DESIGN & DEVELOPMENT OF SINGLE PHASE ELECTRONIC LOAD CONTROLLER FOR MICRO HYDRO POWER PLANT

A DISSERTATION

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

of

MASTER OF TECHNOLOGY

in

ALTERNATE HYDRO ENERGY SYSTEMS

By

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CANDIDATE'S DECLARATION

This is to certify that the report which is being presented in this dissertation entitled "***DESIGN & DEVELOPMENT OF SINGLE PHASE ELECTRONIC LOAD CONTROLLER FOR MICRO HYDRO POWER PLANT*** " in partial fulfillment of the requirements for the award of the degree of ***Master of Technology*** in ***Alternate Hydro Energy Systems***, submitted in the **Alternate Hydro Energy Centre**, Indian Institute of Technology-Roorkee, is an authentic record of my own work carried out during a period from July, 2003 to June, 2004 under the Supervision of **Shri. S. N. Singh** "senior scientific officer" of Alternate Hydro Energy Centre, Indian Institute of Technology-Roorkee.

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

Date: - 28 June, 2004 **(SURENDRA PRATAP SINGH)**

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

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(Surendra Pratap Singh)

SYNOPSIS

In case of small isolated generating unit driven by non-conventional energy source such as small hydro the use of conventional control mechanism is not advisable option because of higher initial investment and performance factors. In the absence of mechanical governor, the Electronic Load Controller can be used to maintain the generator output voltage and frequency, irrespective of the amount of load connected to the generator. It does it by automatically dissipating any surplus power produced by the generator in additional loads, known as ballast load.

With the variable mark space ratio chopping technique, the amount of power to be dissipated in the ballast load is controlled by varying the mark space ratio, before the ballast is switched on by means of MOSFET or IGBT arrangement. The variable mark-space ratio chopping technique realized by analog circuits and different hardware modules are designed, fabricated and tested for: power supply and voltage reference circuit, voltage sensing circuit, triangular waveform generator circuit, and comparator and IGBT gate-drive circuits. In addition to this, a possibility of realizing the PLC based controlled system also explored.

CONTENTS

Title	Page No.

Publication

1. Paper reported "**Cost Effective Governing of Micro Hydropower Plant by Using Electronic Load Controller**", in first international conference on **Renewable Energy**, organized by Central Board of Irrigation and Power, 6-8 October 2004-Delhi, India.

2. Paper reported "**Development of Electronic Load Controller for Micro Hydropower station** " in fifth international conference on **Development And Management of Water And Energy Resources**, organized by Central Board of Irrigation and Power, 15-18 February 2005 - Bangalore, India.

LIST OF FIGURES

NOMENCLATURE

ELC	:	Electronic Load Controller
IGBT	:	Insulated Gate Bipolar Transistor
IGC	:	Induction Generator Controller
kW	:	Kilo Watt
kVA	:	Kilo Volt Ampere
MOSFET	:	Metal Oxide Semiconductor Field Effect Transistor
PLC	:	Programmable Logic Controller
Pin	:	Input Power
P_{out}	:	Output Power
$P_{ballast}$	:	Ballast Power
P_{gen}	:	Generator Power
P_{user}	:	User Power
AVAR	:	Automatic Voltage Regulator
IC	:	Integrated Circuit
PCB	:	Printed Circuit Board
BJT	:	Bipolar Junction Transistor
OP-Amp	:	Operational Amplifier
LED	:	Light Emitting Diode

INTRODUCTION

1.1 GENERAL

Man had enthusiasm to learn more and more from the beginning of civilization. As civilization developed man make strategies to convert the form of energy available in nature. When men become familiar with hydropower potential, then he used it in his house to run the gharats (water mills) for grinding purpose. In these gharats hydropower directly converted in to mechanical power by falling water on wheel of gharat.

When it is required to use the hydro energy for the purpose of lighting then this hydropower potential is converted into electrical energy. Electrical energy is simplest form of energy, which can be easily transmitted over a long distance. Also it can be easily converted into any other from of energy like mechanical energy, light energy etc.

To transmit the energy over long distance different grids are connected to each other. These grids almost run every part of country. But still there are some remote places where grid is not present and also not possible since it become too much costly and become unaffordable although these areas have a lot of hydropower potential. So we need to focus on large number of micro and mini hydropower potential in remote areas. As we know that there is a rapidly declining fossil fuel, thermal power in which thermal energy of fossil fuel is converted into electrical energy, has ceased to be offering any long term solution for our increasing energy demand. Again large hydropower projects create a lot of problem to environment in different ways. To overcome these problems and to ensure a basic living standard of remote communities it is required to develop micro hydropower projects. Also these micro hydropower projects are important where grid is not available. As the capacity of hydropower projects decreases then per unit cost increases. Hence to afford a remote hydropower plant cost of the components should be as low as possible and plant must be simple as far as possible to install and to maintain. In India, Hydropower Schemes are classified as given in table: 1

Table: 1 Classification of small hydropower scheme in India [1]

Type	Station capacity	Unit capacity
Micro hydropower	Up to 100 kW	Up to 100 kW
Mini hydropower	Above101 kW to 2000 kW	Above101 kW to1000 kW
Small hydropower	Above2001 kW to 25000 kW	Above1001kW to 5000 kW

Generators used for this purpose may be synchronous generator or induction generator. But a research shows that for small capacity induction generator is more reliable and less costly than synchronous generator of same size also induction motors are easily available in market and induction motors can be used as induction generator. Hence no special design is required an induction generator of small capacity but above 30 kVA synchronous generator becomes cheaper then induction generator. Induction generator can be used either grid connected to feed the active power to grid or in standalone mode for local use. When small induction generator is used to feed the active power to grid and its frequency is unable to alter the grid frequency therefore frequency control is not required in grid-connected mode. But when induction generator is used in isolated mode then it is required to control voltage and frequency generated output because different equipment are designed to operate at constant voltage and frequency. Controlling the flow of water to turbine, which is costly method to do so, On the other hand diverting surplus power to other equipment can also be used for frequency control hence for voltage. This method is called load flow control method

1.2 FUNCTION OF GOVERNOR

The primary function of the hydraulic turbine governor when controlling a unit directly connected to a generating system

(a) To maintain and adjust unit speed before the unit goes on line.

(b) To maintain system frequency after synchronization by adjustments to the input of the turbine

(c) To adjust the output of the unit in response to operator or the other supervisory commands

(d) To protect the unit from uncontrolled runaway due to sudden isolation from the electrical load or to initiate a unit shutdown in response to an abnormal condition.

1. 2.1 Basic Governing Principles

A governor has three major sections, shown schematically in figure 1. 1. These are

(a) A speed sensing element that senses turbine speed and provides an output that is proportional to speed

(b) A control element that compares the turbine speed to the desired speed set points and provides an output signal that represents the required control action

(c) A power amplification element that produces the mechanical force needed to position the water flow-controlling devices (wicket gates, blades, needles, or deflectors) in response to the control element's output signal.

1.2.2 Basic Block Diagram of a Governor

This fig 1.1 shows the three major sections of a governor. Every governor contains a speed-sensing element that senses turbine speed and provides an output proportional to a speed (a control element that compares the turbine speed to the desired set point, and provides an output signal for the required control action) and a power amplification element that produces the mechanical force to position the water flow-controlling devices in the control element. The control element of a governor consists of those components that receive and act upon external signals such as speed, wicket gate position feedback, power, and pond level to produce appropriate commands to the governor power amplification element. The major difference between hydro-mechanical, analog, and digital governors occurs in the control elements employed.

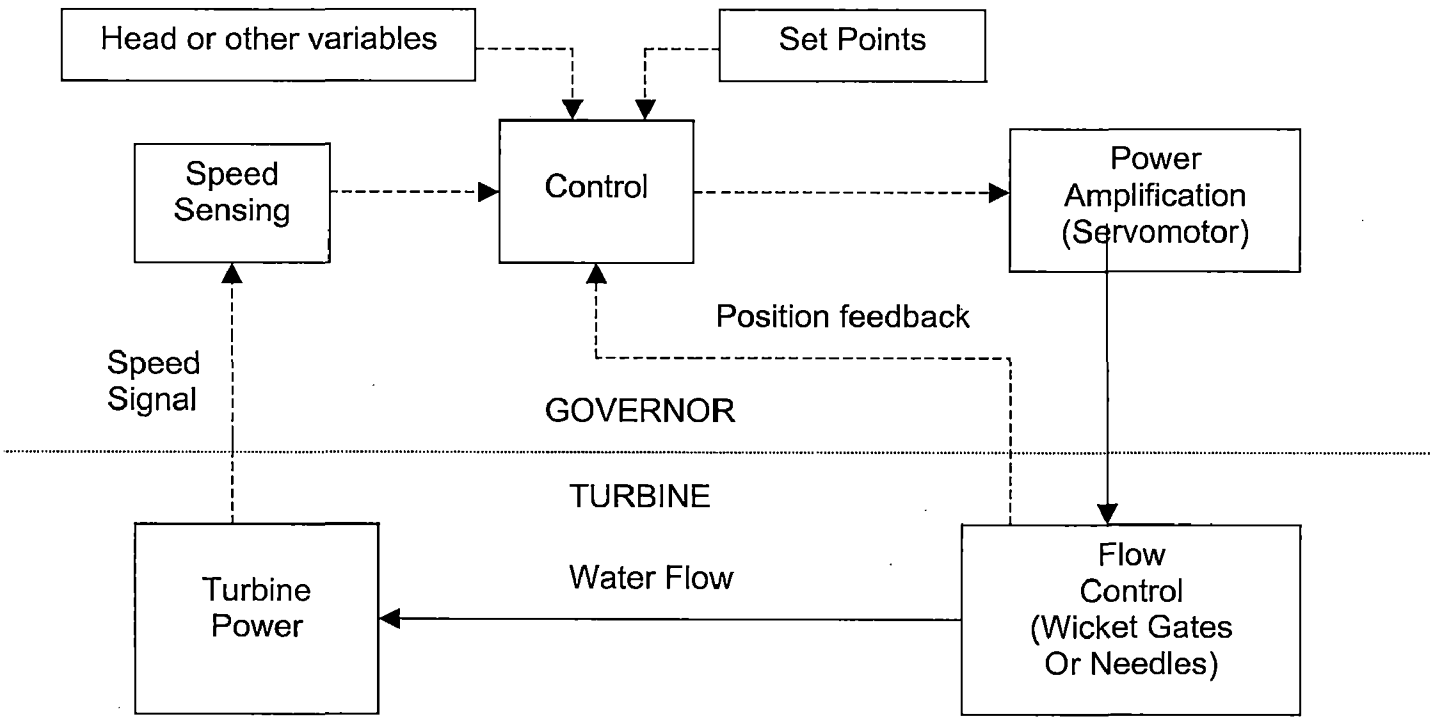


Fig.1.1: Basic Principle of Governing

An electronic load controller (ELC) for induction generator, which is working as a stand-alone generator in Micro-Hydropower schemes, is known as Induction Generator Controller (IGC). In Micro-Hydropower system induction motor operates as an induction generator by connecting capacitors across its terminal. It is a stand-alone system powering some local loads. The induction generator system powering the load in stand-alone configuration, it is necessary to keep the turbine speed within the acceptable range to maintain the load frequency within fairly close limits, otherwise the load frequency will change too, with the change in the user load, causing the variations in turbine speed. The system frequency closely matched with the turbine speed; therefore, to maintain such variations within an acceptable range a special controller device (usually called governor) is required.

1.3 BASIC METHODS FOR FREQUENCY CONTROL

Generally in micro hydropower system the hydropower at turbine input (P_{in}) is closely matched the electrical power at the generator output (P_{out}). Therefore, on of the basis of this relation, it is find that the speed (hence frequency and voltage) of turbine/generator set can be kept constant by controlling either input power (i.e. hydropower at turbines) or output power (i.e. electrical power at induction generator). Hence it can be archived by two methods as described in 1.3.1 and 1.3.2 respectively.

