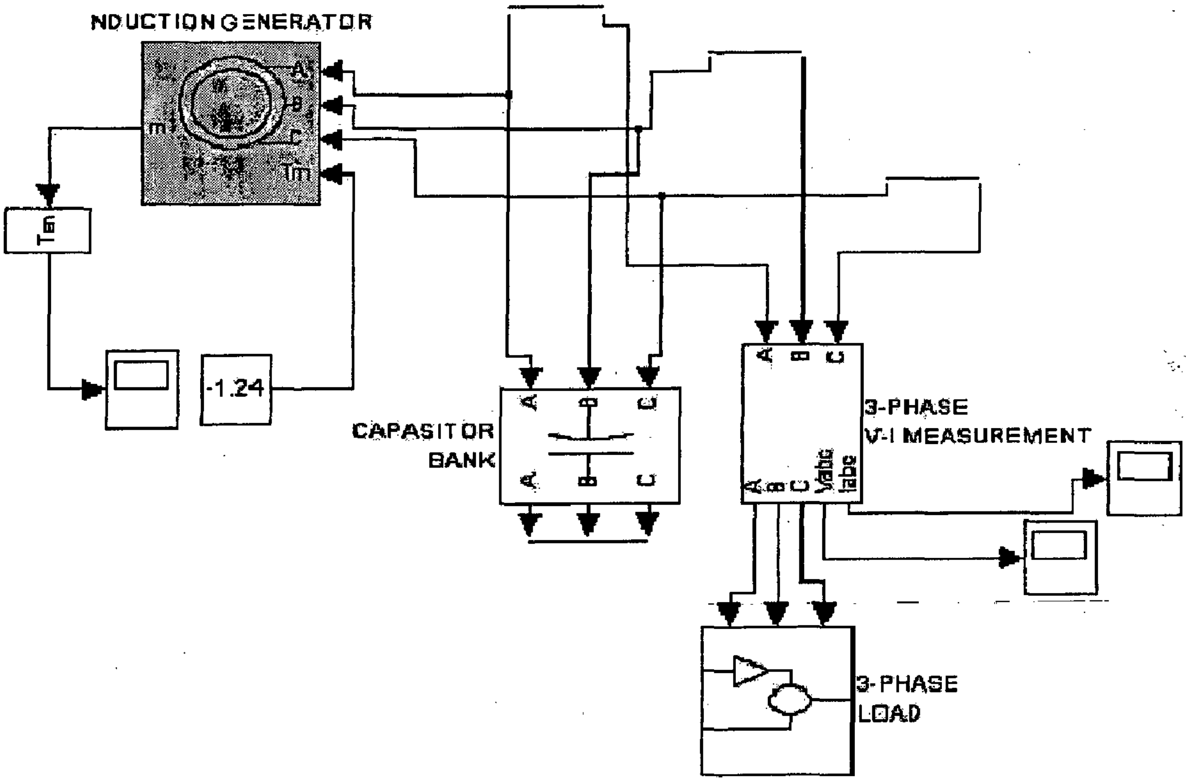
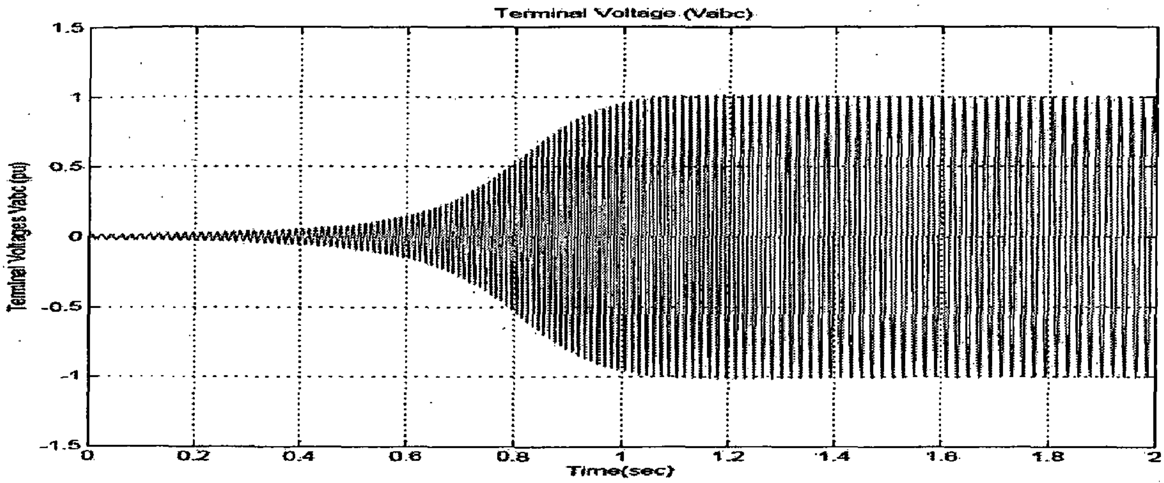
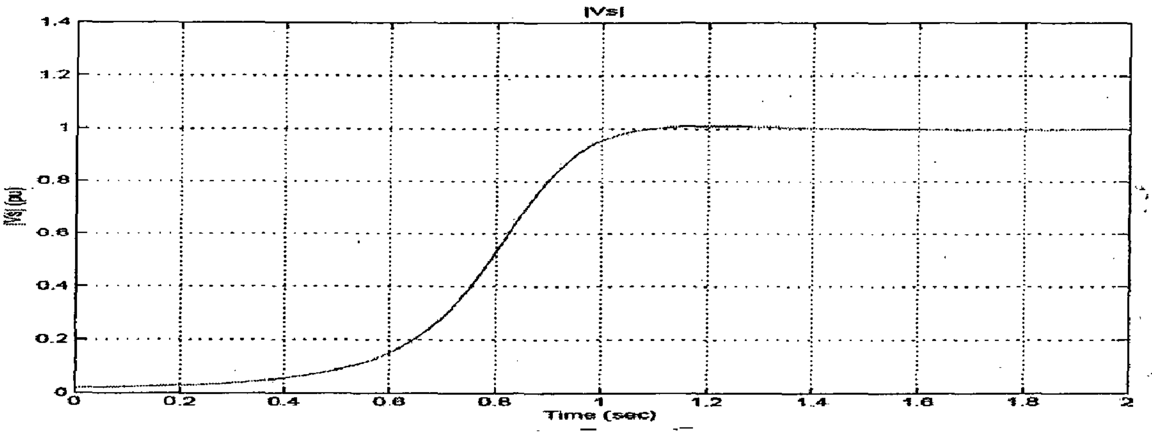


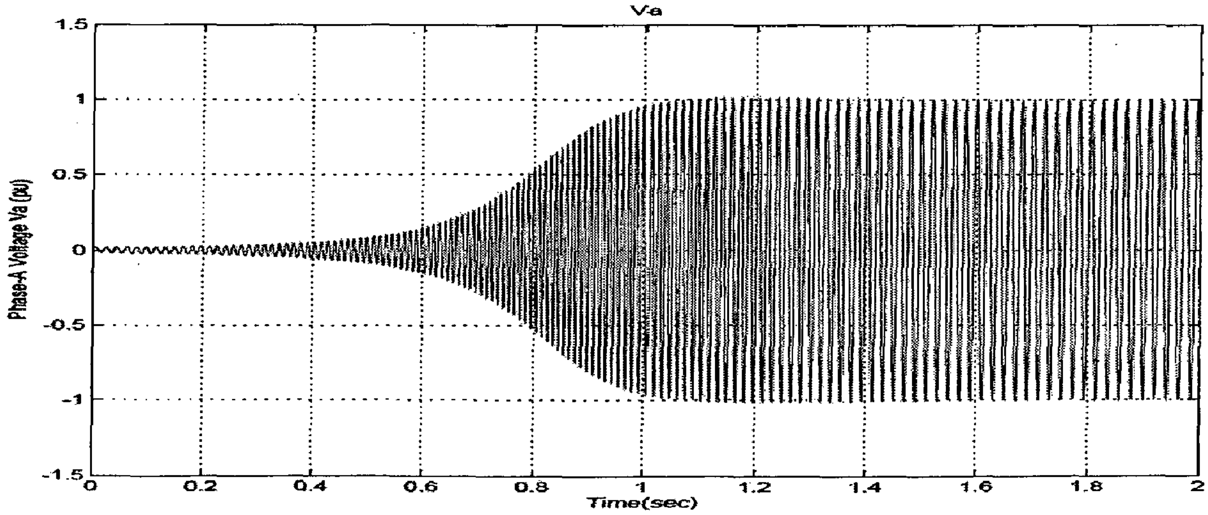

**Figure 2.2 MATLAB simulation Diagram of Self-Excited Induction Generator**




**(a)**



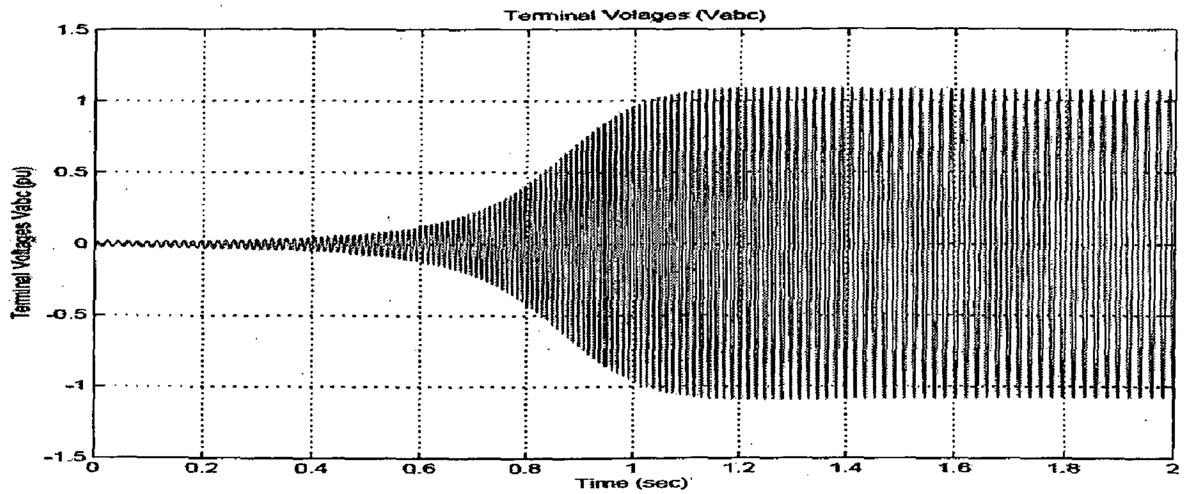

**(b)**



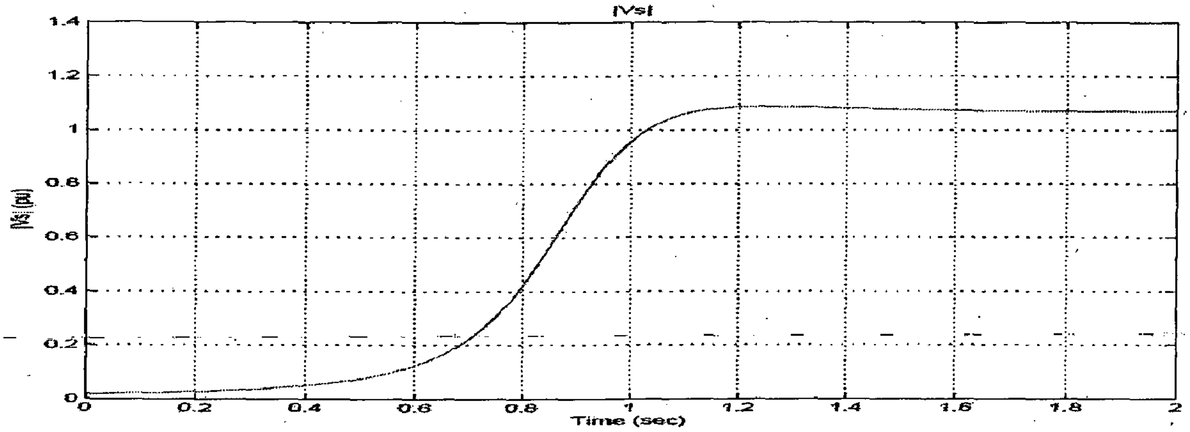

**(c)**

**Figure 2.3 Waveforms of SEIG at no load with C=100μf/phase**

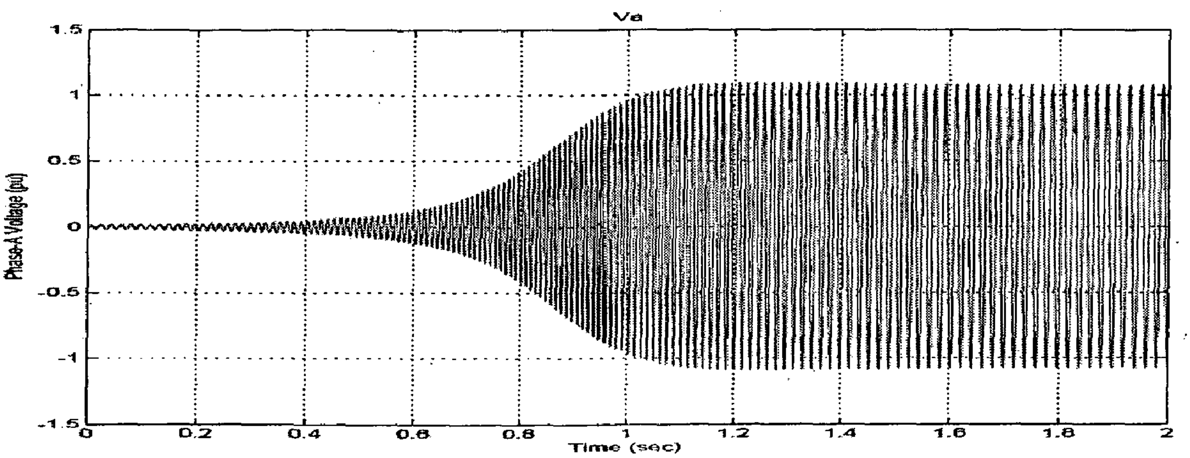
**(a) Vabc (b) |Vs| (c) Va**




(a)



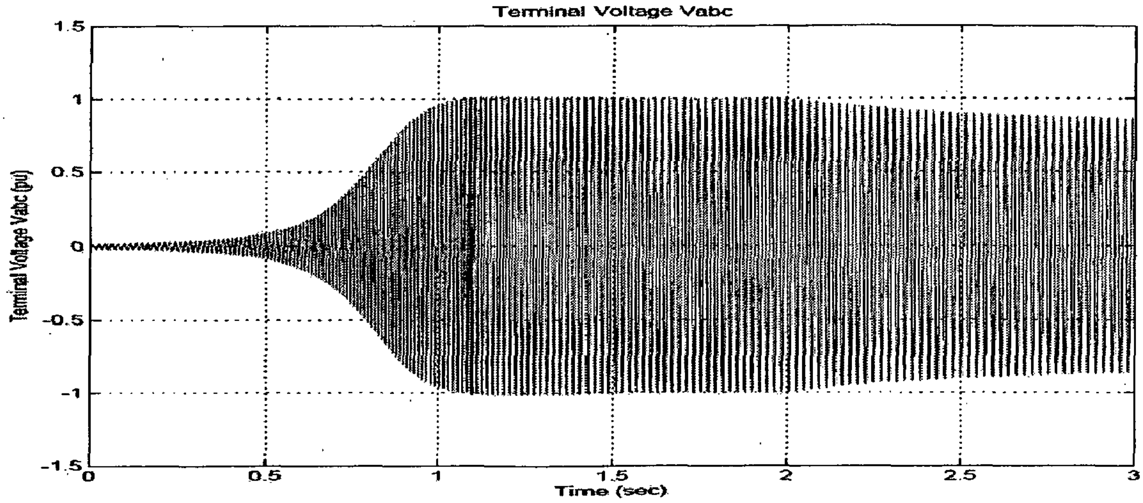

(b)



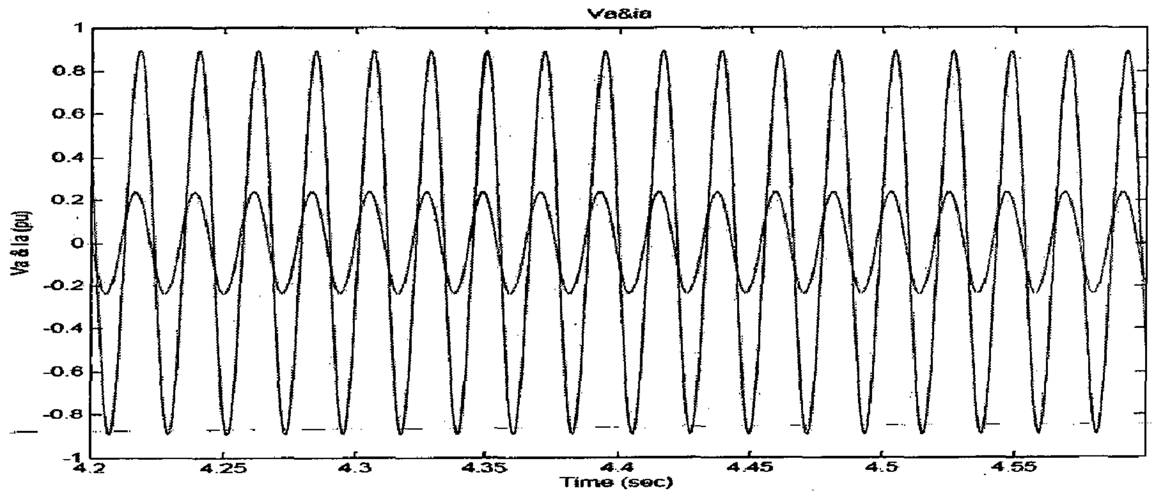

(c)

**Figure 2.4 Waveforms of SEIG at no load with C=120µf/phase**

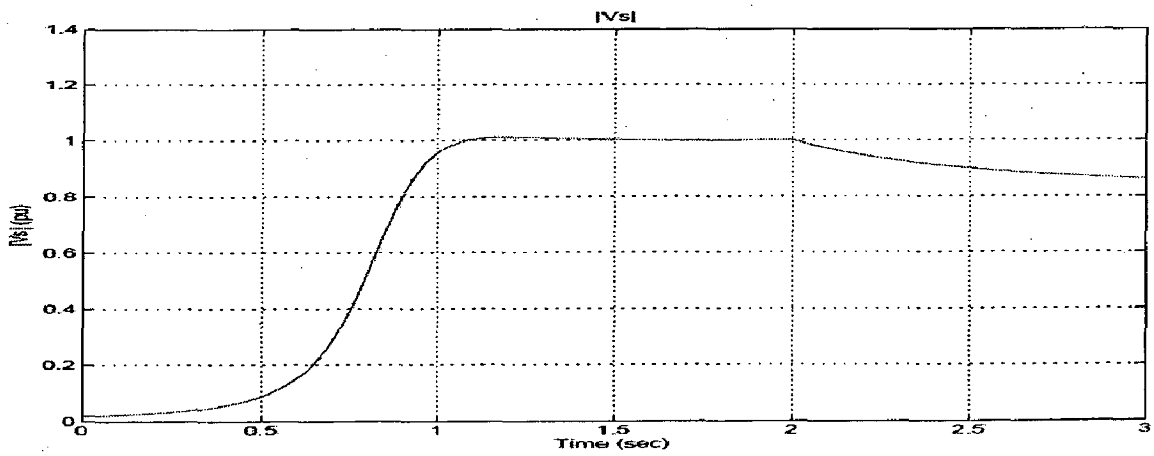
**(a) Vabc (b) |Vs| (c) Va**



(a)



