PERFORMANCE INVESTIGATIONS ON VOLTAGE CONTROLLED SELF-EXCITED INDUCTION GENERATOR

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power Apparatus and Electric Drives)

By

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CANDIDATE'S DECLARATION

I hereby declare that work which is being presented in this dissertation entitled **"PERFORMANCE INVESTIGATIONS ON VOLTAGE CONTROLLED SELF-EXCITED INDUCTION GENERATOR"** submitted in partial fulfillment of the requirement for the award of degree of **Master of Technology** in **Electrical Engineering** with specialization in **Power Apparatus and Electric Drives** of the institute, is an authentic record of my work under supervision of **Dr. Pramod Agarwal,** Professor & **Shri Y. P. Singh,** Assistant 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.

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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.

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ABSTRACT

Now a days world is hungry for power. Every country develops more and more energy from its each and every possible resource for driving their economic and social growth towards new heights. India is no exception in that. For that so many scientist and engineers are working in finding more economic and viable power generating solutions which are also concerned with green and clean energy and also for reason of increasing cost of fuel. Renewable sources fits in this requirements. As of now India's most power (about 70%) is generated through thermal power plant which uses coal and we have huge unexplored potential of wind and mini and micro hydro power in different parts of country.

Power in every village is also a dream up to now because their geographic locations and other infrastructure problems. For this reason country like ours there are huge potential and demand for small isolated power generation systems.

The squirrel cage induction generators are widely used for low and medium power generation. These are ideally suited for non-conventional energy generation and have number so advantages over synchronous generator like low cost, simple construction, ruggedness, and brushless rotor, absence of DC source, maintenance-free nature and self-protection against short circuits.

In a stand-alone operation, the three-phase induction generator operates in the self-excitation power generation mode when a capacitor bank connected in parallel with its stator terminal ports and driven by a renewable energy prime mover as wind turbine.

However, they must deliver power to the consumer with acceptable quantity in terms of voltage, frequency, and waveform. Self Excited Induction Generator is suffered from change in voltage and frequency with change in loading and speed of prime-mover SEIG requires suitable controllers to be developed and the crucial function of such controllers would be to provide required Variable Capacitive Reactive power (VAR) to maintain constant voltage across the load at all time.

A new controller for variable speed, constant voltage operation of induction generator, in self-excited mode has been developed in this dissertation; a simple control

scheme is proposed for self-excitation control of induction generator. In this scheme, only the controller current is sensed and forced to track the reference current. The controller does not require any real time mathematical computation. The control technique also does not require information about rotor speed and position. This eliminates need for mechanical sensors, minimizing hardware and reducing overall cost. Direct sensing of the controller current enables protection of the controller from over-current. Low rating current sensors are required for this scheme as the sensors have to sense only the controller current.

The complete controller with CC-VSI and associated circuitry has been developed. All hardware components are working in co-ordination. The voltage buildup process in SEIG has been simulated in MATLAB Simulink software and the operation of SEIG is experimentally verified. The CC-VSI is simulated. The results of simulation and hardware implemented works as expected.

CONTENTS

LIST OF SYMBOLS

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

CC-VSI	Current Controlled Voltage Source Inverter
SEIG	Self-Excited Induction Generator
MMF	Magneto Motive Force
f_s	Synchronous Frequency
Ns	Synchronous speed in rpm
Vg	Air-gap Voltage
V_{abcs}	Stator Voltages
I_{abcs}	Stator Currents
V_{abcr}	Rotor Voltages
I_{abcr}	Rotor Currents
R_s, r_s	Stator Resistance
R_r, 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
θ	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
ω	Speed in rad/sec.
ω_r	Rotor Speed in rad/sec
ω_e	Synchronous speed in rad/sec
ω_s	Sleep speed (ω_e- ω_r) in rad/sec.
L_m	Mutual Inductance in Henery

C	Excitation Capacitance per Phase in farads
R_f	Filter Resistance
L_f	Filter Inductance
Te	Electromagnetic Torque
P	Number of Poles
Ic	Compensating Currents
|Vs|	Magnitude of Terminal Voltage
HCC	Hysteresis Current Controller
PWM	Pulse Width Modulation
C_{dc}	DC side Capacitance of Inverter
V_{dc}	DC side Capacitor Voltage
E	Counter EMF

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1. Introduction:

With the improvement in human society, standard of living and socio-economic development, demand for energy increases day-by-day. Due to Very steep increase in fuel cost and environmental problems like green house gases, people start thinking of using unexplored or little explored sources of energy and this lead us towards use of non conventional energy sources such as wind and small hydro powers. For distributed population the distribution of energy to remote locations where cost of infrastructure is very high isolated generation system solve this purpose. Induction generation emerges as strong choice for small size generators with its proven advantages over synchronous generator.

It is well known that an externally driven induction machine can be successfully operated as an induction generator with sustained self excitation when any source capable of circulate excitation current through machine stator and develop magnetism in it. If induction machine is connected to utility grid this power is supplied from grid. In this case supply voltage and frequency is governed by utility grid. An appropriate value of a capacitor bank is appropriately connected across the terminals of the induction machine can do the same work very satisfactorily. In this case the three-phase stand alone self-excited induction generator (SEIG) determines its own generated terminal voltage and its output frequency, which depend on the excitation capacitance, the three-phase induction machine parameters, electrical passive load constants, and the prime mover speed.

The terminal voltage of the three-phase SEIG with variable loads can be maintained constant by adjusting the value of the excitation capacitance or by controlling the prime mover speed. It demanded suitable controllers to be developed for SEIG. The crucial function of such controllers would be to provide required variable leading and lagging reactive power (VAR) to maintain constant voltage across the load at varying prime mover speed and external load.

Extensive information is available in literature on capacitive VAR requirements for SEIG at varying speed, load, and power factor. It has been found that the required capacitive VAR; a) increases with load power, b) increases with lagging VAR of load, and c) decreases with prime mover speed. Therefore, an effective capacitive VAR controller has become central to the success of SEIG system for stand-alone applications. Reactive power may be provided by switched capacitors, static VAR compensator (SVC), and static compensator (STATCOM) or CC-VSI. A switched-capacitor scheme is cheaper, but it regulates the terminal voltage in discrete steps. Electromechanical switches are found to cause unstable chattering and solid state switching needs correct timing. Static VAR compensator uses either thyristor-switched capacitor (TSC) or a thyristor-controlled reactor (TCR) with fixed capacitor. In SVC schemes, large valued capacitors and reactors are required.

STATCOM employs a current controlled voltage source inverter (CC-VSI), which internally generates capacitive/inductive reactive power. It has been found that the steady state, as well as transient performance, can be improved with CC-VSI.

In this dissertation a new controller scheme is proposed using CC-VSI its performance is found to be satisfactory on stand-alone SEIG.

Advantages of Self-Excited Induction Generator:

1. Simple and rugged construction.
2. Lower capital cost as squirrel cage induction machine is cheap among all of same rating machines.
3. 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.
4. The variable speed prime mover need not be governed.
5. 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.
6. SEIG can be operated in parallel with out any problem of synchronization i.e. they may operate at different speed and still share load.
7. Main feature is the automatic protection against external short circuit, which causes the excitation to collapse and consequently no current flow.

Disadvantages of Self-Excited Induction Generator:

1. It has poor inherent frequency and voltage regulation.
2. Its efficiency is comparatively less due to higher core and magnetizing current losses.
3. The terminal voltage waveform is likely to be distorted because of the need to stabilize the excitation for saturated conditions.
4. More heating in rotor.
5. 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 and stand alone application.
6. The most severe 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.

SEIG 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.

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 made 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 voltage control of self-excited induction generator.

1.2 Literature Review:

It has been known from decades 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 drawing lagging current for its magnetizing either from grid or synchronous generator or synchronous condenser of comparable capacity, which means system is not capable of autonomous power generation.

First experiment in this sense to operate induction machine as self excited induction generator with the help of capacitor is reported by Bassett and Potter in their paper [1] in 1935. Before that induction machine is not much used as generator.

In plenty of papers many of the concepts related to self excited induction generator have been discussed and explained. All these can be summarized in following headings [2]-[4].

1) Process of self-excitation and voltage buildup [1], [5]-[8],
2) Modeling of SEIG [9]-[20],
3) Steady-state and performance analysis [15]-[29],
4) Transient/dynamic analysis [30]-[34],
5) Voltage control and frequency control aspects [35]-[49],
6) Parallel operation of SEIG [50]-[56],
7) Induction generator for wind power system applications [57], [58].

1) Process of self-excitation and voltage buildup:

Bassett and Potter [1] 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.

Wagner [5] in 1939 gave an approximate method of analysis of self-excited induction generator at above condition by separating the real and reactive parts of the circuit. The generated terminal voltage at time of self excitation was determined by equating reactive VAR to zero, and slip by equating real power to zero.

Barkle and Ferguson [6] has presented the approximate model of both grid-connected and SIEG for studying the general aspects like power factor and short circuit behavior. They found that the induction generator does not contribute to the interrupting duty of the breaker and makes only the sustained contribution to the momentary rating of the device connected to the generator and they also give a method of analysis of SEIG using modified synchronous machine transient theory.

B.C.Doxy [7] in his paper concluded that the basic requirement for the induction motor to work as a SEIG is the leading current of correct magnitude and indicated some of its application areas.

Ooi and David [8] have studied the use of synchronous condenser in place of static capacitor for the purpose of providing excitation current and voltage regulation of induction generator. The synchronous condenser provides the reactive VARs to induction generator through slip rings, while the induction generator supplies the real power to synchronous generator.

2) Modeling of SEIG:

Various models and their applications have been presented [9]-[13] to analyze the steady-state as well as transient performance of induction machine. Same model with slide modifications can be suitably used for SEIG analysis.

Out of all available reference frames, for symmetrically operated induction generator, stationary and synchronous rotation reference frame is most suitable explained clearly by C.M.Ong [13]

A .D-q Reference Model:

D–q reference model was first proposed by Krause *et al.* [9]. After a slight modification, many authors have formulated a d–q reference model for a three-phase induction generator.

. Using the d-q reference frame model of a three phase induction generator, the transient performance [14] and unbalance operation have been studied by A. L. Bahrani and N.H. Malik [15].

B. Impedance-Based Model:

Murthy *et al.* [16] have been studied the performance of the SEIG using an analytical model based on a conventional single-phase equivalent circuit with per-unit (pu) parameter. The model used in [16] has been extended for the evaluation of various steady state performance characteristics of stand-alone generators, such as the effect of shaft variation [17], change in generator pole number by Singh *et al.* [18] etc

Raina *et al.* [17] have included the effects of injected harmonic currents due to the electronic controller on generator losses in the steady-state model of SEIG.

Rajakaruna *et al.* [19] have included the unregulated prime mover characteristic in the steady-state model of a three-phase-balanced induction generator.

C. Operational Circuit-Based Model:

Tandon *et al.* [20] presented an alternative approach to the steady-state performance analysis of a stand-alone SEIG is presented. An operational equivalent circuit in terms of operator $p = (1/\omega)\, d/dt$ replacing f in an impedance based model is developed, where $\omega = 2\pi f$. The solution of a fifth-order polynomial for lagging load gives the values of f and x_m.

3) Steady-state and performance analysis:

Steady-state analysis of SEIG is of interest, both from the design and operational points of view. In an isolated power system, both the terminal voltage and frequency are unknown and have to be computed for a given speed, capacitance, and load impedance. A large number of articles have appeared on the steady-state analysis of the SEIG [2], [15]–[29].

Murthy *et al.* [16] developed a mathematical model to obtain the steady-state performance of SEIG using the equivalent circuit impedance of the machine. Two nonlinear equations, which are real and imaginary parts of the impedance, are solved for two unknowns' f and x_m using Newton–Raphson method.

Rajakaruna *et al.* [19] have used an iterative technique which uses an approximate equivalent circuit and a mathematical model for B-H curve and the solution is reduced to a nonlinear equation in f.

T. F. Chan [21] has proposed an iterative technique by assuming some initial value for f and then solving for a new value considering a small increment until the result converges. This technique, however, lacks in making a judicious choice of an initial value and number of iterations required.

Singh *et al.* [22] tried an optimization technique by formulating this as a multivariate unconstrained nonlinear optimization problem. The impedance of the machine is taken as an objective function. The f and x_m are selected as independent variables, which are allowed to vary within their upper and lower limits so as to achieve practically acceptable values of the variables. The Rosenbrock's method of rotating coordinates has been used for solving the problem.

Sandhu et al. [23] have proposed an approach, which leads to a quadratic equation in slip making the steady-state analysis simple and comprehensive.

Wang et al. [25] have presented an eigen value-based approach to predict both minimum and maximum values of capacitance required for self-excitation of SEIG.

Steady-state analysis and performance of SEIG driven by regulated and unregulated turbines have been presented by T.F.Chan [26] and S. M. Alghuwainem [27]. In case of regulated turbines for CSCF operation, the per-unit speed is determined directly by solving a quadratic equation. For unregulated turbines, an additional iteration procedure using the Secant method has been used for dealing with the variable- speed nature of the turbine.

Using the method of symmetrical components, a general analysis for three-phase SEIG with an asymmetrically connected load and excitation capacitance is presented by Chan *et al.* [28].

4) Transient/dynamic analysis:

Many articles been appeared on the transient/dynamic analysis of SEIG [20], [30]–[34] and most of the transient studies of induction generators are related to voltage buildup due to self-excitation and load perturbation.

Tandon *et al.* [20] explained the voltage buildup of SEIG due to switching of the three-phase capacitor bank at rated speed at no load. It is observed that depending on the machine parameters, the generator voltage builds up from small voltage due to residual magnetism to its rated value in nearly 1 s.

Shridhar *et al.* [30] presented the transient performance of short-shunt SEIG. It is seen that it can sustain severe switching transients, has good overload capacity, and can re-excite over no load after loss of excitation. It is also observed that except for the most unusual circumstances (the short circuit across the machine terminals across the series capacitor), the short-shunt SEIG supplies adequate fault current to enable over current protective device operation.

Singh *et al.* [31] have been investigated the transient analysis of SEIG feeding an induction motor (IM) to analyze the suitability of the SEIG to sudden switching, such as starting of the IM. It is seen that reliable starting of an IM on SEIG is achievable with the value of capacitance determined through steady-state investigation; however, the capacitance should be applied in two steps: first to self-excite the generator, and second along with the motor or after switching on the motor.

Wang et al. [32] have presented the transient performance of stand-alone SEIG under the voltage buildup process, suddenly switching off one excitation capacitor and suddenly switching off two excitation capacitors. It is seen that when one of the three balanced excitation capacitors is switched off from the machine, SEIG can still maintain self-excitation and generates adequate voltage on other two phases. When two of the three balanced excitation capacitors are switched off from the machine, the generated voltage of the SEIG collapses and gradually reduces to zero.

Wang et al. [33] have presented a comparative study of long-shunt and short-shunt configurations on dynamic performance of an isolated SEIG feeding an induction motor load. Results show that the long shunt configurations may lead to unwanted oscillations while the short shunt provides the better voltage regulation.

Transient performance of three-phase SEIG during balanced and unbalanced faults is presented by Jain *et al.* [34], considering the effects of main and cross flux saturation for load perturbation, three-phase, and line-to-line short circuit, opening of one capacitor, two capacitors and a single line at the capacitor bank, opening of single-phase load, two-phase load, etc.

5) Voltage control and frequency control aspects:

Reactive power consumption and poor voltage regulation and frequency variation under varying speed and load requirements are the major drawbacks of the induction generators, but the development of static power converters has facilitated the control of the output voltage of induction generators. In literature so many methods have been found [35]-[49]

The terminal voltage of the three-phase SEIG with variable loads can be maintained constant by adjusting the value of the excitation capacitance or by controlling the prime mover speed. Adjustment of prime mover speed is not always possible. Therefore, the appropriate method is the adjustment of the capacitor value continuously. The adjustable excitation capacitor value can be achieved by many control strategies using power electronics technology. Some of the authors proposed the use of inverters and field-orientation algorithms to excite and control the induction generator.

Some of these methods are based on a shunt-connected pulse width-modulation (PWM) voltage-source inverter, supplying constant-frequency voltage, and some others supplying reactive current to the induction generator by a capacitor bank and an inverter simultaneously based on the instantaneous reactive power theory [35], [36]

Methods to improve voltage and frequency regulations:

2) **Switched capacitor:** Regulates terminal voltage but in discrete steps.
3) **Saturable core reactor:** Mishra *et al.* [38] proposed voltage controller in which 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.
4) **Long shunt and short shunt compensation:** Wang *et al.* [39] investigated the effect of long shunt and short shunt compensation on the terminal voltage of SEIG. It 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.
5) **Static VAR Compensation (SVC):** The Static VAR Compensator consists of thyristor phase controlled reactor in parallel with thyristor switched capacitor and fixed excitation capacitor used for voltage control by Ahmed *et al.* [40]. It faces the problem of weight losses in the inductor.

6) **Stator field-oriented control:** This enables stiff voltage regulation and high efficiency. As a drawback, the field orientation requires costly and unreliable mechanical position sensing systems such as encoders or resolvers.

7) **Electronic load controller/Induction generator controller:** Electronic load controller controls both voltage and frequency regulation [41]-[42].

Due to low power ratings (less than 100kW) uncontrolled turbines are preferred, which maintain the input hydropower constant, thus requiring the generator output power to be held constant at varying consumer loads. This requires a controllable dump load connected in parallel with the consumer load so that the total power consumed is held constant. Different types of such electronic load controllers (ELCs) can be used. Two types of ELCs have been tried. One is an AC controller with back-to-back thyristor feeding a fixed resistive dump load. Firing angle control varies power in the dump load. The second is a rectifier-chopper feeding a fixed resistance on the DC side proposed by Singh *et al.* [41].

Singh *et al.*[41] 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.

8) **Current-controlled voltage source inverter:** Current-controlled voltage source inverter acts as a voltage regulator for maintaining constant terminal voltage [43]-[49].

A three-phase PWM inverter may also be used as a static reactive power source. The inverter can supply leading or lagging reactive current. The excitation current can be controlled by controlling the modulation index and phase of fundamental inverter voltage with respect to the generator voltage.

The reactive load current and excitation current required for maintaining constant output voltage of an induction generator have to be supplied by the PWM inverter. Complicated high speed electronic circuits are required to determine reference generator current under varying load and rotor speed conditions.

Kuo and Wang [44] investigated voltage regulation and current-harmonic suppression of a self-excited induction generator (SEIG), under unbalanced and/or nonlinear loading conditions using a current-controlled voltage source inverter (CC-VSI). They used a hybrid induction-machine model based on the three-phase a-b-c and the d-q frames of reference to describe the dynamic performance of the studied system. The three-phase a-b-c induction-machine model is employed to derive dynamic equations of the SEIG under nonlinear loading conditions. The synchronously rotating reference frame based on a d-q axis model is used to decompose three-phase load currents into active and reactive power currents.

Marra *et al.* [45] 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.

Singh *et al.* [46], [47] 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.* [48] designed the optimum values of different components of STATCOM for different rating machines.

6) Parallel operation of SEIG:

In places where natural resources are available in abundance, usually SEIGs operate in parallel to utilize the full potential of natural resources [50]-[56]. Parallel operation of SEIG requires extensive investigation with regard to different aspects of parallel operation, such as influence of parameter variations on parallel operation, VAR control, etc.

Bahrani *et al.* [50] studied the voltage-control behavior of multi-induction generators operating in parallel with one three phase bank of excitation capacitors connected to a common bus and load. It has been reported that voltage regulation under varying load conditions is improved by controlling either the capacitance or speed of one or more generators. Under controlled terminal voltage operation, it is noticed that the capacitive reactive power and speed (active power/frequency) demand increase with the increased load. Under the similar condition of controlled terminal voltage, the system frequency also depends on load power and terminal voltage.

Chakraborty *et al.* [53]-[54] have analyzed the effects of parameter variations on the performance of parallel-connected SEIG operating in stand-alone mode. The investigation outlines the parameter influence on the performance of individual generators as well as on the system as a whole. Effects of parameter deviations on the power sharing, current sharing, VAR requirements, and on the voltage regulation have been examined in this paper. Rotor resistance is found to have the largest influence on current and power sharing of individual machines and also on terminal frequency.

Wang *et al.* [55] have presented an Eigen value-based methodology to analyze the dynamic performances of parallel-operated SEIG supplying an IM load to find the minimum starting value of capacitance required for self-excitation. Steady-state and sensitivity analysis of different capacitance values with respect to different system parameters have been investigated. The responses of the output voltage of parallel-operated generators during suddenly switched on and off of an induction motor load have also been reported.

An analysis has been carried out by Bhatti *et al.* [56] to control the reactive power of isolated wind–diesel/wind–diesel–micro hydro hybrid systems in which the induction generator is used for wind and micro-hydro systems and synchronous generators for a diesel generator set.

7) Induction generator for wind power, mini/micro-hydro power system applications:

Induction generators are increasingly being used in non conventional energy systems such as wind, micro/mini-hydro etc. Various authors presented their suitability for their use. The advantages of using an induction generator instead of a synchronous generator are well known some of them are reduced unit cost and size, ruggedness, brushless (in squirrel cage construction), absence of separate dc source, ease of maintenance, self-protection against severe overloads and short circuits, etc.[42], [57], and [58]

N. P. A. Smith [42] 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.

1.3. Organization 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. It also contains the literature review which give a look on work done up to now in field of SEIG.
2. **Chapter-2:** This chapter contains the modeling and analysis of SEIG. In this basically the SEIG is simulated on No Load and its voltage build up process is observed.
3. **Chapter-3:** In this chapter the Current Control principle of Voltage Source Inverter is explained and CCVSI is modeled and simulated; its PWM signal is obtained from hysteresis current control
4. **Chapter-4:** The complete scheme for proposed voltage regulation technique for SEIG by using current controlled voltage source inverter has been explained and analyzed.
5. **Chapter-5:** This chapter gives brief idea about hardware developed and their operation and their details.
6. **Chapter-6.**In this final chapter the results of hardware made has been given and various observations taken from experiments has been shown.