1.3.1 Flow Control

In this method the water flow through the turbine is adjusted by the governing system so that the electrical power at generator is same as the power required by the electrical load as shown in fig.1.2. Usually this method requires mechanical governor and most of them are expensive and require careful maintenance, making the micro-hydropower system more expensive and less reliable. From efficiency point of view, using a governor that steers a flow control valve on the turbine would be much better. But then energy is saved by reducing water consumption of the turbine so it only makes sense if water can be stored in a reservoir for future use. Usually micro-hydropower systems do not have such large reservoirs. They are 'run of river' systems and any water that is not used right away, gets lost in an overflow. Now a day's only mini-hydropower or full-scale hydropower systems have governors as these often have large reservoirs so that water that is saved can be stored.

1.3.2 Load Control

The total load power P_{out} is kept constant, equal to the input power P_{in} at the turbine. An Electronic Load Controller (ELC), together with the dump load(s) connected to it, diverts so much power to the dump load(s) that frequency is kept at nominal value. In this way, there is no need for turbine with a governor to control generator speed. This scheme is shown in fig.1.3. Governors used to be the most expensive and least reliable component in Micro Hydro power plant on past [2].

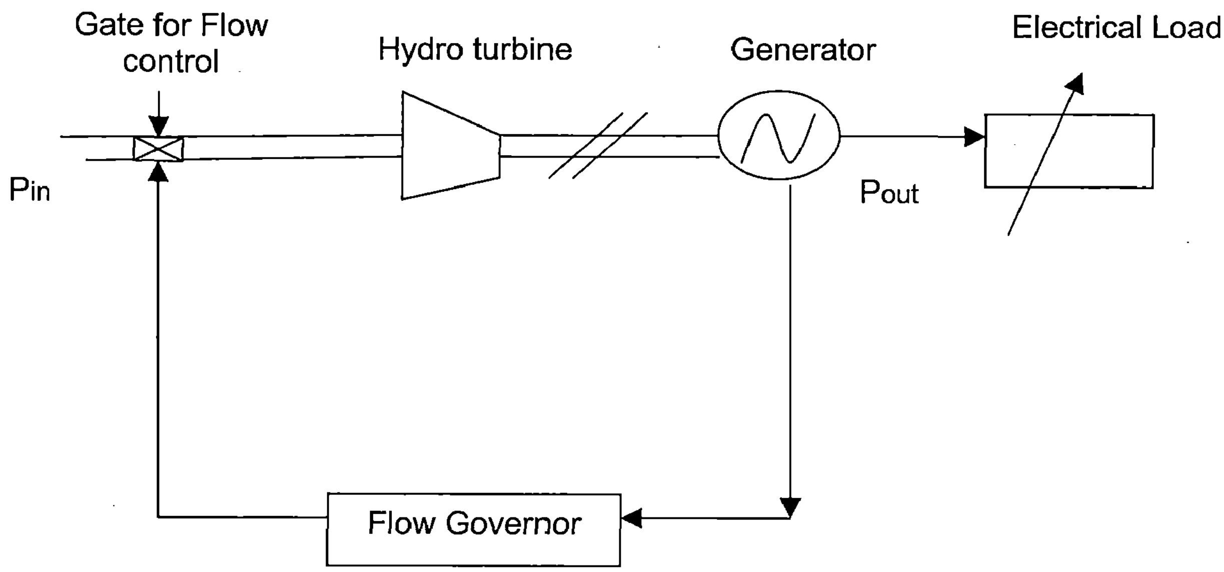


Fig.1.2: Flow Controlling Principle

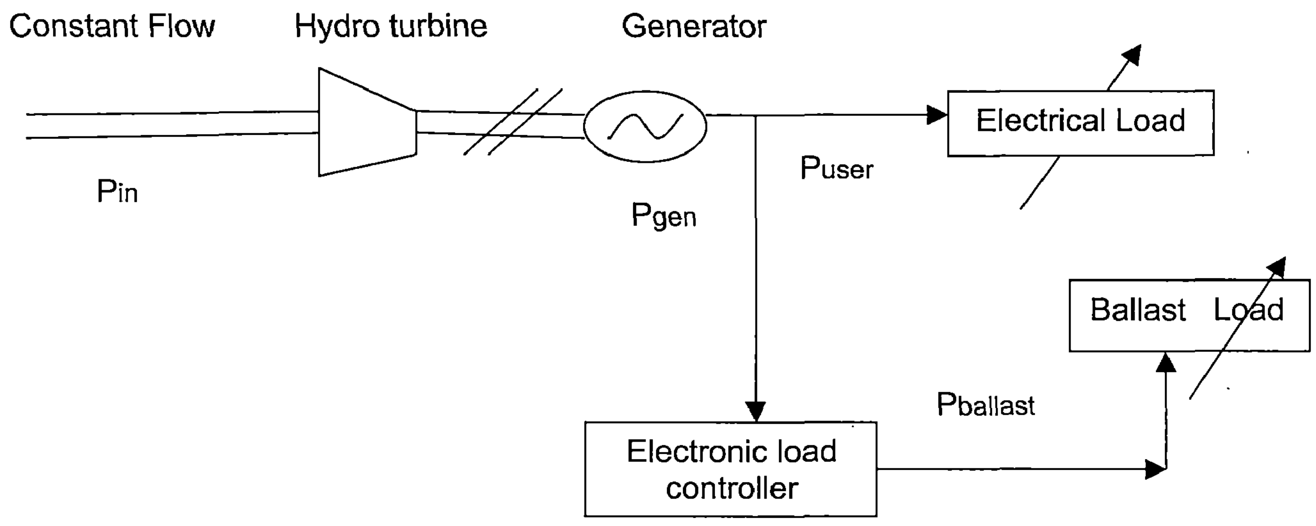


Fig. 1.3: Load controlling Principle

1. 4 COMPARISON OF TWO TYPES OF CONTROL SYSTEM

The comparison between two systems i.e. the Micro Hydropower plant having Flow control governing system and the Micro Hydropower plant having Electronic load controller, shows that the cost of the Micro Hydropower plant having Electronic load controller reduces by about 40% in comparison to the Micro Hydropower plant having Flow control governing system. From table: 2 it evident that this cost is reduces mainly due electronic load controller.

Table: 2 Comparison between ELC and flow control governing system for100 kW 130 m Head, 120liters/sec Discharge, SHP system [3]

S.No	ITEMS	Cost of ELC System in Rs	Cost of Flow Control System in Rs	Percentage Difference
1	Intake Weir	100,000	100,000	0
2	Settling tank system	75,000	75,000	0
3	Canal	400,000	400,000	0
4	Forebay	100,000	120,000	-20%
5	Penstock & anchors	850,000	1,150,000	-22%
6	Power house	100,000	100,000	0
7	Turbine & derives	1,1000,000	1,1450,000	-30%
8	Alternator	350,000	300,000	+15%
9	Governor, Protection, & Instrumentation	180,000	700,000	-76%
10	Contraction, transportation, installation	450,000	500,000	-10%
11	Commissioning	50,000	60,000	-20%
12	Sub total	3,655,000	4,955,000	
13	Engineering cost (25%)	913,750	1,238,750	
14	TOTAL	4,568,750	6,193,750	-36%
15	TOTAL Cost/kW	45,688	6,1938	

1.5 INDUCTION MOTOR AS INDUCTION GENERATOR

A recent development in micro hydropower technology is the use of an induction motor (the standard industrial motor) with a suitable set of capacitors as generator, and an Induction Generator Controller (IGC) to keep voltage in check. Due to characteristics of the induction motor with capacitors, it is possible to keep the frequency reasonably constant as long as power factor of user loads is above 0.8 [4].

The main Advantages of induction motor as an induction generator are

(a) **Availability**

Induction motors are much widely available than synchronous generator. New machines can be easily purchased and, in some cases, second hand machines can be obtained and reconditioned in order to further reduce cost

(b) **Cost**

Induction generator, including their excitation capacitor, is generally cheaper then synchronous generator. This is true for low power rating, for example 10 kW induction generator is typically half the cost of a synchronous generator for same capacity.

(c) **Robustness**

Induction machines are very robust and have simple construction. They have no winding, diodes or slip rings on their rotor. Solid, normally cast bars, replaces the rotor winding and enable the rotor to withstand considerable speed. In addition, the machines are normally totally enclosed, ensuring good protection against dirt and water. They are designed for continuous operation with belt drives under arduous industrial conditions.

Disadvantages

(a) **Difficulties in making induction motor as induction generator**

Whilst synchronous generator can be purchased ready for use, the induction motor will not work as induction generator with out connecting capacitors of suitable size.

(b) **Problem with voltage and frequency control**

Whilst synchronous generator contains inbuilt automatic voltage regulator (AVRs) but this is not the case with induction generator and unacceptable voltage variations will occur unless the load and the frequency are controlled.

(c) **Poor Efficiency**

Poor efficiency is obtained with induction generator especially with single- phase systems. Therefore it is recommended that induction generators for systems below 30 kW capacity as induction generators are cheap, robust, can stand over-speed, require very little maintenance and are available with lower nominal speeds so that transmission ratio can be lower. Only above 30 kW, a synchronous generator would become cheaper than an induction generator with capacitors [4].

However, a synchronous generator below 30 kVA with ELC might also be useful because:

(a) It can be loaded at poor power factor (provided that the generator is sized accordingly).

(b) It permits large electrical motors to be started direct on line.

(c) Modern generators, that have a nominal speed of 1500 probably can stand 70 % over-speed and are suitable for a micro-hydropower scheme with a cross-flow turbine.

1.6 OVER ALL CONTROL OF STAND ALONE INDUCTION GENERATOR

The separate voltage regulator units for stand-alone induction generators can be designed out by using the intrinsic characteristics of the turbine and induction machine. Both the turbine power-speed characteristic and the relatively high magnetic saturation of the modern induction motors are used as advantage.

As shown in fig 1.4, for constant voltage operation of an induction machine a small increase in the frequency will result in a significant reduction in magnetizing current. In addition, extra VARs are produced by the excitation capacitors due to reduced impedance. With the increase in the frequency the magnetizing current is reduced as the inductive reactance increase, and at the same time capacitive reactance decreases and additional VAR are available to the load. The combined effect of reduced magnetizing current and increased leading VARs, which results from high frequency operation, can be used to advantage for power factor correction of the lagging power factor loads, this function was previously performed by the voltage regulator unit.

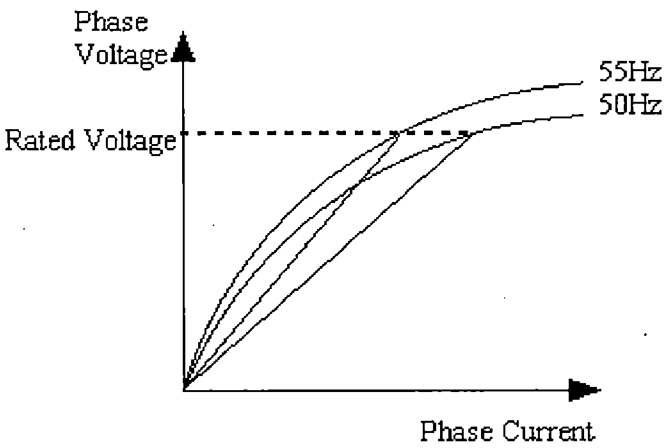


Fig.1.4: No load excitation characteristics for an induction machine operated at two different frequencies

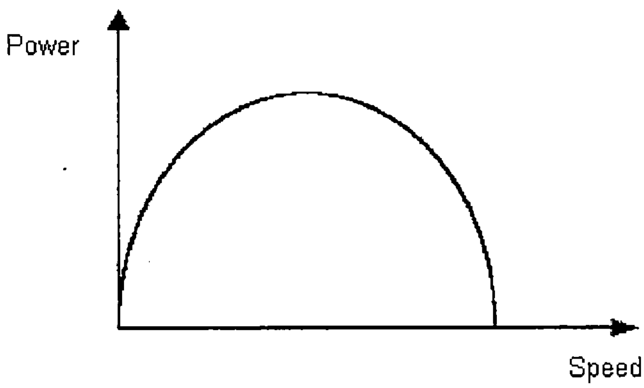


Fig 1.5: Typical Power-Speed characteristic for an impulse turbine

Hydro turbines are classified as impulse and reaction machines. All standard types of impulse turbines have power-speed characteristics similar to that shown in fig 1.5. The turbine and drive system are designed so that the turbine operates at the speed, which produces maximum power output for the head and flow available as shown in fig 1.5, small variations in the speed about the maximum power output speed have little effect upon the power output. All the common types of the reaction turbine have similar flat power-speed characteristics at close to maximum power output. Hence, the generator frequency to rise and provide leading VARs to compensate for inductive loads has little effect on the power output of the system. With the new control approach, both voltage and frequency can be controlled by an Induction Generator Controllers (IGC); they sense and directly control voltage rather than frequency.