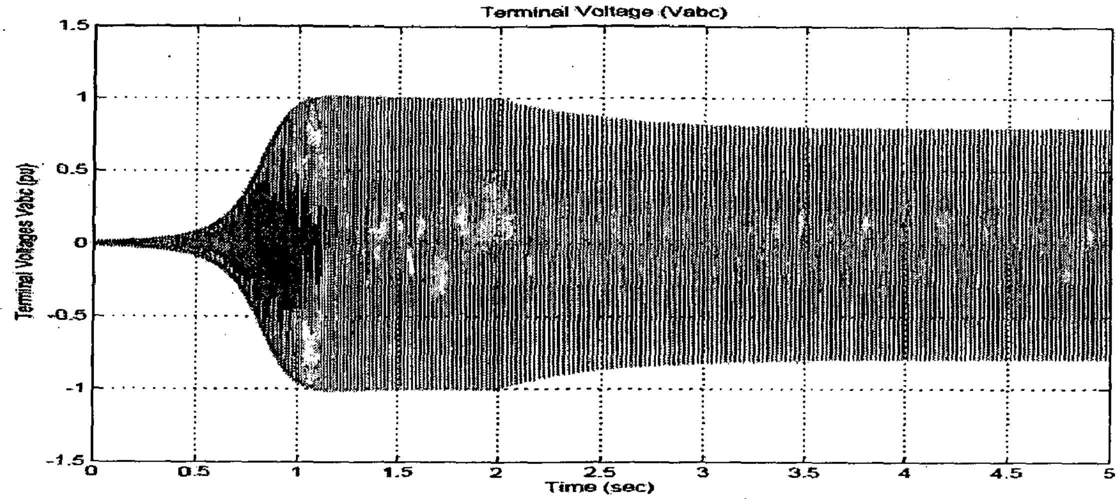
(b)



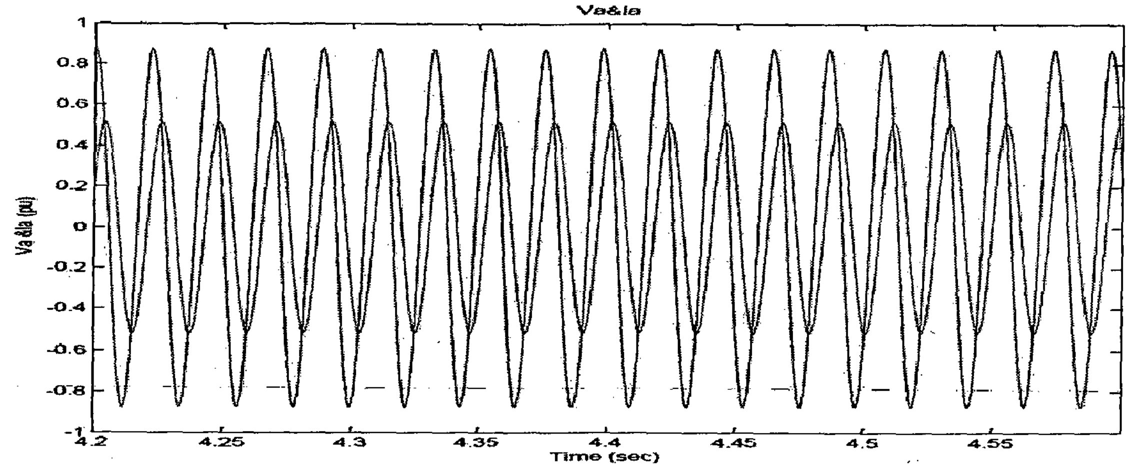
(c)

**Figure 2.5 Waveform of SEIG with load change from no load to 200w/phase**

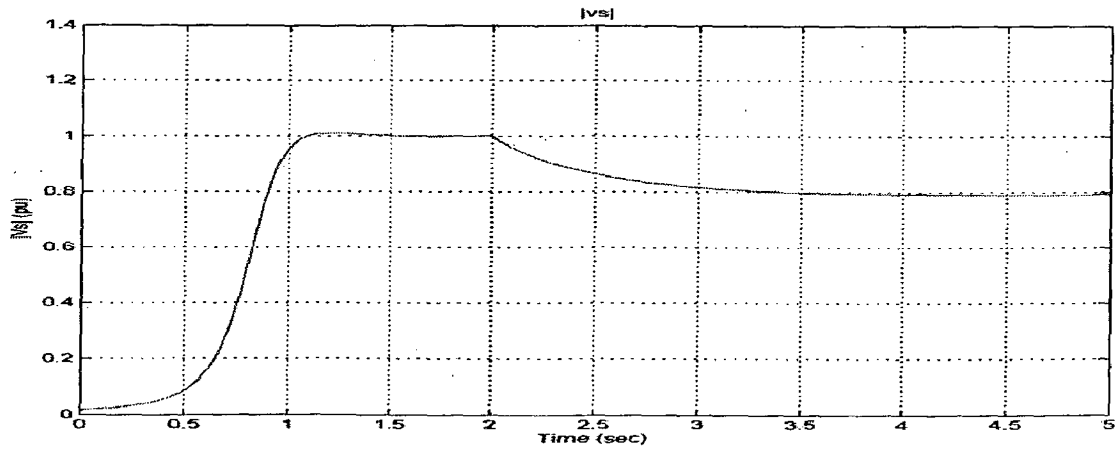
**(a) Vabc (b) Va&Ia (c) |Vs|**



(a)



(b)



(c)

**Figure 2.6 Waveforms of SEIG with the load change from no load to (200+j12) VA**

**(a) Vabc** (b)Va&Ia (c) **|Vs|**

## 2.6 Results and Discussions:

The simulated results in different cases mentioned above are shown in different figures for which the specifications are given in Appendix-A. a capacitance bank of 100μf/phase is connected across the terminals of Self-Excited Induction Generator.

### 2.6.1 At no-load

Fig 2.3 shows the terminal voltages $V_{abc}$, |Vs|, and Va in per units at no-load. In this case the simulation is carried out for two different cases. In first case the value of the capacitance is 100μf/phase while in second case its value is 120μf/phase.the machine is brought to its rated speed by applying the rated torque and a capacitance of 100μf/phase is connected at its terminals of self-excited induction generator. The voltage buildup is shown in Fig 2.3. The per unit steady state phase voltages are obtained. Varying the capacitance makes various observations. This is shown in Fig-2.4 in which the capacitance value is 120μf/phase. The steady state value in this case is 1.05pu.

### 2.6.2 Load Changes:

**(a) Resistive load change:** the different characteristics of Self-Excited Induction Generator under resistive load change are shown in Fig 2.5. Here first the machine is running under no-load. The value of terminal voltage is 1pu. Suddenly at time t=2sec the load is increased to 250w/phase. Then the terminal voltage is reduced to 0.88 pu. Fig 2.5(b) shows that the phase-A voltage and currents are always in phase because of resistive load.

**(b) Inductive load change:** The characteristics of SEIG under inductive load change are shown in Fig 2.5. Here again the same machine is running under no load with the same initial torque. The terminal voltage is 1pu. Fig 2.6(b) shows that the load current is lagging. Suddenly the inductive load is changed to (200+j12) VA. The terminal voltage is again reduced to 0.8pu. The angle of lag of load current is less in this case.

## 2.7 Conclusions:

Varying the capacitance makes various observations. By reducing the capacitance the terminal voltage is reduced and the voltage buildup process is slow. On the other hand by increasing the capacitance the terminal voltage is increased and the voltage buildup process is fast. Whenever sudden load is applied at the terminals of SEIG terminal voltage will be reduced.

Chapter 3

# CURRENT CONTROLLED PWM VSI INVERTER

## 3.1 GENERAL:

DC-to-AC converters are known as inverter. The function of an inverter is to change dc input voltage to symmetrical ac output voltage of desired magnitude and frequency. A variable output voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand when the dc input is fixed is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by pulse-width-modulation (PWM) control with in the inverter. The inverter gain may be defined as the ratio of the output ac voltage to dc input voltage.

Inverters are broadly classified either as voltage source or current source inverters. The voltage fed/voltage source inverter (VSI) is powered from a stiff, or low impedance dc voltage source such as battery or rectifier, the output voltage of which is smoothed by an LC filter. The large filter capacitor across the inverter input terminals maintains a constant dc link voltage. The inverter is therefore an adjustable frequency voltage source, the output voltage of which is essentially independent of load current. On the other hand the current fed/current source inverter (CSI) is supplied with a controlled current from a dc source of high impedance. Typically, a phase controlled rectifier feeds the inverter with a regulated current through a large series inductor. Thus the load current rather than load voltage is controlled, and the inverter output voltage is dependent upon the load impedance.

The output voltage waveform of the ideal inverter should be sinusoidal. However, the waveforms of the practical inverters are non sinusoidal and contain certain harmonics. For low and medium power applications, square wave and quasi square wave voltages may be acceptable; and for high power applications, low distorted sinusoidal waveforms are required. With the availability of high-speed power semi conductor devices, the harmonic content of the output voltages can be minimized or reduced significantly by switching techniques.

The basic circuit diagram of quasi-square voltage source inverter is shown in figure 3.1. The current and voltage waveforms are shown in figure 3.2.

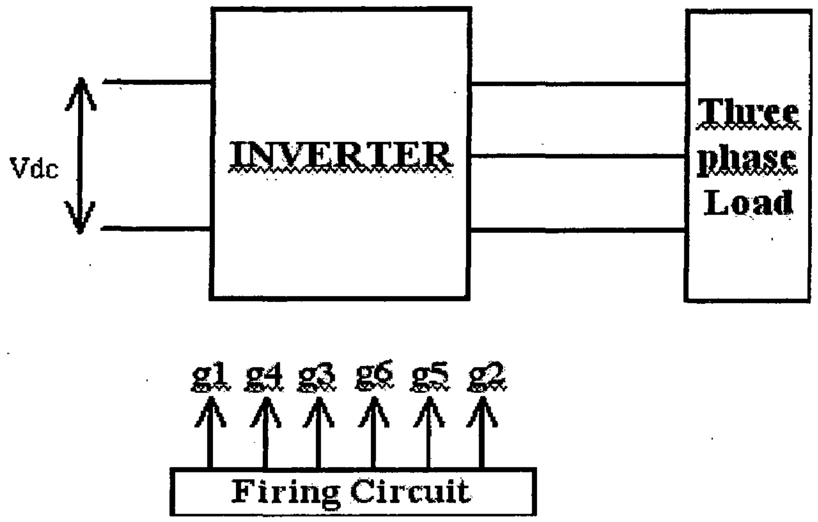



**Figure 3.1: Basic diagram OF inverter**

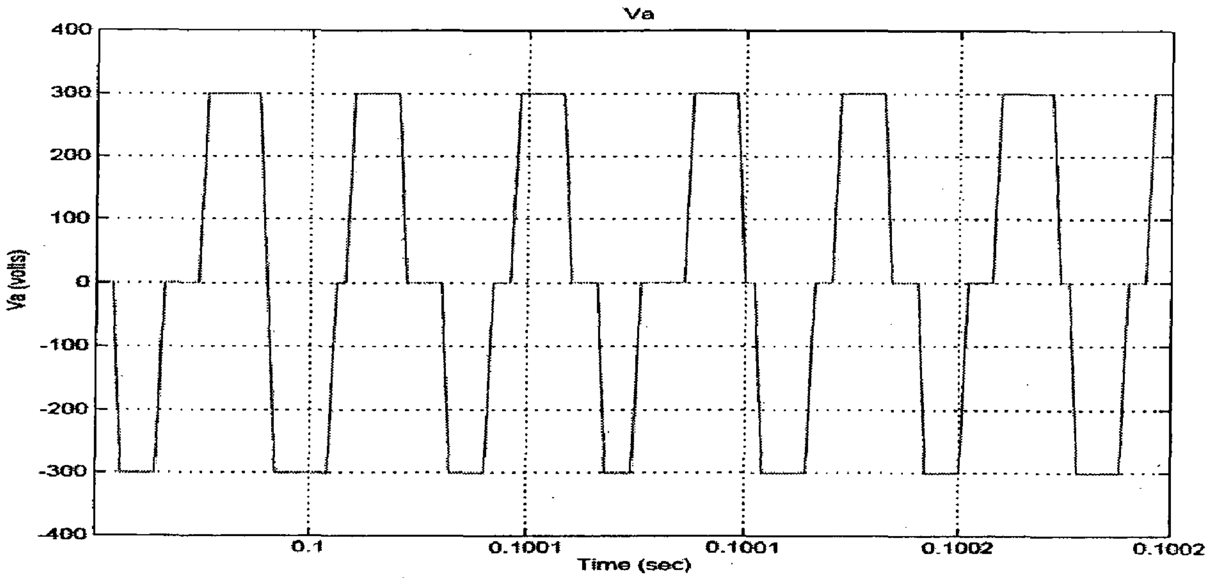



**Figure 3.2: Line Voltage Waveform of inverter output**

The current waveform of the conventional three-phase inverter is non sinusoidal in nature, so the total harmonic distortion (THD) is very high. To make the current waveform sinusoidal and THD with in permissible limit current controlled inverter is required.

## 3.2 CURRENT CONTROLLED PWM INVERTER

The current controlled PWM inverter consists of conventional PWM voltage source inverter fitted with current regulating loops to provide a controlled current output. If the inverter has a high switching frequency, the stator currents of the synchronous or induction motor can be rapidly adjusted in magnitude and phase. As in dc drive, high quality dynamic control of motor current is particularly important for the implementation of a high performance single motor ac drive. Servo drives, in particular, must satisfy exacting performance specifications with respect to dynamic response and smoothness of rotation down to zero speed. These characteristics are highly dependent on the quality of current control. Therefore current control of PWM inverter is one of the most important subjects of modern power electronics.

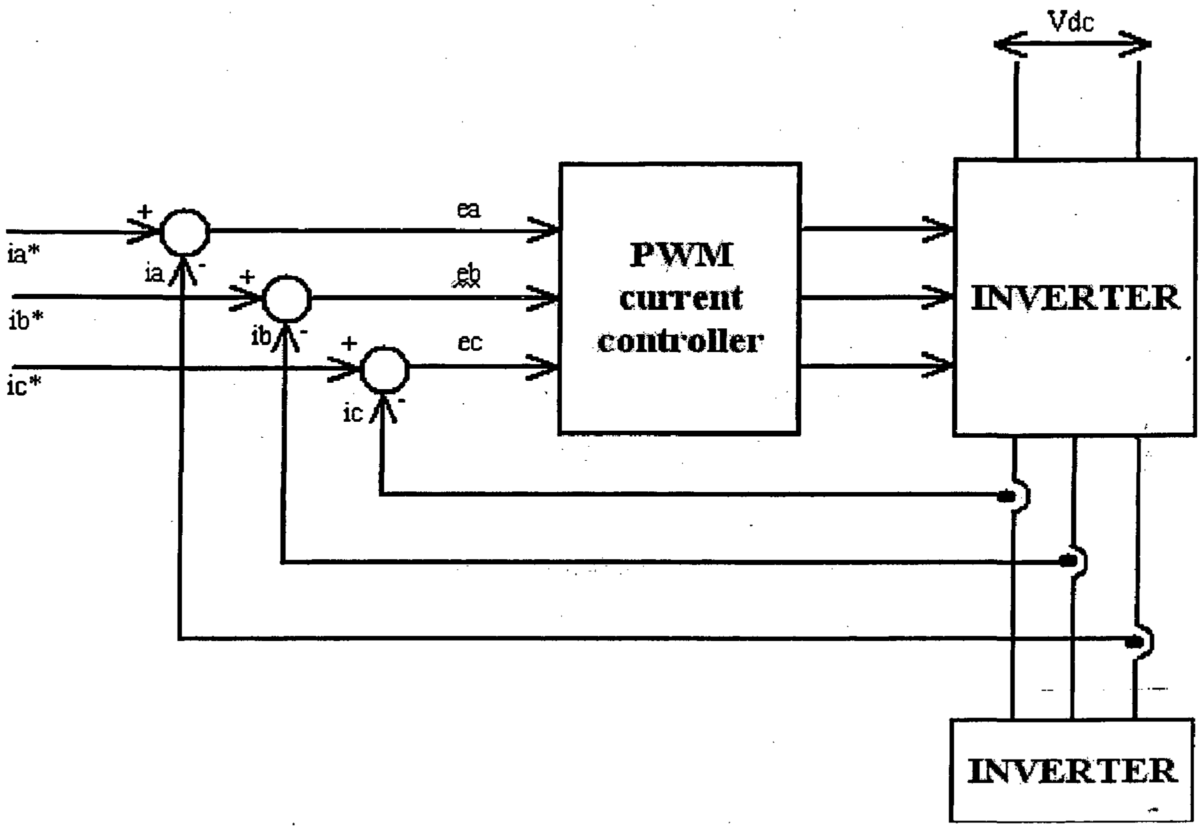



**Figure 3.3: Basic block diagram of CC-PWM inverter**

In comparison to conventional open loop voltage PWM inverters, the current controlled PWM inverters have the following advantages [neel mani.1]

1) Control of instantaneous current waveform with high accuracy.
2) Peak current protection.
3) Over load rejection.
4) Extremely good dynamics.
5) Compensation of effects due to load parameter changes(resistance & reactance).
6) Compensation of semiconductor voltage drop and dead time of converter.
7) Compensation of dc link and ac side voltage changes.

A high performance current-controlled PWM VSI must have quick current response in the transient state and low current harmonics in the steady state. The controller switches the voltage source inverter such that the motor current follows a set of reference current waveform. Among the various techniques of the current control, the hysteresis current control techniques are widely used because of simplicity, outstanding robustness, lack of tracking error and extremely good dynamics limited only by the switching speed and load time constant. Usually, a sinusoidal current waveform is generated and fed to the comparator, together with actual measured current of the load. The simplest approach uses the comparator error to switch and devices so as to limit the instantaneous current error. If the load current waveform is more positive than the reference value, the upper device is turn-off and the lower device is turn-on, causing the load current to decrease and vice-versa. In three phase system usually an independent current controller for each phase are required. Standard lockout circuitry is required to ensure the sufficient dwell time between successive switching in an inverter leg. In this chapter the different types of the hysteresis current controllers are discussed in brief.