Finally a conclusion has been made at last and scope of further work is given followed by the references and appendix.

CHAPTER 2

SELF EXCITED INDUCTION GENERATOR (SEIG)

2.1 Introduction:

Induction machine has been used in a wide variety of applications as a means of converting electric power to mechanical work. The primary advantages of the induction machines are its rugged brushless construction, lower cost with high efficiency. These machines are very economical, reliable, and are available in the ranges of fractional horse power (FHP) to multi–megawatt capacity. Also, unlike synchronous machines, induction machines can be operated at variable speeds. For economy and reliability many wind power systems use induction machines, driven by a wind turbine through a gear box, as an electrical generator. The need for gearbox arises from the fact that lower rotational speeds on the wind turbine side should be converted to high rotor speeds, on the electrical generator side, for electrical energy production.

There are two types of induction machine based on the rotor construction namely, squirrel cage type and wound rotor type. Squirrel cage rotor construction is popular because of its ruggedness, lower cost and simplicity of construction and is widely used in stand-alone wind power generation schemes. Wound rotor machine can produce high starting torque and is the preferred choice in grid-connected wind generation scheme. Another advantage with wound rotor is its ability to extract rotor power at the added cost of power electronics in the rotor circuit. This kind of system is known as Double Output Induction Generator (DOIG) [4].

This chapter focuses on the Self excited induction generator part of developed system. After a brief introduction of the induction machine, the electrical generator used in this dissertation, a detailed analysis of the induction machine operated in stand-alone mode is presented. As a generator, induction machines have the drawback of requiring reactive power for excitation. This necessitates the use of shunt capacitors in the circuit. The effect of magnetization inductance on self-excitation of the induction generator is discussed. Also, this chapter presents the method to analyze the process of self-excitation in induction machine and the role of excitation-capacitors in its initiation.

The process of voltage build up and the effect of saturation characteristics are also presented and shown through simulations and the magnetization curve my machine used is presented which we got from machine's no load and blocked rotor test and calculating different parameters.

2.2. Induction Machine:

In the electromagnetic structure of the Induction machine, the stator is made of numerous coils with three groups (phases), and is supplied with three phase current. The three coils are physically spread around the stator periphery (space-phase), and carry currents which are out of time-phase. This combination produces a rotating magnetic field, which is a key feature of the working of the induction machine. Induction machines are asynchronous speed machines, operating below synchronous speed when motoring and above synchronous speed when generating. The presence of negative resistance (i.e., when slip is negative), implies that during the generating mode, power flows from the rotor to the stator in the induction machine.

2.2.1. Equivalent Electrical Circuit of Induction Machine

The theory of operation of induction machine is represented by the per phase equivalent circuit shown in Figure. 2.1 [9]-[13]

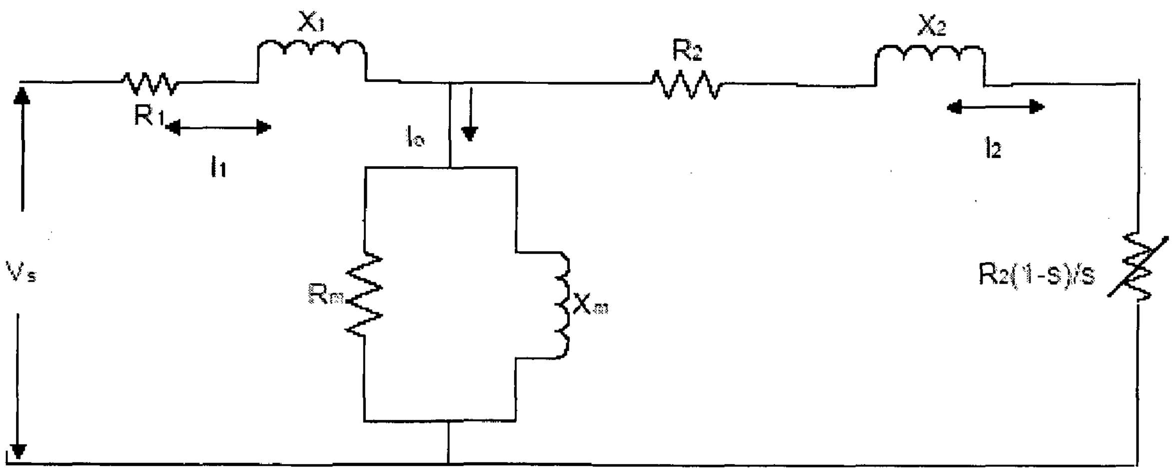


Figure 2.1. Per phase equivalent circuit of Induction machine referred to stator

In the above figure, R and X refer to the resistance and inductive reactance respectively. Subscripts 1, 2 and m represent stator; rotor values referred to the stator side and magnetizing components, respectively.

Induction machine needs AC excitation current for its running. The machine is either self-excited or externally excited. Since the excitation current is mainly reactive, a standalone system is self-excited by shunt capacitors. In grid-connected operation, it draws excitation power from the network, and its output frequency and voltage values are dictated by the grid. Where the grid capacity of supplying the reactive power is limited, local capacitors can be used to partly supply the needed reactive power.

2.3. Self-Excited Induction Generator (SEIG):

Self-excited induction generator (SEIG) works just like an induction machine in the saturation region except the fact that it has excitation capacitors connected across its stator terminals. These machines are ideal choice for electricity generation in stand-alone variable speed wind energy systems, where reactive power from the grid is not available. The induction generator will self-excite, using the external capacitor, only if the rotor has an adequate remnant magnetic field. In the self-excited mode, the generator output frequency and voltage are affected by the speed, the load, and the capacitance value. The steady-state per-phase equivalent circuit of a self-excited induction generator is shown in the fig.2.2.

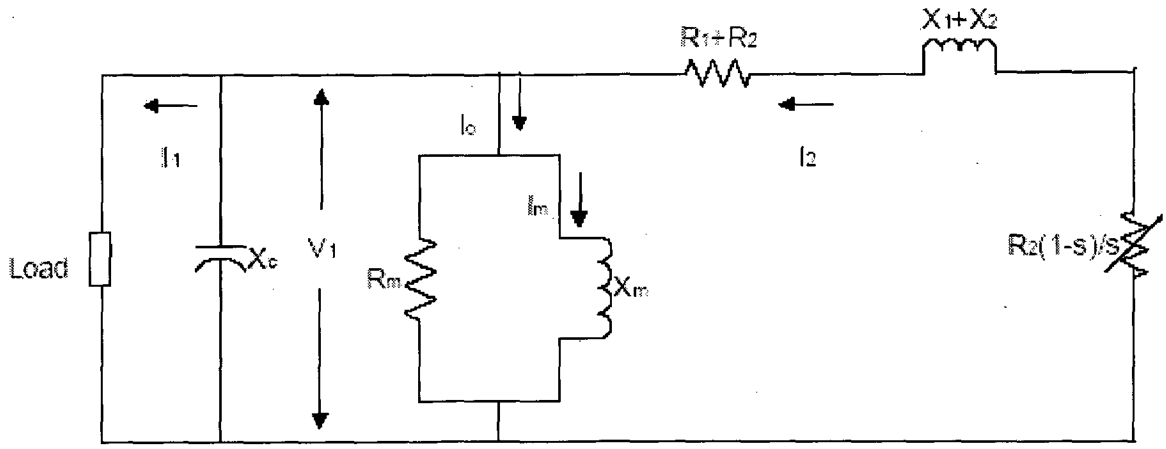


Figure 2.2 Self-excited induction generator with external capacitor.

The process of self-excitation in induction machines has been known for many decades [1]. When capacitors are connected across the stator terminals of an induction machine, driven by an external prime mover, voltage will be induced at its terminals. The induced electromotive force (EMF) and current in the stator windings will continue to rise until the steady-state condition is reached, influenced by the magnetic saturation of the machine. At this operating point the voltage and the current will be stabilized at a given peak value and frequency. In order for the self-excitation to occur, for a particular capacitance value there is a corresponding minimum speed [59], [60]. So, in stand-alone mode of operation, it is necessary for the induction generator to be operated in the saturation region. This guarantees one and only one intersection between the magnetization curve and the capacitor reactance line, as well as output voltage stability under load as seen in the fig.2.3.

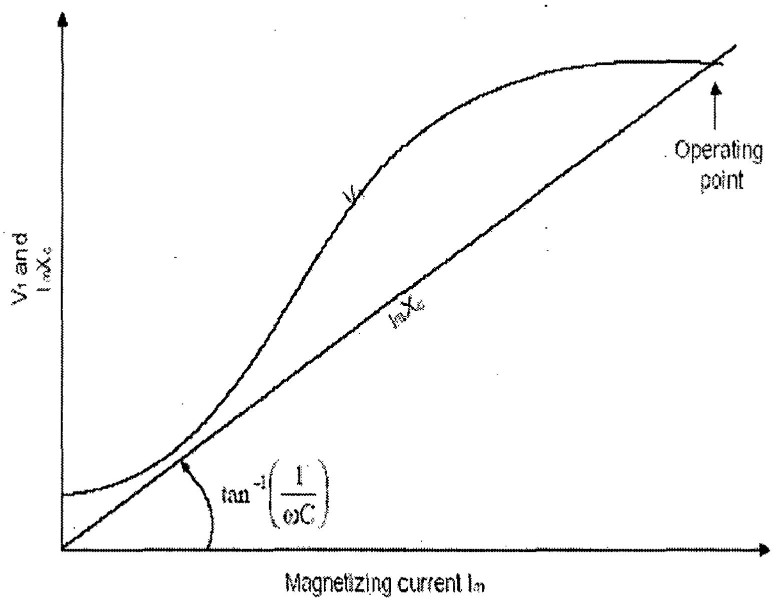


Figure.2.3 determination of stable operation of induction generator.

At no-load, the capacitor current $Ic = V_1/Xc$ must be equal to the magnetizing current $Im=V_1/Xm$. The voltage V_1 is a function of Im, linearly rising until the saturation point of the magnetic core is reached. The output frequency of the self-excited generator is, $f=1/2\pi CXm$ and $\omega=2\pi f$, where C is self-exciting capacitance.

2.3.1. Method of Analysis

There are two fundamental circuit models employed for examining the characteristics of a SEIG. One is the per-phase equivalent circuit which includes the loop-impedance method adopted by Murthy *et al* [16] and Malik and Al-Bahrani [61], and the nodal admittance method proposed by Chan [62]. This method is suitable for studying the machine's steady-state characteristics. The other method is the *dq*-axis model based on the generalized machine theory proposed by Elder *et al* [59] and is employed to analyze the machine's transient state as well as steady-state.

2.3.2. Steady-state Model

Steady-state analysis of induction generators is of interest both from the design and operational point of view. By knowing the parameters of the machine, it is possible to determine the performance of the machine at a given speed, capacitance and load conditions.

Loop impedance and nodal admittance methods used for the analysis of SEIG are both based on per-phase steady-state equivalent circuit of the induction machine (fig.2.4), modified for the self-excitation case. They make use of the principle of conservation of active and reactive powers, by writing loop equations [16], [61], or nodal equations [16], for the equivalent circuit. These methods are very effective in calculating the minimum value of capacitance needed for guaranteeing self-excitation of the induction generator. For stable operation, excitation capacitance must be slightly higher than the minimum value. Also there is a speed threshold, below which no excitation is possible, called as the cutoff speed of the machine. In the following paragraph, of loop impedance method is given for better understanding.

The per-unit per-phase steady-state circuit of a self-excited induction generator under RL load is shown in fig.2.4 [16].

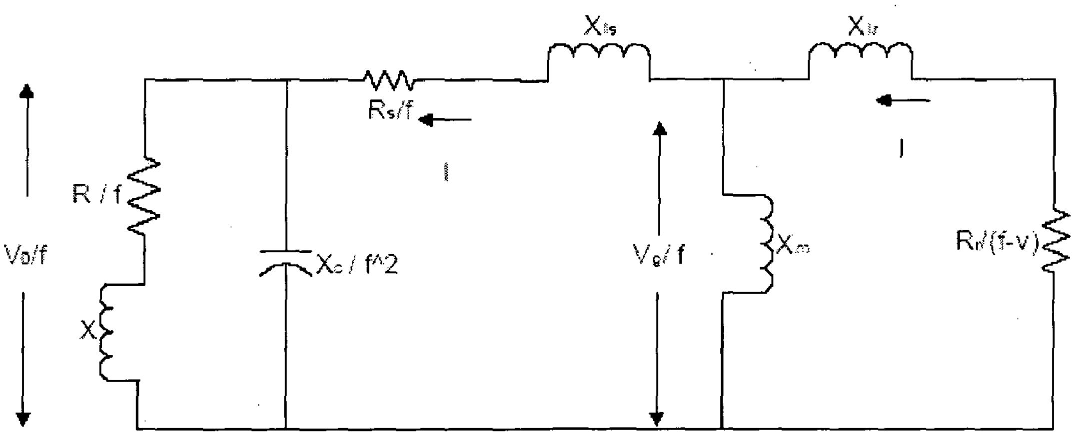


Figure 2.4 Equivalent circuit of self-excited induction generator with R-L Load.

Where;

Rs, Rr, R : p.u. per-phase stator, rotor (referred to stator) and load resistance respectively.

Xls, Xlr, X, Xm : p.u. per-phase stator leakage, rotor leakage (referred to stator), load and magnetizing reactance (at base frequency), respectively.

Xsmax : p.u. maximum saturated magnetizing reactance.

C : per-phase terminal-excitation capacitance.

Xc : p.u. per-phase capacitive reactance (at base frequency) of the terminal excitation capacitor.

f, v : p.u. frequency and speed, respectively.

N : base speed in rev/min

Zb : per-phase base impedance

fb : base frequency

Vg, V_0 : per-phase air gap and output voltages, respectively.

In the analysis of SEIG the following assumptions were made [16]:

1. Only the magnetizing reactance *Xm* is assumed to be affected by magnetic saturation, and all other parameters of the equivalent circuit are assumed to be constant. Self-excitation results in the saturation of the main flux and the value of *Xm* reflect the magnitude of the main flux. Leakage flux passes mainly in the air, and thus these fluxes are not affected to any large extent by the saturation of the main flux.
2. Stator and rotor leakage reactance, in per-unit are taken to be equal. This assumption is normally valid in induction machine analysis.
3. Core loss in the machine is neglected.

For the circuit shown in Figure 3.4, the loop equation for the current can be written as:

$$I\,Z = 0 \tag{2.1}$$

Where *Z* is the net loop impedance given by

$$Z=\left(\left(\frac{Rr}{f-v}\right)+jXlr\|jXm\right)+\frac{Rs}{f}+jXls+\left(\frac{-jXc}{f}\left\|\left(\frac{R}{f}+jX\right)\right.\right) \tag{2.2}$$

Since at steady-state excitation $I \neq 0$, it follows from (9) that $Z = 0$, which implies that both the real and imaginary parts of Z are zeros. These two equations can be solved simultaneously for any two unknowns (usually voltage and frequency). For successful voltage-buildup, the load-capacitance combination and the rotor speed should result in a value such that $Xm=Xcmax$, which yields the minimum value of excitation capacitance below which the SEIG fails to self-excite.

2.4. Modeling of Induction Generator:

The process of self-excitation is a transient phenomenon and is better understood if analyzed using a transient model. To arrive at transient model of an induction generator, *abc-dq0* transformation is used.

2.4.1 *abc-dq0* transformation:

The *abc-dq0* transformation transfers an *abc* (in any reference frame) system to a rotating *dq0* system. Krause *et al.* [9] noted that, all time varying inductances can be eliminated by referring the stator and rotor variables to a frame of reference rotating at any angular velocity or remaining stationary. All transformations are then obtained by assigning the appropriate speed of rotation to this (arbitrary) reference frame. Also, if the system is balanced the zero components will be equal to zero [9].

A change of variables which formulates a transformation of the 3-phase variables of stationary circuit elements to the arbitrary reference frame may be expressed as [9]:

$$f_{qdos} = K_s f_{abcs} \tag{2.3}$$

Where:

$$f_{qdos} = \begin{bmatrix} fqs \\ fds \\ fos \end{bmatrix}; \quad f_{abcs} = \begin{bmatrix} fas \\ fbs \\ fcs \end{bmatrix}; \quad K_s = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix};$$

$$\theta = \int_0^t \omega(\xi)d\xi + \theta(0);$$

ξ is the dummy variable of integration.

For the inverse transformation:

$$(K_s)^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix}$$

In eqn. (3), f can represent voltage, current, flux linkage, or electric charge. The subscript *s* indicates the variables, parameters and transformation associated with stationary circuits. This above transformation could also be used to transform the time varying rotor windings of the induction machine.

The equations of transformation may be thought of as if the f_{qs} and f_{ds} variables are directed along axes orthogonal to each other and rotating at an angular velocity of ω, whereupon f_{as}, f_{bs}, and f_{cs} (instantaneous quantities which may be any function of time), considered as variables directed along stationary paths each displaced by 120^0. Although the waveforms of the *qs* and *ds* voltages, currents and flux linkages, and electric charges are dependent upon the angular velocity of the frame of reference, the waveform of the total power is same regardless of the reference frame in which it is evaluated [9].

2.4.2 Voltage equations:

The voltage equations in machine variables can be expressed as [9]:

$$V_{abcs} = r_s i_{abcs} + p\lambda_{abcs} \quad (2.4)$$

$$V_{abcr} = r_r i_{abcr} + p\lambda_{abcr} \quad (2.5)$$

Where:

Subscript *s* denotes parameters and variables associated with the stator.

Subscript *r* denotes parameters and variables associated with the rotor.

V_{abcs}, V_{abcr} are phase voltages.

I_{abcs}, I_{abcr} are phase currents.

λ_{abcs} , λ_{abcr} are the flux linkages and $p = d/dt$.

By using the *abc-dq0* transformation and expressing flux linkages as product of currents and winding inductances, we obtain the following expressions for voltage in arbitrary reference frame [9]:

$$V_{qdos} = r_s\, i_{qdos} + \omega\lambda_{dqs} + p\lambda_{qdos} \tag{2.6}$$

$$V'_{qdor} = r'_r\, i'_{qdor} + (\omega - \omega_r)\, \lambda'_{dqr} + p\lambda'_{qdor} \tag{2.7}$$

Where:

ω is the electrical angular velocity of the arbitrary reference frame.

ω_r is the electrical angular velocity of the rotor.

$(\lambda_{dqs})^T = [\lambda_{ds} \quad -\lambda_{qs} \quad 0]\ ;\ (\lambda'_{dqr})^T = [\lambda'_{dr} \quad -\lambda'_{qr} \quad 0].$

"′" denotes rotor values referred to the stator side.

Using the relations between the flux linkages and currents in the arbitrary reference frame and substituting them in (2.6) & (2.7), the voltage and flux equations are expressed as follows:

$$V_{qs} = r_s i_{qs} + \omega\lambda_{ds} + p\lambda_{qs} \tag{2.8}$$

$$V_{ds} = r_s i_{ds} - \omega\lambda_{qs} + p\lambda_{ds} \tag{2.9}$$

$$V'_{qr} = r'_r i'_{qr} + (\omega - \omega_r)\lambda'_{dr} + p\lambda'_{qr} \tag{2.10}$$

$$V'_{dr} = r'_r i'_{dr} - (\omega - \omega_r)\lambda'_{qr} + p\lambda'_{dr} \tag{2.11}$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m(i_{qs} + i'_{qr}) \tag{2.12}$$

$$\lambda_{ds} = L_{ls} i_{ds} + L_m(i_{ds} + i'_{dr}) \tag{2.13}$$

$$\lambda'_{qr} = L'_{lr} i'_{qr} + L_m(i_{qs} + i'_{qr}) \tag{2.14}$$

$$\lambda'_{dr} = L'_{lr} i'_{dr} + L_m(i_{ds} + i'_{dr}) \tag{2.15}$$

Where:

L_{ls} and L_{ms} are leakage and magnetizing inductances of the stator respectively.

L_{lr} and L_{mr} are leakage and magnetizing inductances of the rotor respectively.

Magnetizing inductance, $L_m = \frac{3}{2} L_{ms}$

The voltage and flux linkage equations suggest the following equivalent circuits for the induction machine:

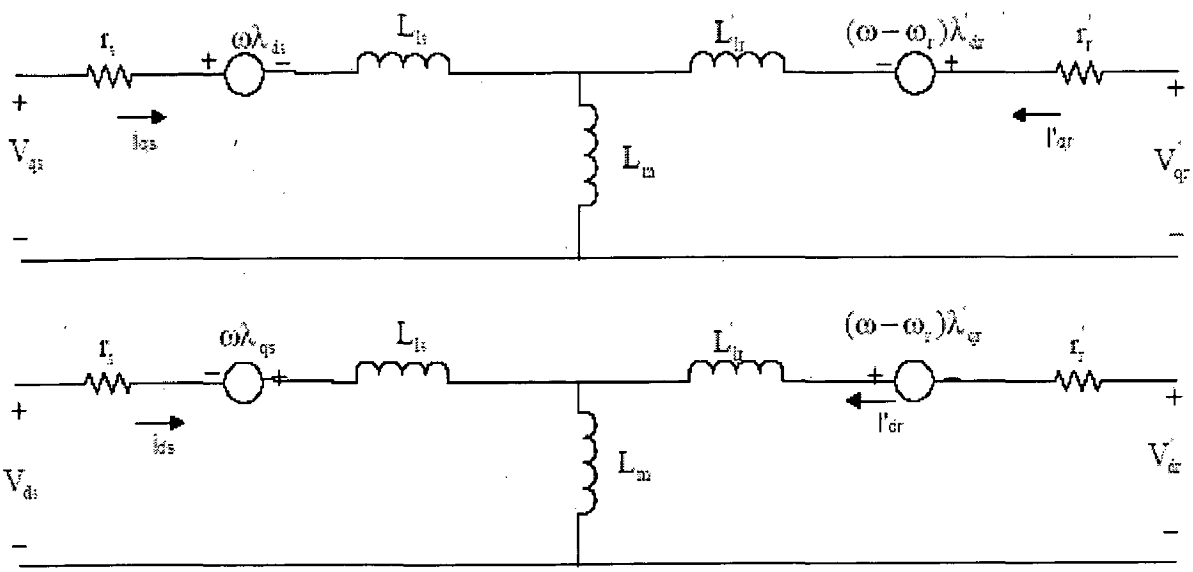


Figure 2.5. Arbitrary reference-frame equivalent circuits for a 3-phase, symmetrical induction machine.