When an inductive load is connected to the generator the voltage will decrease and the IGC will respond by reducing the ballast load. The reduced load will cause an almost instantaneous increase in frequency due to reduced slip. The rise in frequency results an increase in voltage and a corresponding increasing load. A stable operating point will be reached when the load on the turbine has increased sufficiently to match the power output of the turbine.

The increase in frequency will depend on the power factor of induction motor. Since modern induction machine is highly saturated, so the frequency regulation with variation in load power factor is quite small.

1.7 LIMITS OF FREQUENCY VARIATION

The small increase in the frequency variation results when inductive loads are connected to induction generator as shown in fig 1.4, the magnetizing current of induction motor is reduced at higher frequency. This has the advantage of reducing stator-winding loss and increasing insulation life. The main constraint is to increase the frequency acquired with the load that has the power requirement that increase sufficiently with speed. For example: pumps and fans. The effect of such loads can be appreciable, since induction motor shaft speed increases approximately linearly with frequency. And the power requirement of fan increases at nearly of cube of speed. A 10% increase in frequency is acceptable even with such highly speed dependent load. The reasons for this are as follows.

(a) Because of over-sizing, most motors run at only 60 to 80% of the rated output when operate at rated frequency.

(b) The higher frequency operation reduces the magnetizing current, thereby offsetting some of the increase in load current

(c) The cooling of the machine improves with the increased shaft speed.

1.8 THE PROPOSED SCHEMES

The following schemes for voltage regulation are proposed for single-phase induction generator powering the local load in stand-alone configuration:

(a) Suitable Series and Shunt Capacitor

The suitable series and shunt capacitor connected to the generator terminal can be used for voltage regulation purpose.

(b) Electronic Load Controller

It maintains a near constant generator output voltage, irrespective of load connected, by dissipating any surplus power in a ballast load. The ELC is a simple and low cost solution for using induction machine as stand-alone generator in micro-hydro schemes. The controller is made especially for single-phase induction generator powering resistive type load in stand-alone configuration. The analog electronic circuits are developed for this scheme and concept of Programmable Logic Controller (PLC) is also introduced.

LITERATURE REVIEW

The electronic load controller is a simple and low cost concept for using induction motor as stand alone generator in micro-hydropower schemes. It is a relatively new approach of regulating the induction generator frequency. In recent years the induction generators are increasingly being used these days to harness renewable energy sources because of its advantageous features. These features include maintenance and operational simplicity, brushless and rugged construction, lower unit cost, good dynamic response, self-protection against fault and ability to generate power at various speeds. Due to its practical advantages related to cost and construction, the induction generator has been identified as a strong candidate to generate power in micro-hydro power application.

Various literatures are available on induction generator used in micro-hydro system. The Electronic Load Controller, is a relatively new concept of governing turbine-generator sets, has met with increasing interest in recent years. Very few technical literatures are available on Electronic Load Controller.

A. Pittet and B. Oettli [2] have described the functional prototypes and design aspects of Electronic Load Controller (ELC). They have presented plenty of technical details met with interest of development of ELC for induction generators. In 1978, when satisfactory ELC was not available, the Swiss Association for Technical Assistance (SATA) initiated the development of an Electronic Load Controller. In this controller frequency was sensed at the generator terminal and compared with reference signal, hence an error signal is produced, and this error signal used to fire the thyristor for determining the unused power to divert in ballast load.

Jan Portegijs [4] has described detailed technical aspects of Electronic Load Controller. They have developed the Electronic Load Controller. They have described many technical information and design considerations for building and troubleshooting an ELC. They have focused on phase angle regulation technique with two ballast loads. Control schemes and over/under voltage, over-speed protection features are also emphasized.

Singh et al. [5] have presented a paper on the performance of induction motor as induction generator; in this paper static capacitor bank is considered for self-excitation of induction machine and to maintain its terminal voltage constant. The effect of speed for excitation purpose has discussed. An algorithm to obtain machine characteristic using Newton Raphson method and steady-state equivalent circuit has also presented.

Nigel P. A. Smith [6] has described a new and simpler control approach to controlling induction generator on stand-alone micro-hydro systems. This paper has explained three techniques for governing the voltage and frequency variations, these were phase-angle control, switched binary-weighted loads and variable mark-space ratio chopping.

R. Bonert et al. [8] has proposed an electronic impedance controller to control the voltage and frequency of a stand-alone induction generator. The controller concept and its control range are also discussed in this paper. This paper also deals with the reduction of harmonic caused by the controller and its design aspects. The impedance controller takes up the difference between the power absorbed by the generator and load. Consequently speed is maintained speed, hence frequency.

Bhim Singh et al. [9] has proposed the concept of voltage control of Self Excited Induction Generator (SEIG) employing reactive power compensation comprising solid state switching devices. In this paper the performance of a solid state voltage regulator for a SEIG using static compensator (STATCOM) is analyzed for voltage build up of SEIG and at different types of loads. The versatility of STATCOM for control of SEIG is studied with motor load and parallel operation of SEIGs. This paper also deals with the optimum utilization SEIG rating while operating in unsaturated region.

Olorunfemi Ojo et al. [10] have presented the modelling and transient performance of a single phase Induction Generator with series or parallel-connected load. The system of equations is expressed in terms of flux linkages and includes the effect of magnetizing flux linkages saturation.

WORKING PRINCIPLE OF ELECTRONIC LOAD CONTROLLER

3.1 INTRODUCTION

In hydropower plants hydro turbine-generator set are used to generate the electricity. The hydro turbine converts the potential energy of water into mechanical energy; hydro turbine is connected to generator directly or by means of belt-pulley or gear. The mechanical energy available at the hydro turbine shafts is converted into electrical energy by generator. The speed of turbine should be as constant as possible, in spite of variation of load connected to generator. If load on the generator changes the speed of generator, therefore speed of hydro turbine changes causing unacceptable variation in voltage and frequency.

$$f = \frac{P\,N}{120}$$

Where,

P is number of magnetic poles

N is the speed of generator

f is frequency of output

The terminal voltage of generator is given by [11]

$$V = E - I\,Z$$

Where,

V is out put terminal voltage of generator

E is e.m.f per phase

Z is generator impedance

I is load current

As the frequency is directly proportional to speed and also terminal voltage depends on e.m.f and the load current. Hence a controller is required to control the speed and voltage.

3.2 PURPOSE OF CONTROLLING THE OUT PUT OF GENERATOR

When electricity is generated at an isolated site the speed of the generator and the no of poles determines its frequency say a four-pole generator generates a voltage of 50 Hz only if it runs at speed of 1500 rpm. If this speed increases or decreases, the frequency of generated voltage is also increases or decreases respectively. Although most of the generators have some form of voltage regulation but the out put voltage is also affected somewhat by the change in speed.

Electrical equipments are designed to operate at a specific voltage and frequency and any variation in voltage and frequency other than the designed value can seriously affect the performance of electrical equipment. For example an electrical motor becomes hot if the frequency is too low or may burn out rather then if motor is stared with too low voltage. Some control on generator speed is there for needed .as the hydro-turbine determines the speed of generator; the speed of hydro turbine must be regulated. The governing device control the speed of the hydro turbine-generator set in response to changing's in the external electrical loads placed on the generator.

3.3 VOLTAGE AND FREQUENCY TOLERANCE

To specify a controller, it is necessary [12] to know the tolerance of end user machinery to the variation in voltage and frequency. Although most equipment tolerant up to +/- 10% voltage fluctuation and frequency is usually held much closer to the nominal value.

3.3.1 Heating Equipment

Heating loads are most tolerant of variation in voltage. Frequency variations do not affect these loads at all. Under-voltage increases the life of heating element but reduces heat output. Over-voltage can generate excess heat but cause the element to burn out. An over-voltage of 10% can cause and increase of 2.1% in heating output.

3.3.2 Lighting Equipment

Incandescent lamps are not affected by the frequency variation. Under-voltage decreases light output very sharply but significantly increases bulb life, unless there are significant fluctuation in supply voltage. On the other hand over-voltage greatly reduces bulb life. An over-voltage of only 5% reduces the life of bulb by up to 50%.

Fluorescent lamps are affected by both voltage and frequency variation. If voltage is more than 15% down, the lamp will not light. If the lamp is already operating, it will flicker more as voltage decreases. If the voltage drops more then 25%, the lamp will burn out.

Over-voltage may lead too the choke overheating, but this is likely to be less limiting than the effect of over-voltage on the incandescent bulbs.

Fluorescents lamps should operate correctly in the frequency range -5% to +10% of nominal frequency.

3.3.3 Transformer

Transformer losses appear as heat. As losses increases, the heat generated with in the transformer and consequently temperature rises.

At fixed frequency, all theses losses are very approximately related to the square of the voltage. Over-voltage therefore can pose a problem and voltage is usually allowed to increases about 5% at rated load. However, under-voltage does not pose a problem.

At fixed voltage, decreases in frequency lead to increased losses and heat generation and operation below related frequency at rated should be avoided. Operation at up to 20% over the rated frequency present no problem as losses decreases.

3.3.4 Motor load

Induction motors and transformers are affected in similar manner. Under-frequency with steady voltage causes high current and over-heating. Under-voltage at steady frequency has similar effect on both these and other types of motor.

Induction motors takes starting current up to six times their rated current in order to produce their rated torque. Thus manufactures often specify that motor will start and operate satisfactorily, if voltage is with in 10% of their rated value. If a motor is started under a large load, such as a motor is driving a compressor in a refrigerator, the longer period of low speed and high current may cause the winding of the motor to over-heated and fail.

3.4 FUNCTIONS OF ELECTRONIC LOAD CONTROLLER

The electronic load controller should be able to perform following functions

(a) Replace conventional governor and regulators.

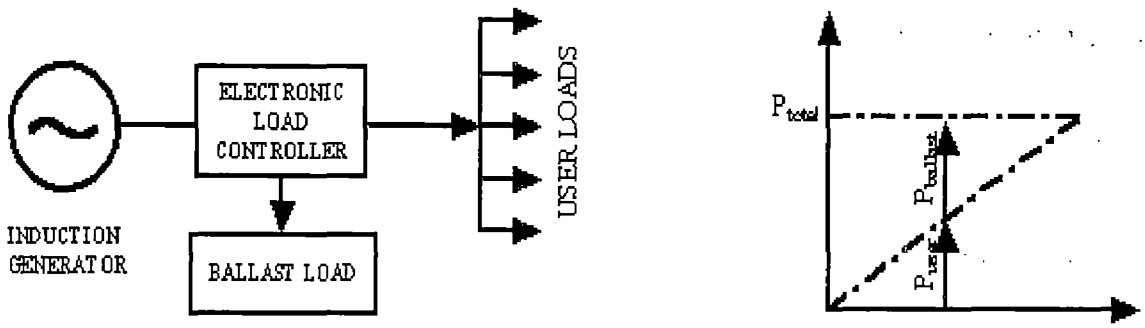
(b) To achieve high load factor.

(c) Provide stability for low inertia hydro generator in isolated and inter connected systems.