### 3.3 CURRENT CONTROLLER PROPERTIES:

Before analyzing the specific current controllers, the general properties of current controller are examined.

#### 3.3.1 Effect of DC voltage limit:

For a current controller to operate properly there must be sufficient voltage to force the line currents in the desired direction. For a load with low counter EMF the DC bus voltage is not critical, but as the counter EMF is increased, a point is reached where the current controller is not able to command the desired current. This condition is reached when the line-to-neutral voltage approach a six-step quasi-square wave. In this presentation it is assumed that there is sufficient voltage to command the line current.

#### 3.3.2 Inverter switching frequency:

To determine the factors that influence the inverter switching frequency, let one phase of load is described by the following differential equation:

$$V = Ri + Ldi/dt + e \qquad (4.1)$$

Where

V line-to-neutral voltage,

I line current,

E counter EMF,

L leakage inductance.

The time $\Delta t$ in which the line current will increased by $\Delta i$ can be found from equation (3.1) assuming that V and e do not change appreciately over the interval that the resistance is negligible:

$$\Delta t = L\Delta i/(V\text{-}e) \quad (4.2)$$

Equation 3.2 shows that the inverter switching frequencies influenced by several factors: inductance and counter EMF of load, DC bus voltage and current ripple. The fundamental of the line-to-neutral voltage and the counter EMF vary periodically. Therefore, either the inverter switching frequency or/and the current ripple will vary over a fundamental inverter period.

## 3.4 CLASSIFICATION OF CC-PWM INVERTER

### 3.4.1 Fixed band hysteresis current control [24]:

In this scheme the hysteresis bands are fixed through out the fundamental period as shown in fig 2.1(b). The algorithm for this scheme is given as

$i_{ref} = i_{max}\sin(wt)$

Upper band ($i_u$) = $i_{ref}$ + Hb

Lower band ($i_l$) = $i_{ref}$ - Hb

Where Hb = hysteresis band limit

If $i_a > i_u$, $V_{ao}$ = -Vdc/2.0;

If $i_a < i_l$, $V_{ao}$ = Vdc/2.0;

### 3.4.2 Sinusoidal band hysteresis current control [24]:

In this scheme the hysteresis band vary sinusoidally over a fundamental period as shown in fig 2.1(c).

The upper and lower bands are given as follows

$I_{ref} = i_a^* = i_{max}\sin(wt)$

Upper band ($i_u$) = $(i_{ref} + Hb)\sin(wt)$

Lower band ($i_l$) = $(i_{ref} - Hb)\sin(wt)$

Where Hb = hysteresis band limit

The algorithm as follows,

For $i_{ref}>0.0$:

If $i_a > i_u$, $V_{ao} = -V_{dc}/2.0$;

If $i_a < i_l$, $V_{ao} = V_{dc}/2.0$;

for $i_{ref}<0.0$:

If $i_a < i_u$, $V_{ao} = V_{dc}/2.0$;

If ia>$i_l$, $V_{ao} = -V_{dc}/2.0$;

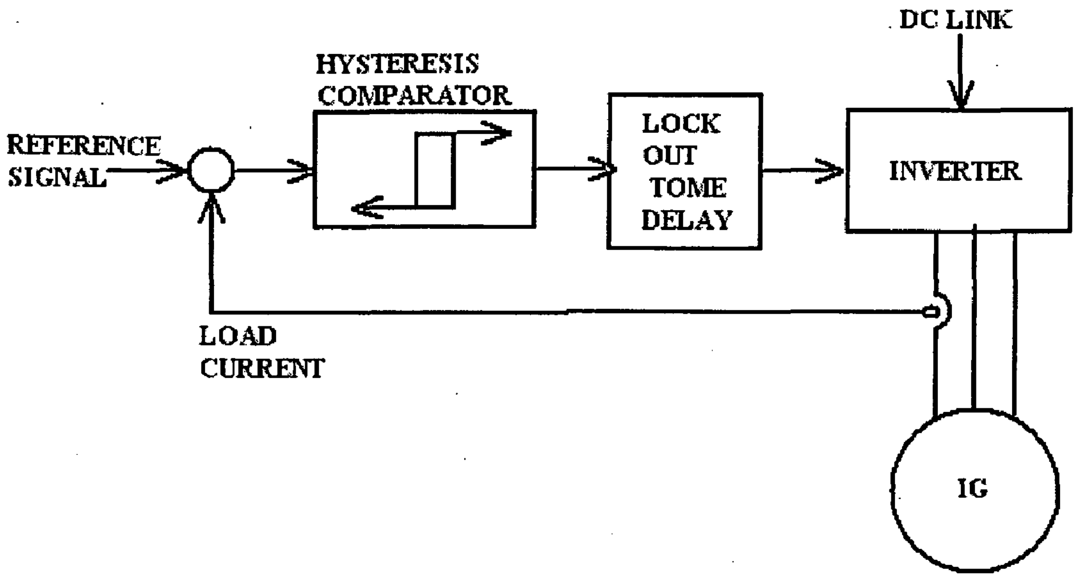



**Figure 3.4 Hysteresis current controller for one Inverter leg**

### 3.5 Drawback of Conventional Hysteresis current controller:

There are several drawback of conventional HCC, due to witch it is not used for high rating application.

- There is no intercommunication between the individual hysteresis current controllers of three-phase, and have no strategy to generate the zero vectors.
- There is tendency at lower speed to lock in to the limited cycle of the high frequency switching, witch comprises only non-zero vectors.
- The current error is not strictly limited. The signal will leave the hysteresis band whenever the zero vectors is turned on while a back EMF vector has a component that opposes the previous switching state vector. Double the current error magnitude permitted by one HCC can occur at maximum.
- Hysteresis current controller should be operated at higher switching frequency for compensate their inferior quality of modulation.

### 3.6 Advantages of Current Controlled Voltage Source Inverter:

In comparison to conventional open loop voltage PWM inverters, the current controlled PWM inverters have the following advantages

1) Control of instantaneous current waveform with high accuracy.
2) Peak current protection.
3) Over load rejection.
4) Extremely good dynamics.

5) Compensation of effects due to load parameter changes (resistance & reactance).

6) Compensation of semiconductor voltage drop and dead time of converter.

7) Compensation of dc link and ac side voltage changes.

### 3.7 Simulation of CC-VSI

The power circuit and connection diagrams of current controlled voltage source inverter are shown in Fig 3.5 and Fig 3.6.

It comprises the main components as:

- Power circuit
- Hysteresis controller
- Load, and
- Scopes

For simulation of CC-VSI, IGBTs are used, whose specifications are given below. The reference signals are generated by using sin block of SIMULINK. For firing the devices (IGBTs) the pulses are generated by hysteresis current controller, which generates the pulses by comparing the output currents with the respective reference currents with in a hysteresis band. Here the hysteresis band is taken as Hb=0.2. the load is of R-L type.

IGBT specifications:

| | |
|---|---|
| On state resistance (Ron) | 0.01 ohm |
| On state inductance (Lon) | Ie-6 H |
| Snubber circuit resistance (Rs) | 10 ohm |
| Snubber circuit capacitance (Cs) | 0.01e-6 F |

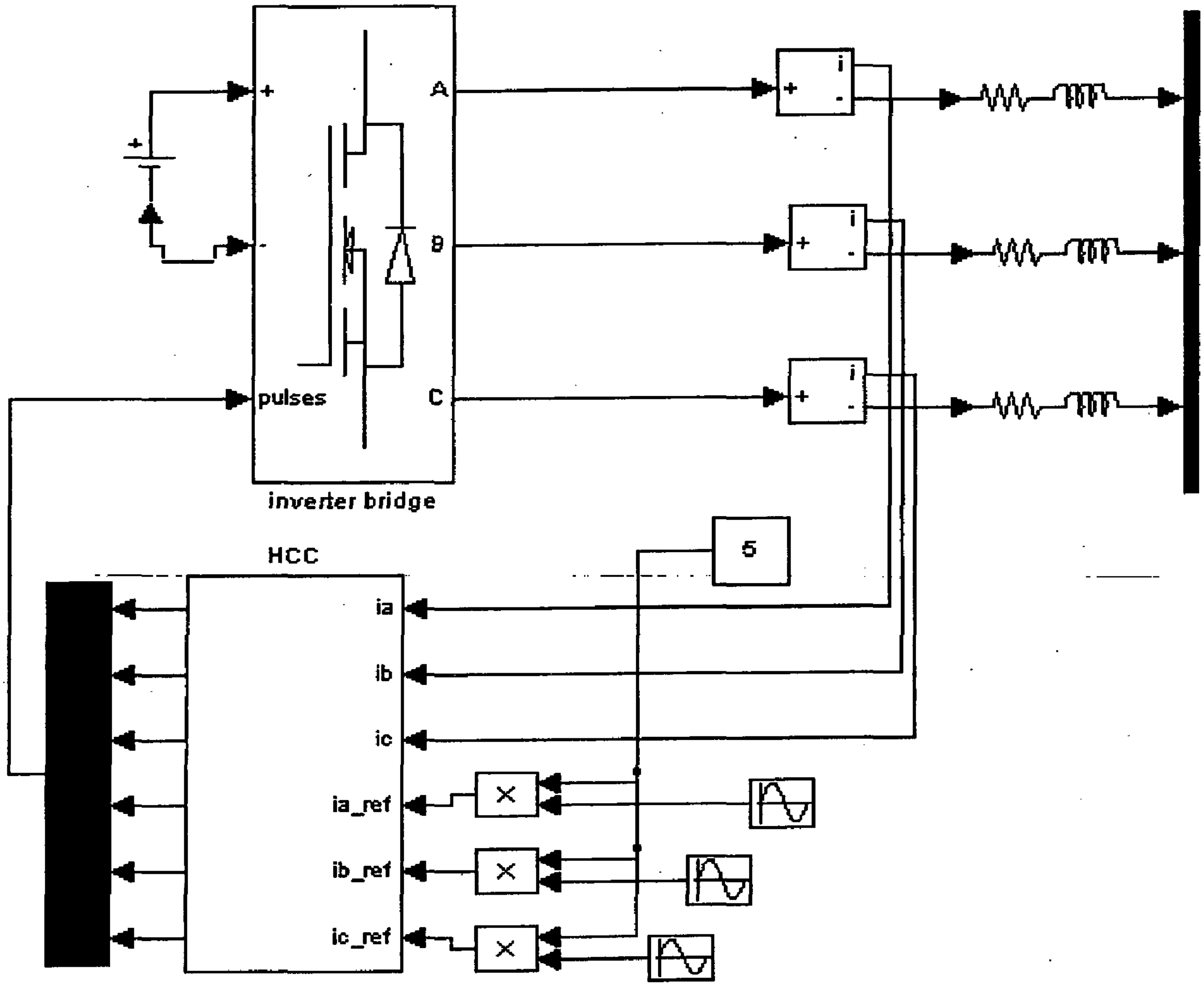



**Figure 3.5 Power circuit diagram of CC-VSI in MATLAB**

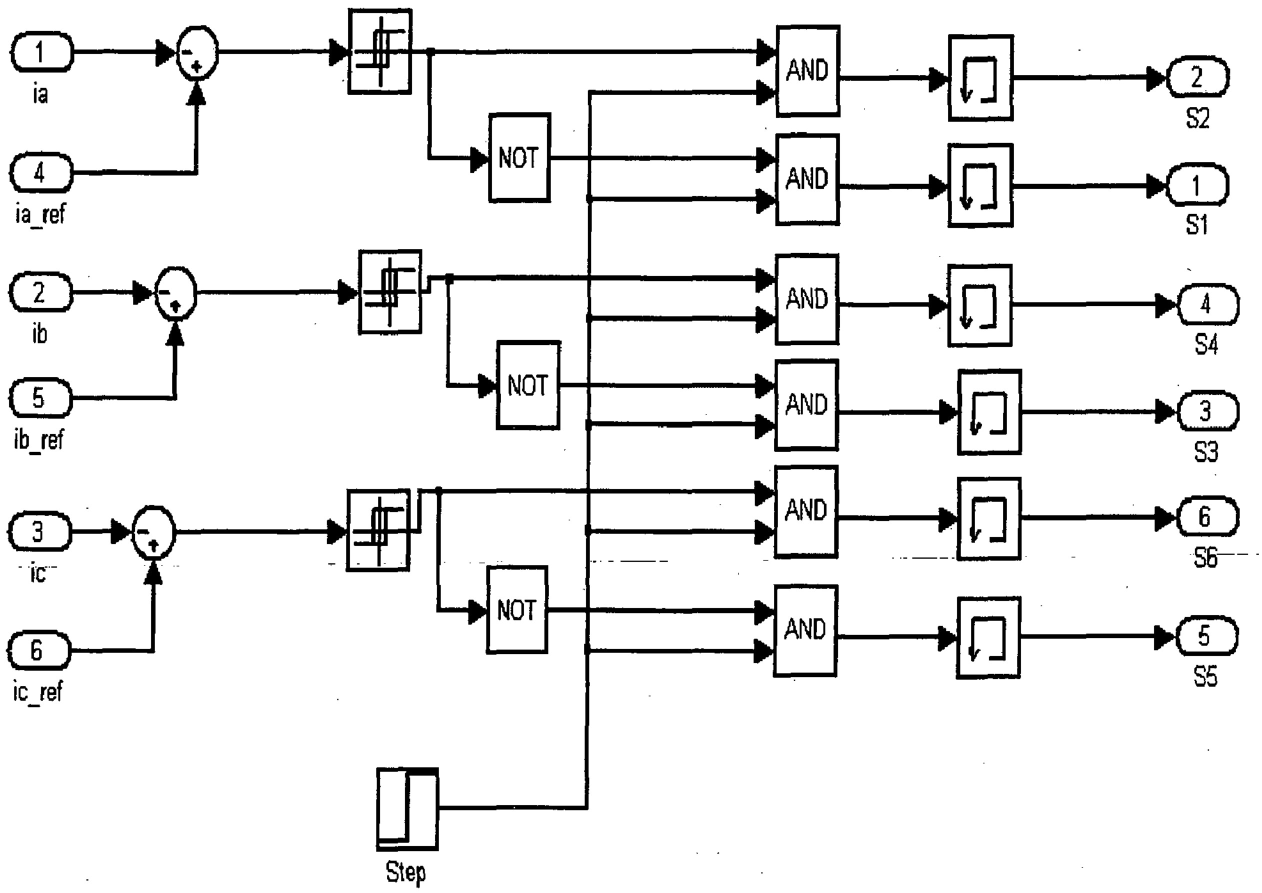
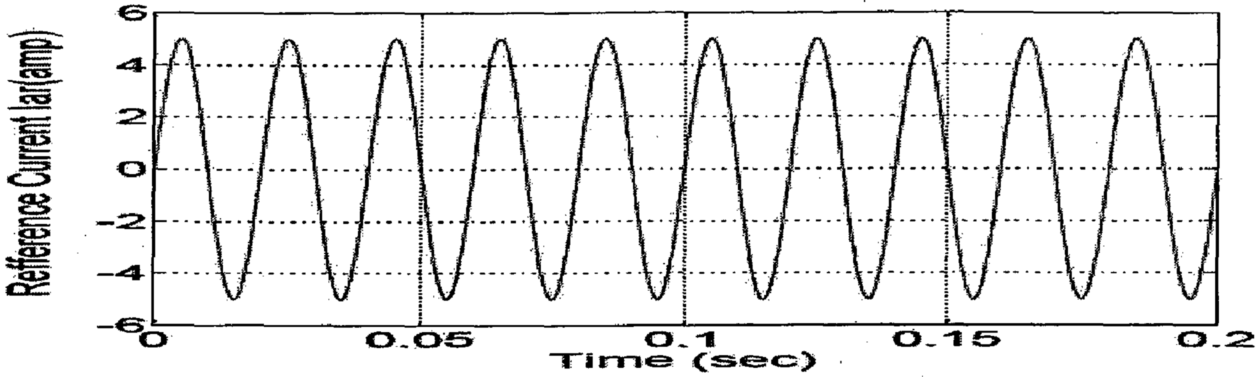
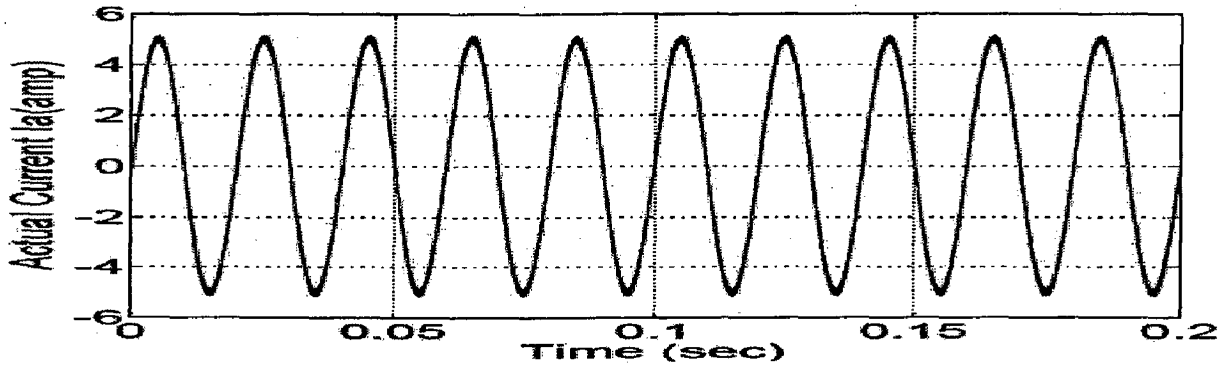
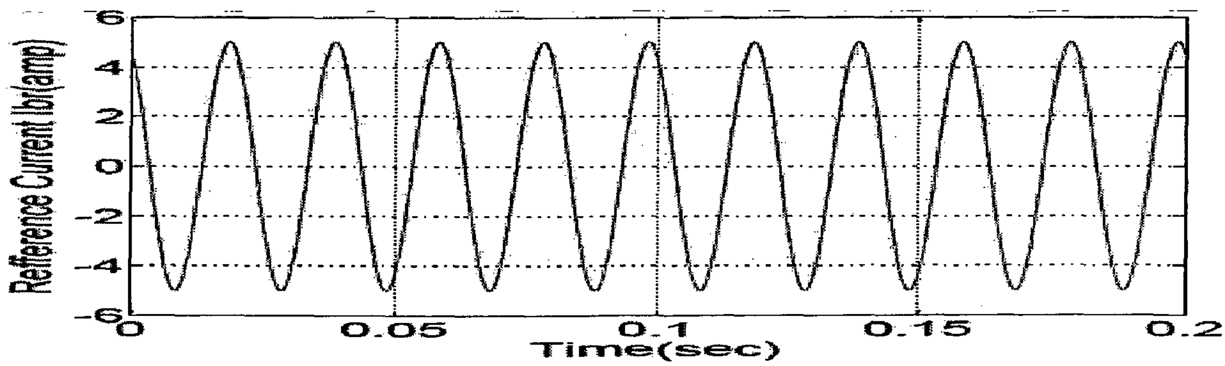
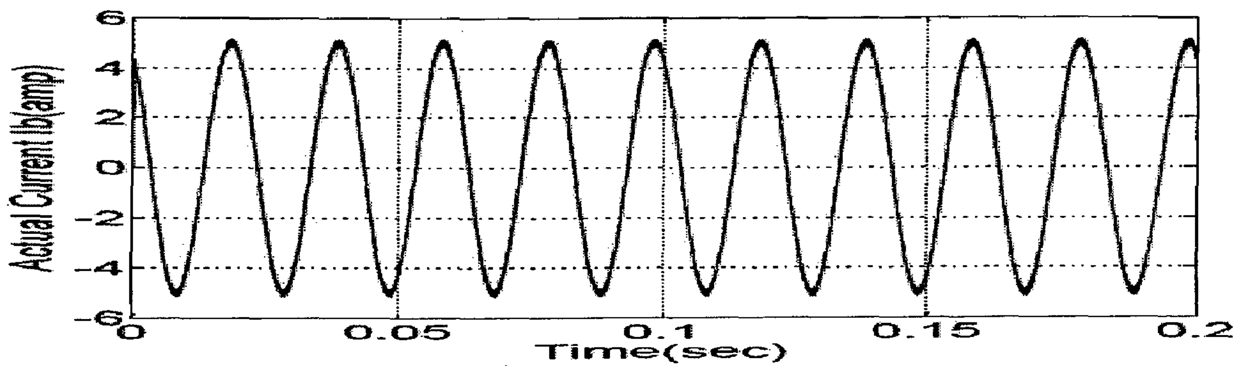