2.4.3. Torque Equations:

The expression for electromagnetic torque, positive for motor operation and negative for generator operation, in terms of the arbitrary reference variables can be expressed as [63]:

For motor action, $T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right) L_m \,(i_{qs} i'_{dr} - i_{ds} i'_{qr})$ (2.16)

For generator action, $T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right) L_m \,(i_{ds} i'_{qr} - i_{qs} i'_{dr})$ (2.17)

The torque and speed are related by the following expressions:

For the motor operation, $T_{e\text{-}motor} = J\left(\frac{2}{P}\right) p\omega_r + T_M$ (2.18)

For the generator operation, $T_M = J\left(\frac{2}{P}\right) p\omega_r + T_{e\text{-}gen}$ (2.19)

Where:

P: Number of poles.

J: Inertia of the rotor in (Kg m2).

T_M: Drive torque in (Nm).

2.4.4. Stationary Reference Frame:

Although the behavior of the induction machine may be described by any frame of reference, there are three which are commonly used [9]. The voltage equations for each of these reference frames can be obtained from the voltage equations in the arbitrary reference frame by assigning the appropriate speed to ω. That is, for the stationary reference frame, $\omega = 0$, for the rotor reference frame, $\omega = \omega_r$ and for the synchronous reference frame, $\omega = \omega_e$.

Generally, the conditions of operation will determine the most convenient reference frame for analysis and/or simulation purposes. The stator reference frame is used when the stator voltages are unbalanced or discontinuous and the rotor applied voltages are balanced or zero. The rotor reference frame is used when the rotor voltages are unbalanced or discontinuous and the stator applied voltages are balanced. The stationary frame is used when all (stator and rotor) voltages are balanced and continuous. In this dissertation, the *stationary reference frame* $(\omega=0)$ is used for simulating the model of the self excited induction generator (SEIG).

In all asynchronously rotating reference frames $(\omega \neq \omega_e$ with $\theta(0) = 0$ see (2.3)),the phasor representing phase *a* variables (with subscript *as*) is equal to phasor representing *qs* variables. In other terms, for the rotor reference frame and the stationary reference frame, $f_{as} = f_{qs}$, $f_{bs} = f_{as} < 120$ and $f_{cs} = f_{as} < 240$ [9].

2.4.5. SEIG Model:

As discussed above, the *dq* model of the SEIG in the stationary reference frame is obtained by substituting $\omega = 0$ in the arbitrary reference frame equivalent of the induction machine shown in fig 2.5. fig. 2.6 shows a complete *dq*-axis model, of the SEIG with load, in the stationary reference frame. Capacitor *C* is connected at the stator terminals for the self-excitation. For convenience, all values are assumed to be referred to the stator side and here after "′" is neglected while expressing rotor parameters referred to the stator.

For no-load condition of three-phase SEIG the voltage-ampere equations in stationary qd axes references frame are:

$$[V] = [R]\,[i] + [L]\,p\,[i] + \omega_r\,[G]\,[i] \tag{2.20}$$

From which, current derivatives can be expressed as:

$$p[i] = [L]^{-1} \{ [V] - [R] [i] - \omega_r [G] [i] \} \tag{2.21}$$

Where

$[V] = [V_{ds}\ V_{qs}\ V_{dr}\ V_{qr}]^T;$

$[i] = [i_{ds}\ i_{qs}\ i_{dr}\ i_{qr}]^T;$

$[R] = diag\ [\ r_s\ r_s\ r_r\ r_r].$

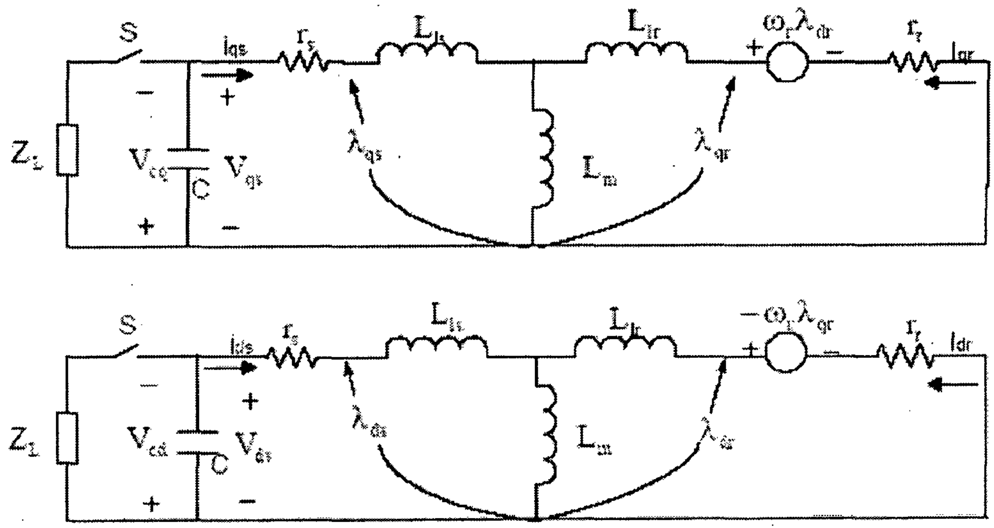


Figure 2.6 dq model of SEIG in stationary reference frame (All values referred to stator).

Equation 2.21 can also be derived from fig 2.6 as:

$$pI = AI + B \tag{2.22}$$

Where:

$$A = \frac{1}{L}\begin{bmatrix} -L_r r_s & -L_m^2 \omega_r & L_m r_r & -L_m \omega_r L_r \\ L_m^2 \omega_r & -L_r r_s & L_m \omega_r L_r & L_m r_r \\ L_m r_s & L_s \omega_r L_m & -L_s r_r & L_s \omega_r L_r \\ -L_s \omega_r L_m & L_m r_s & -L_s \omega_r L_r & -L_s r_r \end{bmatrix}; \quad B = \frac{1}{L}\begin{bmatrix} L_m K_q - L_r V_{cq} \\ L_m K_d - L_r V_{cd} \\ L_m V_{cq} - L_s K_q \\ L_m V_{cd} - L_s K_d \end{bmatrix}$$

$$I = \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}; \quad V_{cq} = \frac{1}{C}\int i_{qs}\,dt + V_{cq}\big|_{t=0}; \quad V_{cd} = \frac{1}{C}\int i_{ds}\,dt + V_{cd}\big|_{t=0}$$

$L_s = L_{ls}+L_m;\ L_r = L_{lr}+L_m;\ \&\ L = L_sL_r-L_m^2$

K_d and K_q are constants representing initial induced voltages along the *d*-axis and *q*-axis respectively, due to the remaining magnetic flux in the core.

The load can be connected across the capacitors, once the voltage reaches a steady-state value. The type of load connected to the SEIG is a real concern for voltage regulation. In general, large resistive and inductive loads can vary the terminal voltage over a wide range. For example, the effect of an inductive load in parallel with the excitation capacitor will reduce the resulting effective load impedance (*Zeff*).

$$Z_{eff} = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{2.23}$$

This change in the effective self-excitation increases the slope of the straight line of the capacitive reactance (*fig* 2.3), reducing the terminal voltage. This phenomenon is more pronounced when the load becomes highly inductive.

2.5. Simulations and Results:

A model based on the first order differential equation (2.22) has been built in the MATLAB/Simulink to observe the behavior of the self-excited induction generator. The parameters used, obtained from No load and blocked rotor test on used machine.

From the previous subsection, it can be said that with inductive loads the value of excitation capacitance value should be increased to satisfy the reactive power requirements of the SEIG as well as the load. It is assumed in this thesis that, such a reactive compensation is provided to the inductive load, and the SEIG always operates with unity power factor.

2.5.1. Saturation Curve:

As explained in the previous section, the magnetizing inductance is the main factor for voltage build up and stabilization of generated voltage for the unloaded and loaded conditions of the induction generator (Figure 2.3). Singh *et. al.* [48] presents a method to determine the magnetizing inductance curve from lab tests performed on a machine. The saturation curve used for the simulation purposes is obtained from no load test performed on the machine, shown in *fig* 2.7.A set of values of magnetizing current (I_m) and magnetizing inductance (Lm) is fed to the Microsoft Excel (standard software) and by selecting the curve-fitting option, a polynomial equation for Lm is found as:

$$Lm = 0.2152 + 0.1177*I_m - 0.0679*I_m^2$$

Here $I_m = \sqrt{[(ids + idr)^2 + (iqs + iqr)^2]}$

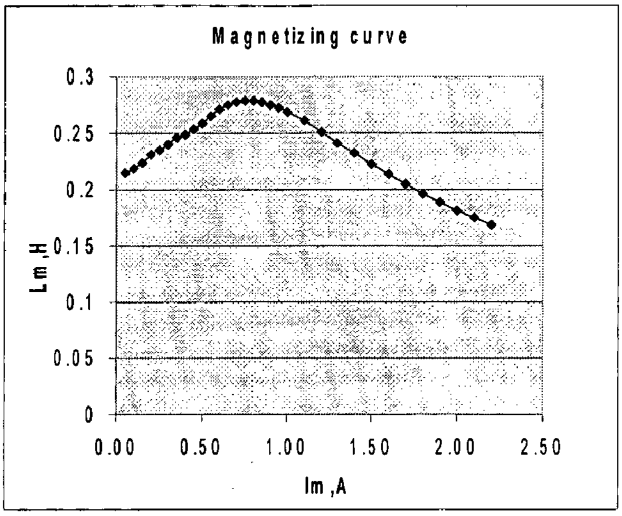


Figure 2.7. Magnetizing curve for Induction machine

For numerical integration, the residual magnetism cannot be zero at the beginning; its role fades away as soon as the first iterative step for solving (3.25) has started.

2.5.2. Process of Self-excitation:

With time varying loads, new steady-state value of the voltage is determined by the self-excitation capacitance value, rotor speed and load. These values should be such that they guarantee an intersection of magnetization curve and the capacitor reactance line (Figure 2.3), which becomes the new operating point.

The following *fig*.2.8 shows the process of self-excitation in an induction machine under no-load condition.

From *fig*. 2.8, it can be observed that the phase voltage slowly starts building up and reaches a steady-state value. We can say that the self-excitation follows the process of magnetic saturation of the core, and a stable output is reached only when the machine core is saturated.

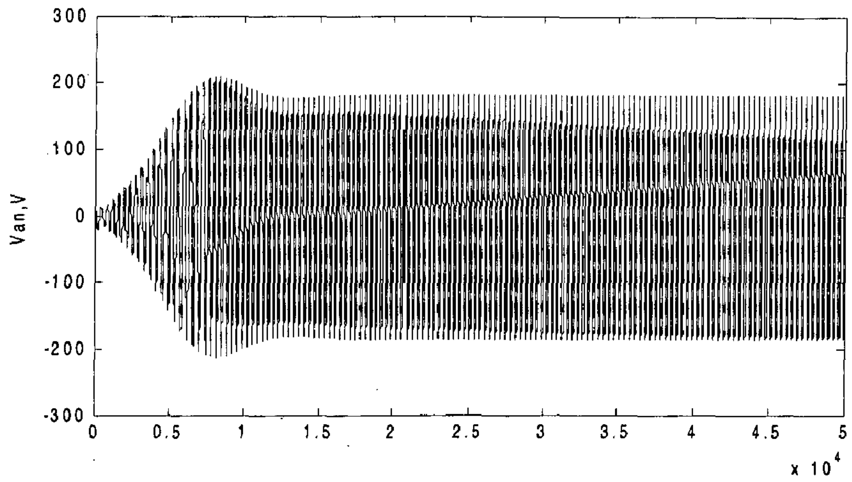
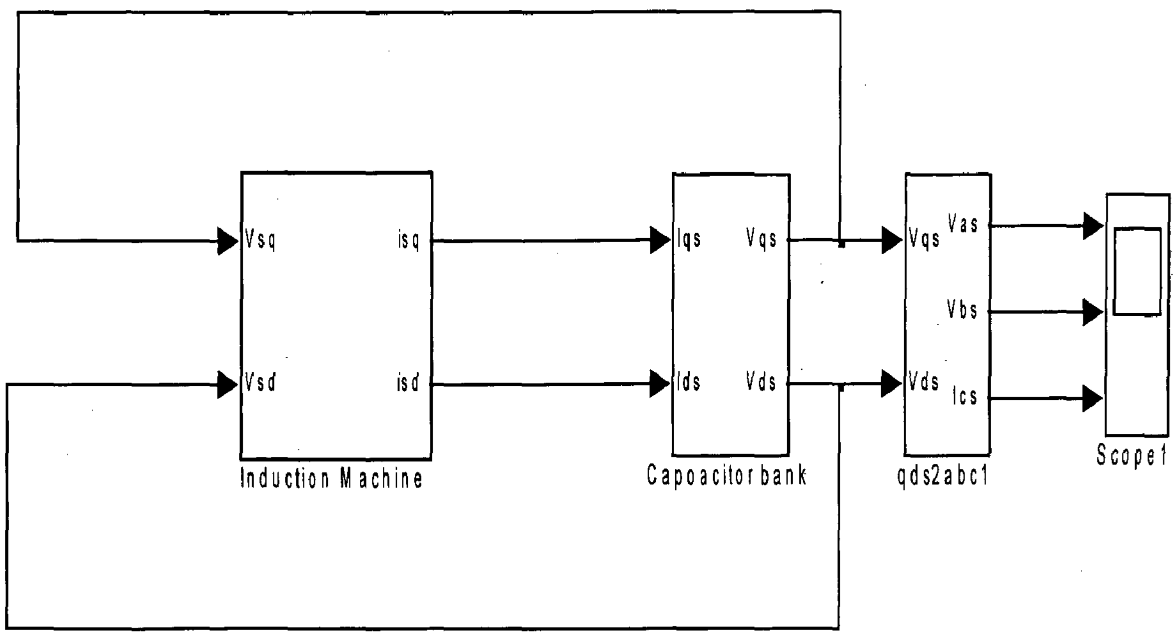


Figure 2.8 Voltage build up in a self-excited induction generator.

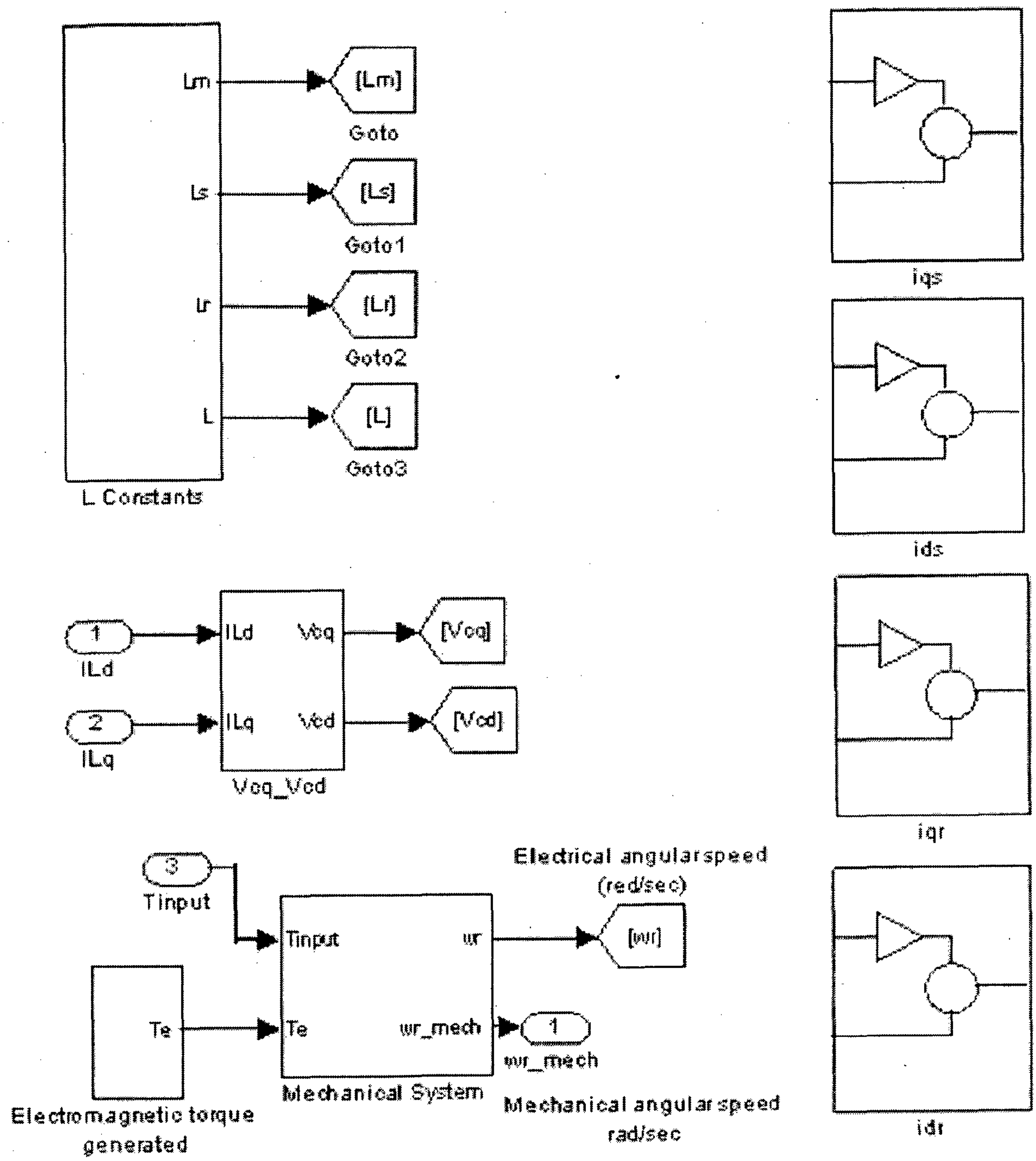
In physical terms the self-excitation process could also be explained in the following way. The residual magnetism in the core induces a voltage across the self-exciting capacitor that produces a capacitive current (a delayed current). This current produces an increased voltage that in turn produces an increased value of capacitor current. This procedure goes on until the saturation of the magnetic filed occurs as observed in the simulation result shown.

2.5.3. Simulation Blocks:

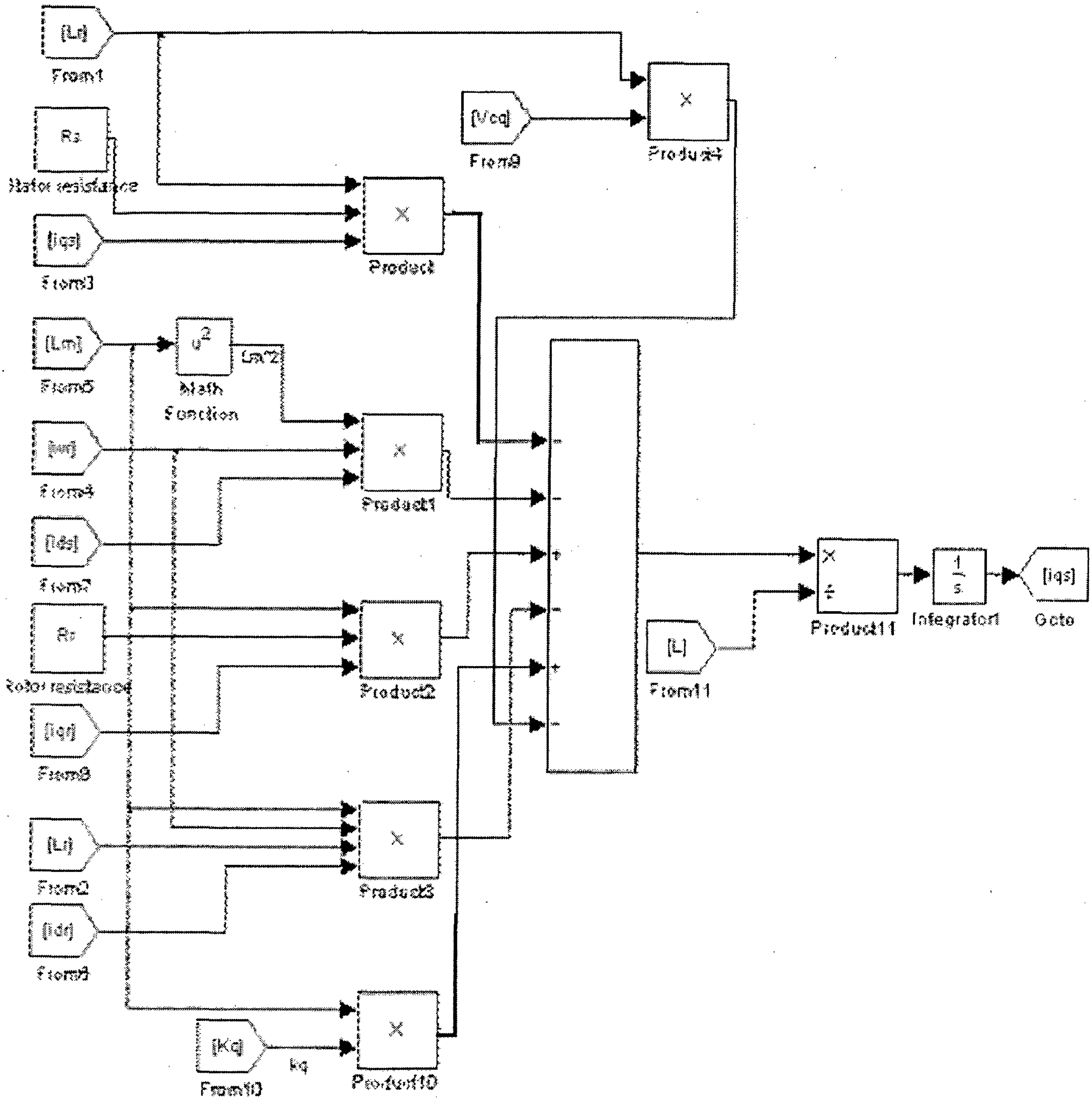
(a) Self Excited Induction Generator



(b) Blocks Inside SEIG:

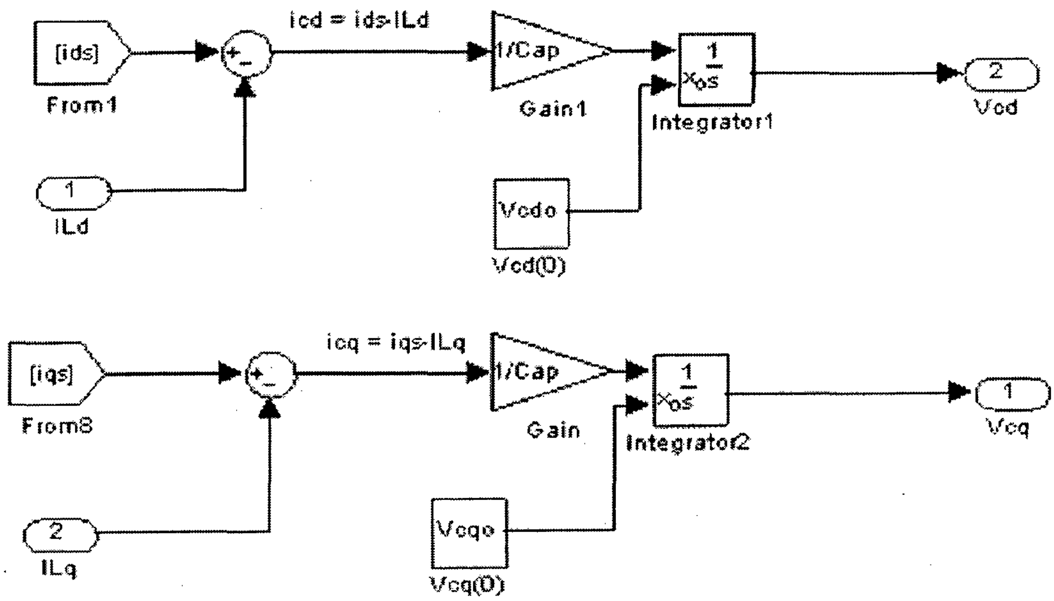


(c) Calculation of iqs:



(d) Calculation of Stator Voltage: Vcd, Vcq

Vcd = -Vsd & Vcq = -Vsq



CHAPTER 3

CURRENT CONTROLLED VOLTAGE SOURCE INVERTER (CC-VSI)

3.1 Introduction:

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 [64].