(d) Simplify operation and maintenance

3.5 BASIC PRINCIPLE OF ELECTRONIC LOAD CONTROLLER

The induction generator is a source of real power and absorbs reactive power while most of the system loads absorb real and reactive power. To maintain a power balance the controller must be able to absorb any generated power that is not absorbed by the load while supplying the reactive power required by the generator and system load. The capacitor bank supplies maximum amount of reactive power required by the generator and system load. As shown in fig 3.1, the ELC compensates for variations in the main load by automatically varying the amount of power dissipated in the resistive load, known as the 'ballast' load, in order to keep the total load constant.



(a) Schematic diagram (b) Division of power between loads

Fig 3.1: Basic principle of Electronic Load Controller

The amount of real power that must be absorbed by the ballast load to maintain the power balance given by:

$$P_{ballast} = P_{gen} - P_{user}$$

Therefore, the power into the ballast load has to be varied according to the power requirement of the user.

3.6 ADVANTAGES OF ELECTRONIC LOAD CONTROL

The Principle of advantage electronic load controller is that the overall system is less complex and less costly as compared to flow control type conventional governor.

It is not only eliminates the need for precision–engineered mechanism, but it may also allows the designer of the hydro turbine to be simplified, because there is no need for the guide vanes to be adjustable since the turbine is always running at full load (turbine is operating at single point)

Other advantages are as follows

(a) The induction generator always generates the maximum power possible. The generation if not immediately required then generated power can be used in secondary load i.e. blast load. Hence the over all efficiency can be extremely high.

(b) The response of the electronic load controller to a change in frequency is faster and more accurate as compared to the mechanical governing system.

(c) No moving parts are required in electronic load controller while the conventional flow governing requires relatively fast and accurate mechanical movement to control the input water to the turbine.

(d) As all the components are electronics, electronic load controller requires practically no maintenance. The disadvantage is that if electronic components fail in the field, they cannot be repaired there and then. However most of the units are composed of separate printed circuit boards, which can be replaced.

(f) Use of electronic load controller eliminates water hammer, which complicates the flow control incase of flow control governor. The water hammer results from having to accelerate and decelerate the moving water in the penstock.

(g) Using electronic load controller the overall cost of unit reduced by 30-40% in comparison to conventional plant with hydraulic governor. This is major advantage of using electronic load controller in remote areas.

3.7 USEFUL APPLICATIONS OF BALLAST POWER

It is assumed that power diverted to ballast load(s) is wasted. For small micro-hydro stations feeding local grid or residential loads, a two or more ballast loads can be used for ELC, power diverted to dump load will be switched fully on during off-peak hours. During off-peak periods it maybe possible to use the surplus power for:

3.7.1 Battery charging

People living too far away to be connected to the mini-grid, might be interested to use batteries for lighting and other purpose.

3.7.2 Heating water

From the point of view of energy conservation, this is an attractive option because energy can be stored as heat in the hot water.

3.7.3 Street lighting using incandescent lamps

The street lighting can also be used as a dump load. From streetlights, operator can see whether the system has still spare capacity left to switch on more appliances without causing an overload situation.

3.7.4 Cooking

Simple electrical cookers can be used as a dump load. To make sure that they cannot be switched off, the temperature selector should be removed. By putting a pot only partly over the cooker, the cooking can still be regulated. Since cooking requires a lot of power, only few users could avail free energy for cooking by using these dump load cookers. Cooking is usually done at night, the cookers might work all day except when needed because then all available power is used for lighting. This makes it attractive to use some kind of heat storage mechanism.

3.8 REACTIVE POWER CONTROL

As long as the electrical loads on the induction generator are purely resistive, the reactive power demand of the induction generator remains constant and can be supplied by a fixed size of capacitor. When an inductive load (e.g., an induction motor) is connected to the induction generator, the reactive power demand of the system will increase. The additional reactive power is required by the inductive load (load power factor $\cos\Phi<1$) and is not the part of the magnetizing requirement of the induction generator; these remain the same due the constant active power demand (P_{load} + $P_{ballast}$) always constant, as shown in fig.3.2.

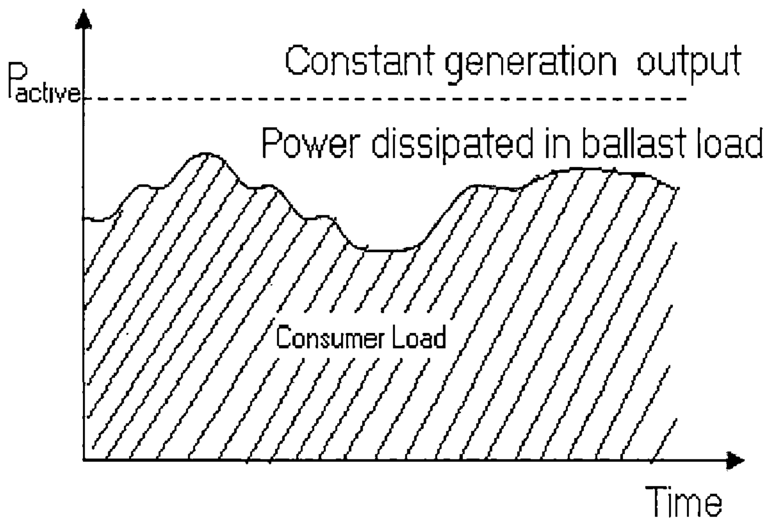


Fig. 3.2 Division of power between consumer and ballast load

However, the fixed set of the capacitors cannot supply additional reactive power without a corresponding drop in voltage. The ELC senses this voltage drop and subsequently reduces the power dissipated in the ballast load: Being basically an active power controller the ELC can only compensate for the active power of the inductive load. The reactive power can be supplied only by an increase of speed/frequency of the induction generator (negative slip increases). The increase of frequency has two effects: first, the magnetizing requirement of the induction generator is reduced (magnetization curve steeper) and, secondly, the VAR produced by the capacitors increases. Since, these two effects both provide for the reactive power demand of the load (at nominal voltage), the increase of frequency is fairly small, typically 5% for a load power factor of 0.9 and 10% for 0.8 [5]. This is mainly due to the fact that modern induction generators generally show a high level of saturation (nonlinearity of the magnetizing curve starts at low voltage), which can be, produced large changes in reactive power at low frequency variations. Hence, from the point of view of stability (frequency variations due to inductive loads), the saturated induction generator has an advantage over the non-saturated one. This is quite the contrary to what is required from the point of view of efficiency and electric power output generator mode. Nevertheless, it is recommended that motors with a low level of saturation be preferred since frequency variation 0% and up to 10% are usually acceptable for rural applications. Additionally, improvements are possible by direct power factor correction on individual loads, which are highly inductive.

A problem arises if large induction motor is started direct online in Micro-Hydropower plants using an induction generator. The reactive power demand at startup may reach 6 to 8 times that of normal operation (high starting current at low power factor). Compensation of such high reactive power requirement by the capacitors and their automatic disconnection when the motor comes to speed (e.g., with a DC relay and a delay time capacitor) is not economical for larger motors. Direct online start of large motor load may therefore cause very high frequency variation of the induction generator (danger for other consumers) and may even cause excitation to collapse

3.9 CONTROL TECHNIQUES USED IN ELECTRONIC LOAD CONTROLLER

3.9.1 Phase Angle Regulation [6]

With phase angle control, the ballast load is switched on at some moment during each half period of sine wave shaped generator voltage and remains switched on for the rest of this half period as shown in fig 3.3.

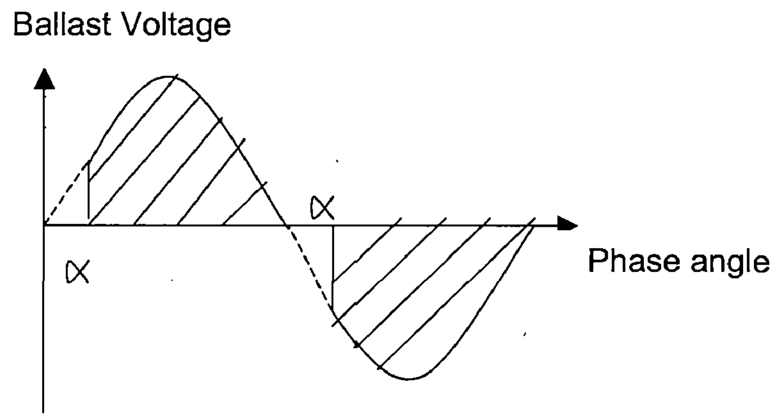


Fig. 3.3: Principle of phase angle regulation: A dump load is switched on during only the latter part of each half cycle

The power dissipation in the ballast is varied by the delay angle (i.e. phase angle), α, before the ballast is switched in by means of triac or thyristor arrangement. The moment at which the dump load is switched on, is expressed as a phase angle or delay angle, α. right at the beginning of a half period, phase angle is 0^{σ} and towards the end, it is 180. Phase angle control is often used with synchronous generators but variable lagging power factor is produced as a result of the ballast current lagging the voltage. The power dissipation in the ballast is varied by the delay angle, α, before the ballast is switched ON by means of triac or thyristor arrangement. For phase angle regulation, almost always triacs or thyristors are used as power element. These electronic devices can be switched on by a short trigger pulse on their 'gate' connection and then remain conducting for the remainder of that half period. By then, generator voltage drops to zero, current through the dump load and triac or thyristor drops to zero and they stop conducting or 'extinguish' by themselves. Triacs can conduct in both directions, so they can operate during both positive and negative half periods of generator voltage. Thyristors can conduct only in one direction so two thyristors would be needed to steer one dump load.

Advantages of Phase Angle Regulation

(a) The triacs or thyristors are cheap, widely available and can withstand rough operating conditions.

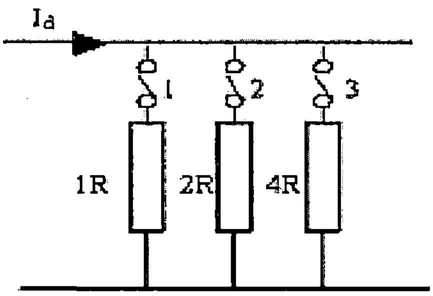
(b) Thyristor can switch thousands of amperes at voltages into kilo-Volt range and at quite high frequencies.

Disadvantages of Phase Angle Regulation

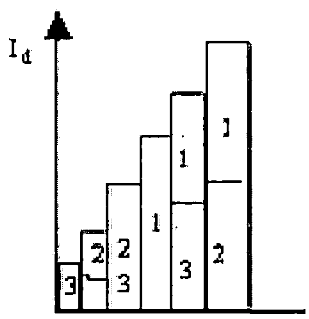
A major disadvantage of phase angle regulation is that the electronic noise is created when a triac is triggered while generator voltage is high, so at around 90° trigger angle, the load appears as an inductive load to the generator. For use in an ELC or IGC, dump load capacity will be even slightly higher than generator capacity and noise is impressive. This makes that for use with a phase angle regulation ELC, the generator must be over-rated.

3.9.2 Switched Binary Weighted Loads [6]

The second method is by using a set of Binary-weighted Loads. This is a series of dump loads in which each subsequent dump load has half the capacity of the former, higher ranking one. With n dump loads, a total of 2^n combinations can be switched on, each of which are represent a different total capacity of dump loads being switched on, as shown in fig 3.4.



(a) Binary-weighted Load



(b) Switching Closure

Fig.3.4: Binary-weighted load controller and ballast current range

Advantages

(a) Producing unity power factor ballast.

(b) It does not cause any waveform distortion. For switching these dump loads, a series of Solid State relay can be used. These contain triacs or thyristors, but produce no electronic noise since they are either triggered just after the beginning of a half period, or remain off completely. Again, steering electronics can be quite simple. Since they are either triggered just after the beginning of a half period, or remain off completely.

Disadvantages

(a) The complexity resulting from using a number of ballast loads, each with its connections, wire and switching device.

(b) Costs of Solid State relay are much higher than the triacs inside them.

(c) Binary-weighted load contain the number of dump loads and the associated wiring. To achieve smooth regulation, these dump loads should all have exactly the right capacity.