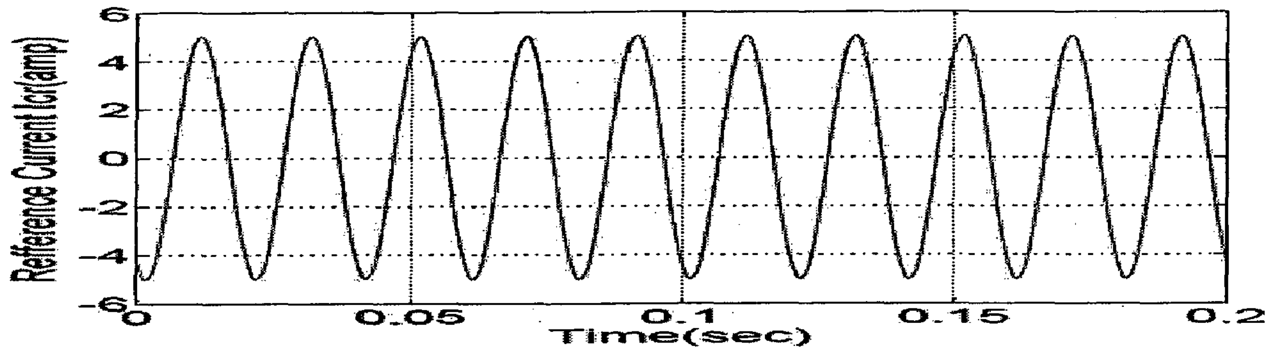

**Figure 3.6 MATLAB Simulation Diagram of Hysteresis Current Controller**


Refference Current Ia(amp)
6
4
2
0
-2
-4
-6
0
0.05
0.1
0.15
0.2
Time (sec)
(a)

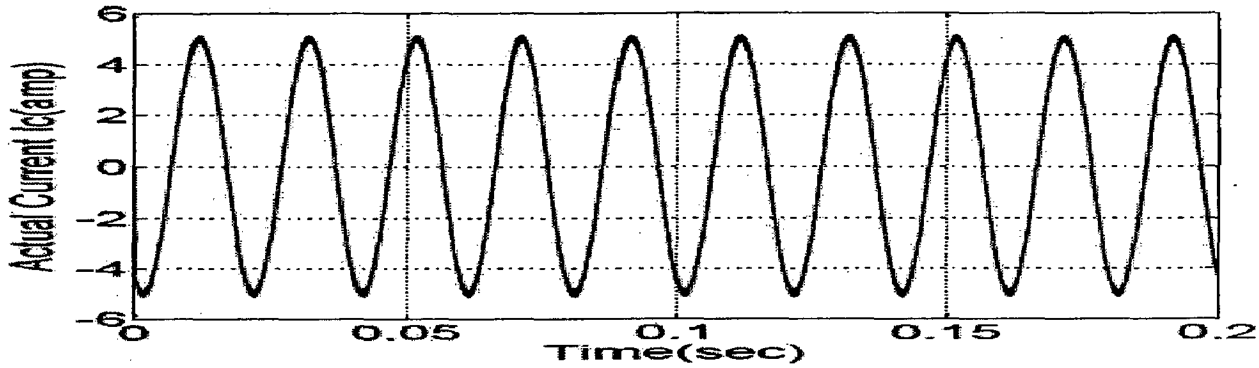

Actual Current Ia(amp)
6
4
2
0
-2
-4
-6
0
0.05
0.1
0.15
0.2
Time (sec)
(b)


Refference Current Ib(amp)
6
4
2
0
-2
-4
-6
0
0.05
0.1
0.15
0.2
Time(sec)
(c)


Actual Current Ib(amp)
6
4
2
0
-2
-4
-6
0
0.05
0.1
0.15
0.2
Time(sec)
(d)




(e)




(f)

**Figure 3.7 Current Waveforms of CC-VSI in Balanced Reference Currents.**

(a) Reference current of phase-A

(b)Actual output current of phase-A

(c) Reference Current of phase-B

(d) Actual output Current of phase-B

(e) Reference current of phase-C

(f) Actual output current of phase-C

### 3.8 RESULTS AND DISCUSSIONS:

Here the CC-VSI is simulated in the following mode

1. The reference signals are taken to be balanced i.e. equal in magnitude and displaced in phase by $120^o$ from each other.

### 3.8.1 For Balanced Reference Currents:

Here the reference signals are $I_{ar}$ = sin(wt), $I_{br}$ = sin(wt-$120^o$) and $I_{cr}$ = sin(wt+$120^o$) i.e. the maximum amplitude of reference signals are 1 amp. This results of reference signal and actual current output signals are shown in fig 3.7. here the actual output currents from CC-VSI follows the respective reference signals with in a hysteresis limit of 0.2 i.e. the magnitude and the phase of actual currents $I_a$, $I_b$ and $I_c$ are same as their respective reference currents $I_{ar,}$ $I_{br}$ and $I_{cr.}$

# VOLTAGE REGULATION IN SEIG

SEIGs have received more attention due to its low cost, simplicity in construction, no DC excitation requirements, reduced maintenance cost and better transient performances over conventional generators and they have been widely employed in suitable isolated power sources such as wind, tidal and small hydroelectric renewable energy.

Although the SEIGs have many advantages, a capacitor excited induction generator suffers from its inherent voltage regulation and hence its practical application into the power system has been limited. A number of methods have been proposed for regulating the voltage profile of a SEIG.

In the previous chapter-1 it has been seen that by increasing the load on Self-Excited Induction Generator, its terminal voltage is reduced and by reducing the load its terminal voltage increased. The terminal voltage of SEIG can be regulated by providing the reactive power required by induction generator by some external means.

## 4.1 VOLTAGE CONTROL OF SEIG BY USING CC-VSI

This technique proposes a static compensator based technique in order to provide excitation for the induction generator with the load connected at the stator terminals of the IG. CC-VSI inverter provides the excitation current. The proposed controller regulates the induction generator terminal voltage against varying rotor speed and changing load conditions. This scheme doesn't require computation and information regarding rotor speed for calculating the excitation current, there by minimizing the cost of the controller. The schematic of the system is shown in Fig 4.1.

### 4.1.1 System Description

The block diagram of the proposed voltage regulator by using CC-VSI for a SEIG feeding an arbitrary three-phase load is shown in Fig.4.1 It comprises of an induction generator, 3-phase load, CC-VSI, PLL, and a hysteresis current controller. A fixed capacitor bank (C) supplies the exciting current to sustain the voltage generation of the studied SEIG under no-load condition. The CC-VSI provides the reactive power to regulate the terminal voltage profile of the SEIG under various

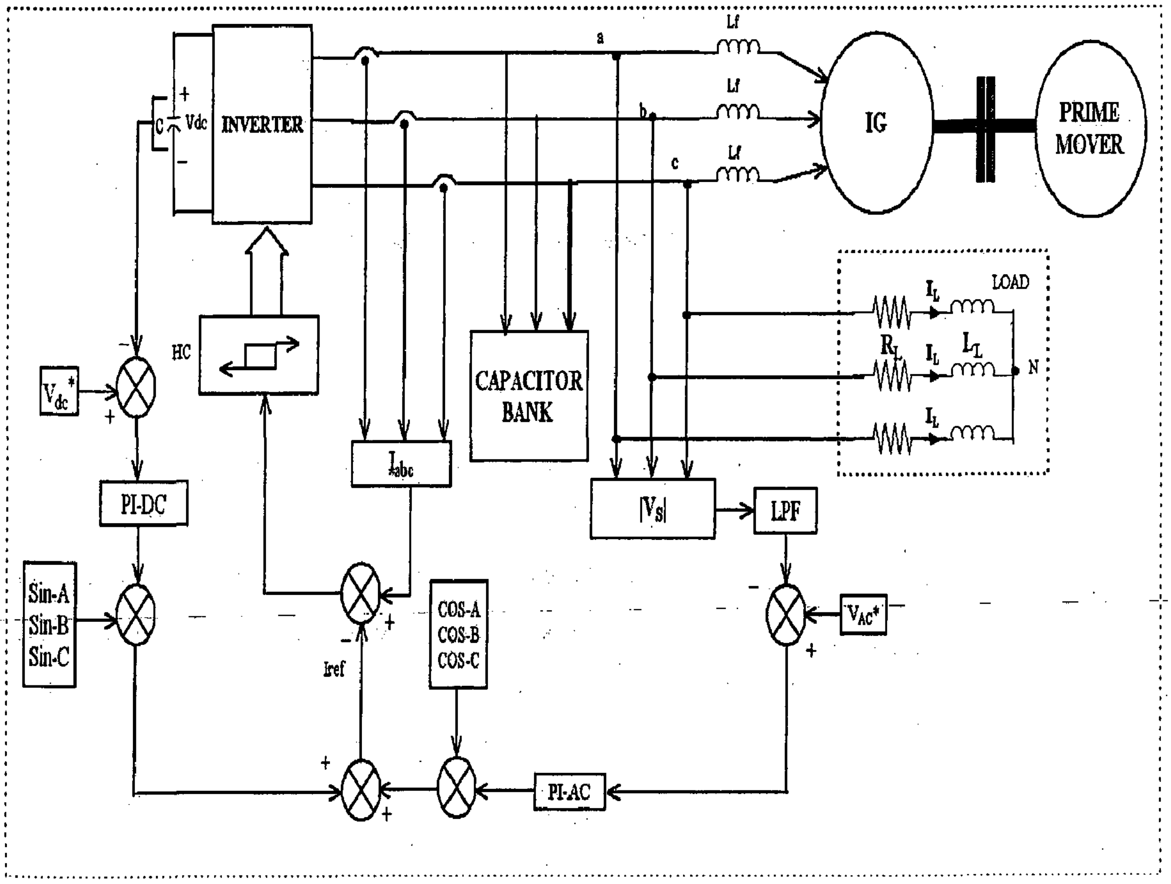



**Figure 4.1. Overall System Block Diagram**

loading conditions. The AC side of the inverter is connected to the stator terminals of the SEIG through the inductor *($L_f$)*. Combining the inductor *($L_f$)* with the capacitor bank *(C),* a second-order filter is used to filter out the high-order harmonic components, which are caused by the switching action of the inverter. The DC link of the inverter is composed of an electrolytic capacitor as the DC side voltage source. Since the VSI has no real power source in the DC link, a small active power fed from the SEIG is required for compensating the losses of the inverter to maintain the voltage of the DC capacitor at a specified level. The vector form of the terminal voltage is calculated from the components of the d-q axis reference frame. The voltages of the AC mains and the DC bus voltage of the inverter are controlled by two PI voltage controllers. Hysteresis current controller is used for giving current commands for CC-VSI in order to inject calculated three-phase currents into the lines of the SEIG system.

### 4.1.2 Control Strategy

The concept of voltage regulation for a SEIG is considered as being that the controlled reactive currents, which are supplied by the CC-VSI, are injected into the line currents of the SEIG. The three-phase voltages of the SEIG are sensed and transferred into vector form as a feedback voltage, whose absolute value is a DC quantity, and it is compared with the prespecified reference voltage. After the error voltage is processed by the controller, the output signal of the controller is used to control the reactive power flow of the studied system. If the feedback voltage is larger than the reference voltage, the CC-VSI provides the lagging reactive power for reducing the degree of saturation of the SEIG, and hence, the magnitude of the output voltage of the SEIG is also decreased. On the contrary, the leading reactive power is required when the feedback voltage is smaller than the reference voltage. The function of this control strategy is operated well when the system is under a balanced condition.

To get the space vector form of the generated voltages, the three-phase voltages are transformed into orthogonal two-axis components based on a stationary $d^s$-$q^s$ reference frame. The transformation equation is of the form:

$$\upsilon_{s(dq0)} = K_s \upsilon_{(abc)}$$

Where the transformation matrix, $K_s$, is given by

$$K_s = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix}$$

Since the $d^s$-$q^s$ axes are orthogonal co-ordinates and the $d^s$-axis is aligned with a-axis of the three-phase a-b-c frame of reference, the stator voltages $v_{ds}$ and $v_{qs}$ can be converted to a polar form. The absolute value of the vector stator voltage, $|v_s|$, is expressed as:

$$|v_s| = \sqrt{v_{ds}^2 + v_{qs}^2}$$

The sensed voltage $|v_s|$ is compared with the reference Voltage $|v_s|^*$, and the error is sent to the input point of the first PI controller (PI-AC).

In addition to the AC voltage being regulated, the DC bus voltage should also be regulated. Since the switching losses and conductor losses of the inverter cause the DC bus voltage to be varied, the additional power supplied from the SEIG is needed to keep the DC bus voltage at a constant value. The control loop for the DC bus voltage regulation is also shown in Fig. 1. The error between the DC bus voltage, $V_{dc}$ and the reference voltage, $V_{dc}^*$, is fed to the second PI controller (PI-DC). The function of the CC-VSI in the system is to produce reactive power and absorb difference in active power produced by the generator and load requirement during transient conditions.

The reference in-phase inverter current is obtained by multiplying the dc link error with reference voltage derived from the supply voltage. Similarly, active current components for the other two phases are derived by multiplying the respective phase voltages. The quadrature reference current is decided by the net excitation current of the IG. This excitation current of IG determines the generator voltage. The quadrature reference current is obtained by comparing the generator voltage with a reference voltage. The error is multiplied by corresponding cosine template.

The proposed controller uses a hysteresis current controlled, voltage source PWM inverter to supply the desired excitation current for induction generator. In Fig4.1, there are two control loops. The inner current control loop forces the actual inverter current to follow the reference current generated by the outer loop. The reference current ($I_{ref}$) is derived by adding two current components. The in-phase active current component represents losses in the inverter. The difference in active load current demand and the active component of generator current flows through the inverter. This mismatch in current is rejected in the variation of dc link voltage of the controller.

## 4.2 Simulation for Voltage Regulation by Using CC-VSI

Data of machine used for simulation are given in appendix-A. the circuit diagram for the voltage regulation of SEIG by using current controlled voltage source inverter is shown in Fig 4.2 & 4.3.

This system consist of

- Induction machine
- Current measurement
- Voltage measurement
- CC-VSI
- Vabc to |Vs|
- PLL circuit
- HCC
- PI-AC and PI-DC

etc

These subsystems are shown in Appendix-B.