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 voltage source, that is, its Thevenin impedance should ideally be zero. 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 general name converter is given because the same circuit can operate as an inverter as well as rectifier [12].

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. 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.

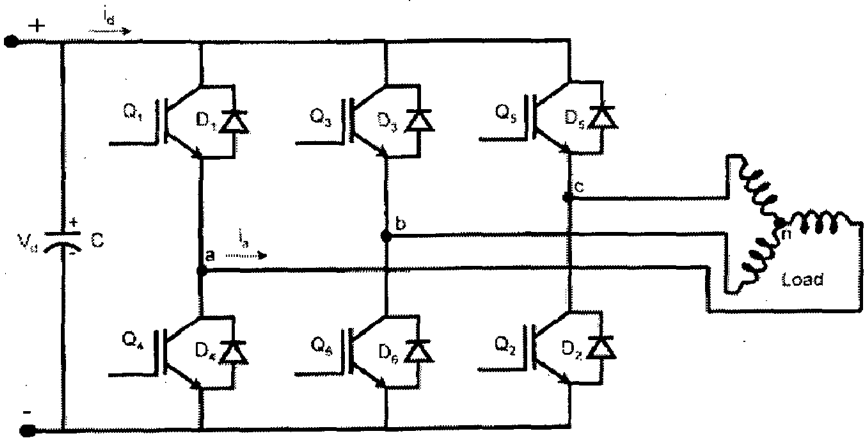


Figure 3.1: schematic diagram of three phase bridge inverter

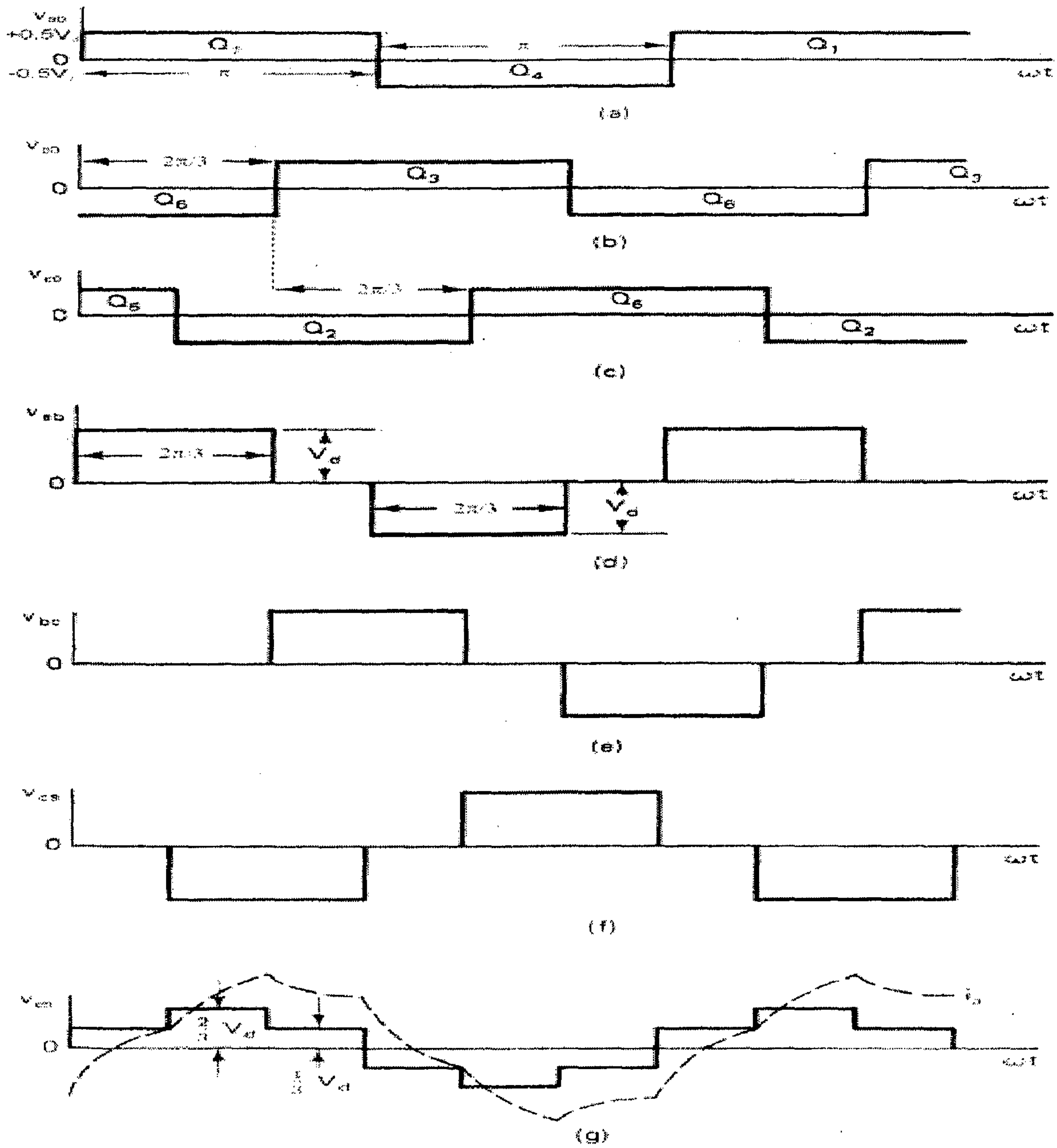


Figure 3.2. Phase voltage(a,b,c) line voltage(d,e,f) and line current (g) waveform in square-wave mode of voltage source inverter

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 PWM principle to control the output voltage is easily understood by fig 3.3. The fundamental voltage V_1 has the maximum amplitude ($4V_d/\pi$) at square wave but by creating two notches as shown, the magnitude can be reduced. If the notch widths are increased, the fundamental voltage will be reduced.

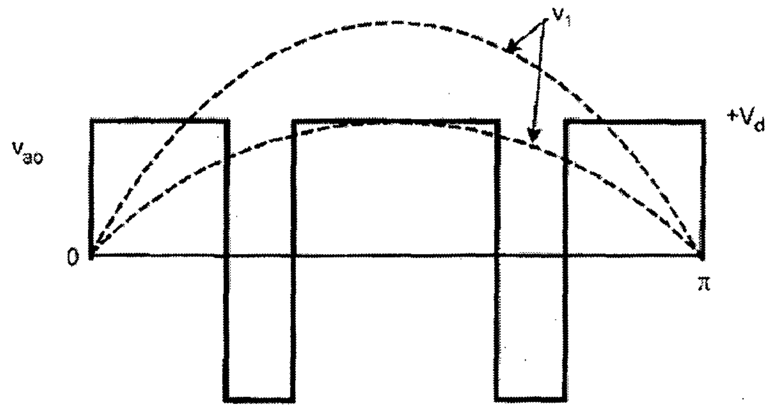


Figure 3.3. PWM principle to control output voltage.

High performance drives invariably requires current control. In case of SEIG, A PWM voltage-fed inverter for voltage control purpose, a feedback current loop can be applied. In such cases inverter operated as reactive power and current supplier [19],[25].

3.2 Current Controlled PWM Voltage Source Inverter:

The current controlled PWM VSI 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. Therefore current control of PWM inverter is one of the most important subjects of modern power electronics.

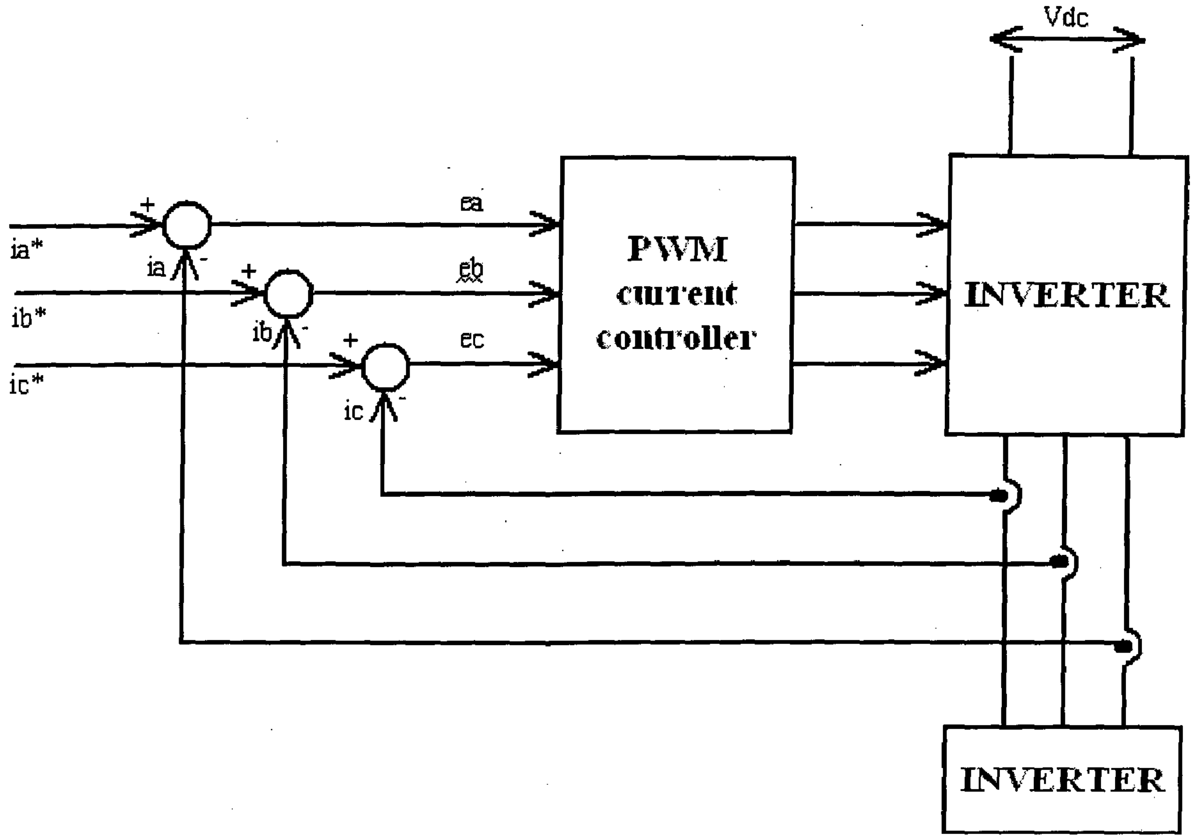


Figure 3.4: Basic block diagram of CC-PWM inverter

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

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 Classification of Hysteresis Current Control:

3.3.1 Fixed band hysteresis current control:

In this scheme the hysteresis bands are fixed through out the fundamental period as shown in *fig* 3.5(a). 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 $i_a < i_l$, $V_{ao} = Vdc/2.0$;

3.3.2 Sinusoidal band hysteresis current control:

In this scheme the hysteresis band vary sinusoidally over a fundamental period as shown in fig 3.5(b).

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

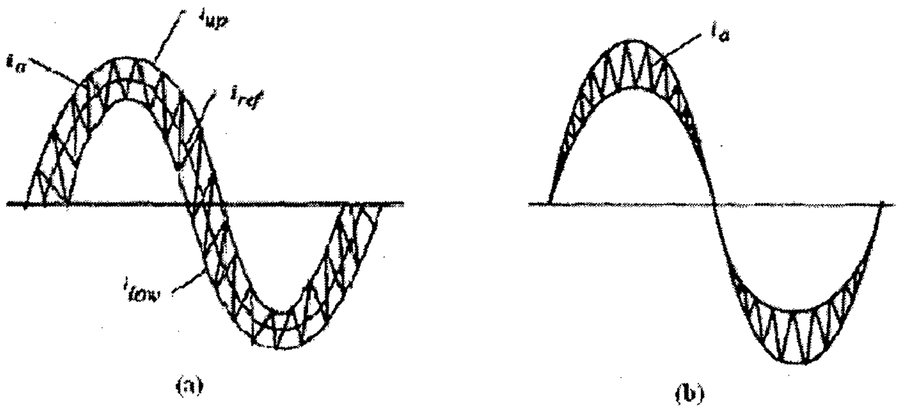


Figure 3.5. Waveforms of hysteresis current controller. (a) Fixed band. (b) Sinusoidal band.

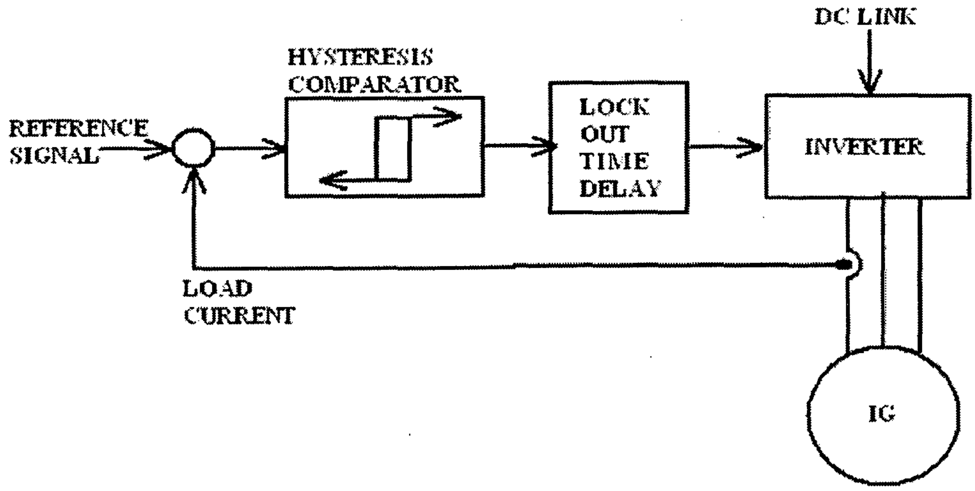


Figure 3.6 Hysteresis current controller for one Inverter leg

3.4. 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.

3.5. 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.

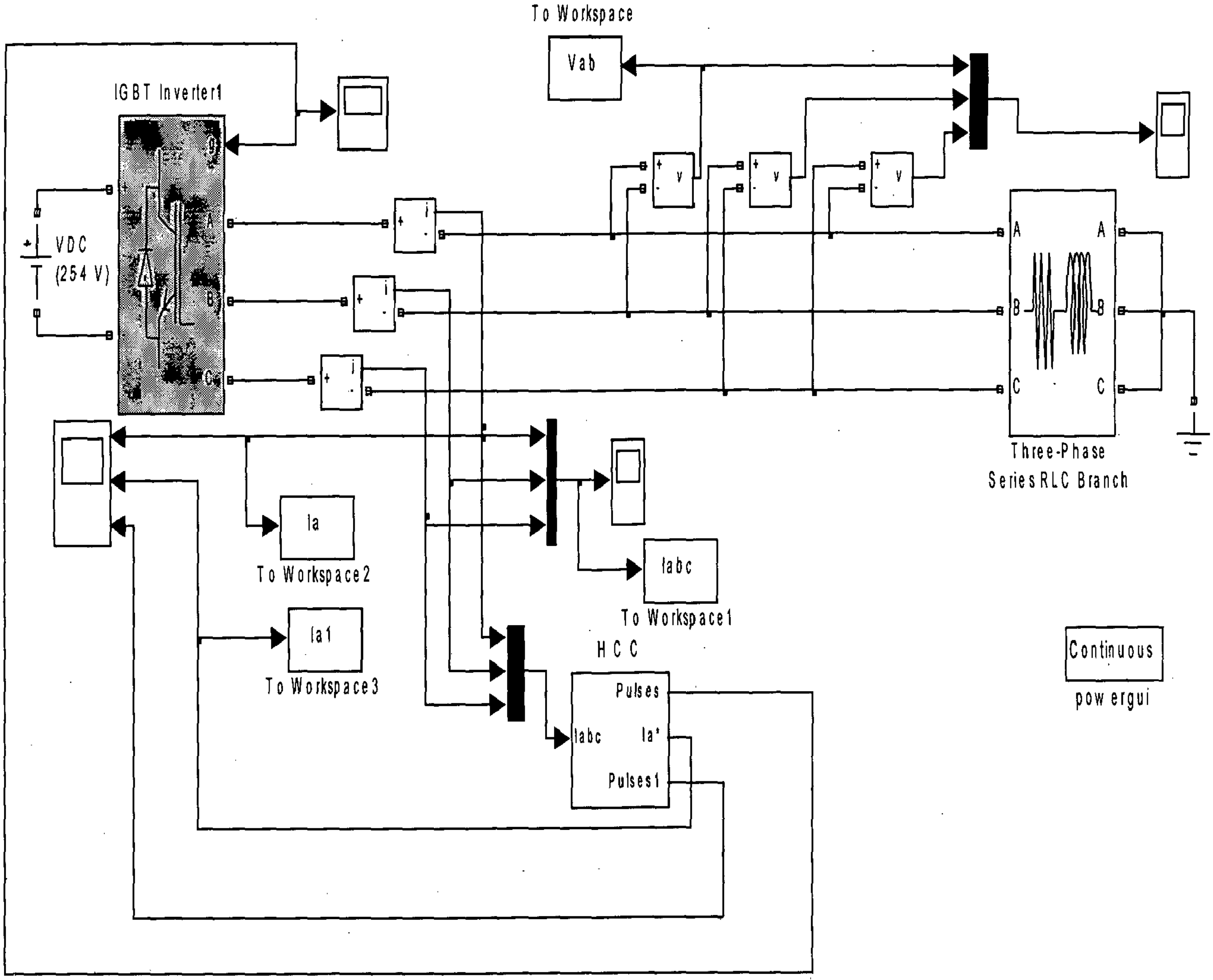
3.6. Voltage control Using CC-VSI:

A three-phase PWM inverter may also be used as a static reactive power source. The inverter can supply leading or lagging reactive current. The excitation current can be controlled by controlling the modulation index and phase of fundamental inverter voltage with respect to the generator voltage [43], [44].

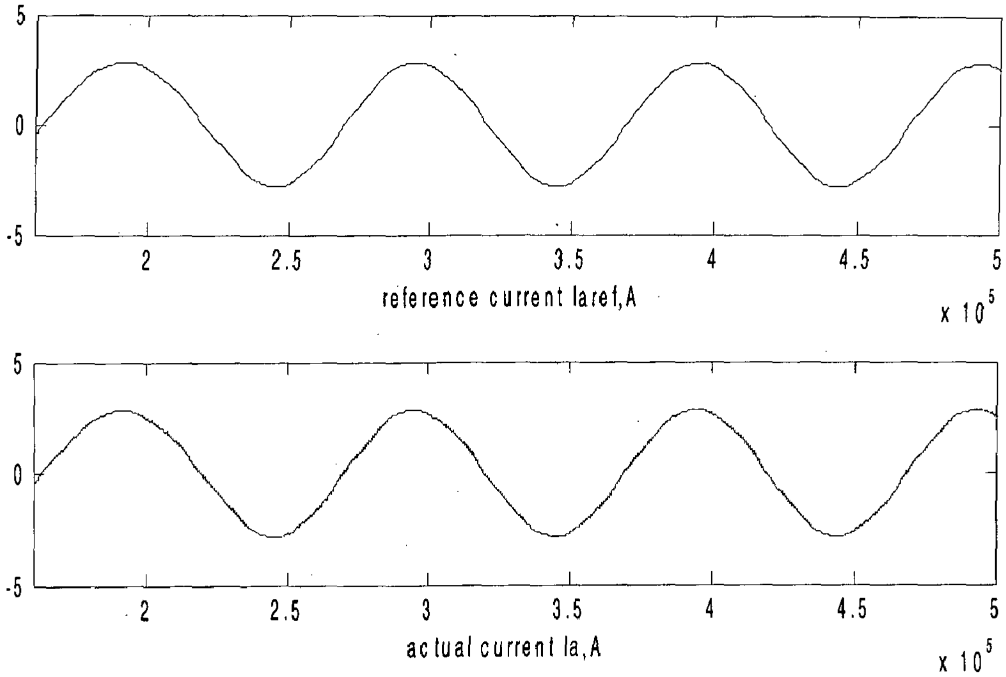
The reactive load current and excitation current required for maintaining constant output voltage of an induction generator have to be supplied by the PWM inverter. Complicated high speed electronic circuits are required to determine reference generator current under varying load and rotor speed conditions.