(d) With a low number of dump loads, steps between dump load combinations remain too large and the system cannot regulate smoothly.

3.9.3 Pulse Width Modulation or Mark-Space Regulation [6]

Another way to regulate power diverted to a dump load is Pulse Width Modulation or Mark-Space regulation; the basic switching circuit is shown in fig. 3.5.

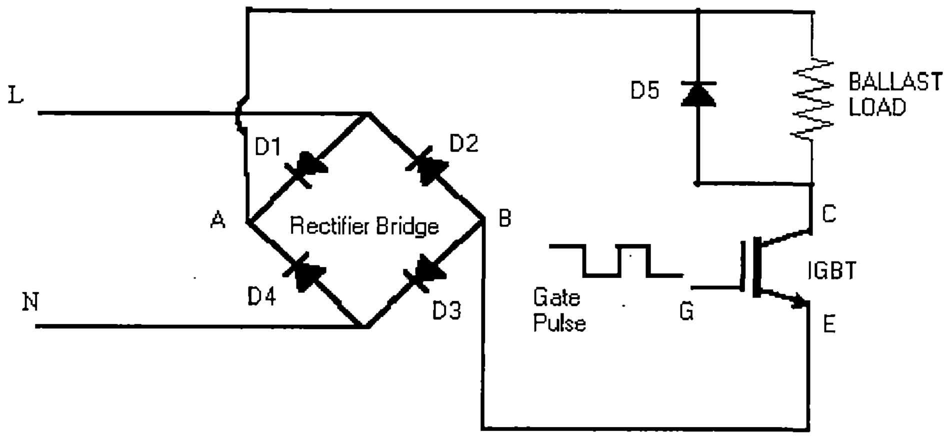


Fig. 3.5: Basic switching circuit for a single-phase mark-space ratio-controller

The mean value of rectified voltage can be regulated by adjusting the duty cycle (the fraction of the time that a dump load is switched on) usually; this is done by changing the duration of each pulse while time between pulses remains constant, as shown in fig.3.6.

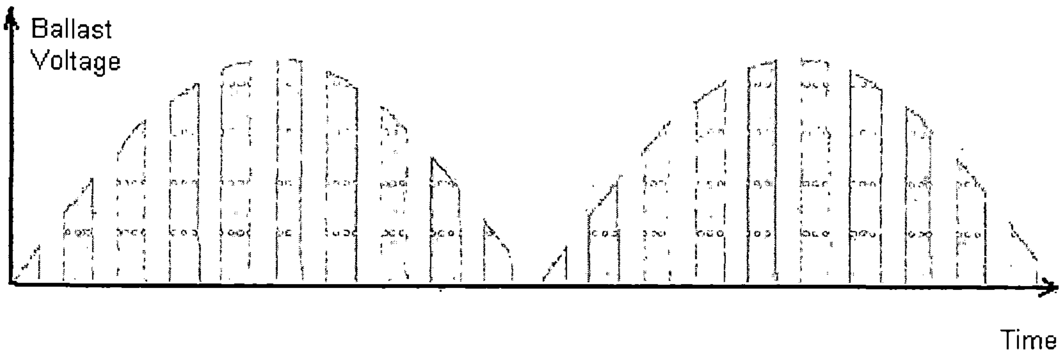


Fig.3.6: Typical ballast voltage waveform for a single-phase mark-space ratio controller

But of course changing time between pulses while pulse width remains constant could also do it. High capacity Pulse Width Modulation systems use thyristors as power elements. With D.C., the main thyristor will not stop conducting automatically at the end of a half period so an extra thyristor circuit is used that produces short, negative pulses that makes the main thyristor extinguish. For Micro-Hydro purposes, this would become too complicated and modern power transistor types are used, e.g. Insulated Gate Bipolar Transistor (IGBT) or MOSFET's. These power elements can be steered directly by tiny IC outputs: They conduct as long as voltage at their 'gate' connection is sufficiently high. Trapezoidal Modulation is shown in fig.3.7and Pulse width modulation with different duty cycle is shown in fig.3.8.

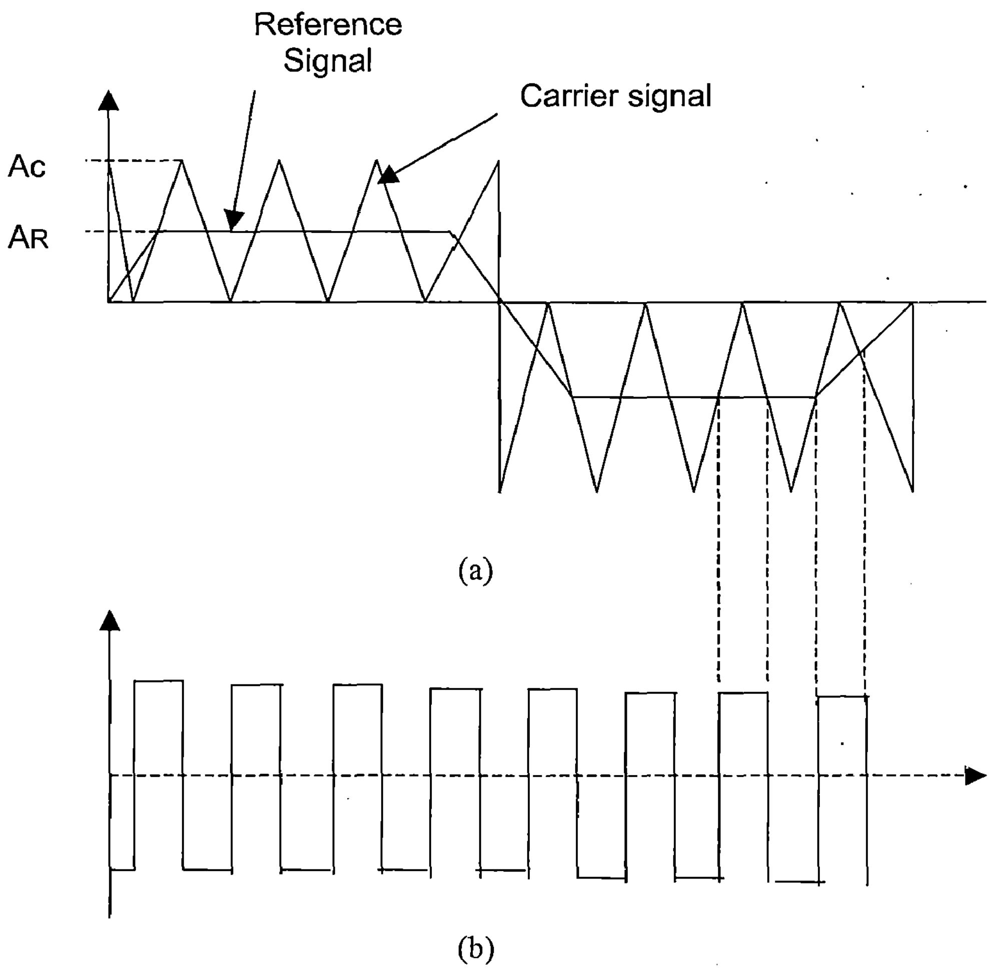


Fig.3.7: Trapezoidal Modulation:

(a) Reference trapezoidal and triangular wave

(b) Modulated waveform.

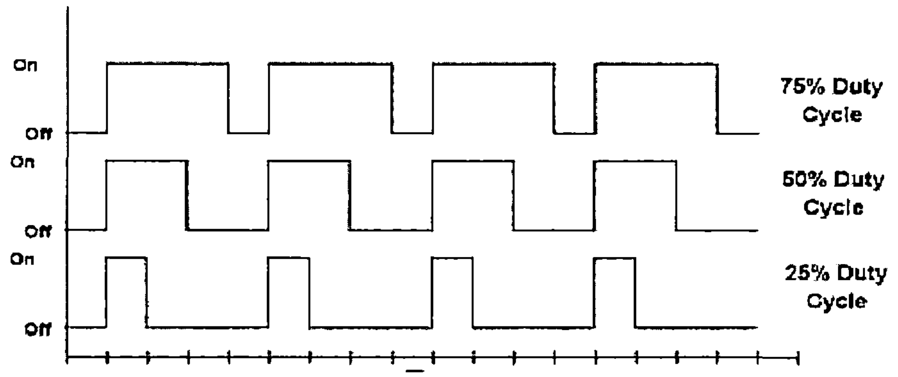


Fig.3.8: Pulse Width Modulation at different Duty Cycle

Advantages

(a) The main advantage of Pulse Width Modulation is that it produces a variable unity power factor load with just single ballast.

(b) Waveform distortion resulting from the chopping action is reduced by the action of the excitation capacitor.

(c) It requires a simple electronic circuit for steering the power transistor.

(d) The switching time of the Dump load to the main load is made faster.

Disadvantage

Modern power transistors have relatively high cost, poor availability and sensitiveness. Also dissipation in such a controller is higher since generator voltage first has to be rectified before it can go to the power transistor itself. Therefore, they need a larger heat sink than a phase angle regulated controller with the same capacity.

3.10 FEATURES OF THE INDUCTION GENERATOR CONTROL

3.10.1 Voltage Stability

The IGC will maintain a near constant generator output voltage, provided generator is not overloaded. If the generator is overloaded, due to excessive user load, then the voltage will fall.

3.10.2 Frequency Stability

With resistive user loads, such as heaters and light bulbs, the IGC will keep the electrical frequency constant. However, if partially inductive loads, such as motors and tube-lights, are connected the frequency will increase. The frequency variation can be reduced by connecting the power factor correction capacitors across inductive loads.

3.10.3 Over-Voltage Protection

When the IGC and ballast loads are functioning correctly over-voltages will not occur. If a fault occurs that causes the voltage to rise, the controller will automatically disconnect the user loads, protecting them from damage

3.10.4 Ballast Short-Circuit Protection

If short-circuit occurs within the ballast load, or its leads, the ballast is automatically disconnected so as to protect the controller.

3.10.5 Determine Generator Operating Voltage

The voltage rating of the three-phase induction motor to be used as a single-phase generator must be carefully selected. If the rating is too high, the generator will be unstable. If the rating is too low it will not be possible to achieve the required generator voltage without overheating the windings.

TABLE 3.1: RECOMMENDED MOTOR VOLTAGE

No. Of poles	Motor Ratings →	0.11-0.55(KW)	1.5-3.0(KW)	4.0-7.5(KW)
2 pole	Recommended Motor Voltage	V_{GEN} +6%	V_{GEN} +3%	V_{GEN}
4 pole	Recommended Motor Voltage	V_{GEN} +9%	V_{GEN} +6%	V_{GEN} +3%
6 pole	Recommended Motor Voltage	V_{GEN} +12%	V_{GEN} +9%	V_{GEN} +6%

The operating voltage of the generator (V_{GEN}) is usually set slightly higher than the national single-phase voltage to allow for the voltage drop on the distribution system. Table 3.1 shows the recommended motor voltage, in relation to the generator voltage, for different motor sizes and speeds. This will give stable operation and near optimum efficiency. The reason why smaller and slower speed generators require higher motor voltage ratings is to compensate for their lower power factors. The acceptable limits for the voltage rating are ±6% of the recommended voltage. The effect of increasing the voltage of the motor can be achieved by increasing the frequency by the same percentage.

3.11 ESTIMATION OF POWER RATING FOR ELECTRONIC LOAD CONTROLLER

3.11.1 Determine the Power Rating For the Controller

Estimating the maximum electrical power output, P_{MAX}, by calculating the hydraulic power and assuming an overall efficiency of 60% (unless actual efficiencies are available). The power rating for the controller must be greater than or equal to the maximum electrical power output.