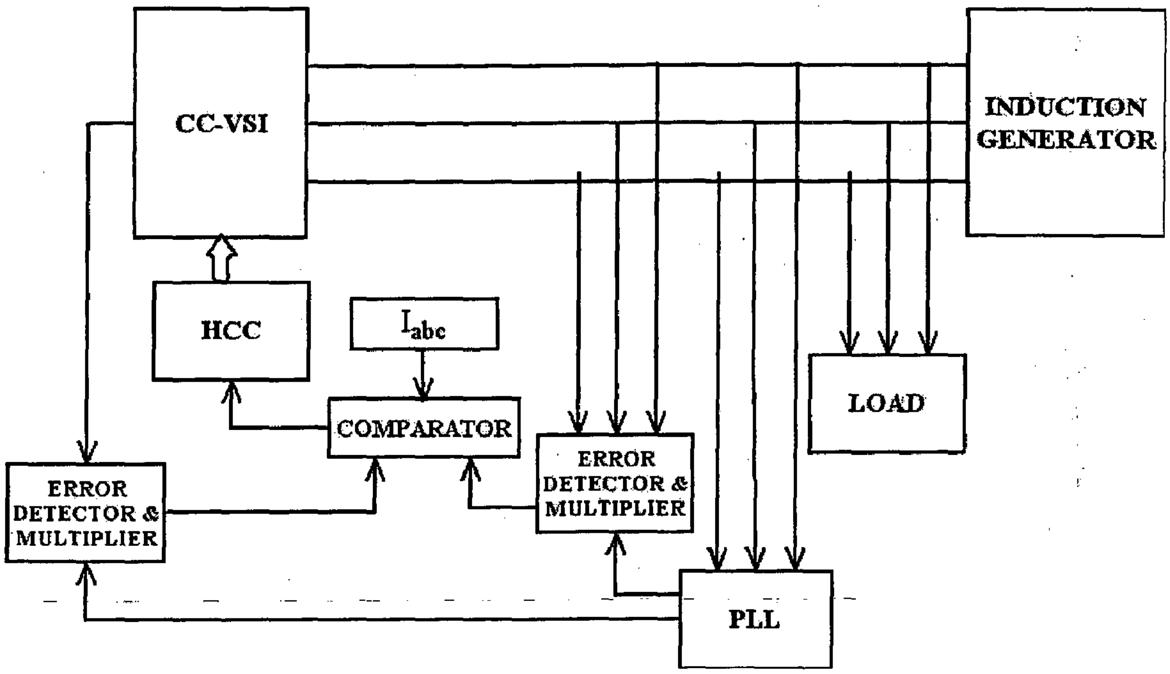



**Figure 4.2. Overall system block diagram for simulation**

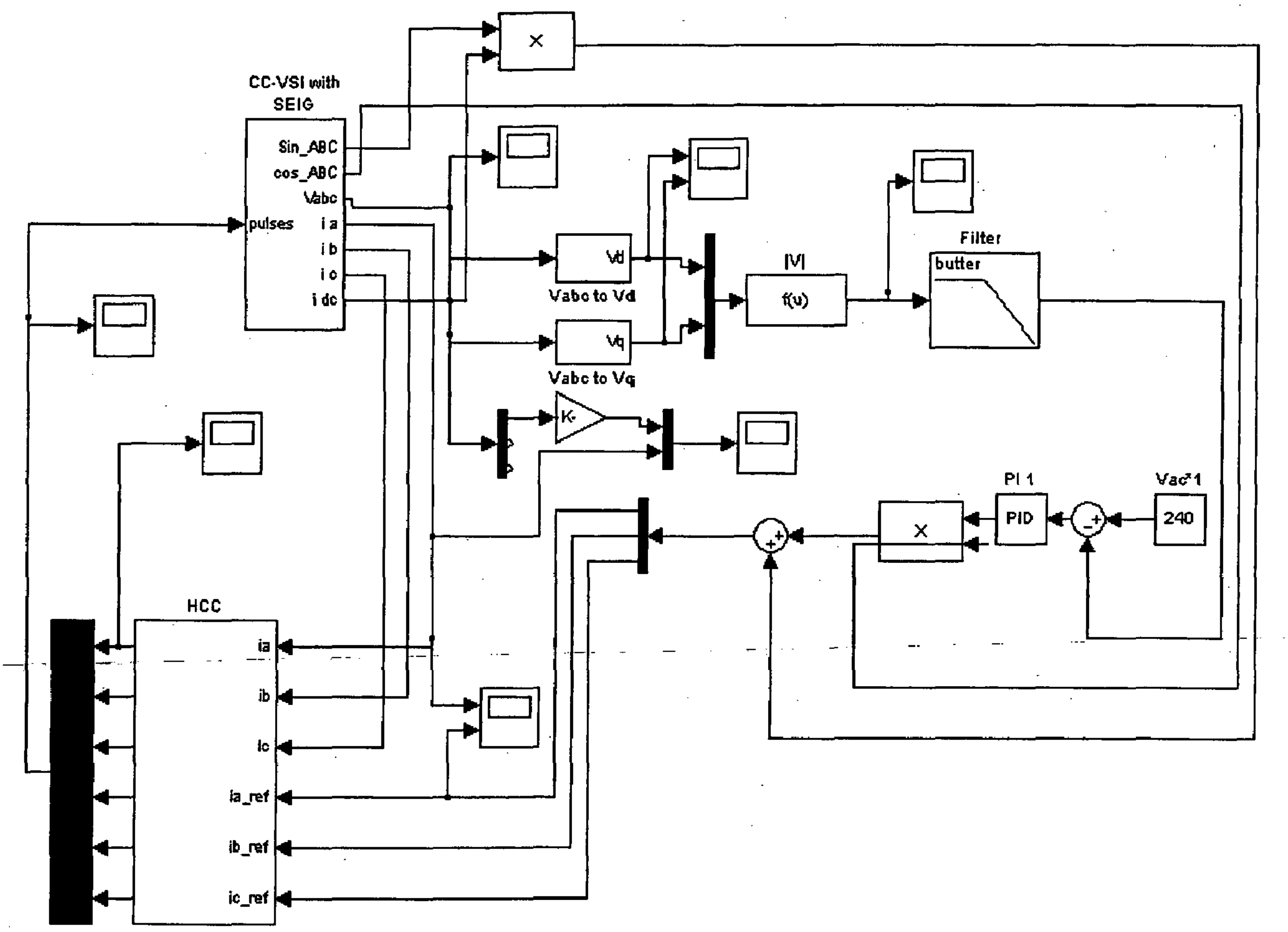



**Figure 4.3. Overall system diagram in MATLAB**

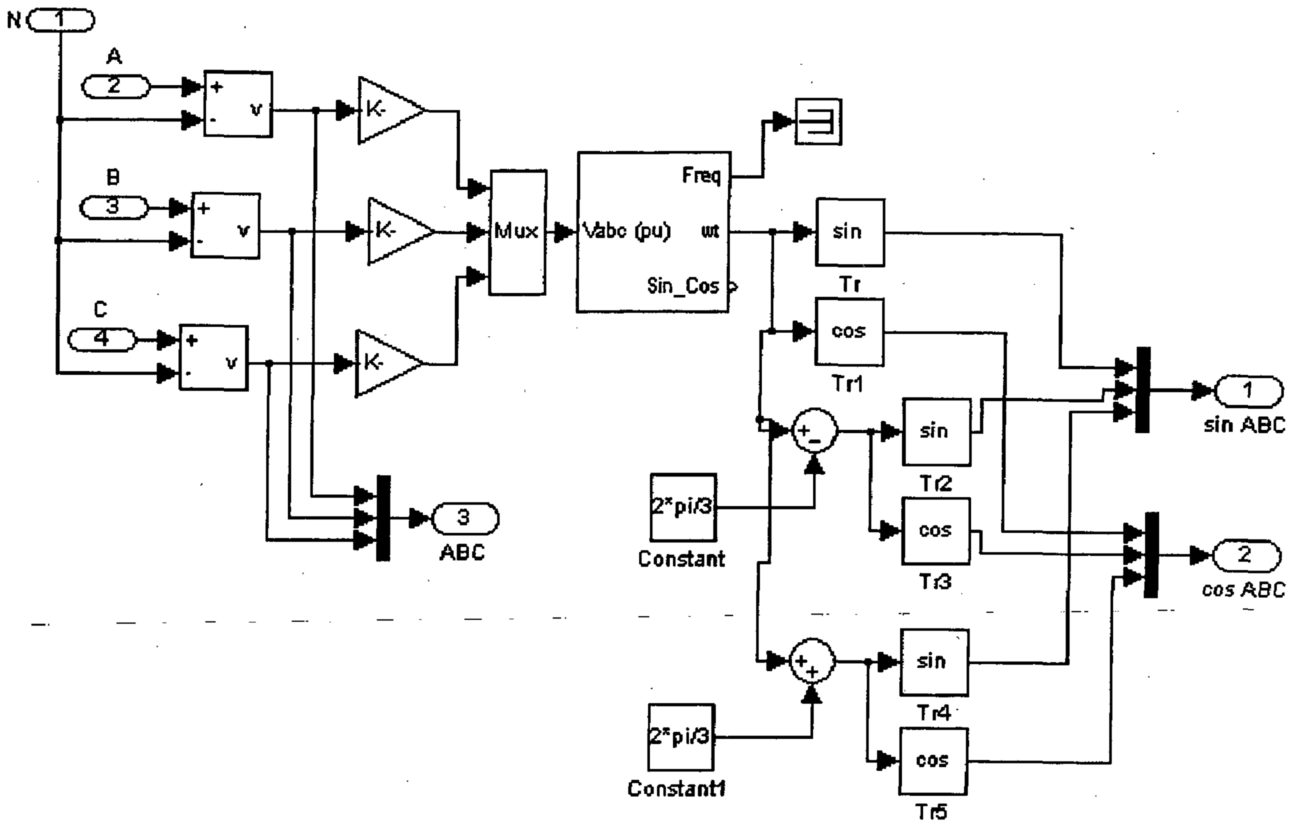
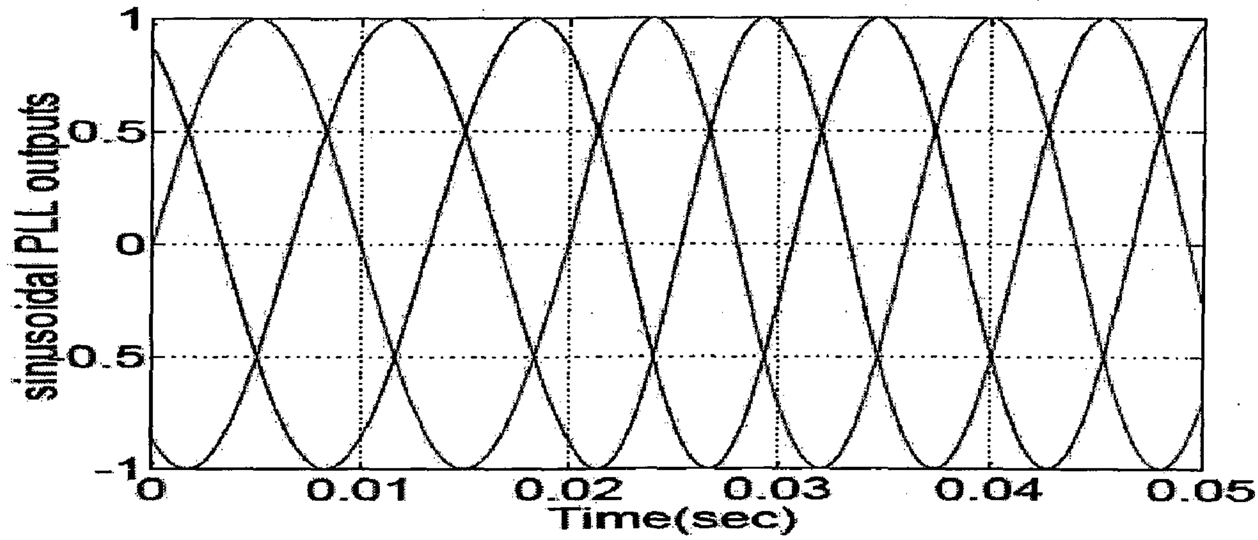



**Figure 4.4 Matlab Simulation Diagram of PLL circuit**

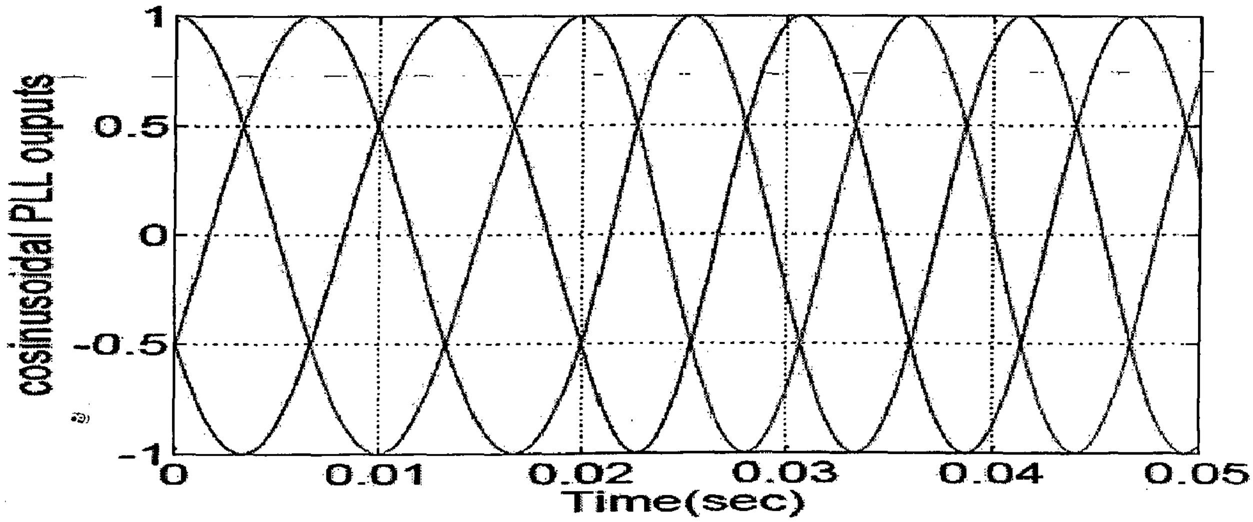
Phase-locked loops are used widely in modern communication systems. There are several kinds of phase locked receivers on the market for a variety of applications. These applications include demodulation of information carrying signals, synchronization, tracking, and ranging. Because of the importance of the application of the phase-locked loops (PLL), there has been a tremendous amount of work done in- this area.

In the early development of the PLL, the work was primarily on analog phase-locked loops (APLL). All the preceding books primarily consider the APLL. However, with increasing emphasis on digital circuitry because of decreasing cost, increased reliability, smaller size, and freedom from drift, there have been efforts to develop analog-digital (hybrid) PLL, discrete PLL, and digital PLL (DPLL). The emphasis towards the DPLL has been on the increase lately.

A PLL is a device, which continuously tries to track the phase of the incoming signal. In this work PLL is used to develop sine and co-sin templates. The output waveforms of PLL are shown in Figure 4.6.

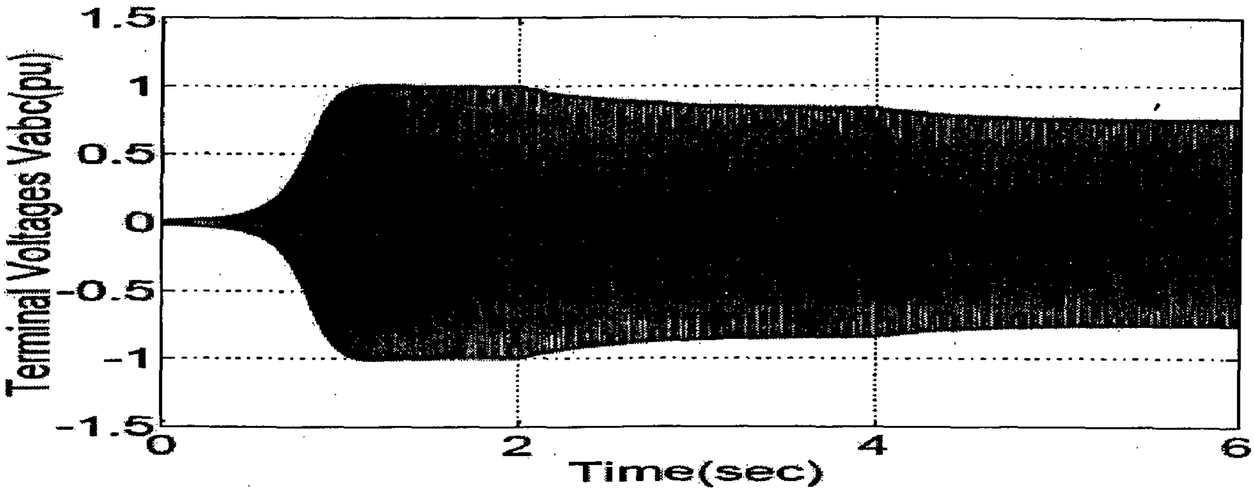



(a)

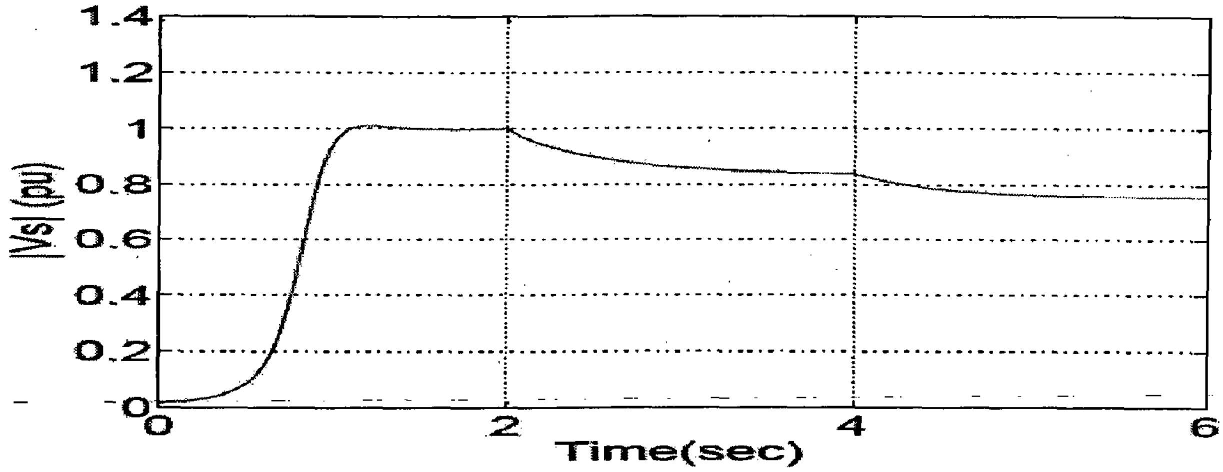



(b)

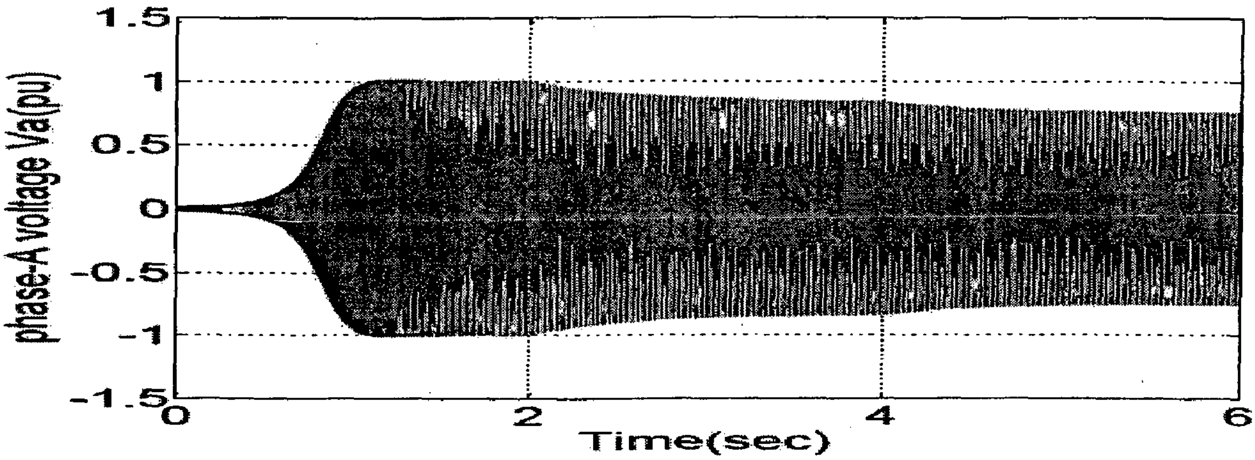
**Figure 4.5 Output Waveforms of PLL circuit (a) Sinusoidal Outputs (b) Co-sinusoidal outputs**




(a)