In this scheme, only the controller current is sensed and forced to track the reference current. The generator voltage is regulated by controlling the excitation current supplied by the controller. The voltage is regulated irrespective of varying rotor speed and changing loads. The controller does not require any real time mathematical computation. The control technique also does not require information about rotor speed and position. This eliminates need for mechanical sensors, minimizing hardware and reducing overall cost. Direct sensing of the controller current enables protection of the controller from over-current. Low rating current sensors are required for this scheme as compared to some other schemes, as the sensors have to sense only the controller current.

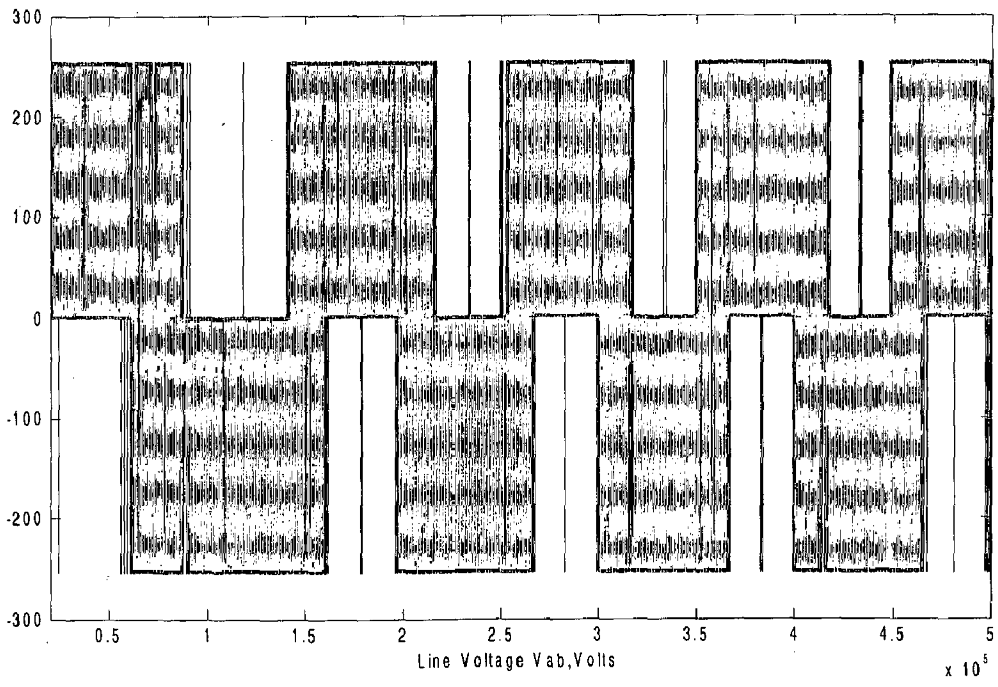
3.7. CC-VSI Simulation:



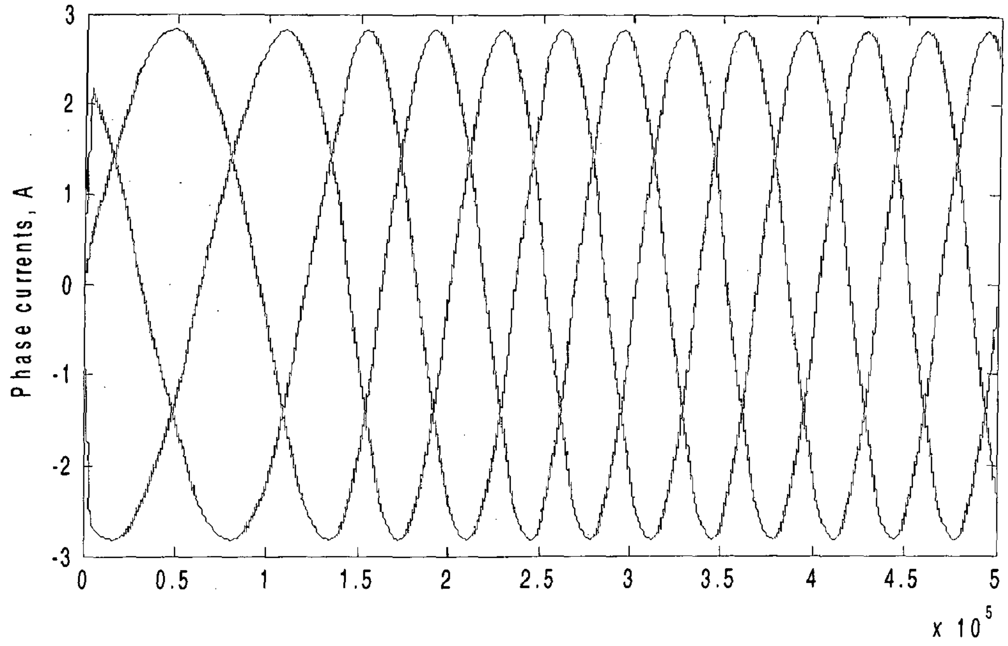
Reference Current and Actual Current:



Line voltage Vab:



Three Phase Current:



CHAPTER 4

VOLTAGE CONTROL OF SEIG

4.1. Introduction:

In the previous chapter 2 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.

The use of a static PWM inverter for controlling excitation gives a better transient response and smooth variation of excitation current. The PWM controller can be placed in series or shunt with induction generator (IG). The series connected controller is used as a PWM controlled ac–dc converter. For supplying ac loads, an additional inverter of full rating is required. Thus, the two-stage controller has to handle active load current and excitation current of the IG and compensate for reactive load current. The active load current is supplied directly by the IG.

The shunt connected PWM controller has to supply only the reactive load current and excitation current of the IG. Thus the shunt connected controller requires devices of lower power ratings. Various schemes have been reported for shunt operation of self-excited IG controller [40]-[49]. A simple V/F control with sinusoidal PWM control is presented in [65]. All these schemes, however, are based on load current sensing. The reactive load current and excitation current required for maintaining constant output voltage of an induction generator have to be supplied by the PWM inverter. Complicated high speed electronic circuits are required to determine reference generator current under varying load and rotor speed conditions.

4.2 Voltage Control of SEIG by Using CC-VSI:

This dissertation 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. . In this scheme, only the controller current is sensed and forced to track the reference current. The developed 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 [43]. The schematic of the system is shown in Fig 4.1

4.3 System Description:

The proposed controller uses a hysteresis current controlled, voltage source PWM inverter to supply the reactive load current and desired excitation current for induction generator. 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.

As shown in the *fig.* 4.1, 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 (*Iref*) is derived by adding two current components, viz. the in-phase current (*Iractive*) and the quadrature current (*Irexcitation*).

$$Iref = Iractive + Irexcitation \tag{4.1}$$

The in-phase active current component overcomes losses in the converter. The difference in active load current demand and the active component of generator current flows through the converter. This mismatch in current is reflected in the variation of dc link voltage of the controller. Thus, the active current component of the generator can be controlled by controlling the in-phase component of inverter current. The reference in-phase inverter current is obtained by multiplying the dc link error with reference template voltage derived from the supply voltage. Active reference current component for phase A is given by:

$$I\text{ractive} = V_{\text{dcerr}} \sin(\omega t) \tag{4.2}$$

Similarly, active current components for the other two phases are derived by multiplying the respective phase voltages.

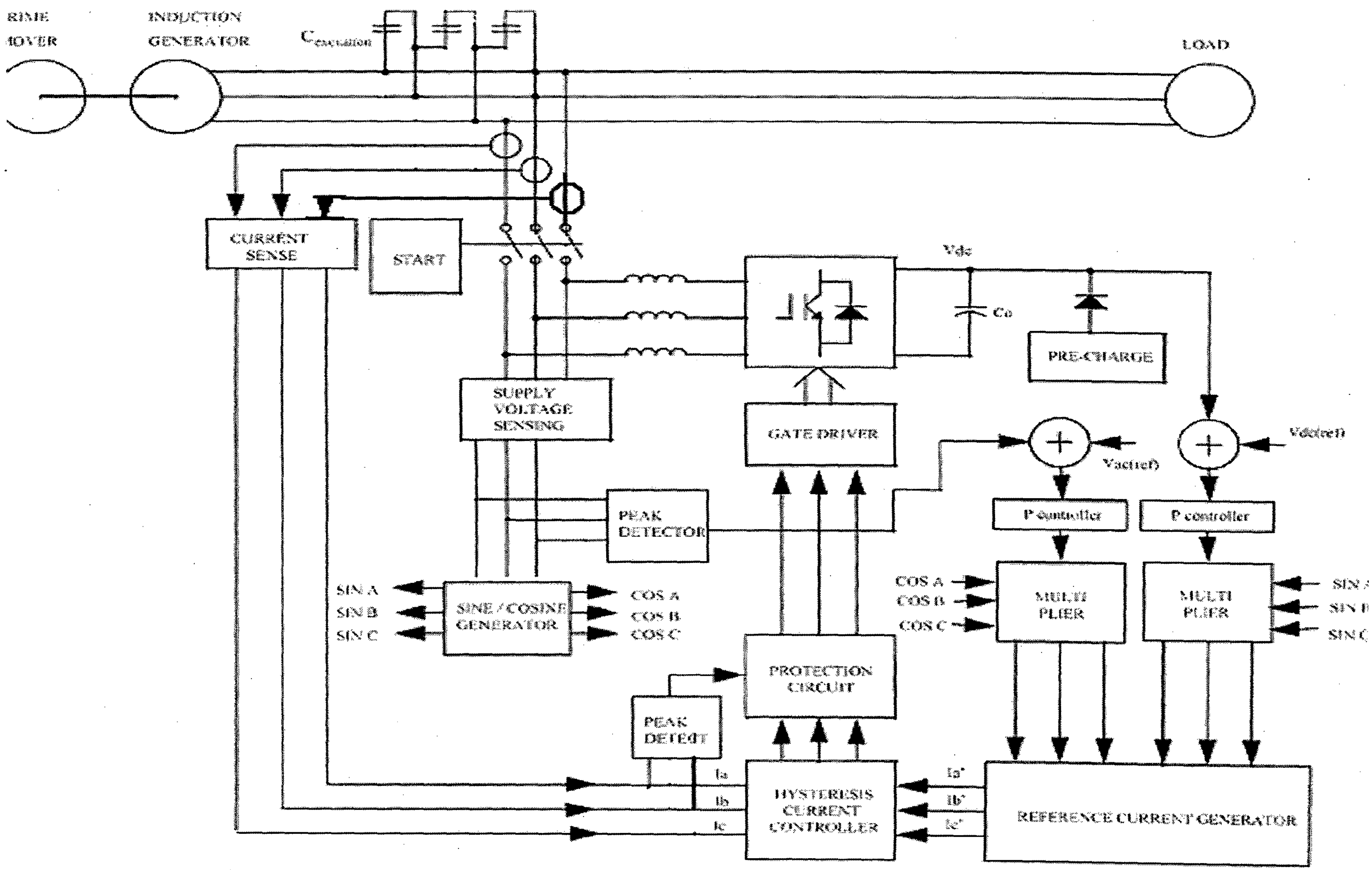


Fig 4.1 proposed voltage controller for self-excited induction generator

The quadrature reference current is decided by the net excitation current of the induction generator and reactive load current demand. This excitation current of IG determines the generator voltage. The quadrature reference current is obtained by comparing the generator voltage with a reference level and the resultant ac voltage error is multiplied with corresponding cosine template. The quadrature reference current component for phase A is:

$$Irexcitation=Vacerr\cos(\omega t) \qquad (4.3)$$

The three phase reference cosine templates required in ac control path are generated through integrator by first steeping down the generator voltages. The sinusoidal template voltages are derived by using simple trigonometric relations as shown below:

$$\begin{aligned} \text{Sin (A)} &= 0.58[\cos(B)-\cos(C)] \\ \text{Sin (B)} &= 0.58[\cos(C)-\cos(A)] \\ \text{Sin (C)} &= 0.58[\cos(A)-\cos(B)] \qquad (4.4) \end{aligned}$$

Initially, the controller is kept disabled. The induction generator is started in the conventional manner using three capacitors of fixed value. When sufficient voltage is generated, the controller is enabled. In this scheme, only the controller current is sensed. The controller is protected against over-current by sensing the current flowing through it and using this information to shut-off the gate pulses of the IGBTs.

4.4. Control Strategy:

Initially the external rectifier bridge charges the capacitor. The minimum initial capacitor voltage required depends on parameters of IG, voltage drop across the devices of the inverter, change in terminal voltage; which is supposed to control by this controller. Self-excitation is the result of the interaction between the speed of prime-mover (in laboratory DC shunt motor with speed control arrangement is used for experimentation), shunt connected fixed capacitor value, parameters of the induction machine and the residual flux. During the voltage buildup process, the magnetizing inductance L_m varies with the air-gap voltage. Due to saturation of the magnetizing flux, the terminal voltage reaches to a steady state and remains constant then load applied at its terminals. This process reduces the generator terminal voltage.

Initially, the controller is kept disabled. The induction generator is started in the conventional manner using three capacitors of fixed value. When sufficient voltage is generated, the controller is enabled.

The controller is now connected in the system. Its dc link capacitor is pre charged to such value so that at start minimum current flow through CC-VSI and system resides in steady-state. Now capacitor get charged to a value correspond to terminal voltage at point of common coupling. CC-VSI converts this dc voltage into ac voltage which supplies the necessary exciting current to improve the air-gap flux of the IG so that IG buildup its voltage again to pre-fixed value. Now system resides at this new steady state condition irrespective of the change in load or prime mover speed. And its voltage is maintained constant by controller action.

If the electric power generated by the IG is higher than the active power required by the load connected across the stator terminals, the so called exceeding power is stored in the capacitor. Hence, the capacitor voltage *(Vc)* increases. Conversely, if the amount of electrical power generated by the IG is less than the active power required by the load, the mismatch in active power is supplied by the CC-VSI to the load. Hence the capacitor voltage decreases. If the amount of power generated by the IG completely matches with the active power required by the load, the capacitor voltage remains constant.

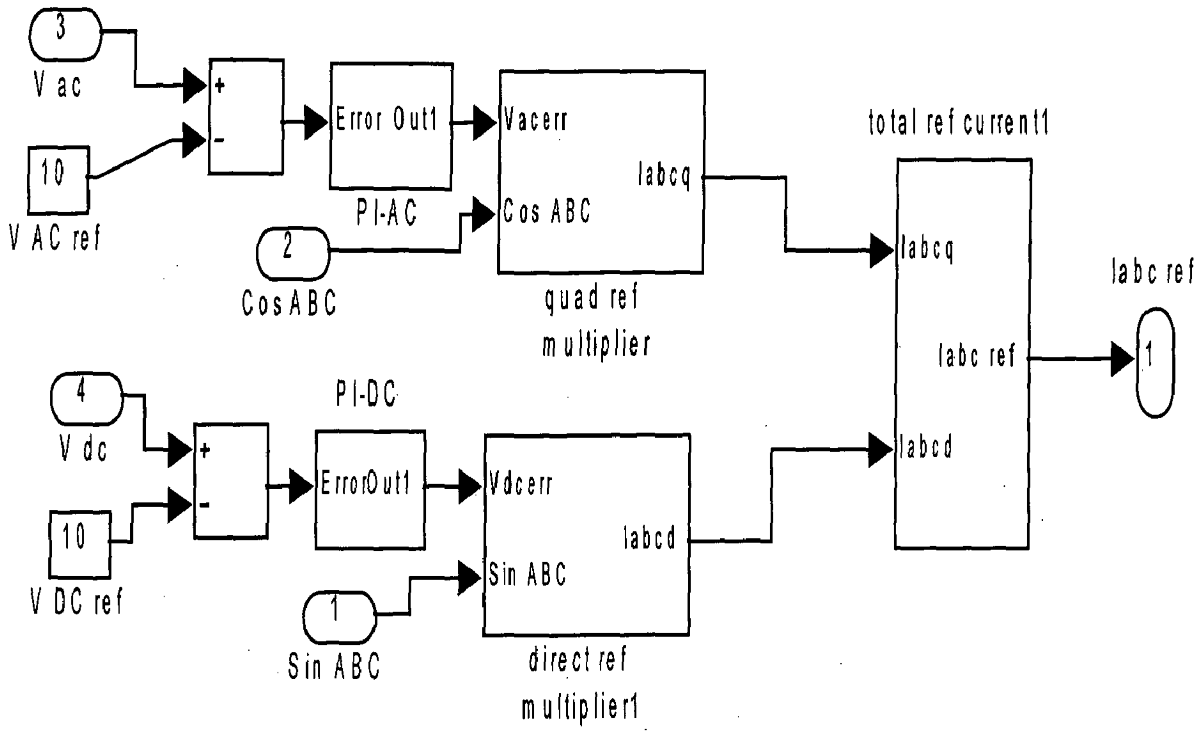
The difference in active load current demand and the active component of generator current flows through the inverter. This mismatch in current is rejected in the variation of dc link voltage of the controller. Thus, the active component of the generator can be controlled by controlling the in-phase component of inverter current

The concept of voltage regulation for a SEIG is considered as being that the controlling of reactive current requirement. The three-phase voltages of the SEIG are sensed and transferred into DC form as a feedback voltage through rectifier, and it is compared with the pre-specified 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.

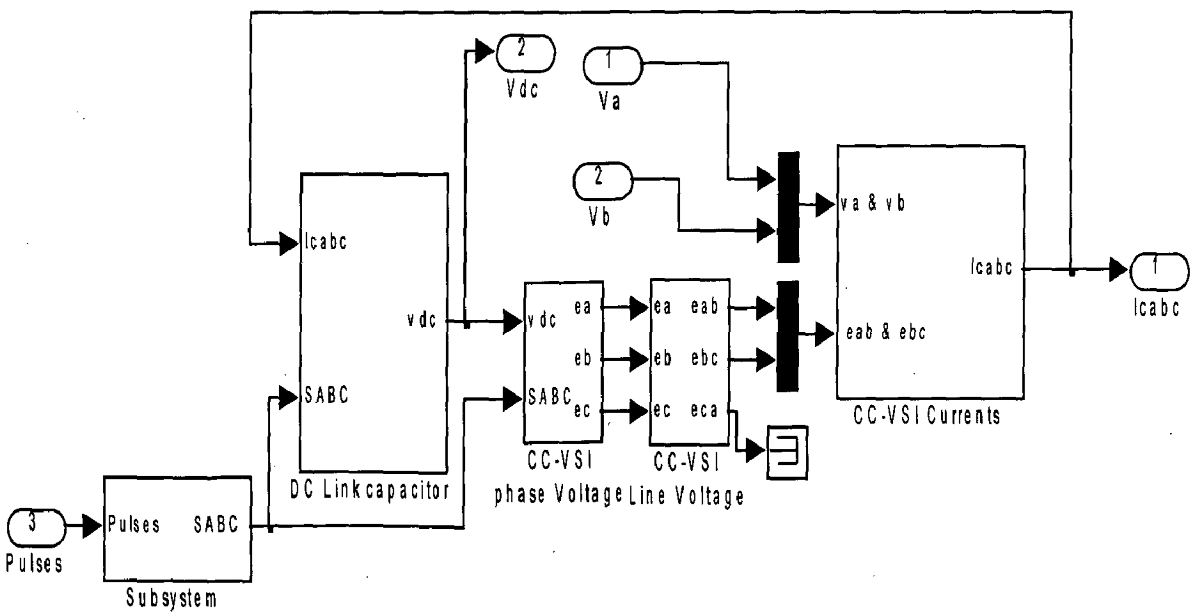
Therefore final gate pulses to CC-VSI are depending on active and reactive power requirement of the system. The controller is protected against over-current by sensing the current flowing through it and using this information to shut-off the gate pulses of the IGBTs.