3.11.2 Determine Generator Current Rating

Use P_{MAX} and the generator voltage (V_{GEN}) to work out the operating current.

$$I_{OP} = 1.1 \times P_{MAX} / V_{GEN}$$

Where, I_{OP} = maximum operating current

V_{GEN} = generator voltage

The (rated) line current of the motor, I_{LINE} must be greater than or equal to the operating current: $I_{LINE} > I_{OP}$

3.11.3 Selection of Over-Current Protection for the Generator and capacitors

The generator windings and cables must be protected from the excessive current. These can cause them to overheat and fail. High currents also damage capacitors. For maximum protection a motor protection switch should be used as tripping current can be adjusted to the precise current rating of the generator.

3.11.4 Excitation Capacitors

Single-Phase induction motor can be used as induction generator, but the problems are with the size and arrangement of capacitor required to achieve excitation with out overloading windings [7]. In addition single-phase induction motors are more expansive than three phase induction motors and only available for small power outputs.

It is possible to use a three-phase induction motor as single-phase generator with only 10%to 20% power de-rating and this has become the preferred approach to providing a single-phase supply.

The capacitors required to make the motor function as a generator are known as the excitation capacitors. They are arranged using the 'C-2C' connection shown in fig.3.9. The '2C' capacitance is twice that of the 'C' capacitance. The excitation capacitors (C-2C) required enabling a 3-phase induction motor to work, as a single-phase generator will determine the frequency of the electricity produced.

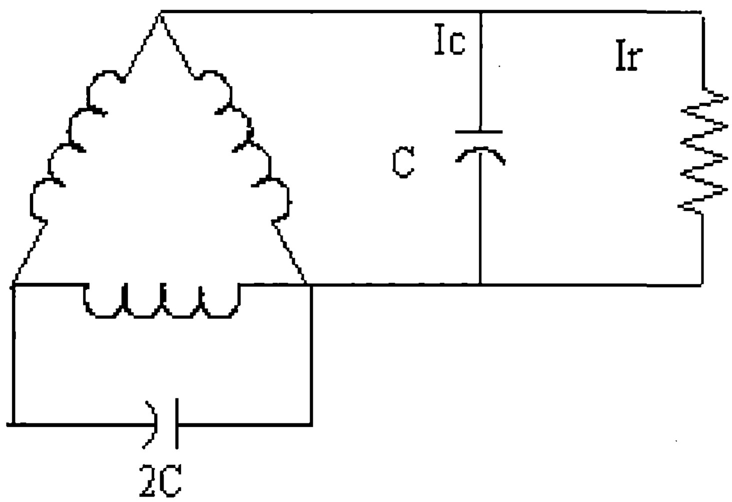


Fig. 3.9: The C-2C'connection for single-phase generation from 3-phase motor

The capacitance required to generate at a particular frequency varies between one motor and another and depends on whether the motor voltage rating is higher or lower than the recommended value in the table 1. The basic rule for calculating the required capacitance C is as follows:

$$C(\mu F) = k \times \frac{I_{line}}{V_{GEN} \times 2\pi f}$$

Where,

f = frequency of the generator (Hz)

k is the multiply factor and it value depends on the voltage rating of the motor which is used. As described earlier, the acceptable limits for the motor voltage rating are +/-6% of the recommended value. The value of multiply factor (k) lies in-between 0.35 to 0.45. The value of C, as calculated above, should be rounded down up to the nearest 5 μF and the 2C rounded down to the nearest 5 μF. It will probably be necessary to adjust these values further in order to obtain the exact frequency required.

The total capacitance C and 2C should be made up of individual capacitors. This will allow some adjustment of the C-2C to be made during installation. The voltage rating of the capacitor should be much greater than the maximum generator voltage, e.g. capacitors should be rated for 380 V AC if generating at 220 V. The 'motor-run' type of capacitors should be used as these are rated for continuous use.

3.12 VOLTAGE AND POWER RATING OF BALLAST

The ballast is essential part of the control system and therefore it is very important that care is taken over the choice of ballast and the wiring of the ballast to the IGC. Unsuitable or poorly installed ballast can damage the IGC or cause it to operate unreliably. The most common source of problem with ELC is the ballast.

3.12.1 Recommended Ballasts

Convector heater is the best type of ballast. They are cooled by the natural flow of air over the heating element and have a long life. They are generally available as wall or floor mounting room heaters. Wall mounting units are preferable, as they cannot be knocked over. Care must be taken to ensure that the ventilation grills are not covered. To prevent this they should be mounted in an inaccessible place, such as high up on a wall. Dust should be cleaned from the air vents at least once per year.

3.12.2 Voltage Rating of Ballast: The voltage rating of the ballast heater should be greater than or equal to the operating voltage of IGC.

3.12.3 Power Rating of Ballast

The power rating of the ballast load(s) should be greater than or equal to the maximum power output of the generator. Ideally, dump load capacity should be between 105 and 115 % of system capacity, but a somewhat higher capacity is still acceptable. However the maximum power rating of the IGC not exceeded. If the voltage rating of the ballast heater is higher than the IGC operating voltage then power rating at the operating voltage must be determined using the formula below

$$P_{op}(W) = P_{Rated}(W) \times \left(\frac{V_{op}}{V_{Rated}} \right)$$

Where,

V_{rated} is the rated voltage of the ballast heater

V_{op} is the operating voltage of IGC

P_{rated} is the rated power rating of the ballast heater at rated voltage

P_{op} is the operating power rating of the ballast heater at the operating voltage.

HARDWARE FOR ELECTRONIC LOAD CONTROLLER

4.1 DESIGN CRITERIA FOR ELECTRONIC LOAD CONTROLLER

The electronic load controller must consist of some means of monitoring the consumer load and automatically adding to it a ballast load so the total will be equal to the full rated load of the system. There exist a number of different designs of electronic load controllers, most of them working on similar base. The main differences between various load controllers are

(a) The base of Design i.e. whether analog or digital based

(b) The method used to dump the excess load in order to bring the total load up to the rated out put of the generator

(c) The method employed to detect the consumer load at any instant.

4.2 CONSUMER LOAD DETECTION

The magnitude of main load on induction generator is varying from zero to full load. The difference in power output available at induction generator terminal and the main load is diverted to the ballast load therefore electronic load controller needs to detect the consumer load in order to control the ballast load accordingly.

There are two methods of measuring consumer load.

(a) Direct method

(b) Indirect method

4.2.1 Direct method

In direct method current and voltage are used to measure instantaneously consumer load. The dynamics of hydro turbine-generator set cannot be accessed only by consumer load. Dumped load and hydro turbine output power also needs to be known to implement load controls. This method needs voltage and current input to analog to digital converter (ADC). This method of load detection requires many voltage and current sensors and converters.

4.2.2 Indirect method

Indirect method of measuring the instantaneous consumer load is normally used. This may be best illustrated by examining the effect caused by reducing the electrical load on induction generator driven by hydro turbine with constant water flow. As the electrical load is reduced, the excess input power causes the hydro turbine speed to increase. This increase in speed in turn increases both frequency and terminal voltage of the induction generator. Either one or both these quantities can be used to indicate the level of consumer load. If either can be held constant at some predetermined value, usually 220 V and 50 Hz, by a variable load (ballast load) connected to the induction generator, the shunt load governor (electronic load controller) has been implemented.

If the load is entirely resistive, frequency alone can be an indictor of the change in consumer load since by keeping the frequency constant a constant voltage will automatically be achieved. If on the other hand, the load is not a purely resistive then both voltage and frequency must be monitored and corrected in order to achieve constant voltage and frequency operation.

4.3 DESCRIPTION OF IMPLEMENTED SCHEME

The mark space control technique is used for developing ELC for single phase Induction Generator. The schematic diagram is shown in fig. 4.1.

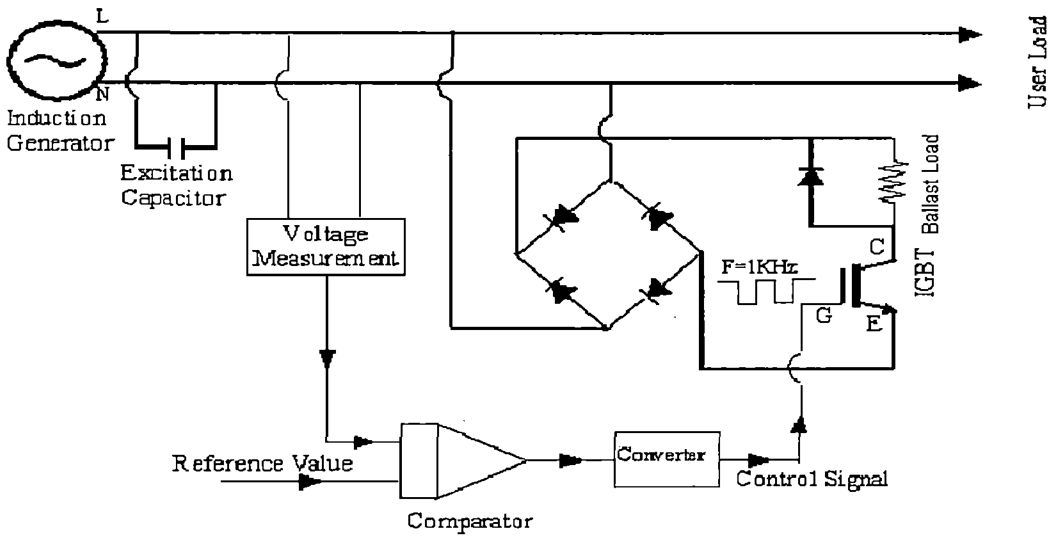


Fig 4.1: The schematic diagram for ELC for single phase Induction Generator

The generated voltage is measured and compared with a reference voltage (nominal voltage). As soon as there is a voltage difference, the comparator/amplifier sends a signal (corresponding to the difference) to a converter where the signal is modulated to rectangular waveform. The pulse width of this signal is proportional to the voltage difference and is measure for the amount of power to be dissipated in the ballast load. The modulated signal supplies a transistor (electronic switch), which opens and closes according to the rate of signal, i.e. the ballast load circuit stays open only during the ON-Time of the modulated signal. Since a transistor allows current to flow only in one direction, the output of the induction generator must be rectified by a full-wave bridge rectifier which comprising four diodes.

4.4 GENERAL FEATURES OF THE DESIGN

Modular structure

The complete electronic circuit of the Electronic Load Controller is a bit hard to understand, test or fabricate. To make it easier to fabricate, it is subdivided into different modules. Each module performs a clearly defined task and has a limited number of named input and output signals.

Most of the modules are simulated first in *ELECTRONICS WORKBANCH EDA version 5.0A* environment. The simulated results for different modules are shown in chapter 6. These modules are tested on breadboard before fabricating on Printed Circuit Board (PCB).

The single sided PCBs are designed for all modules by Express PCB version 3.1.0 application software. The bottom copper layers and top layers (Silkscreen, pads and text) are given in appendix - A. The following circuits are designed, fabricated and tested. The fabricated circuits are shown in Appendix-A

4.4.1 MODULE 1: (Power Circuit for Switching Ballast Load)

This is the main circuit, which determines capacity of the ELC as a whole. The maximum current the MOSFET/IGBT can handle determines the kW rating of dump load. The output of induction generator is fed to the input side of bridge rectifier as shown in fig 4.2(a). The output of single-phase generator is normally 220 V ac and in case of load on the generator decreases the voltage may go up to 250 V ac.

The diodes 1N5408 are used for Rectifier Bridge in this circuit. The rectified output is hence fed to the terminals of switching device, i.e. IGBT or MOSFET. This circuit is fabricated around GT25Q101 IGBT. The gate pulse to this switching device is controlled by a separate circuit (i.e. module 5: IGBT gate-drive circuit) as shown in fig.4.12. The controlled gate pulse automatically decides the amount of unused electric power to be dissipated in the 'ballast' load. Two Selenium diodes or transient voltage suppression diodes (e.g. 1.5KE300A) are also connected in reverse parallel to the IGBT for the protection against transient over-voltages. Normally, these diodes draw very small current from the circuit. However, when an over-voltage appears, the current flow through the selenium diodes increases suddenly, thereby typically limiting the transient voltage to the twice the normal voltage. A selenium diode (or suppressor) must be capable of dissipating the surge energy without undue temperature rise. Due to low internal capacitance, the selenium diodes do not limit the dv/dt to the same extent as compared to the RC-snubber circuits. However, they limit the transient voltages to well-defined magnitudes. In protecting a device, the reliability of an RC circuit is better than that of selenium diodes. The selenium diode has excellent surge handling capacity and flat clamping voltage capability at high current with ultra-fast response time. The OC1 and OC2 are over current test points, given to over current protection circuit. The voltage differences between these tests points are used to identify the over-current/short-circuit condition.