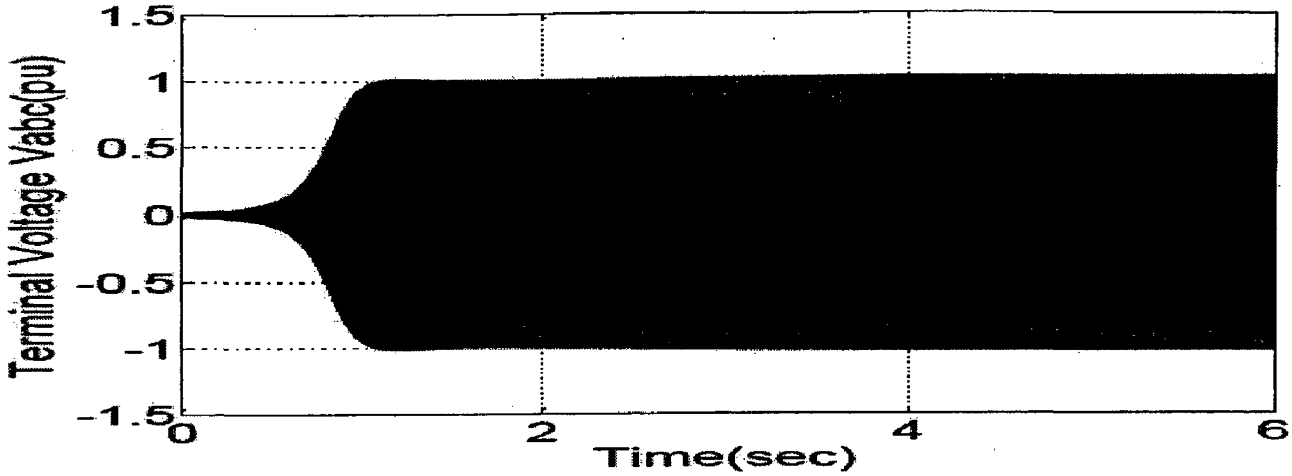

(b)



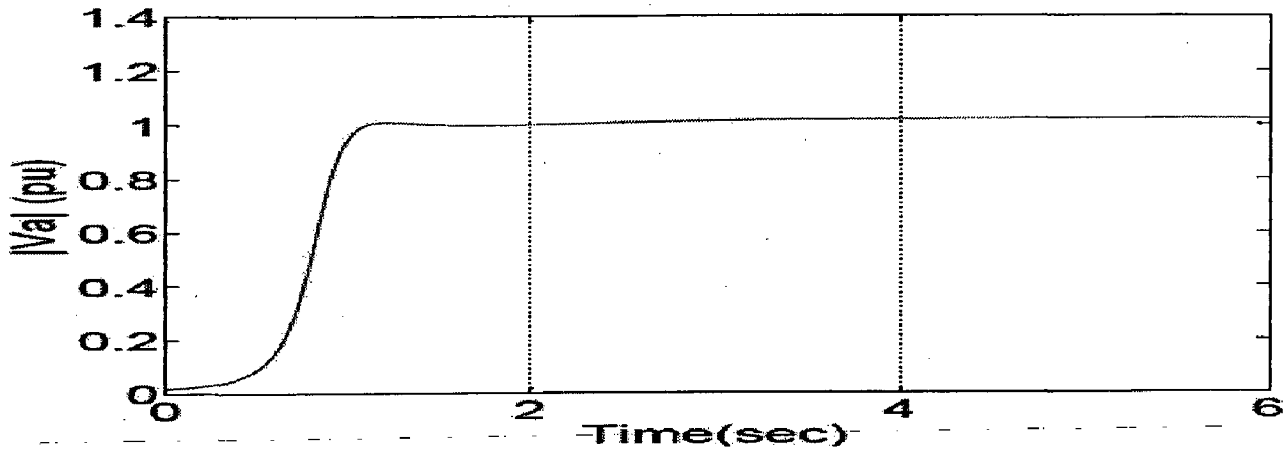

(c)

**Figure 4.6 Waveforms Produced by SEIG without Controller**

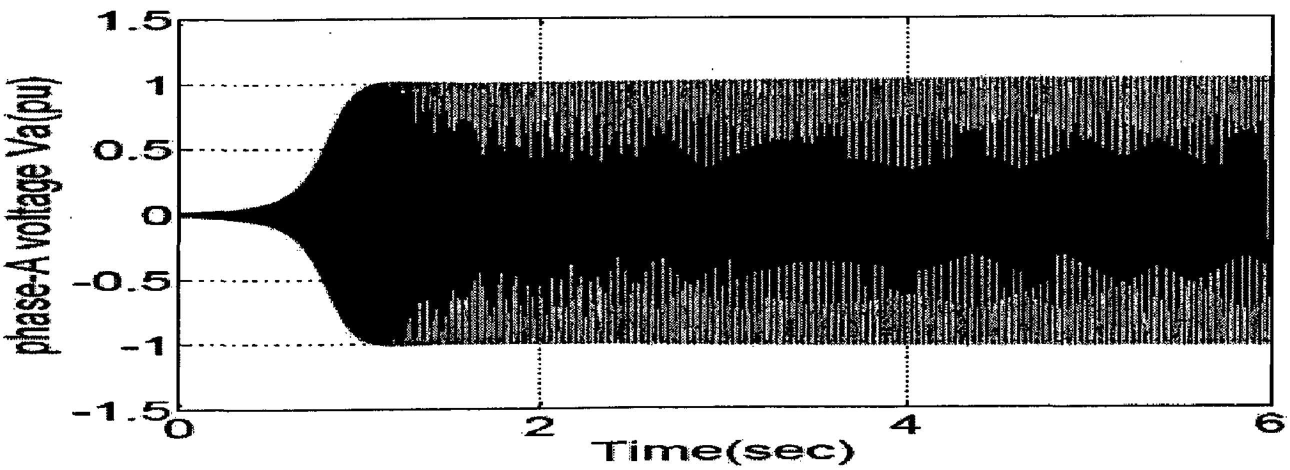
**(a) Vabc (b) |Vs| (c) Va**



(a)



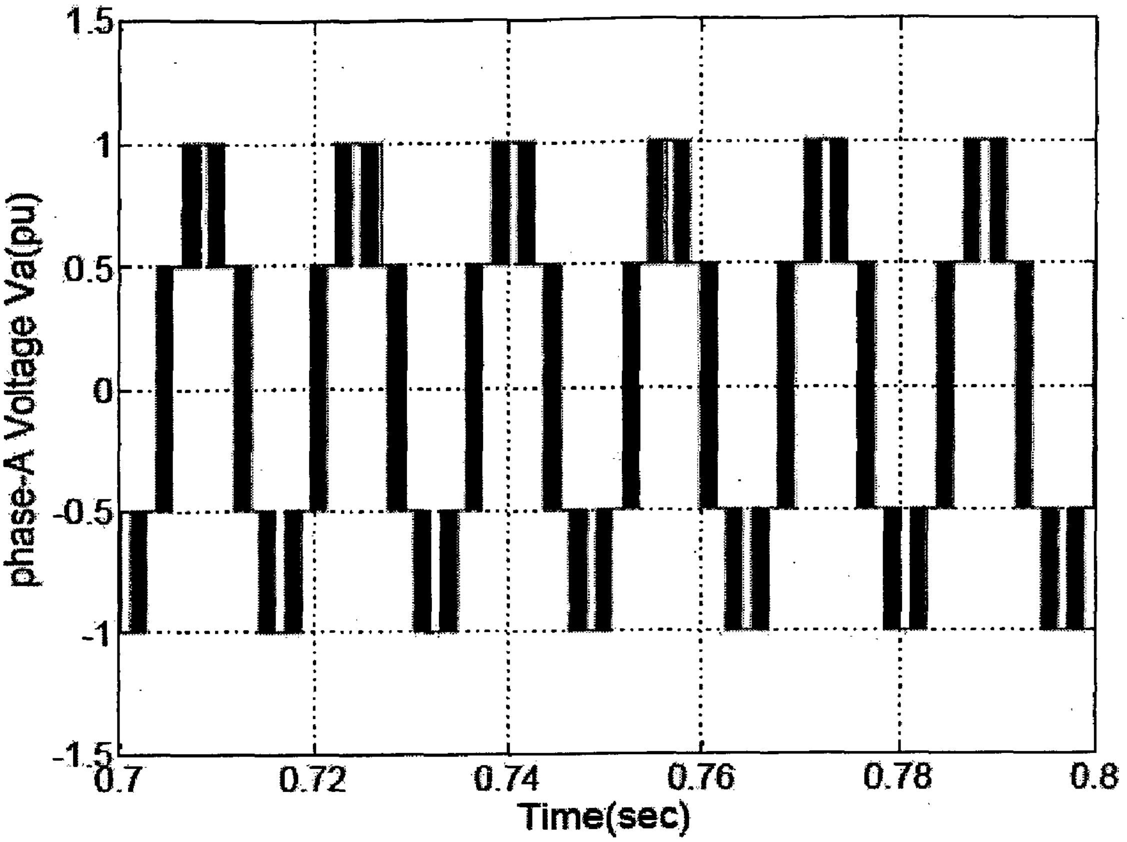
(b)



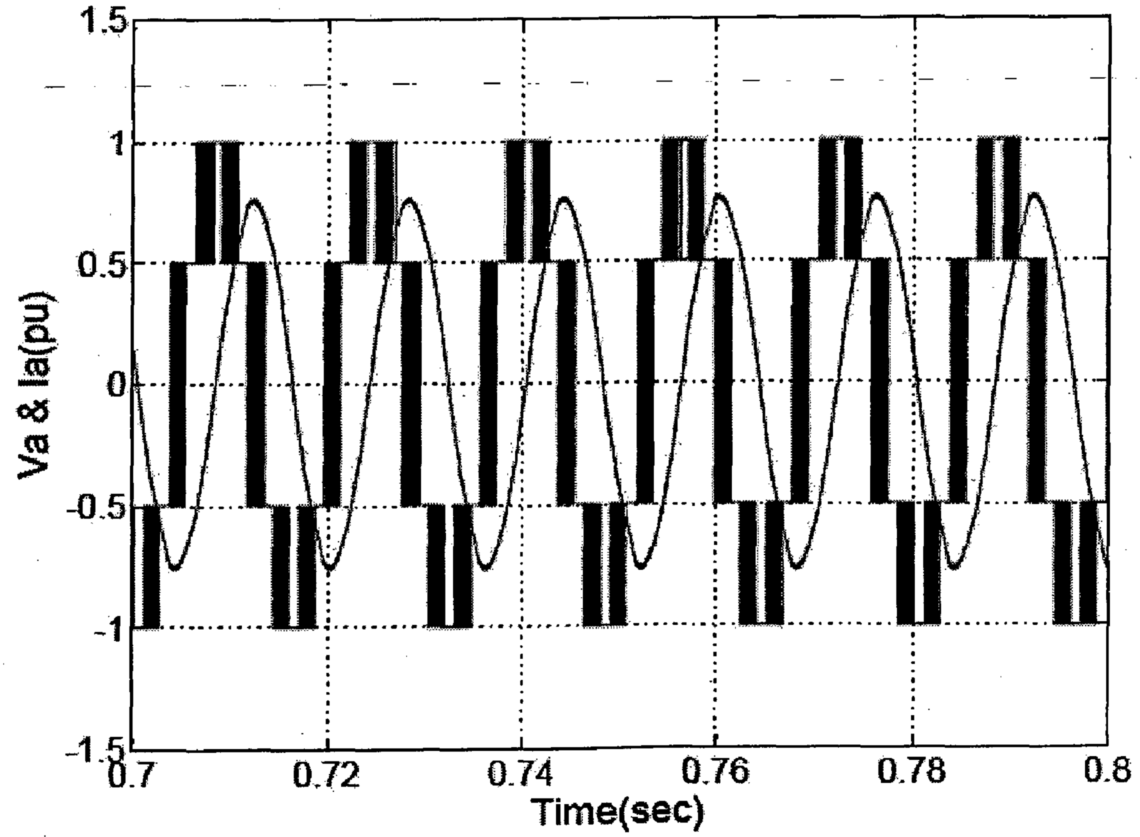
(c)

**Figure 4.7 Waveforms Produced by SEIG with Voltage Controller**

**(a) Vabc (b) |Vs| (c) Va**




(a)




(b)

**Figure 4.8 Waveforms at the Terminals of CC-VSI**

**(a) Va (b) Va & Ia**

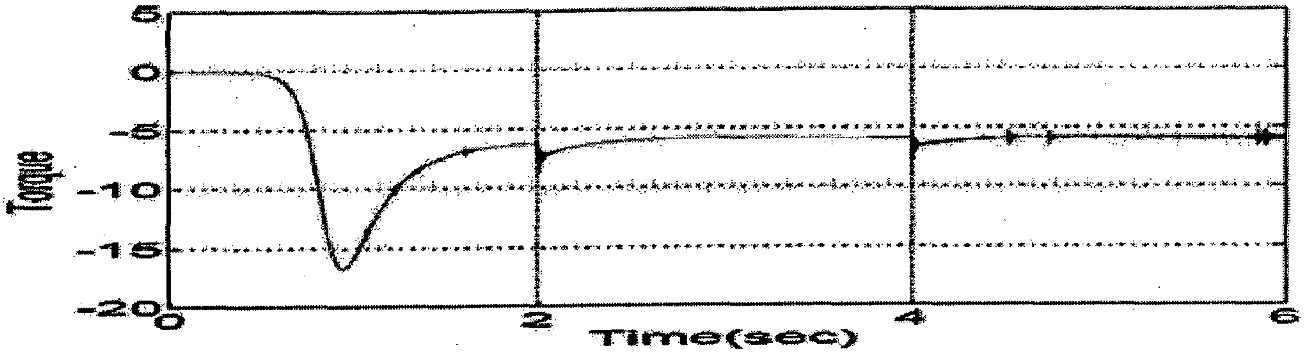
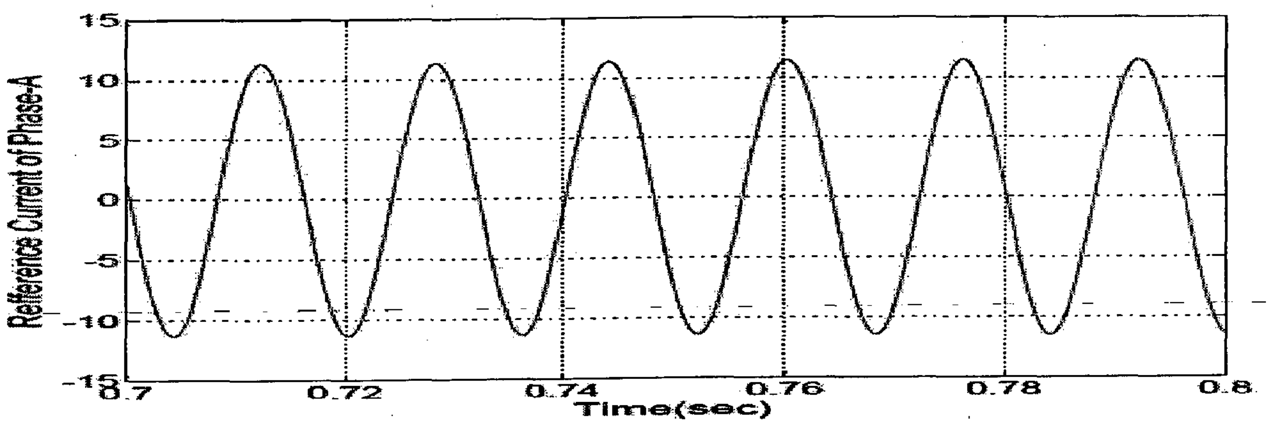
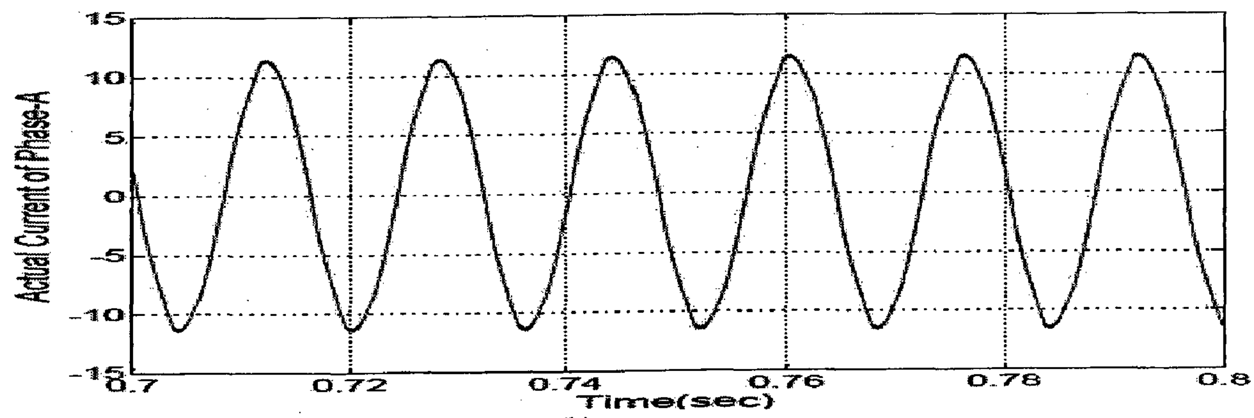



**Figure 4.9 Torque Variation**




(a)




(b)

**Figure 4.10 Waveforms of Reference & Actual Currents of Phase-A of CC-VSI**

### 4.3 Results and discussions:

Since the studied SEIG must be excited by injecting a leading reactive power into the stator, a fixed capacitor bank with 100μF/phase is used to supply the required reactive power under the over-excitation condition, which ensures the generated voltage can be sustained under a no-load condition. The function of voltage regulation is achieved by injecting the proper amount of reactive power from CC-VSI.

Self-excitation is started at t = 0 sec, by connecting capacitor bank to the IG terminals. The capacitor on the DC side of the inverter is charged to 300v. Simulation has been carried out for the 1.1 KW, 127(Δ)/220(Y) V, 60 Hz, 3-φ SEIG with balanced load.

At t = 2 sec, a step load of (250+j10) VA is connected at the terminals of the SEIG. Fig 4.6(a) shows the generated voltage waveform of IG with out any controlling technique. After starting the IG, with in a few seconds it generates rated voltage and when, some load is connected at the terminals the terminal voltage decreases. At t = 4 sec, another load of (50+j2) VA is added. The terminal voltage again decreases. The torque variation is shown in fig 4.9.

The waveforms of the terminal voltages and |Vs| after connecting the proposed voltage controller are shown in fig 4.6 and 4.7. After connecting this controller SEIG generates constant voltage from no-load to full-load. Zoomed waveforms of voltages at the terminals of CC-VSI are also shown in fig 4.8(a)&(b). The effectiveness of the proposed voltage regulator in controlling the terminal voltage of a 3-φ SEIG is evaluated by sudden application of loads. The CC-VSI based voltage regulator plays an important role in controlling the IG output voltage under various loading conditions. The reference and actual currents are in close agreement with each other and are shown in fig 4.10.

# System Hardware Development

## 5.1 Introduction:

A prototype model of traditional voltage source inverter with D.C. link capacitance is developed in the laboratory for experimentation purpose. The control scheme consists of two PI controllers and one hysteresis current controller, which are used to regulate the stator terminal voltage of the induction generator. It has fast dynamic response for regulating the voltage when the SEIG subjected to a sudden changing of load.

## 5.2 Hardware development:

The system hardware can be divided in the following blocks:

- Power circuit
- Power supplies
- Circuit protection
- Pulse amplification and isolation circuit
- AC current measurement circuit
- DC link voltage measurement circuit
- AC voltage measurement circuit
- PI controllers

## 5.3 Universal Hardware Circuits:

To develop a system some circuitry required are common like, DC power supply for the control circuitry, Gate driver circuit and measurements like DC link voltage and current sensing. These are common in all the systems and are developed using standards method which are easily available. All these hardware circuits are universal so they are taken up separately.