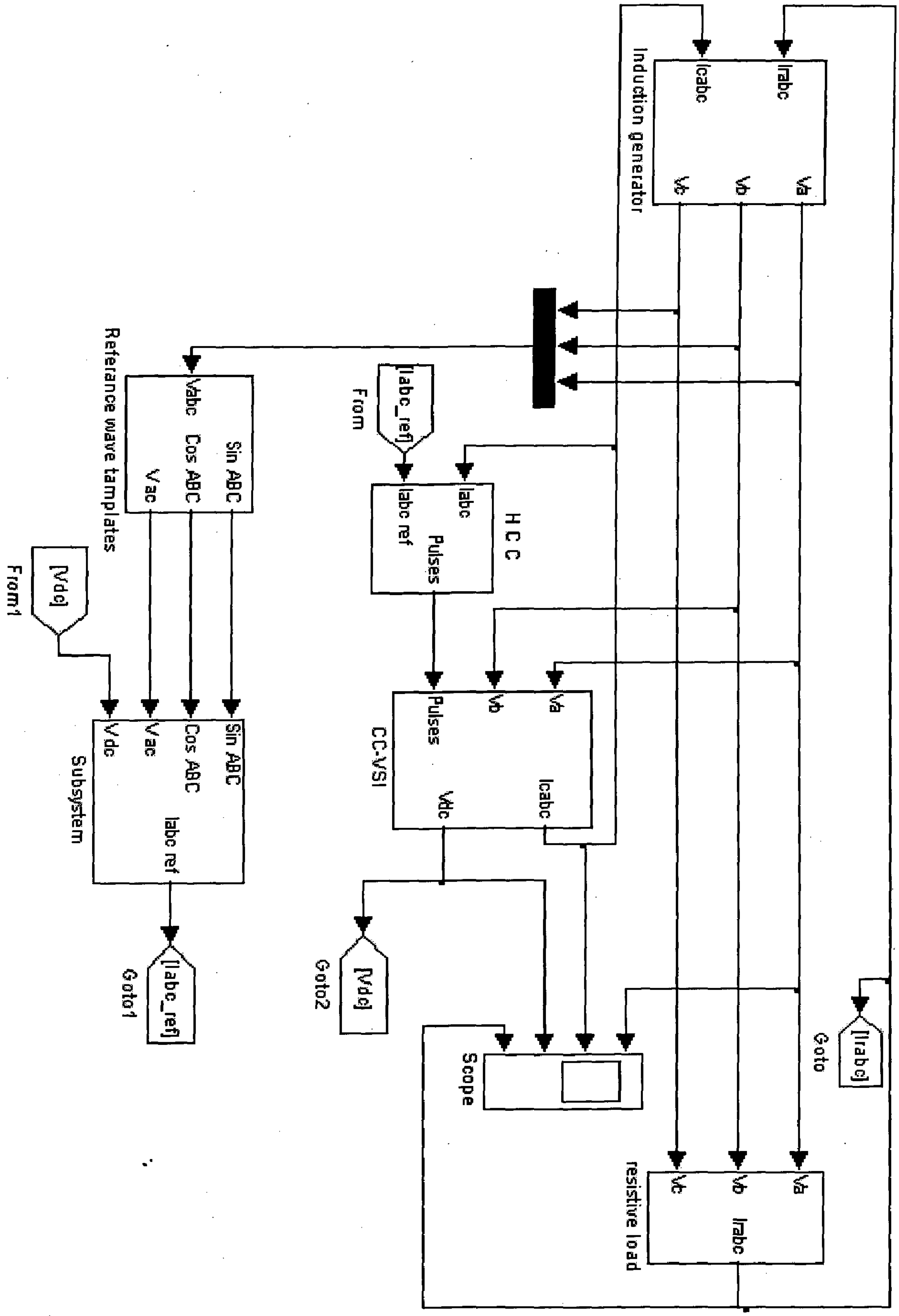
4.5. Simulations for Voltage Controller:

(a) Controller Block:



(b) CC-VSI:





Induction generator
Icabc
Irabc
Vc
Vb
Va
Referance wave tamplates
Vabc
Sin ABC
Cos ABC
Vac
[Iabc_ref]
From
H C C
Iabc
Iabc ref
Pulses
CC-VSI
Pulses
Vb
Va
Vdc
Icabc
[Vdc]
From1
Subsystem
Sin ABC
Cos ABC
Vac
Vdc
Iabc ref
[Iabc_ref]
Goto1
[Vdc]
Goto2
Scope
[Irabc]
Goto
resistive load
Vc
Vb
Va
Irabc

CHAPTER 5

SYSTEM DEVELOPMENT AND EXPERIMENTATION

The complete description of control strategy is explained in previous chapter. We can divide the main part of hardware as:

1) Self-excited induction generator
2) Power circuit
3) Control circuit.

5.1 Self-Excited Induction Generator:

In my system self-excited induction generator(SEIG) is realize by an induction machine connected to dc machine which work as variable speed prime-mover and a capacitor bank is connected across it (fig.5.1) for providing reactive power for helping in voltage buildup. Ratings of machines are given in appendix A.

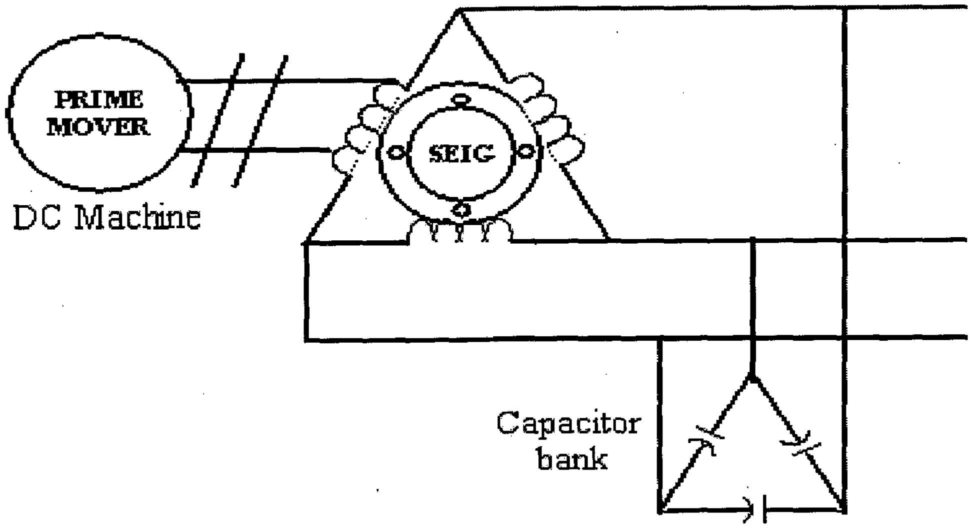


Figure 5.1.Self excited induction generator connection diagram at no load.

The capacitor bank value is selected such that its capacitive reactance at synchronous speed must be equal to machines magnetizing reactance at that speed. Then total lagging reactive power required for voltage build up by generator is supplied by capacitor bank and helps generator to develop its rated no load voltage.

5.2 Power Circuit:

A prototype model of traditional current controlled voltage source inverter with dc link capacitance is developed in the laboratory for experimentation purpose power circuit consists of following circuits:

5.2.1. Current Controlled Voltage Source Inverter:

Fig. 5.2 shows the power circuit of the PWM voltage source inverter. It consists of 6 IGBT switches. Datasheet of applied switch is available in appendix B. Each IGBT switch is used in the circuit consists of an inbuilt anti parallel free wheeling diode. No forced circuits are required for IGBT because these are self commutated device (they turn on when gate signal is high and turn off when gate signal is low). The load inductance restricts large di/dt through IGBTs hence only turnoff snubber is required for protection. An RCD (resistor, capacitor and diode) turn-off circuit is connected to protect the circuit against high dv/dt and is protected against power voltage by connecting MOV (Metal Oxide Varistor).

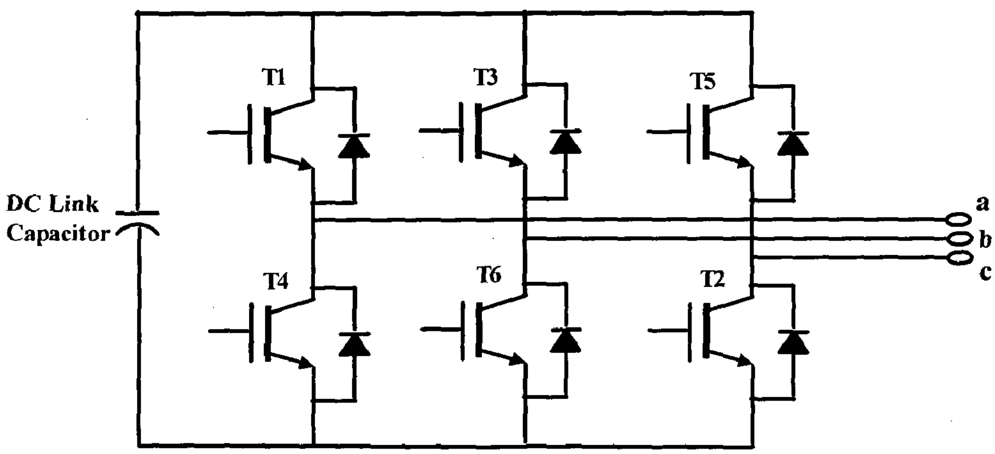


Figure 5.2.Power circuit of Voltage Source inverter using IGBTs

5.2.2. Circuit Protection:

(A) Snubber Circuit for IGBT protection:

IGBTs are increasingly the switch of the choice for PWM converters for use in power electronics applications, 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. Snubber is therefore needed to protect the switch from transients

Snubber is employed to:

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

RCD snubber is 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.

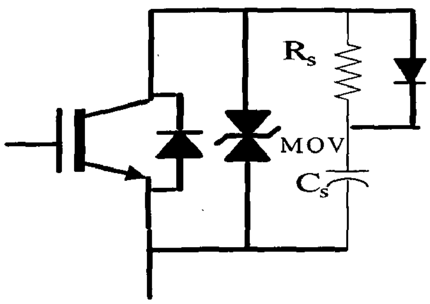


Figure 5.3 Snubber circuit of IGBT

(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.

(E) Over current trip circuit:

In developed controller, at the time of start of generator voltage build-up and its loading controller should be kept disabled; for this process and whenever there is any fault in system for protection of CC-VSI we required to use a trip circuit. In given trip circuit no signal given to IGBT switches until preset switch is pressed. If preset is pressed a high state signal is given to an AND gate which enabled all other AND gate and firing pulses coming from hysteresis controller passes through it and given to the driver circuit. If at any time fault occurred or overload current flow from CC-VSI to load and generator a high state signal is coming to clock input of D-type flip-flop which then passes its D input to output Q which is permanently kept at ground level thus a low state occurred at AND gate input and it disabled all AND gates and no pulses now given to inverter switches In given circuit the Current measured by hall effect current sensor is continuously compared with a reference wave and whenever actual current increases beyond a limit circuit trips off. The circuit diagram is shown in *fig.* 5.3 .here first ac wave is converted to unidirectional wave and then applied to a comparator which in turns ON or OFF BJT switch. Normally a high signal applied across base of transistor and clock input of D-flip flop is at zero level. Now flip flop work according to preset.

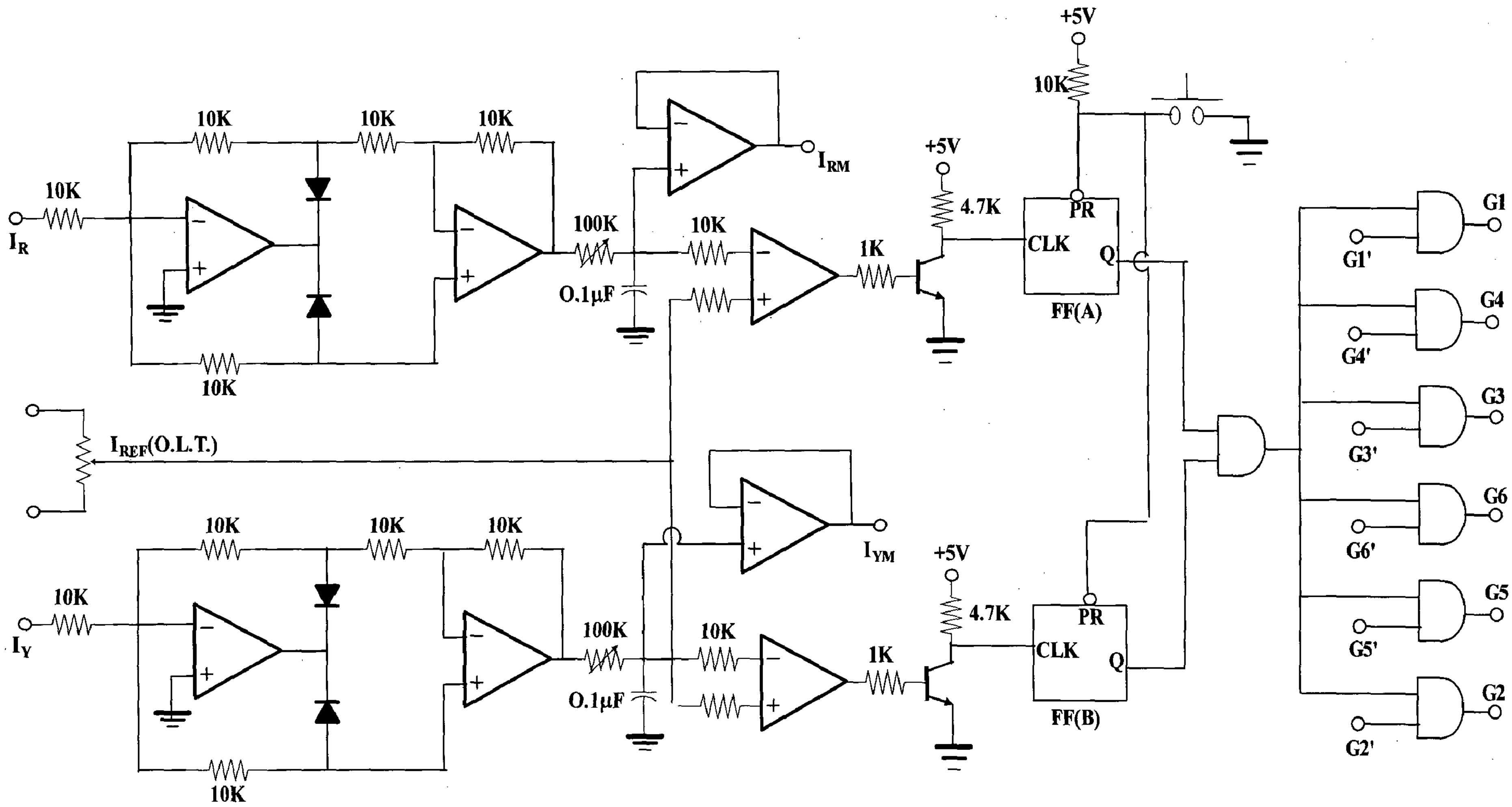


Figure.5.4.Circuit diagram for Over Current Trip

5.2.3. Pulse amplification and isolation circuit (Drivers):

The pulse amplification and isolation circuit for IGBT is shown in *fig.5.5.* The opto-coupler (MCT-2E) provides the necessary isolation between the low voltage control circuit and high voltage power circuit .The pulse amplification is provided by the output amplifier transistor 2N2222.

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 +12V pulse (amplified) appears across its 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 12V zener diode IC connected across the output of isolation circuit. It clamps the triggering voltage at 12V.

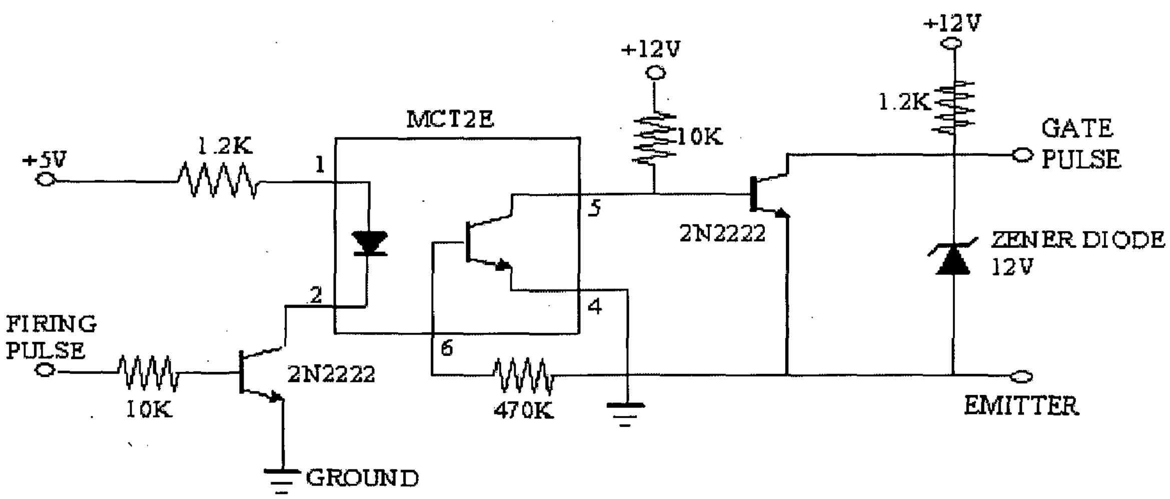


Figure5.5. Pulse amplification and isolation circuit

5.3 Control Circuit:

Control circuits constitute the circuit which drives the CC-VSI and SEIG system and control the reactive power flow and voltage of it. The main parts are:

5.3.1 Power supplies.

5.3.2 AC load voltage averaging circuit.

5.3.3 AC current measurement circuit.

5.3.4 Averaged AC and DC link voltage measurement circuit.

5.3.5 Reference current generation.

5.3.6 PI controller and analog multiplier.

5.3.7 Hysteresis current controller and delay circuit for gate pulses.

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 5.6*; 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.

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

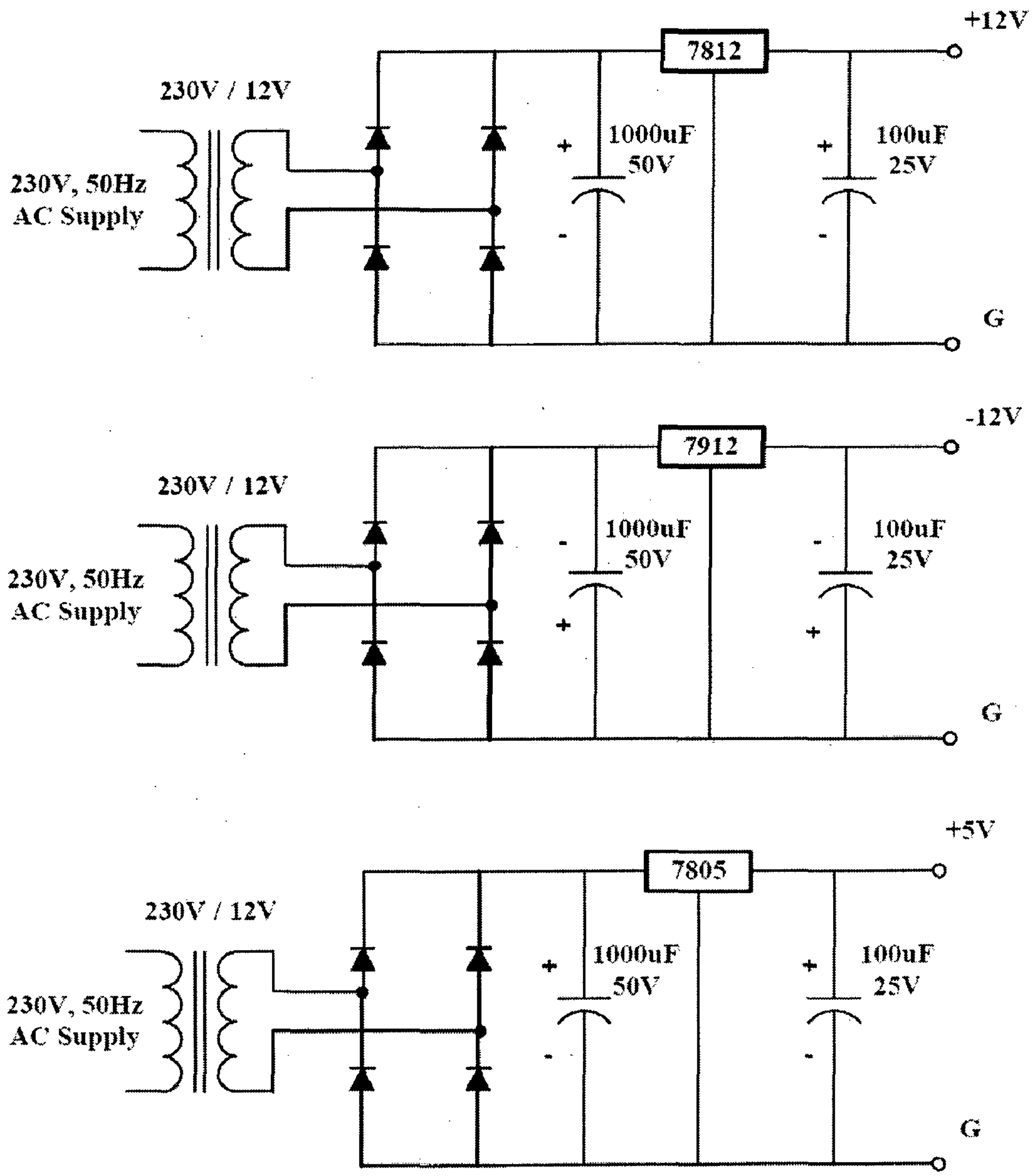


Figure 5.6. Circuit Diagrams for IC regulated Power Supplies

5.3.2 AC Load Voltage Averaging Circuit:

SEIG stator terminal voltage is sensed and converted into dc through 3 phase diode bridge rectifier for generating quadrature component of reference current. This is done by the circuit shown in *fig 5.7.*

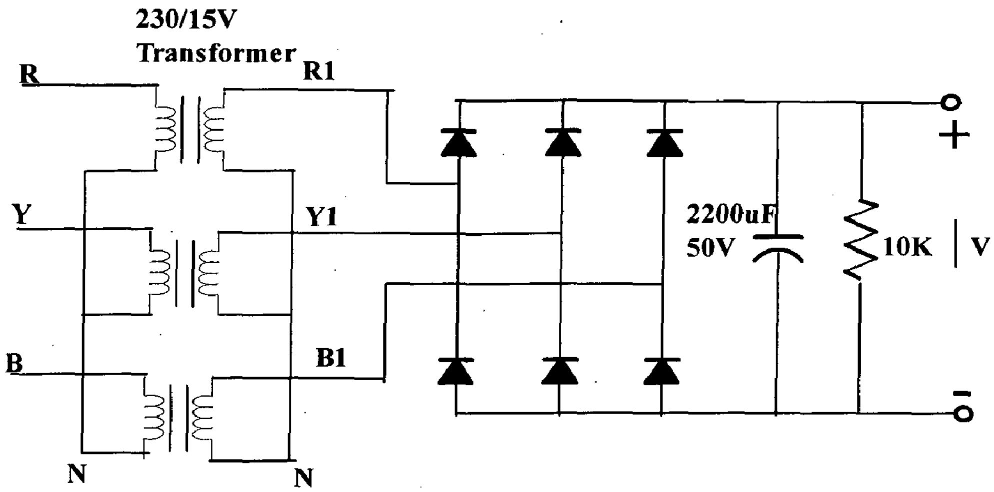


Figure 5.7. AC Load voltage measurement and its averaging circuit

5.3.3. AC Current measurement 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 25A 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 5.8.*

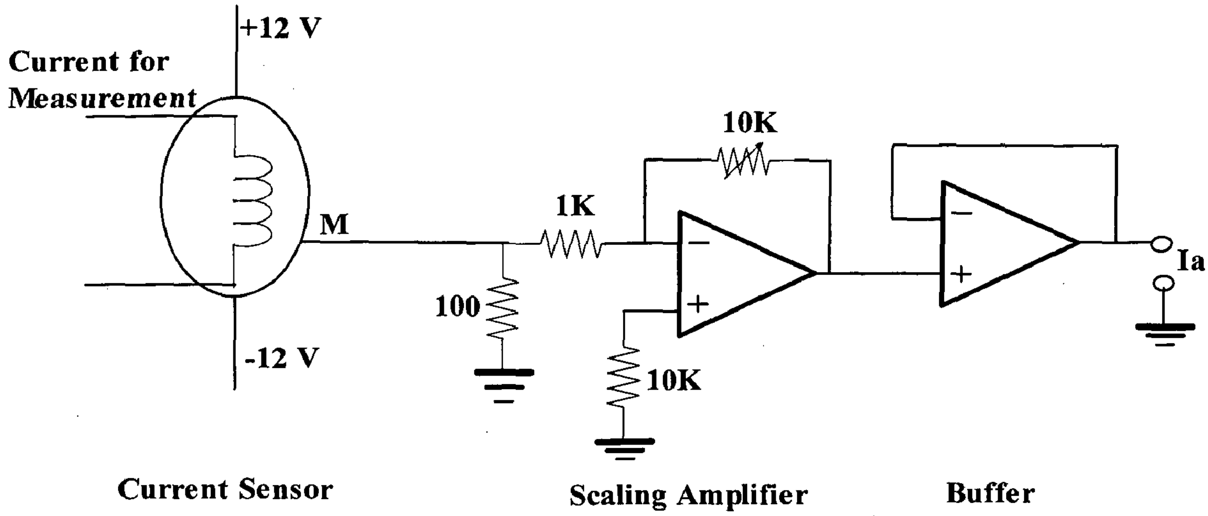


Figure 5.8. AC current sensing and calibration circuit

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 turns, Ns= secondary turns

I_p= primary current, Is = secondary current.