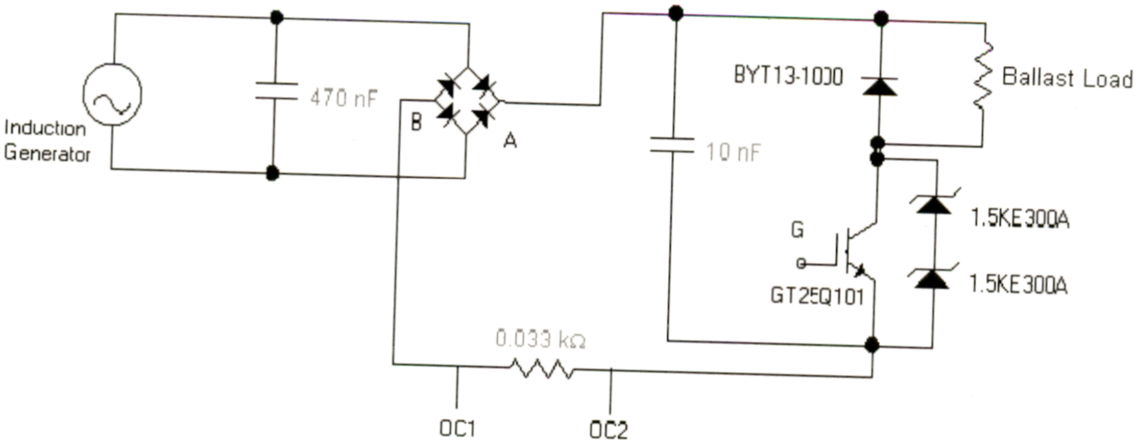


Fig 4.2(a): Power circuit for switching the ballast load

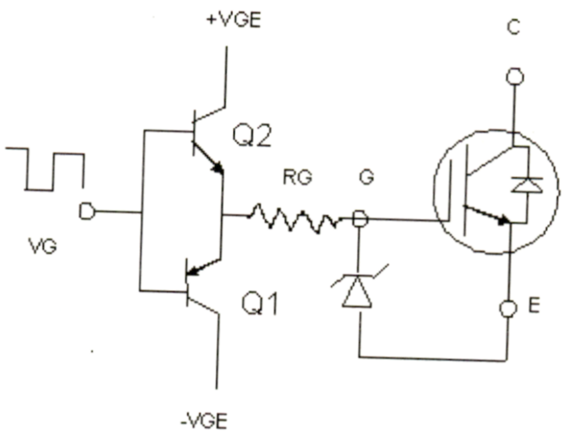


Fig. 4.2(b): Typical gate drive circuit.

Insulated Gate Bipolar Transistor

IGBTs (Insulated Gate Bipolar Transistor) combine the simplicity of drive and excellent fast switching capability of the MOSFET structure with the ability to handle high current values typical of a bipolar device. IGBTs also offer good behavior in terms of voltage drop. The IGBT Structure Diagram and Equivalent Schematic and Symbol are shown in fig.4.3 and fig.4.4 respectively. The insulated gate bipolar transistor (IGBT) combines the positive attributes of BJTs and MOSFETs. BJTs have lower conduction losses in the on-state, especially in devices with larger blocking voltages, but have longer switching times, especially at turn-off while MOSFETs can be turned on and off much faster, but their on-state conduction losses are larger, especially in devices rated for higher blocking voltages. Hence, IGBTs have lower on-state voltage drop with high blocking voltage capabilities in addition to fast switching speeds.

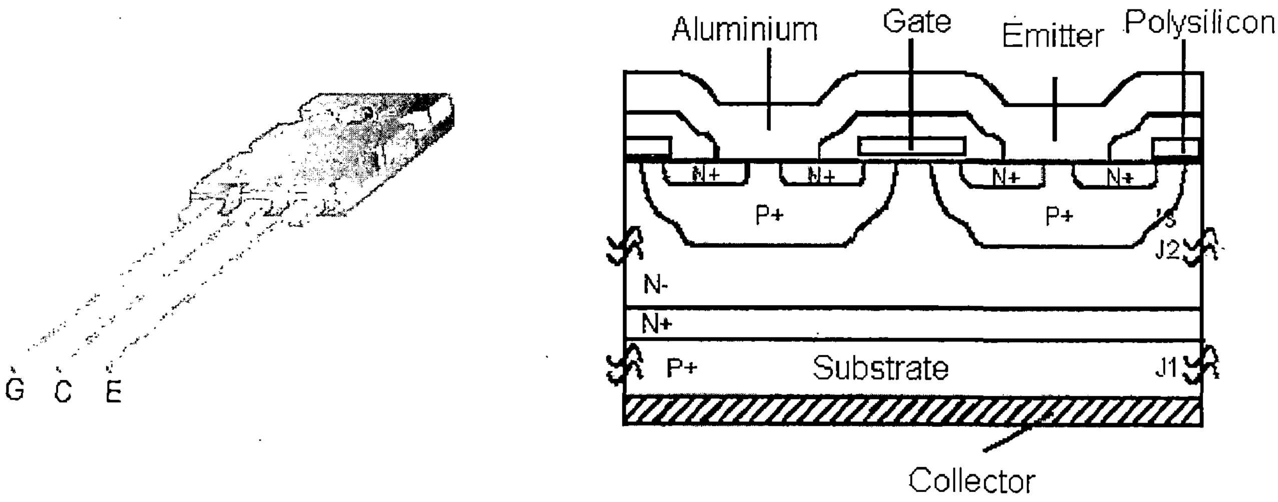


Fig.4.3: IGBT Structure

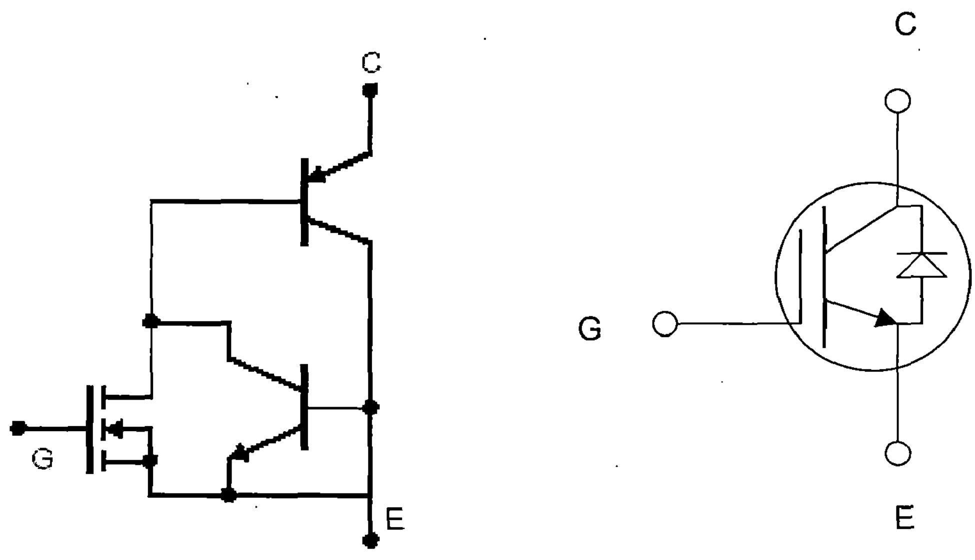


Fig.4.4: Equivalent Schematic and Symbol of IGBT

4.4.2 MODULE 2: (Power Supply and voltage references)

This module produces supply voltages that provide power the other modules or serve as a reference voltage shown in fig.4.5. The voltage at test point TP1 is clipped off rectified wave at voltage 46 V to 50 V, which smoothen due to 100 µF capacitor. The voltage regulator TL 431 gives the output (at TP2) 15.2 V to 16.4 V under normal operation; the reference point of regulator is connected to a voltage divider. The Voltage output of TL 431 depends on the resistances connected to pin no 3 of this regulator. In this module a fixed voltage reference ZREF 50 is used to get a reference voltage of 5.0 V regardless of variations in generator terminal voltage. The voltage levels at different points are shown in fig.4.5. The block diagram and symbol of voltage regulator TL 431 is shown in fig.4.6 and fig. 4.7.

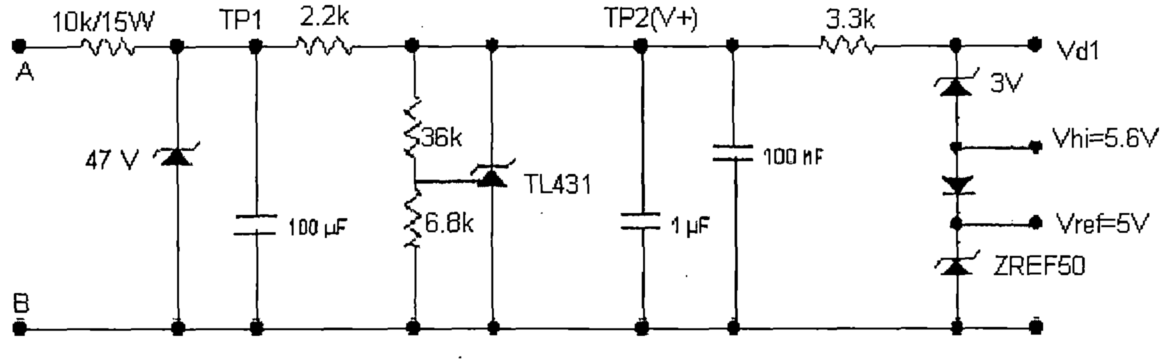


Fig: 4.5: Power Supply And Voltage Reference Circuit

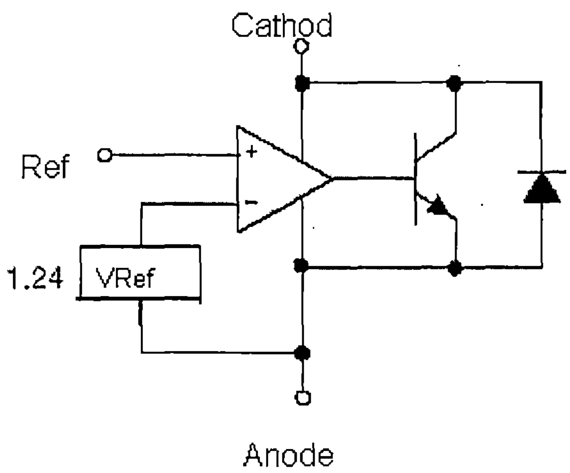


Fig.4.6: Block diagram of voltage Regulator TL 431

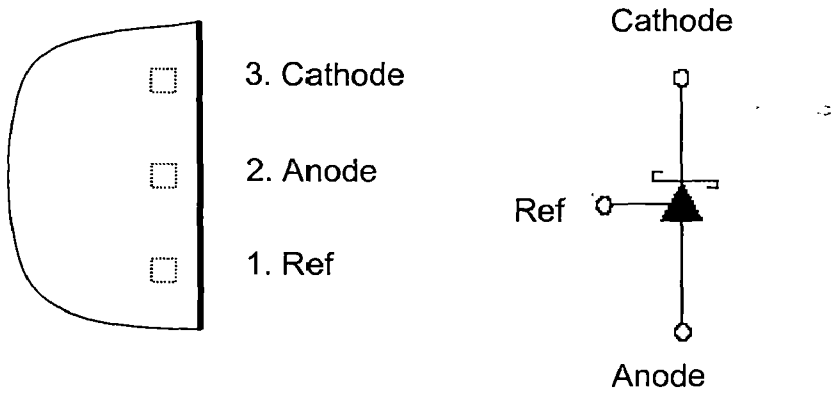


Fig.4.7: Pin and Symbol Diagram of voltage Regulator TL-431

Features of Voltage Regulator TL431

(a) The output of this programmable by using two external resistors from 2.5 V to 36 V.