### 5.3.1 Power Supply 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 5.1*; 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. The data sheets for Voltage Regulators specified above are given in Appendix – C.

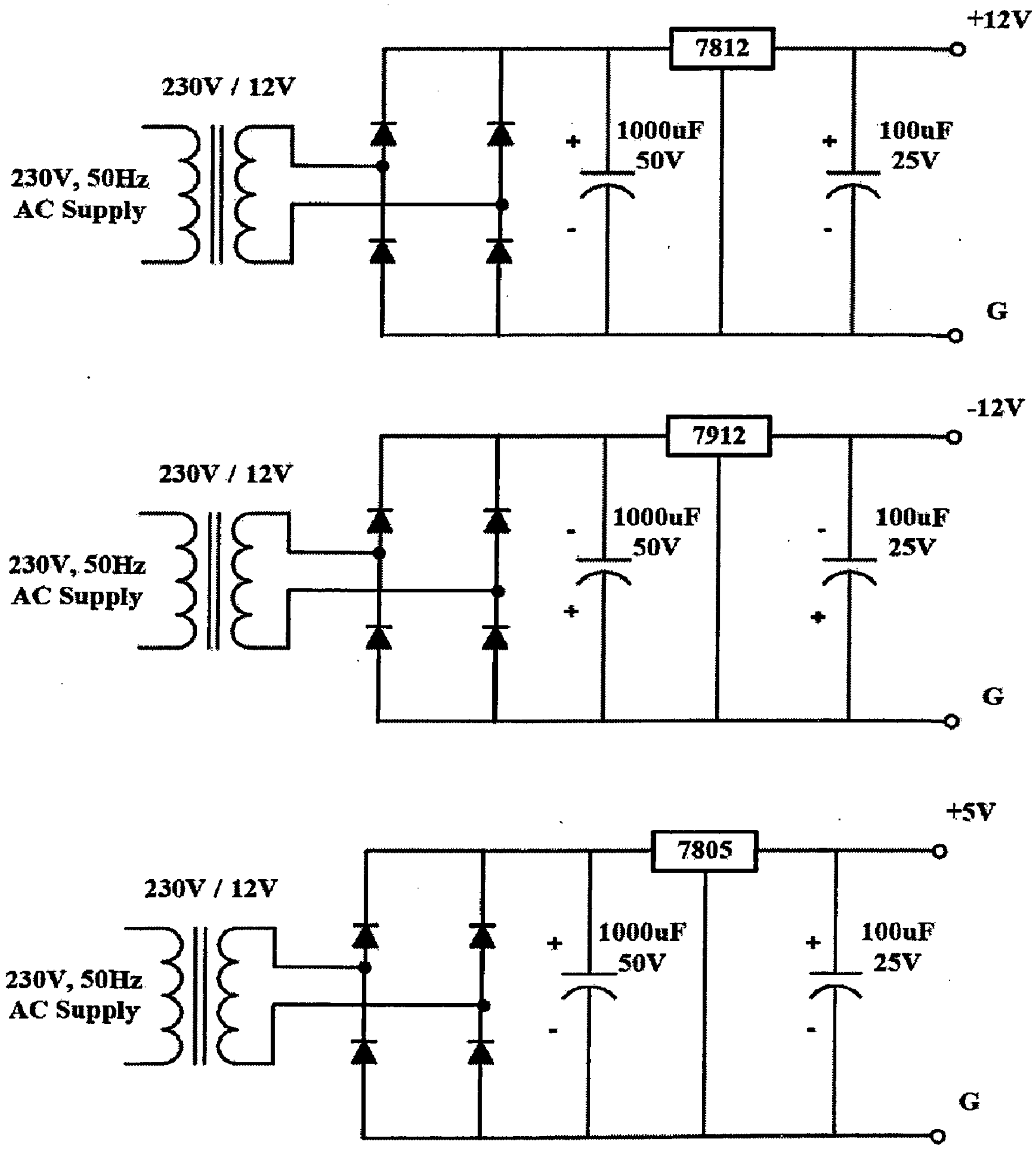



*Figure 5.1: Circuit Diagrams for IC regulated Power Supplies*

| DC VOLTAGE | IC REGULATOR |
|---|---|
| +5V | 7805 (TO-3) |
| +12V | 7812 (TO-3) |
| ±12V | 7812 (220Type), 7912 (220Type) |

## 5.3.2 Pulse Amplification and Isolation Circuit:

The pulse amplification and isolation circuit for IGBT is shown in *figure 5.2*. 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 IC connected across the output of isolation circuit. It clamps the triggering voltage at 12.

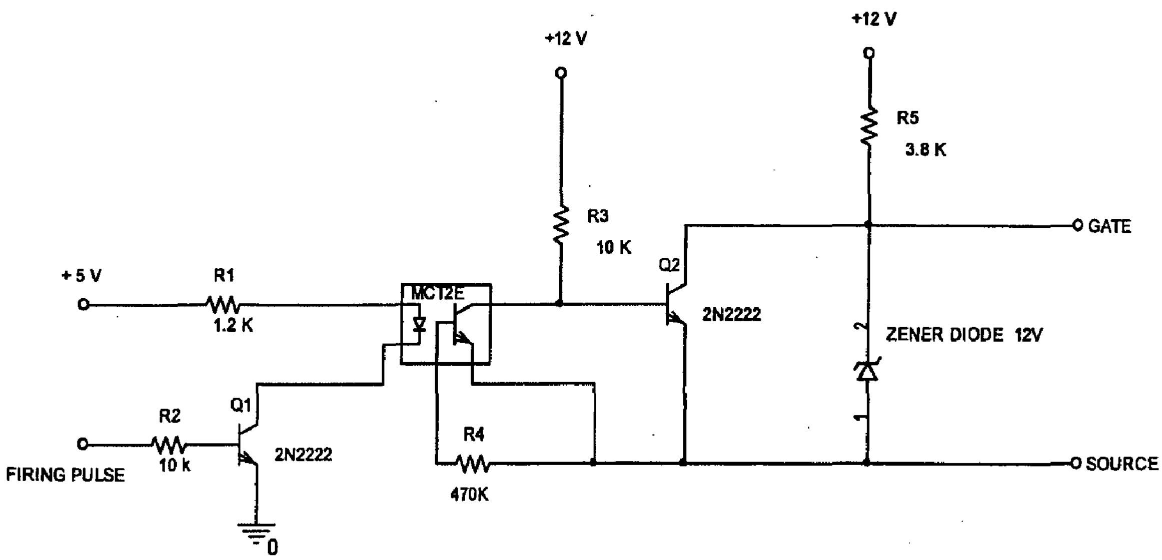



***Figure 5.2: Pulse amplification and isolation circuit***

## 5.3.3 DC Link Voltage Sensing Circuit

The dc output voltage of the capacitor is sensed through isolation amplifier AD202 for the voltage control of the converter. We are using AD202 of SIP configuration, although it is available in DIP configuration. AD202 provide the total galvanic isolation between input and output stages of the isolation amplifier through the use of internal transformer coupling. It gives a bi-polar output voltage +5v, adjustable gain range from 1v/v to 100v/v, +0.025% max non-linearity, 130db of CMR and 75mw of power consumption. Circuit diagram is shown in *fig 5.3* and for IC configuration and special features refer to the Appendix. In the shown figure output amplifier is made using op-amp which will be helpful in calibration. The transient response will deteriorate by using passive filter at the input side of AD202; but to reduce the ripples in measurement and control purpose it cannot be avoided.

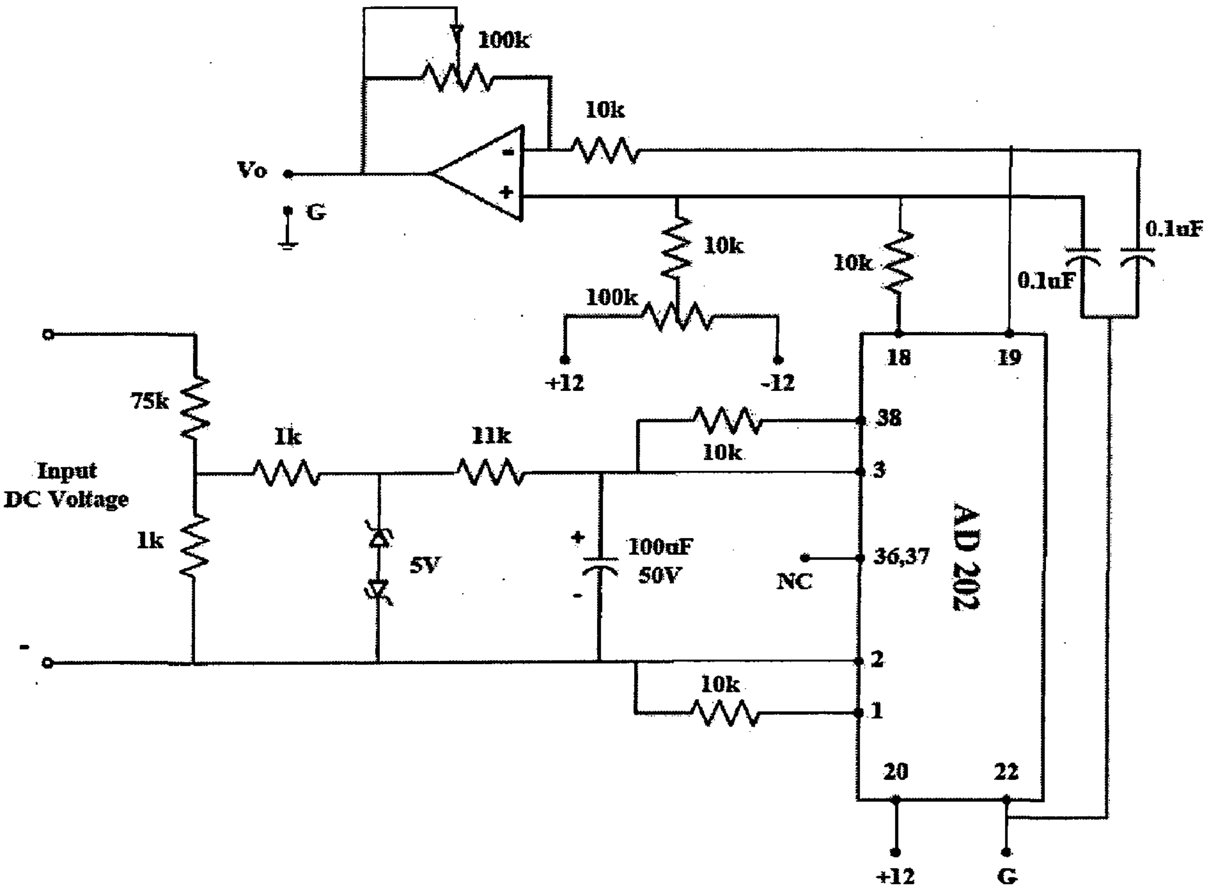



*Figure5.3: Circuit Diagram used for DC-Link Voltage Sensing and Calibration using AD 202.*

## 5.3.4 Current Sensing Circuit

Closed-loop HALL-Effect current sensors are widely used in a variety of applications requiring an accurate, fast response signal proportional to the current being measured. Products are available for panel and PCB mounting covering primary current up to 1000A and provide complete galvanic isolation between the primary and the measuring circuit. The current that passes through the secondary winding is the output current. Main features of the current-sensor used are:

1. High accuracy.
2. Galvanic isolation between primary and secondary.
3. Non-Contact ness.
4. Covers ac, dc and impulse current measurements.
5. Ease of installation.
6. Wide dynamic range.

Closed-loop Hall effect current-sensors use the ampere-turn compensation method to enable measurement of current from dc to high frequency with the ability to follow rapidly changing level or wave shapes. The application of primary current ($I_p$) causes a change of the flux in the air-gap, this in turn produces a change in output from the hall element away from the steady-state condition. This output is amplified to produce a current ($I_s$) which is passed through the secondary winding causing a magnetizing force to oppose that of the primary current, there by, reducing the air-gap flux. The secondary current will increase until the flux is reduced to zero. At this point, the hall element output will have returned to the steady state condition and the ampere-turn product of the secondary circuit will match that of the primary.

The circuit diagram used for converting secondary current to voltage and then calibrating by using an op-amp with buffer is shown in *fig 5.4*.

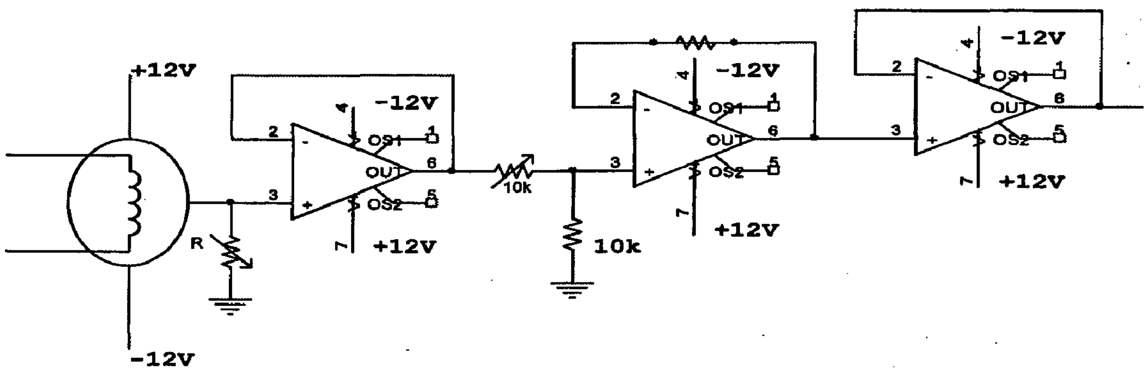



***Figure5.4: Circuit Diagram used for current sensing and calibration.***

The current that passes through the secondary winding is the output current. The transformation ratio is calculated by the standard current transformation equation

$N_pI_p=N_sI_s$

Where

$N_p$= primary current, Ns= secondary current

$I_p$= primary current, Is = secondary current.

## 5.4 PI controller with Analog Multipliers

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 5.5*. The transfer function of the circuit in the linear region of its operation is given;

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

$$where, T_C = C_f R_f and$$

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

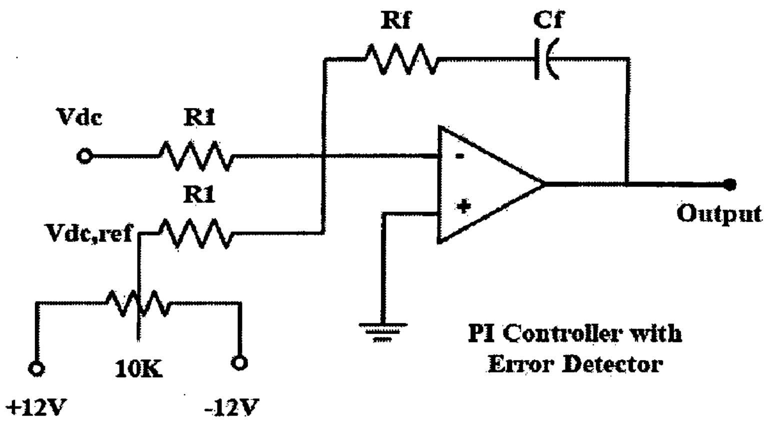



***Figure 5.5: Analysis of PI controller with Error Detector***

The output of the PI controller will estimate the peak of the fundamental current that has to drawn from the source. Using voltage supply templates by multiplying them with the peak value reference currents are estimated. Therefore for multiplication operation IC AD 633 is selected and used to implement the above operation. The above operation is shown in circuit form in *fig 5.6*

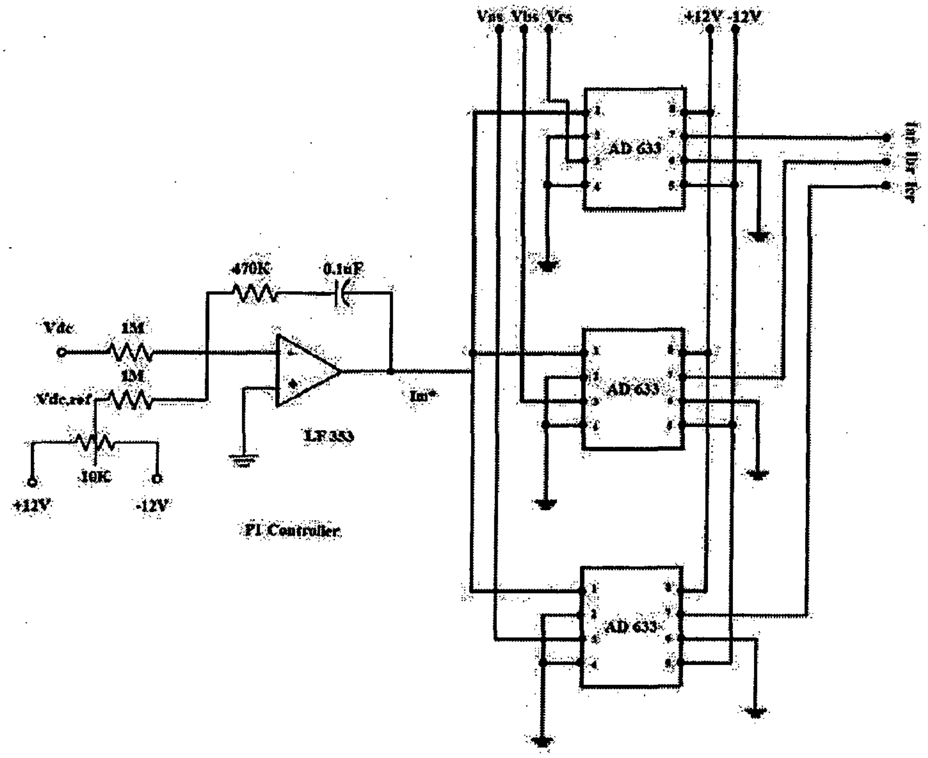



***Figure 5.6: PI controller with error detector and analog Multipliers using AD633***

## 5.5 Error Estimation Circuit

The above discussed circuit is used to generate the reference currents that have to be drawn from the supply. After estimation of reference currents the error has to be estimated which the APF has to supply to the load for compensation. This will be fed to the pulse generation circuit. To estimate the error pcb 2 is made. Here actual currents are sensed using the current sensor circuit, error is estimated and fed to pulse generation circuit. The circuit diagram is shown in *fig 5.7.* There variable gain has been provided for calibration purpose. Same circuit is used to estimate error individually for all phases. The error estimated with non-linear current and sinusoidal reference currents are shown in *fig 5.7.*

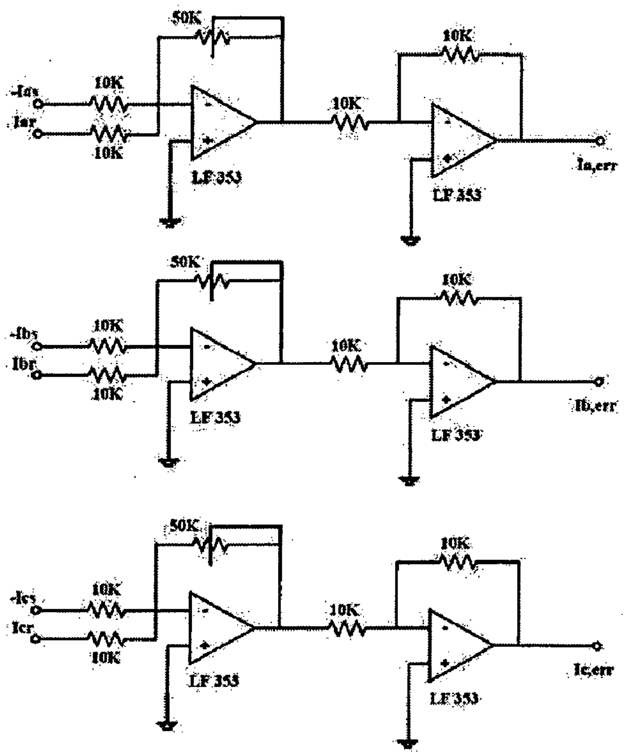



*Figure 5.7: Error estimation circuit for all the three phases.*

## 5.6 Circuit Protection

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

IGBTs are increasingly the switch of the choice for pwm rectifiers for 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

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.