5.3.4 Averaged AC and DC Link Voltage Measurement Circuit:

Averaged AC is now converted into DC through simple 3 phase diode rectifier so its measurement is possible through same circuit but applied voltage levels are different so resistance values are changed. 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 5.9* and for IC configuration and special features refer to the Appendix-C. 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.

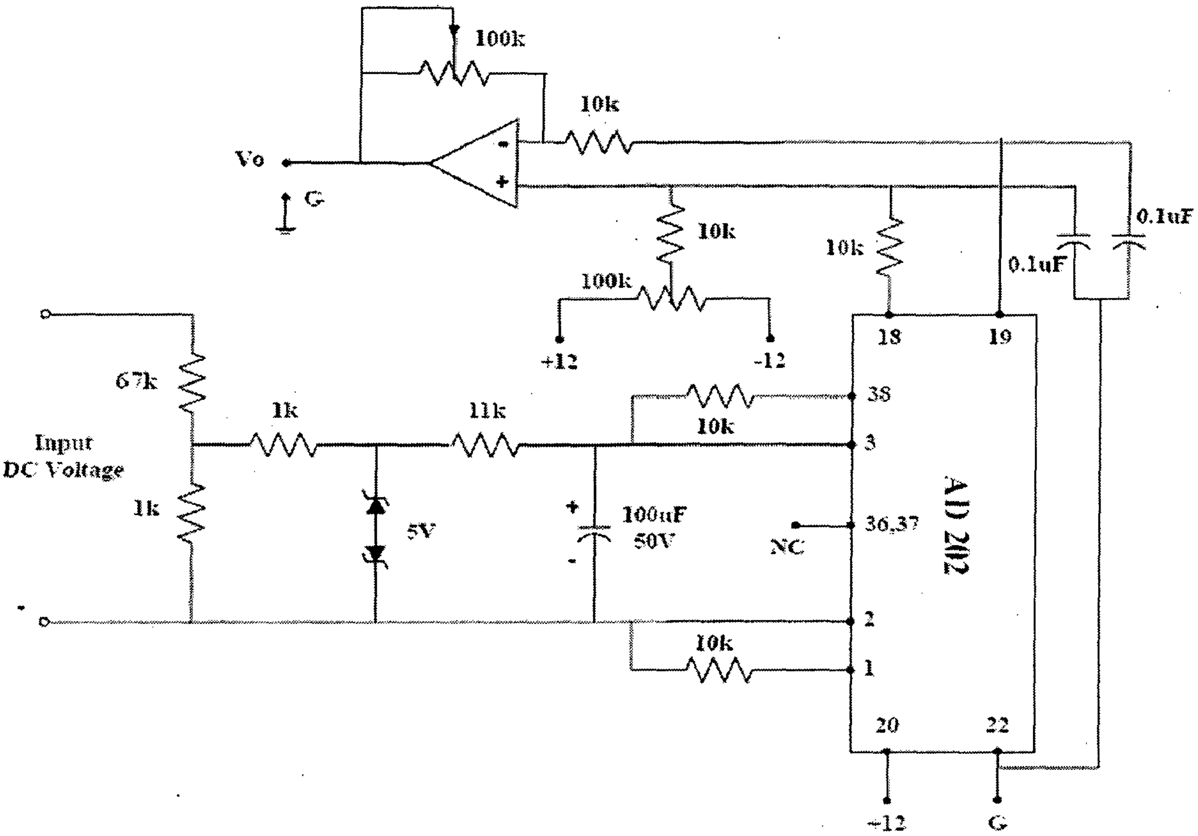


Figure 5.9. Circuit Diagram used for DC-Link Voltage Sensing and Calibration using AD 202.

5.3.5 Reference current generation

Reference current is obtained by adding two component which is in-phase (active) and quadrature (reactive) current component. It generates by multiplying sine and cosine wave template to error in generated ac and dc link voltage from reference values which was processed through PI controller. This is done by adder circuit as shown in *fig. 5.10.*

Sine and cosine wave generation:

Sine and cosine wave template is generated in my system through analog method. Firstly supply voltage (generator voltage) is stepped-down by simple isolating 230/18 V transformer and then is scaled through potential divider to a adjustable level. For my circuit I adjusted it to 5 Vp-p value and passes through an integrator and got an cosine wave template now it can converted to sine wave by simple trigonometric relationship as shown below:

Sin (A) = 0.58[cos (B)-cos (C)]

Sin (B) = 0.58[cos (C)-cos (A)]

Sin (C) = 0.58[cos (A)-cos (B)]

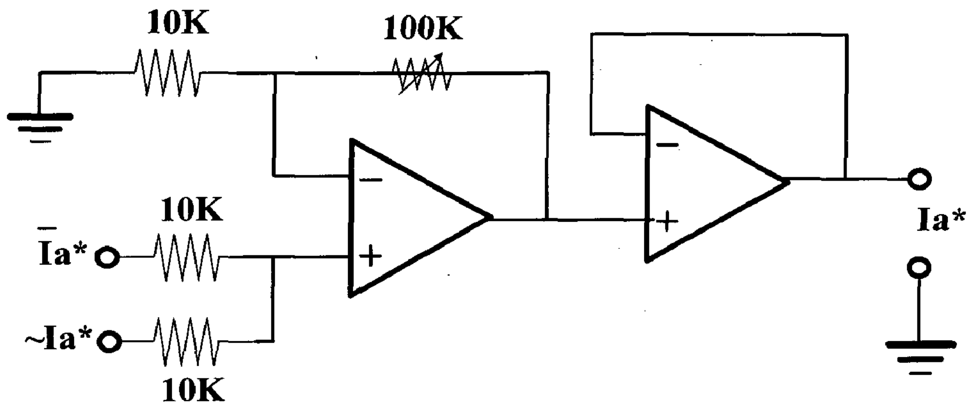


Figure 5.10. Adder circuit for reference waveform generation

5.3.6 PI controller with Analog Multipliers

This is fabricated on PCB. The design and analysis of PI controller to generate the in-phase and quadrature-phase component (or active and reactive current component) of reference current is done and is shown in *fig 5.11*. The transfer function of the circuit in the linear region of its operation is given by;

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

$$where, T_C = C_f R_f and$$

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

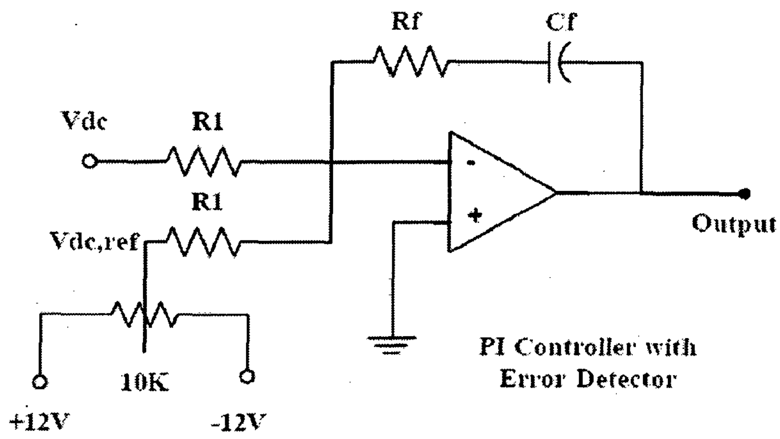


Figure 5.11. Analysis of PI controller with Error Detector

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 5.12*

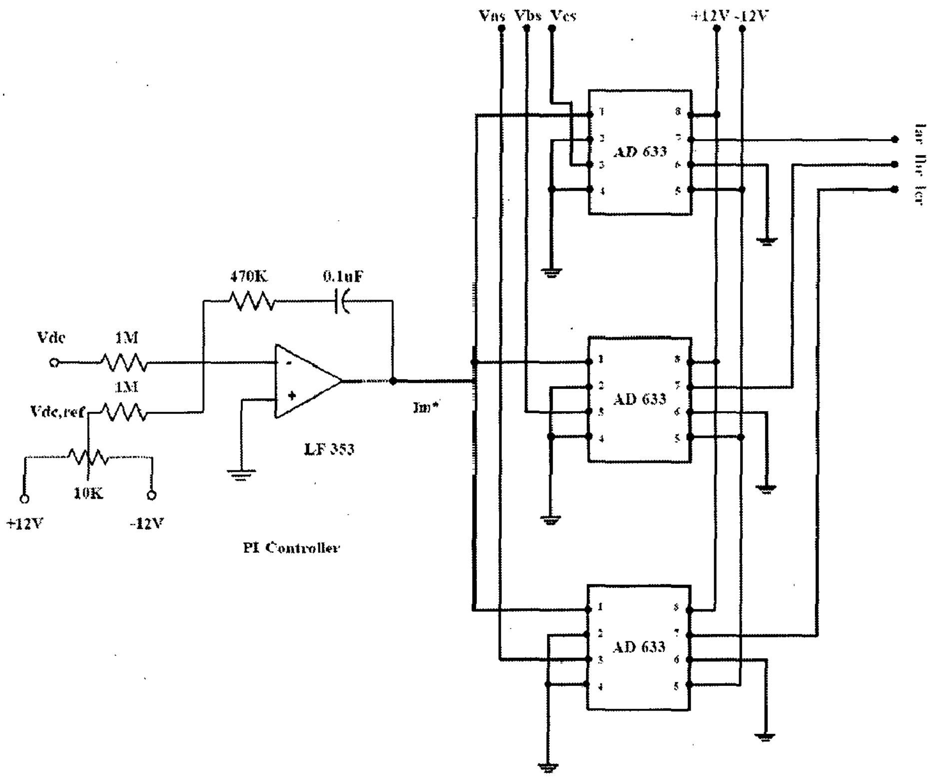


Figure 5.12. PI controller with error detector and analog Multipliers using AD6335

5.3.7 Hysteresis Current Controller and Delay Circuit for Gate Pulses:

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 Inverter has to supply to the load for compensation. To estimate the error PCB 2 is made. Here actual currents are sensed using the current sensor circuit, error is fed to pulse generation circuit.

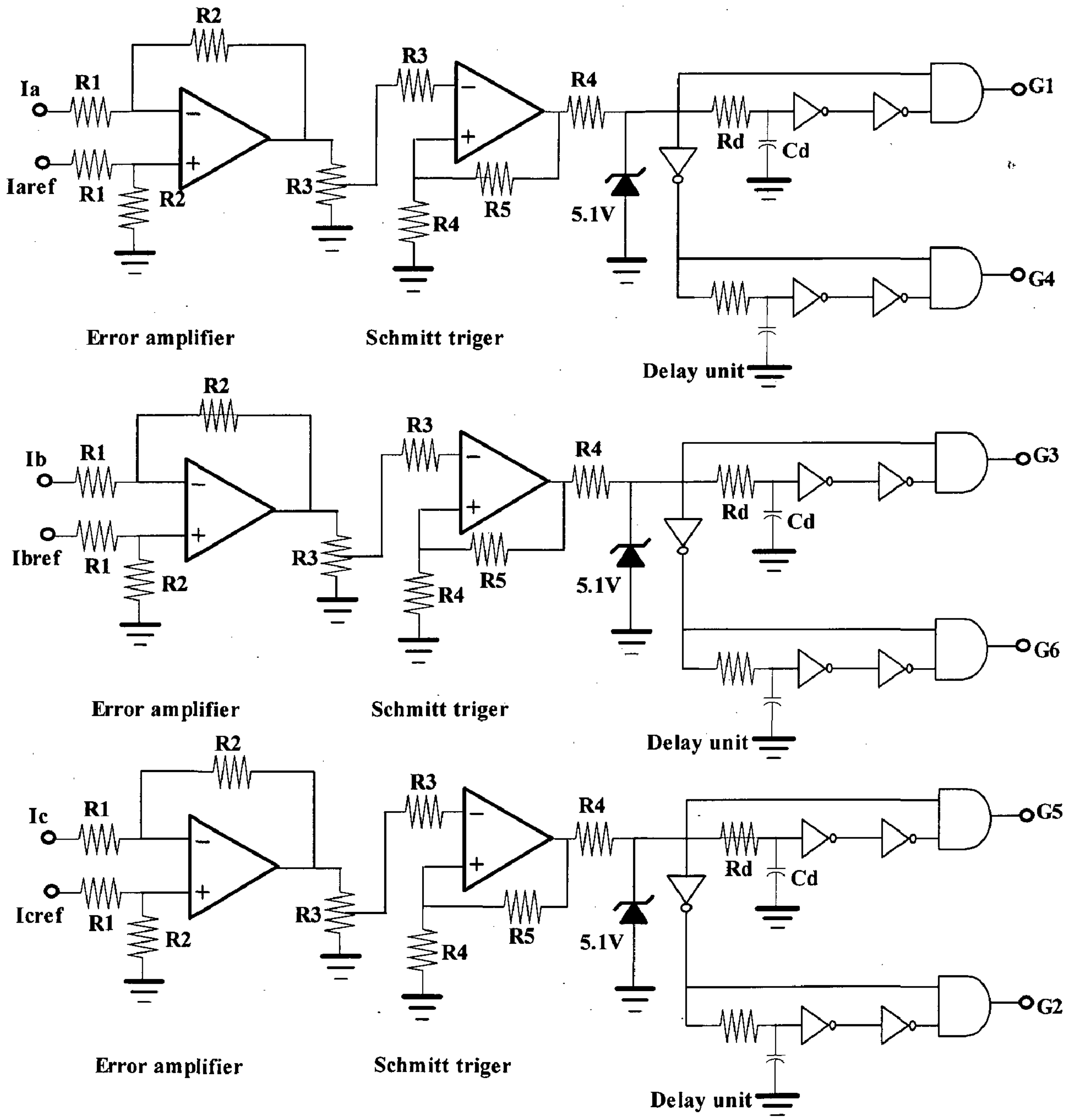


Figure 5.13. Error estimation and Hysteresis current controller

Hysteresis current controller (HCC) circuit consists of error amplifier, Schmitt trigger and lock-out delay circuit. The actual line current is subtracted from the reference current and compared through the Schmitt trigger through the trim-pot. The upper threshold voltage of the Schmitt trigger is +VR4/(R4+R5) and the lower threshold voltage is -VR4/(R4+R5). Hence, hysteresis bandwidth of the Schmitt trigger is Δh=2VR4/(R4+R5).the output of Schmitt trigger is square pulse i.e. high or low signal states depending on the condition of error current. If $(i_a - i_a^*) > (\Delta h/2)$, reverse switching occurs i.e. switch S4 is turned off and switch S1 is turned on. The 5.1V zener clips the amplitude of the pulse at 5.1 V. Values of Rd and Cd is chosen to provide a delay around 5 μs i.e. larger then turn off time of the IGBT. The switching signal from the lockout delay circuit is send to the pulse amplification and isolation circuit.

Calculation for the hysteresis band

Here V=12 V

R4=2.2K, R5=220K, Then

$\Delta h = 0.237V$

There variable gain has been provided for calibration purpose.

5.4. Results and Observations:

Here all detailed about hardware results are mentioned:

A. Self-Excited Induction Generator:

Self excited induction generator is running at constant speed of 1500 rpm and following data has been taken:

Capacitor value: 20 μF

Generated voltage: 180 V at no load,

Voltage collapses at load of 200 ohm per phase

Capacitor value: 26 μF

Generated voltage: 240 V at no load

160 V, 47 Hz at load of 200 ohm per phase,

Capacitor value: 32 μF

Generated voltage: 260 V at no load

190 V at load of 200 ohm per phase

This observation has been made from above that induction machine is self excited and generated voltage achieved its steady-state when capacitive reactance is become equal to magnetizing reactance and its voltage is decreased when it is loaded.

B. Controller Circuits Set Points:

(a) AC load voltage averaging circuit:

It converts AC voltage at point of common coupling to DC value and gives that to voltage sensor circuit.

Input AC	DC Output
200 V	21 V
220 V	25 V
240 V	30 V

Through voltage measurement circuit we get 10 V corresponds to 240 V input

(b) Averaged AC and DC link voltage measurement circuit:

AC side measurement unit is calibrated at 10 V out put when input voltage is 30V

DC side measurement unit measures DC link capacitor voltage for generation of active component of reference wave it is calibrated at 10 V out put when input voltage is 330 V.

(c) AC current measurement circuit:

It is calibrated at 7 V p-p at 1 amp current

(d) Sine and cosine wave templates:

It is generated at 5 V p-p.

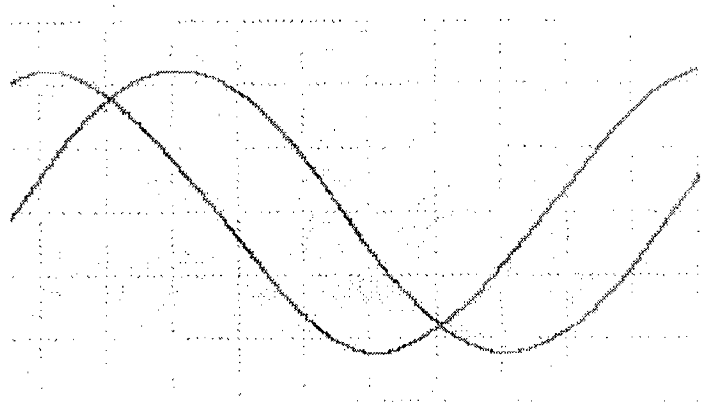


Figure5.14. sine and cosine templates

X-Axis: Time - 2ms/div.

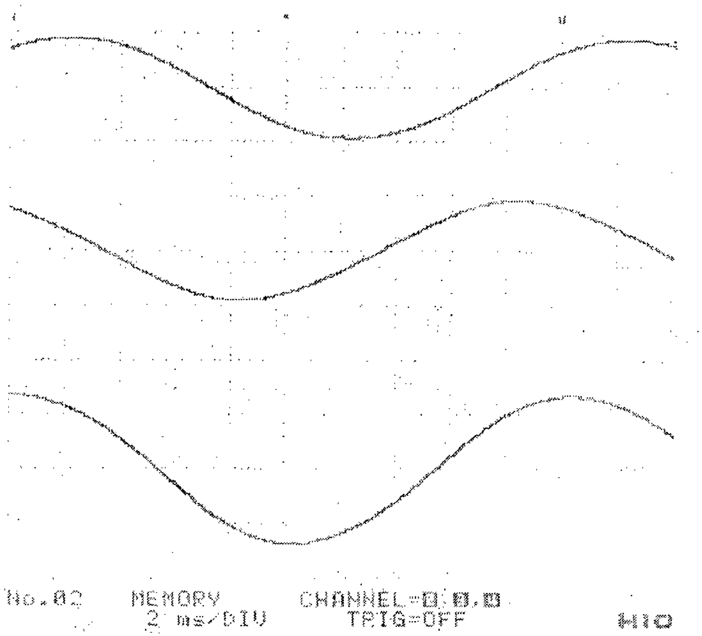
Y-Axis: Voltage amplitude- 1V/div

(e) PI controller and analog multiplier:

Analog multiplier gives output of 7.5 V p-p per phase when error is maximum Its same for both the channels either active components or reactive components

(f) Reference wave Generation:

Reference current generator has adder circuit which gives output of 7.5 V p-p when both active and reactive component is maximum



Channel 1:Sin(wt); Channel 2:Cos(wr); Channel 3:reference output (I_a*)

Figure.5.15 Reference wave for phase A ($I_a^* = I_{aactive} + I_{areactive}$)

(g) Hysteresis current controller and delay circuit for gate pulses:

It has hysteresis band of 0.02 V.

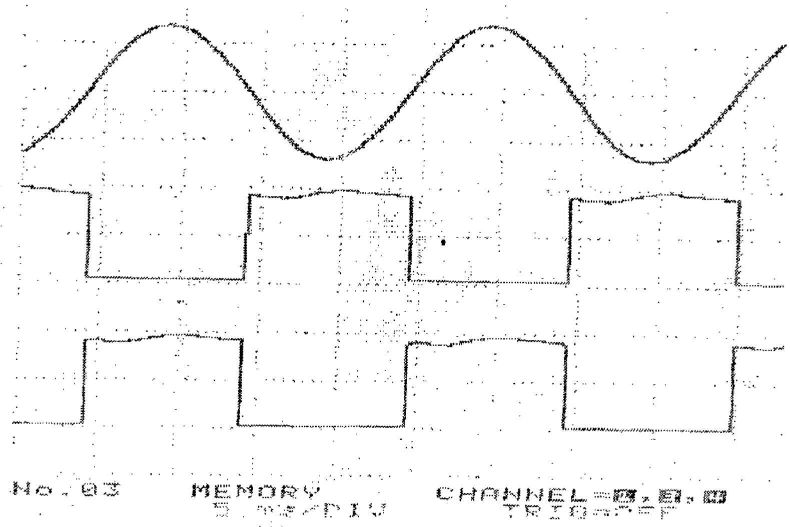


Figure5.16. Pulses From Hysteresis Current Controller for phase A

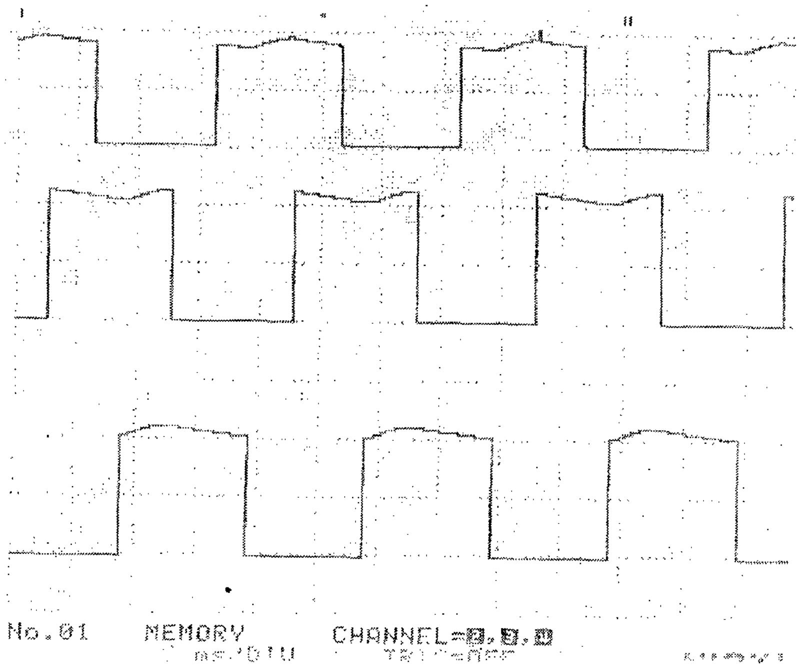


Figure5.17.Firing pulses for Phase A, B and C

(h) Over current trip circuit:

It is set to trip at 1.5 amp.

CHAPTER 6

CONCLUSION AND SCOPE FOR FURTHER WORK

In this dissertation work the concept of self excitation in Induction machine is discussed and observed through simulation. An induction generator is not able to work as generator if capacitance value is not enough and its generated voltage is reduced if its loaded and it is experimentally verified A simple generalized model of SEIG in stationary DQ reference frame has been used for simulation purpose.

CC-VSI as reactive power flow controller and as voltage controller for SEIG has been suggested and analyzed. Hysteresis current controller for CC-VSI is simulated. Control Circuit required for voltage control of Self-excited induction generation has been made and tested for their operation.

Scope for Further Work:

a) Effectiveness of this scheme can be tested for unbalanced and nonlinear loads.

b) Any other reference wave generator can be used to check systems dynamic response.

c) Different PWM technique can be applied for CC-VSI operation.

d) This method of voltage control is also modified with speed governor arrangement for total control of voltage as well as frequency control

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APPENDIX

Appendix-A

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)

I. Isolated Power Outputs
II. Uncommitted Input Amplifier

Applications

I. Multi-channel Data Acquisition
II. Current Shunt Measurements
III. Motor Controls
IV. Process Signal Isolation
V. 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.

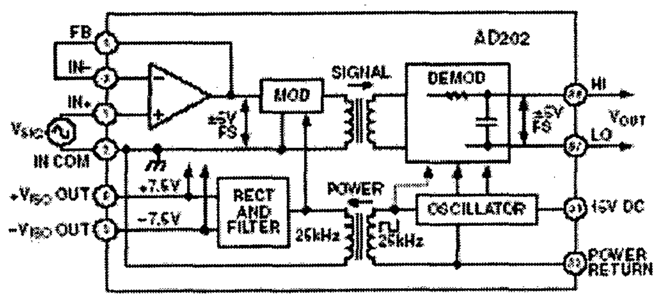


Figure A-1

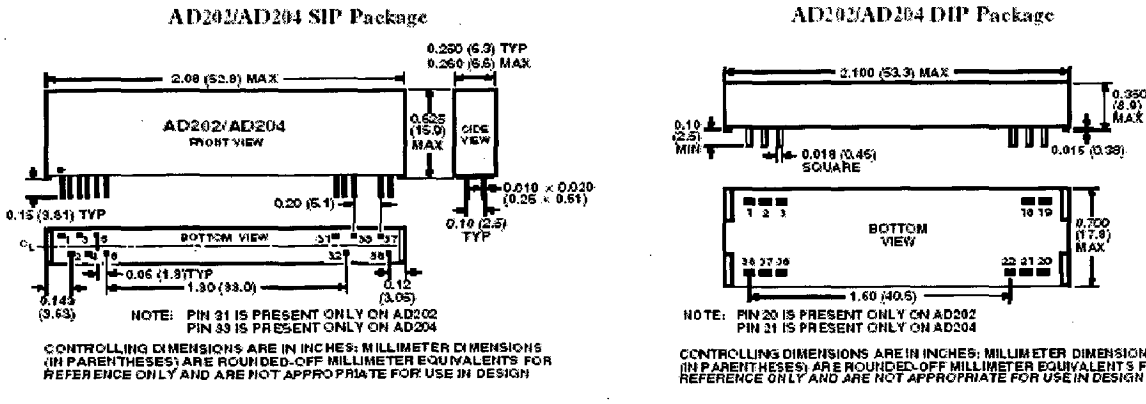


Figure A-2

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.

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:

High accuracy.

Galvanic isolation between primary and secondary.

Non-Contact ness.

Covers ac, dc and impulse current measurements.

Ease of installation.

Wide dynamic range.

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

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-3.*

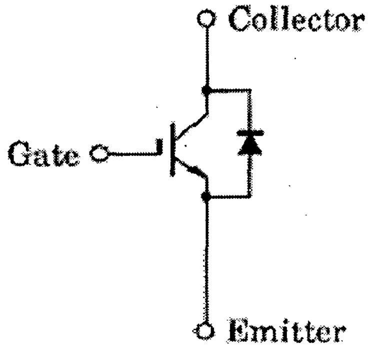


Figure A-3

For system developed N-channel GT15Q101 IGBT switch which has high speed of t_f=0.5µs (max.) and low saturation voltage ($V_{CE(sat)}$) of 4.0V max. and other ratings are given below were used.

MAXIMUM RATINGS (Ta = 25°C)

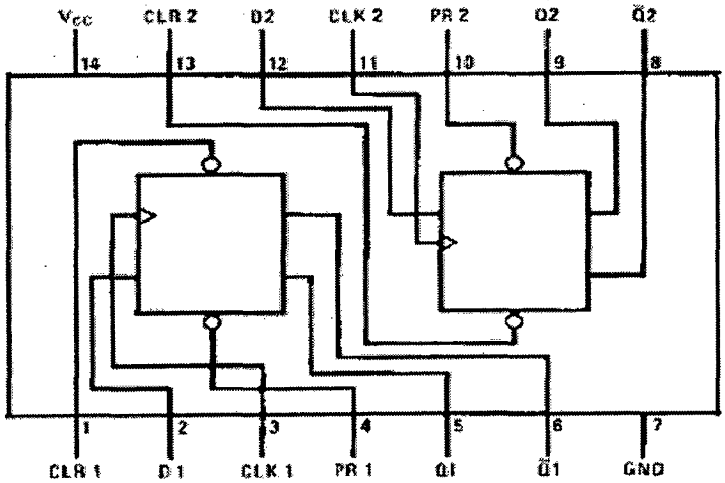
CHARACTERISTIC		SYMBOL	RATING	UNIT
Collector-Emitter Voltage		V_{CES}	1200	V
Gate-Emitter Voltage		V_{GES}	±20	V
Collector Current	DC	I_C	15	A
	1ms	I_{CP}	30	
Collector Power Dissipation (Tc = 25°C)		P_C	150	W
Junction Temperature		T_j	150	°C
Storage Temperature Range		T_{stg}	−55~150	°C

Dual Positive-Edge-Triggered D-Type Flip-Flops with Preset, Clear and Complementary Outputs (DM 7474)

General Description

This device contains two independent positive-edge-triggered D-type flip-flops with complementary outputs. The information on the D input is accepted by the flip-flops on the positive going edge of the clock pulse. The triggering occurs at a voltage level and is not directly related to the transition time of the rising edge of the clock. The data on the D input may be changed while the clock is LOW or HIGH without affecting the outputs as long as the data setup and hold times are not violated. A LOW logic level on the preset or clear inputs will set or reset the outputs regardless of the logic levels of the other inputs.

Connection Diagram



Function Table

Inputs				Outputs	
PR	CLR	CLK	D	Q	$\overline{Q}$
L	H	X	X	H	L
H	L	X	X	L	H
L	L	X	X	H (Note 1)	H (Note 1)
H	H	↑	H	H	L
H	H	↑	L	L	H
H	H	L	X	Q_0	$\overline{Q_0}$

H = HIGH Logic Level
X = Either LOW or HIGH Logic Level
L = LOW Logic Level
↑ = Positive-going transition of the clock.
Q_0 = The output logic level of Q before the indicated input conditions were established.

Note 1: This configuration is nonstable; that is, it will not persist when either the preset and/or clear inputs return to their inactive (HIGH) level.

Appendix –B

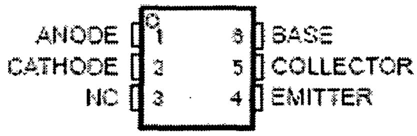
1. MCT2, MCT2E

OPTOCOUPLERS

COMPATIBLE WITH STANDARD TTL INTEGRATED CIRCUITS

- Gallium Arsenide Diode Infrared Source Optically Coupled to a Silicon npn Phototransistor
- High Direct-Current Transfer Ratio
- Base Lead Provided for Conventional Transistor Biasing
- High-Voltage Electrical Isolation . . . 1.5-kV, or 3.55-kV Rating
- Plastic Dual-In-Line Package
- High-Speed Switching: t_r = 5 µs, t_f = 5 µs Typical
- Designed to be Interchangeable with General Instruments MCT2 and MCT2E

MCT2 OR MCT2E . . . PACKAGE
(TOP VIEW)



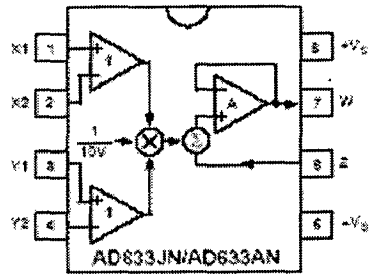
NC – No internal connection

2. LOW COST ANALOG MULTIPLIER

FEATURES
Four-Quadrant Multiplication
Low Cost 8-Lead Package
Complete—No External Components Required
Laser-Trimmed Accuracy and Stability
Total Error Within 2% of FS
Differential High Impedance X and Y Inputs
High Impedance Unity-Gain Summing Input
Laser-Trimmed 10 V Scaling Reference

APPLICATIONS
Multiplication, Division, Squaring
Modulation/Demodulation, Phase Detection
Voltage-Controlled Amplifiers/Attenuators/Filters

CONNECTION DIAGRAMS
8-Lead Plastic DIP (N) Package

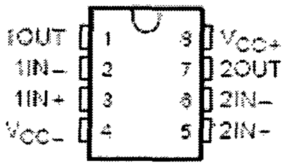


8-Lead Plastic SOIC (SO-8) Package

3. LF353 JFET-INPUT DUAL OPERATIONAL AMPLIFIER

- Low Input Bias Current . . . 50 pA Typ
- Low Input Noise Current
  0.01 pA/$\sqrt{Hz}$ Typ
- Low Input Noise Voltage . . . 18 nV/$\sqrt{Hz}$ Typ
- Low Supply Current . . . 3.6 mA Typ
- High Input Impedance . . . 10^{12} Ω Typ
- Internally Trimmed Offset Voltage
- Gain Bandwidth . . . 3 MHz Typ
- High Slew Rate . . . 13 V/μs Typ

D OR P PACKAGE
(TOP VIEW)

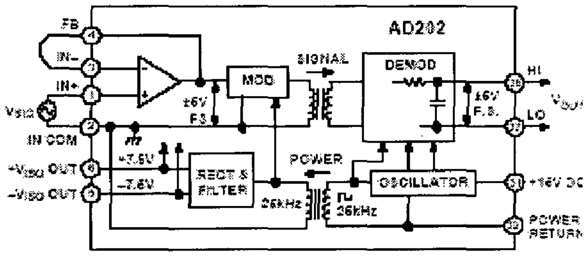


4. LOW COST, MINIATURE ISOLATION AMPLIFIERS

FEATURES
Small Size: 4 Channels/Inch
Low Power: 35 mW (AD204)
High Accuracy: ±0.025% max Nonlinearity (K Grade)
High CMR: 130 dB (Gain = 100 V/V)
Wide Bandwidth: 5 kHz Full-Power (AD204)
High CMV Isolation: ±2000 V pk Continuous (K Grade) (Signal and Power)
Isolated Power Outputs
Uncommitted Input Amplifier

APPLICATIONS
Multichannel Data Acquisition
Current Shunt Measurements
Motor Controls
Process Signal Isolation
High Voltage Instrumentation Amplifier

FUNCTIONAL BLOCK DIAGRAM



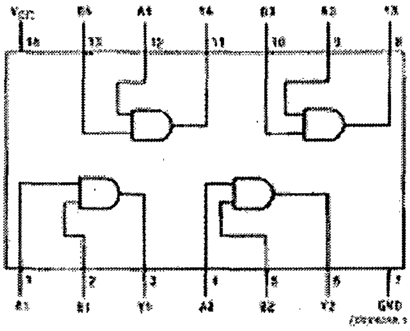
ing. For applications requiring a low profile, the DIP package provides a height of just 0.350".

High Accuracy: With a maximum nonlinearity of ±0.025%

5. QUAD TWO-INPUT AND GATE

Connection Diagram

Dual-In-Line Package



Order Number 5408DMQB, 5408FMQB, DM5408J, DM5408W or DM7408N
See Package Number J14A, N14A or W14B

Function Table

Y = AB

Inputs		Output
A	B	Y
L	L	L
L	H	L
H	L	L
H	H	H

H = High Logic Level
L = Low Logic Level

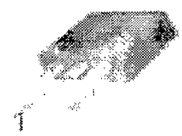
6. THREE TERMINAL POSITIVE VOLTAGE REGULATORS

DEVICE TYPE/NOMINAL OUTPUT VOLTAGE

MC7805AC	5.0 V	MC7812C	12 V
LM340AT-5		LM340T-12	
MC7805C		MC7815AC	15 V
LM340T-5		LM340AT-15	
MC7806AC	6.0 V	MC7815C	
MC7806C		LM340T-15	
MC7808AC	8.0 V	MC7818AC	18 V
MC7808C		MC7818C	
MC7809C	9.0 V	MC7824AC	24 V
MC7812AC	12 V	MC7824C	
LM340AT-12			

TO-220

D-PAK

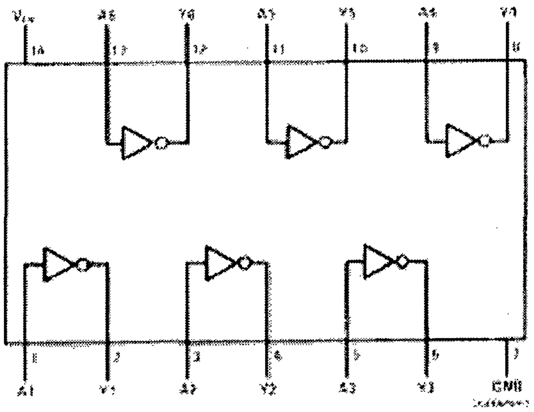


1. Input 2. GND 3. Output

7. HEX INVERTING GATE

Connection Diagram

Dual-In-Line Package



Order Number 5404DMQB, 5404FMQB, DM5404J, DM5404W, DM7404M or DM7404N
See Package Number J14A, M14A, N14A or W14B

Function Table

$Y = \overline{A}$

Inputs	Output
A	Y
L	H
H	L

H = High Logic Level
L = Low Logic Level

8. NPN SWITCHING TRANSISTOR

FEATURES

- High current (max. 800 mA)
- Low voltage (max. 40 V).

APPLICATIONS

- Linear amplification and switching.

DESCRIPTION

NPN switching transistor in a TO-18 metal package.
PNP complement: 2N2907A.

PINNING

PIN	DESCRIPTION
1	emitter
2	base
3	collector, connected to case

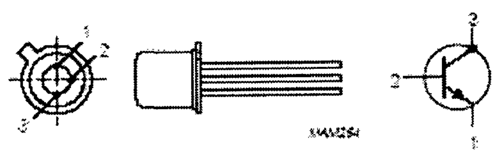


Fig.1 Simplified outline (TO-18) and symbol.

Appendix C

C.1. Machine Rating:

Induction Motor: 400V, Δ Connected, 50 Hz, 3.75 KW, 5 HP, 1440 RPM, 7.5 A.

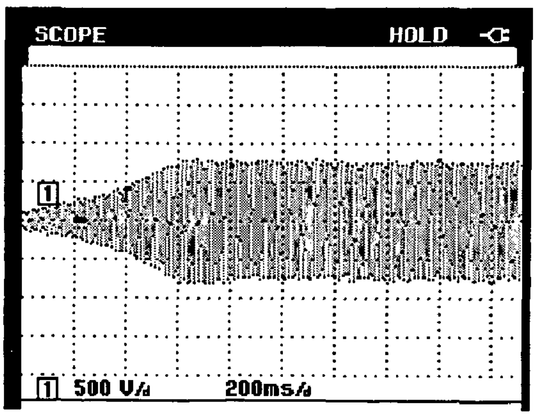
Rs = 1.92 Ω, Rr = 2.67 Ω , X_{ls} = 13.31 Ω , X_{lr} = 13.31 Ω, Xm = 190.7 Ω.

Table C-1

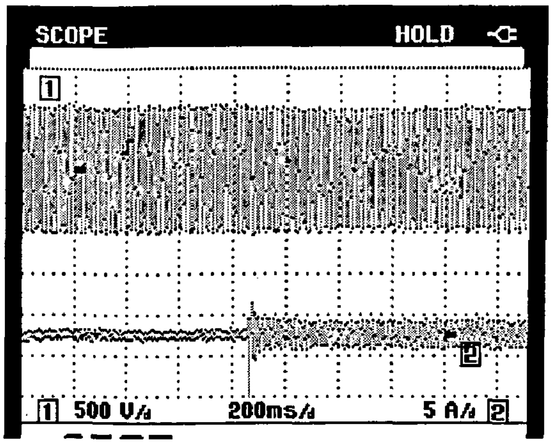
Generated Voltage and Frequency at Different Excitation Capacitor and Loading.

Excitation Capacitor(μF)	Loading in Watts (Per Phase)	Generated Voltage (V)	Current (A)	Frequency (Hz)
5	No Load	453	0.00	52.7
5	200	407.1	0.40	51.2
5	400	290	0.75	50.9
10	No Load	513	0.00	51.7
10	200	483	0.44	50.7
10	400	429	0.90	49.2
10	600	383	1.29	48.7
12	No Load	550	0.00	52.1
12	200	508	0.45	50.2
12	400	472	0.97	49.0
12	600	440	1.37	48.5

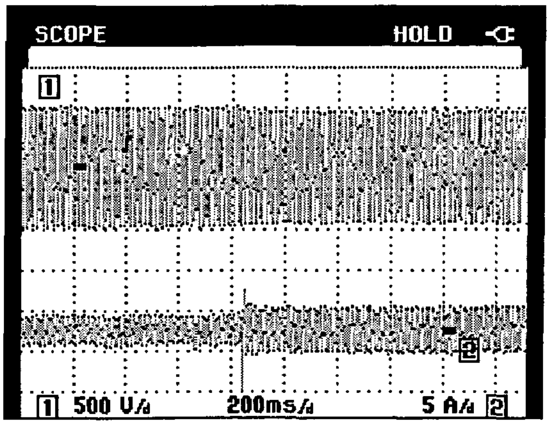
C.2. Experimental Waveforms.



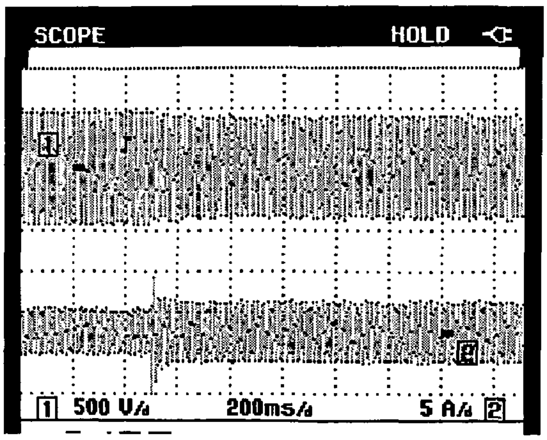
C.1. Voltage build-up at no load



C.2. Change in Voltage and current with load of 200 Watt per phase



C.3. Change in Voltage and current with load of 400 Watt per phase



C.4. Change in Voltage and current with load of 600 Watt per phase