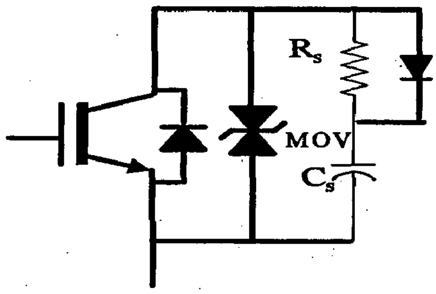



***Figure5.8. Snubber circuit of IGBT***

***(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.

## 5.7 AC voltage sensor

The peak amplitude wave and rectified wave is obtained by using isolation amplifier AD202, which provides isolation between the output and input stages through the use of internal transformer coupling. The divider circuit divides the rectified wave with peak amplitude of the wave. The scaling for AD202 isolation amplifier was adjusted as for 10V input, their will be 1V output.

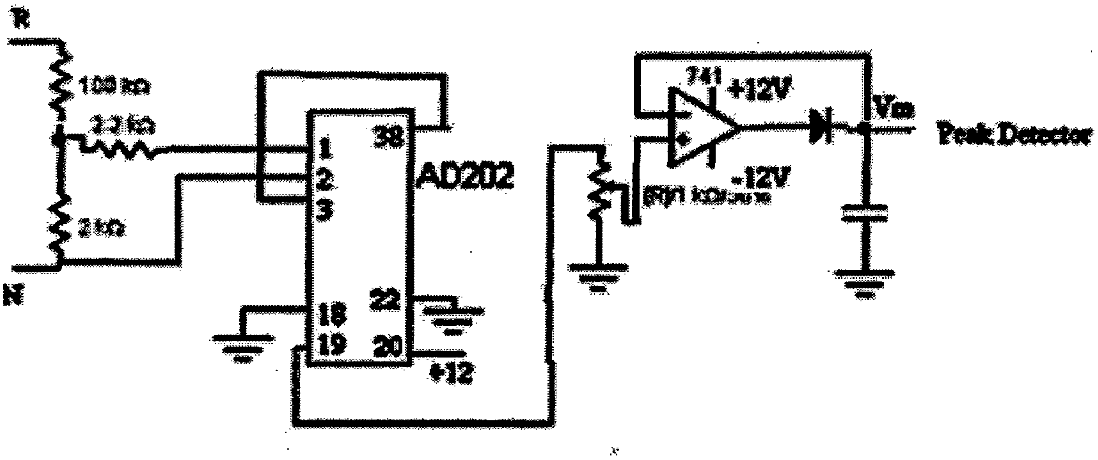



**Figure 5.9 AC voltage sensor**

## 5.8 Experimentation results:

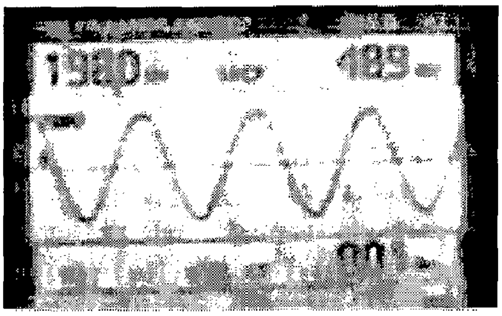


**Figure 5.10 Voltage Sensor Input Waveform**

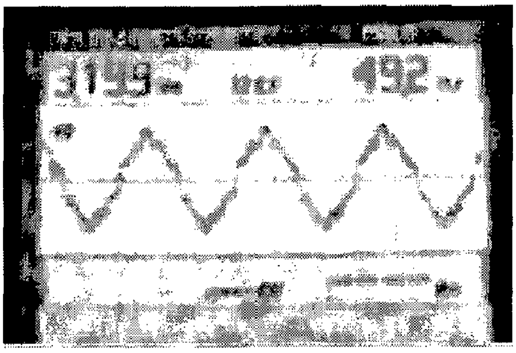


**Figure 5.11 Output Waveform of Voltage Sensor**

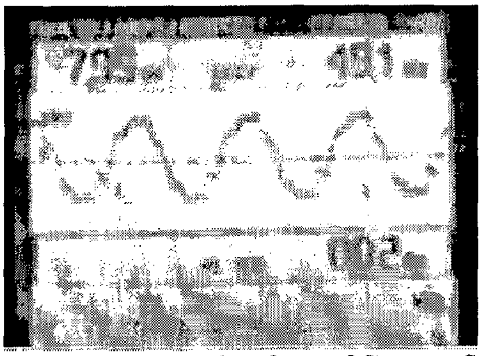


**Figure 5.12 Output Waveform of Current Sensor**

Output waveform of voltage sensor is sincerely following the input. Both input and output Waveforms are shown in Fig 5.10 & 5.11 respectively. These voltage sensors are used to sense the three phase voltages. Current sensor is used to sense the load current. The output waveform of current sensor is shown in Fig 5.12. This Waveform has been obtained by connecting a light load to 220 V supply through current sensor. Only PLL circuit is left out to complete total system hardware.

## CONCLUSION AND SCOPE FOR FUTURE WORK

In this dissertation work the voltage control of employing a voltage regulator to regulate the generated voltage of an isolated self-excited induction generator (SEIG), subject to balanced loading conditions. i.e. the analysis of Self-Excited Induction Generator is done. A simple and generalized dynamic model of SEIG is used in synchronously rotating reference frame. The simulation has been carried out for a stand-alone induction generator system with CC-VSI using MATLAB/SIMULINK software. The scheme by using shunt capacitors and CC-VSI has been considered for reactive power compensation for voltage regulation.

The analyzed results show that the performance of the studied SEIG under balanced loading conditions has been effectively improved by the proposed compensating method. This has faster dynamic response for regulating the voltage when the SEIG is subjected to a sudden load perturbation. The voltage regulating scheme is adaptive to the changing load condition, and hence it is possible to operate the SEIG at constant voltage from no load to filll load condition.

Although this work completed the voltage regulation successfully in balanced load condition, some work can be done in future, which may be listed as

- Effectiveness of CC-VSI can be tested for unbalanced loads.
- Effectiveness can be tested for nonlinear load such as rectifier load.

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# List of Publication Submitted

The publication submitted in *"National Power Systems Conference (NPSC-2006), Indian Institute of Technology, Roorkee 2006"* is listed below. The acceptance will be communicated in July 2006.

[1] "Analysis of Voltage Control for Self-Excited Induction Generator Using a Current Controlled Voltage Source Inverter (CC-VSI)".

# Appendix – A

## Parameters Machine for Study

**Simulation Study**

1.1 kW. 127(. )/220(Y) V, 8.3(. )/4.8(Y) A,

60 Hz, $R_s$=$R_r$= 2.067. , $X_{ls}$ = $X_{lr}$ = 2.382. ,

H = 0.082s.

## Hall-Effect Current Transformers/Sensors

Closed-loop HALL-Effect current sensors are widely used in a variety of applications requiring an accurate, fast response signal proportional to the current being measured. Products are available for panel and PCB mounting covering primary current up to 1000A and provide complete galvanic isolation between the primary and the measuring circuit.

Closed-loop Hall effect current-sensors use the ampere-turn compensation method to enable measurement of current from dc to high frequency with the ability to follow rapidly changing level or wave shapes. The application of primary current ($I_p$) causes a change of the flux in the air-gap, this in turn produces a change in output from the hall element away from the steady-state condition. This output is amplified to produce a current ($I_s$) which is passed through the secondary winding causing a magnetizing force to oppose that of the primary current, there by, reducing the air-gap flux. The secondary current will increase until the flux is reduced to zero. At this point, the hall element output will have returned to the steady state condition and the ampere-turn product of the secondary circuit will match that of the primary. The current that passes through the secondary winding is the output current.

Main features of the current-sensor used are:

1) High accuracy.
2) Galvanic isolation between primary and secondary.
3) Non-Contact ness.
4) Covers ac, dc and impulse current measurements.

5) Ease of installation.
6) Wide dynamic range.

Linearity of the sensor is 0.1% of normal primary current and the operating temperature range is 0-70°C.

## Voltage Sensors AD202/AD204

### Features

I. Small Size: 4 Channels/Inch
II. Low Power: 35mW (AD204)
III. High Accuracy: ±0.025% Max Nonlinearity (K Grade)
IV. High CMR: 130 dB (Gain = 100 V/V)
V. Wide Bandwidth: 5 kHz Full-Power (AD204)
VI. High CMV Isolation: ±2000 $V_{PK}$ Continuous (K Grade) (Signal and Power)
VII. Isolated Power Outputs
VIII. Uncommitted Input Amplifier

### Applications

1) Multi-channel Data Acquisition
2) Current Shunt Measurements
3) Motor Controls
4) Process Signal Isolation
5) High Voltage Instrumentation Amplifier

### General Description

The AD202 and AD204 are general purpose, two-port, and transformer-coupled isolation amplifiers that may be used in a broad range of applications where input signals must be measured, processed, and/or transmitted without a galvanic connection. These industry standard isolation amplifiers offer a complete isolation function, with both signal and power isolation provided for in a single compact plastic

SIP or DIP style package. The primary distinction between the AD202 and the AD204 is that the AD202 is powered directly from a 15 V dc supply while the AD204 is powered by an externally supplied clock, such as the recommended AD246 Clock Driver.

The AD202 and AD204 provide total galvanic isolation between the input and output stages of the isolation amplifier through the use of internal transformer coupling. The functionally complete AD202 and AD204 eliminate the need for an external, user-supplied dc-to-dc converter. This permits the designer to minimize the necessary circuit overhead and consequently reduce the overall design and component costs. The design of the AD202 and AD204 emphasizes maximum flexibility and ease of use, including the availability of an uncommitted op-amp on the input stage. They feature a bipolar ±5 V output range, an adjustable gain range of from 1V/V to 100 V/V, ± 0.025% max nonlinearity (K grade), 130 dB of CMR, and the AD204 consumes a low 35mW of power.

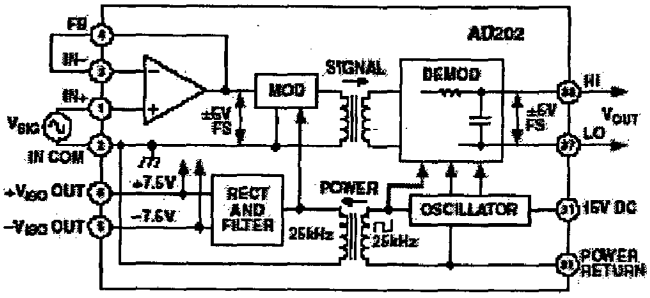


*Figure A-1*

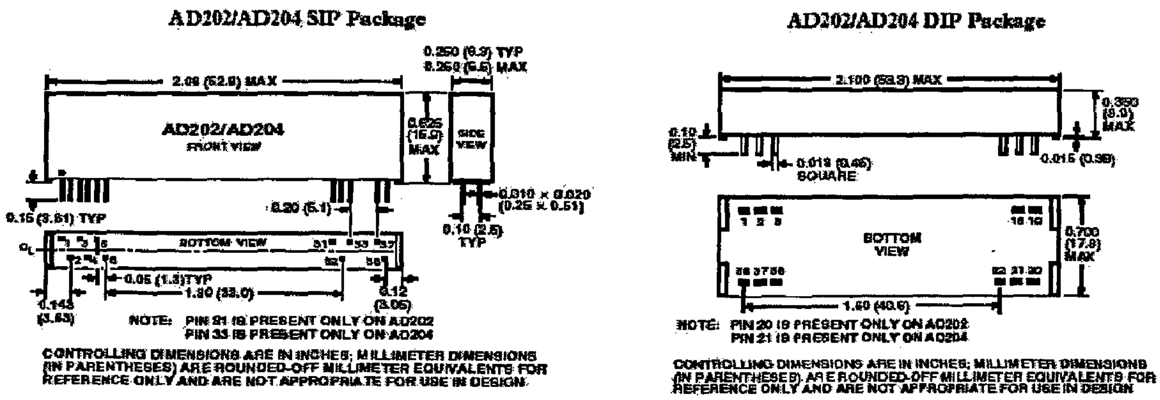


*Figure A-2*

The functional block diagram of AD202 is shown in *fig A-1* and *fig A-2* shows the pin configuration of AD202 in SIP and DIP package respectively.

## Power Semiconductor Switches

Traditionally thyristors have been used as switches in converters. But the PWM technique requires forced-commutation of thyristors that necessitates the need for additional commutation circuitry, thus, adding to the cost, bulkiness and complexity of the converter circuit. Further more, the thyristors can't be switched at higher frequencies and this puts a limit on the switching frequency of the PWM converters. In recent years, more and more power semiconductor devices with high switching frequencies and/or power capability such as bipolar transistors, power MOSFETs, GTOs and IGBTs are becoming quite popular. This makes possible the easy use of the PWM technique to improve the quality of input current waveform and power factor.

## Power Transistor

A power-transistor employed as a solid-state switching device and requires only one signal to turn it ON and it turns OFF automatically on the removal of this signal. Thus, in the PWM voltage-source converters, no commutation circuitry is required and the problems associated with the commutation (of thyristors) are automatically overcome. Further, the control circuitry is much simplified. Since the turn-ON and turn-OFF times of the order of 1μsec or less are achieved in power transistors, the devices can be operated at a high switching frequency. The power transistors suffer from a major problem of the second breakdown (SB), which is a destructive phenomenon, resulting from the current-flow to a small portion of the base and producing localized hotspots. If the energy in these hotspots is sufficient, the excessive localized heating may damage the device. Other drawbacks are the sensitivity to transients and low overload capacity. The schematic block diagram is shown in *fig A-3*.

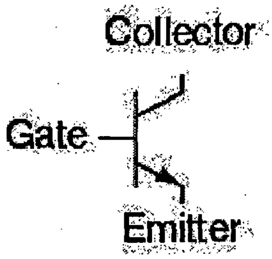


*Figure A-3*

## Gate Turn OFF Thyristors (GTOs)

GTOs seems to hold a lot of promise fo the future. Presently their use is limited because of high cost and non-availability. A GTO can be turned-OFF by a negative gate-pulse and can be triggered by a positive gate-pulse. When a GTO has been turned-ON, it behaves as a thyristor. It can be manufactured for the highest voltage and current ratings (several kV and kA) and is mainly used for high power and/or high voltage equipment. With the obvious advantage of the non-requirement of a commutation circuit, which lays a restriction on the operating frequency of thyristors, the GTO has also some disadvantages. During turn-ON and turn-OFF, a GTO acts like a transistor, running a risk of second breakdown if the gate-pulse is insufficient. A GTO has a higher ON-state voltage as compared to a thyristor and the latching and holding currents are also high.

## Power MOSFET

A Power Mosfet is a voltage-controlled device and requires only a small input current. The switching speed is very high and the switching times are of the order of nano-seconds. Power Mosfet's are finding increasing applications in low-power, high frequency converters. Mosfet's don't have the problems of the second breakdown as do the BJT's. Mosfet's are of two types

1) Deletion Mosfet's and,
2) Enhancement Mosfet's.

The main features of power Mosfet's are summarized as below:

I. Better reliability.
II. Simpler and cheaper driver circuitry.

III. Higher switching frequency (well above 1Mhz) due to fast switching speed and better efficiency, smaller overall circuit size and weight at high frequency.

IV. High overload and peak current handling capability.

V. Absence of second breakdown reduces the snubber circuitry in switching applications and

VI. Better temperature capability.

Like any other semiconductor device, Power Mosfet's do have their own subtleties and these must be recognized for the successful operation of the devices.

STATIC CHARGE: Power Mosfet's can be damaged by static charge when handling, testing or installing into a circuit. However, they have greater self capacitance and are much more able to absorb the static charge. It is wise to employ the elementary precautions such as the grounded wrist straps, electrically grounded stations and grounded soldering irons.

GATE-VOLATGE TRANSIENTS: Excessive voltage applied to the gate of a power Mosfet's will punch through the gate oxide, thus causing a permanent damage. A typical gate-source voltage rating is ±20V. The simplest solution where the gate voltage transients are suppressed is to connect a clamping Zener diode between the gate and the source.

All the power Mosfet's have an integral body-drain diode built into their structure. This is shown in the *fig A–4*.

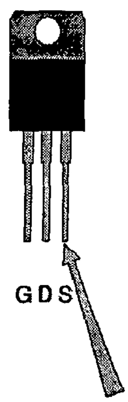


*Figure A-4*

## INSULATED GATE BIPLOAR JUNCTION TRANSISTORS (IGBT'S)

An IGBT combines the advantages of the BJT's and Mosfet's. It has high input impedance like Mosfet's and low ON-state condition losses like BJT's. But there is no second breakdown problem like BJT's.

An IGBT is a voltage-controlled device like a power Mosfet. It has the advantages of ease of gate-drive, peak-current capability and ruggedness. It is inherently faster than a BJT. However, the switching speed is inferior to that of Mosfet's. They have three terminals, and they are Gate (G), Collector(C) and Emitter (E). IGBT's are finding increasing applications in medium-power applications such as dc and ac motor drives, power supplies, etc. The schematic diagram is shown in*fig A-5.*

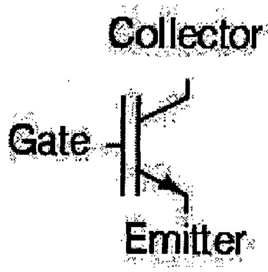


*Figure A-5*