(b) This device offers low out put impedance for improved load regulation.

(c) The typical out put impedance of this device is about 200 m ohm

(d) These devices find application in the feedback path of switching power supply.

4.4.3 MODULE 3: (Voltage Sensing Circuit)

This circuit is used to sense the level of output voltage of the induction generator, which is shown in fig.4.8.

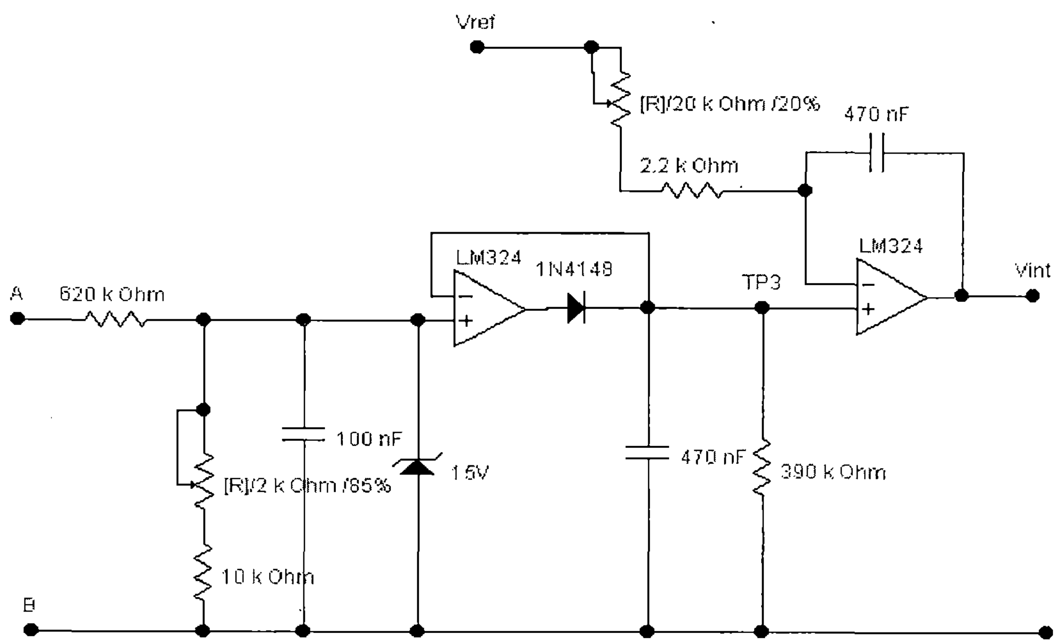


Fig.4.8: Voltage Sensing Circuit

This circuit is fed by the rectifier's output. The first OP-amp (LM 324) is used as negative clipper, which clips off the negative part of the input signal below the reference voltage. The second OP-amp (LM 324) is used as non-inverting integrator, a constant voltage difference between + input and reference voltage is integrated into a rising (or falling) output signal with a constant slope. It compares actual voltage (an input variable) with desired voltage (as a fixed reference voltage) and reacts to the difference. If actual voltage is too high when generator speeds up, it gives high error signal; hence gate-driving module increases pulse width so that more power will be diverted to the dump loads. This will make the generator slow down and frequency will come down to its original value. And the reverse: If actual voltage is too low, the gate pulse width is decreased, so that the power diverted to dump loads decreases and the generator can speed up to rated value for supplying power to user load at rated frequency.

A reference voltage (i.e. the desired output voltage) is also needed to this circuit; corresponding to these to voltages this circuit produces a constant voltage so that by comparing it with a fixed frequency (i.e. 1 kHz) triangular wave (generated from module 4), a mark-space ratio gate pulse is generated such that only unused power is dissipated to the 'ballast' load. The pine configuration of IC LM 324 is shown in fig.4.9.

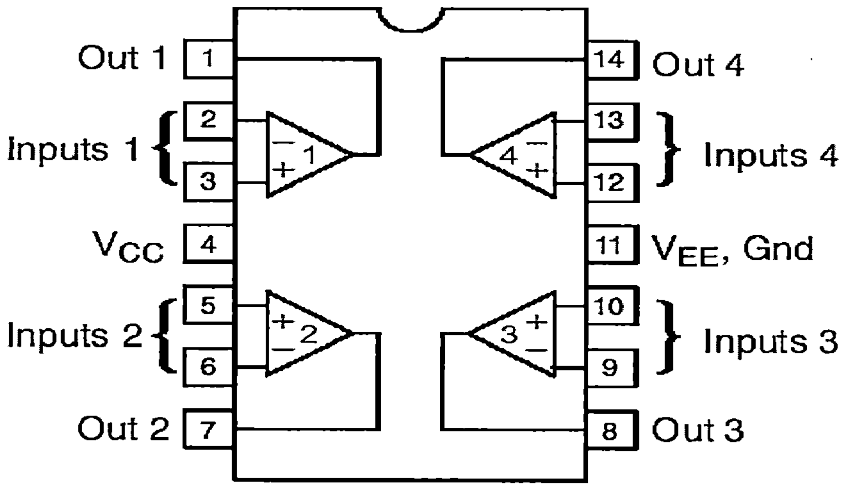


Fig.4.9: Pin Configuration of IC LM 324

4.4.4 MODULE 4: Triangular Pulse Generator

This module gives the triangular pulse of 1 kHz frequency of 8V peak to peak. This pulse is given to the gate drive circuit, which generates firing pulse. This circuit uses two IC's of OP-amp 741.

The triangular waves can be generated using a bistable comparator circuit together with an integrator as shown in fig.4.10.

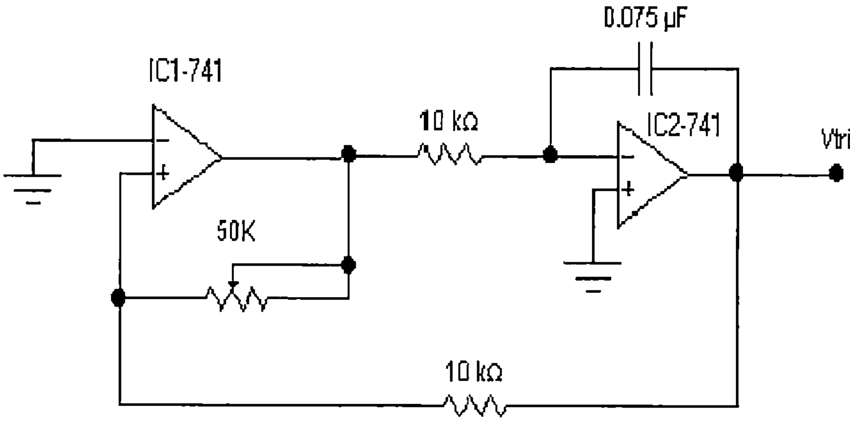


Fig.4.10: Triangular Waveform Generator

The output (triangular wave form) of the integrator circuit serves as input to the bistable comparator and similarly the output (square form) serves as input to the integrator circuit. The integrator causes linear charging and discharging of the capacitor and therefore producing a triangular waveform. If capacitance is varied in the integrator circuit, the periods of both output and input also changes. When the capacitance is increased the period increases and when the capacitance is decreased the period decreases. fig.4.11.shows the Pin Configuration of IC-741.

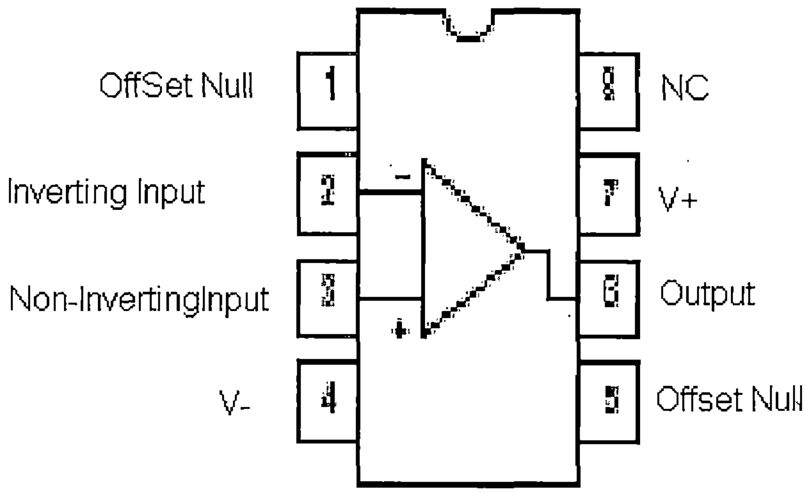


Fig.4.11: Pin Configuration of IC - 741

Features of IC- 741

(a) The IC 741 is a High performance operational amplifier with high open loop gain, high common mode range and exceptional temperature range.

(b) Internal frequency compensation.

(c) Excellent temperature stability.

(d) High input voltage range.

(e) Short-circuit protection.

4.4.5 MODULE 5: *Comparator/IGBT Gate Drive*

This is used to generate the gate trigger pulse that can be obtained by comparing two Inputs of that are V_{int} and V_{tri} i.e. integrated output from module 3 as shown in fig 4.8 and triangular wave from module 4 as shown in fig 4.10. The OP-amp LM 393 is used as comparator as shown in fig.4.12. In this comparator V_{int} is using as reference while the V_{tri} is a fixed frequency carrier waveform.

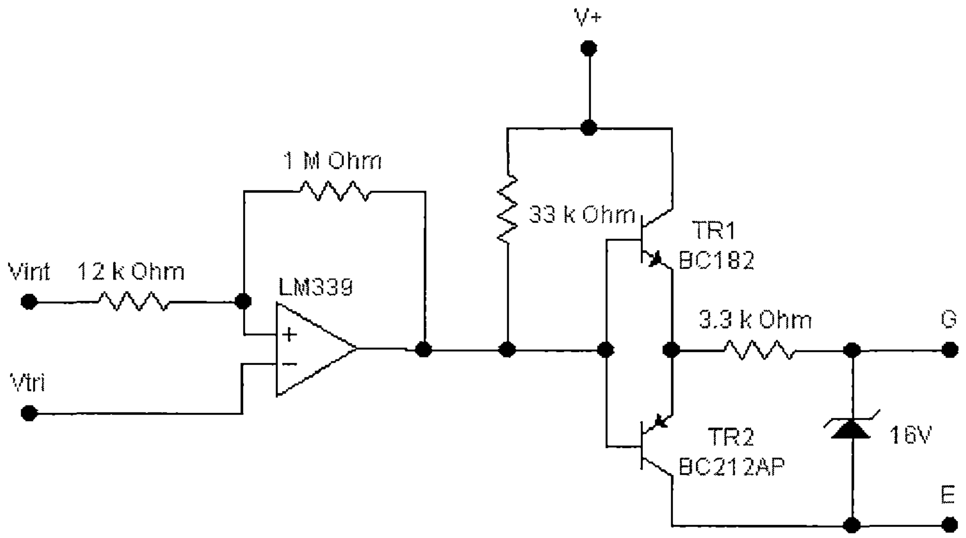


Fig.4.12: The comparator/IGBT Gate-drive circuit

Now the next connection is COMPLEMENTRY EMITTER FOLLOWER in which for positive saturation region the transistor TR1 (BC182) will ON and TR2 (BC212) gets OFF. In this case the gate pulse generated and the current will pass through ballast meter while in the negative saturation region BC182 gets OFF and BC212 gets ON in this case no this case no current will flow and hence no gate pulse will be there. The pulse width of gate pulse is controlled by the output of voltage sensing circuit (i.e. module 3), if generator voltage is too high (i.e. V_{int} signal is high), pulse width is increased, so that more power will be diverted to the dump loads.

The IC LM 393 consists of two independent voltage comparators, designed to operate from single power supply over a wide range. It is a dual differentiator. The pin configuration is shown in fig.4.13.

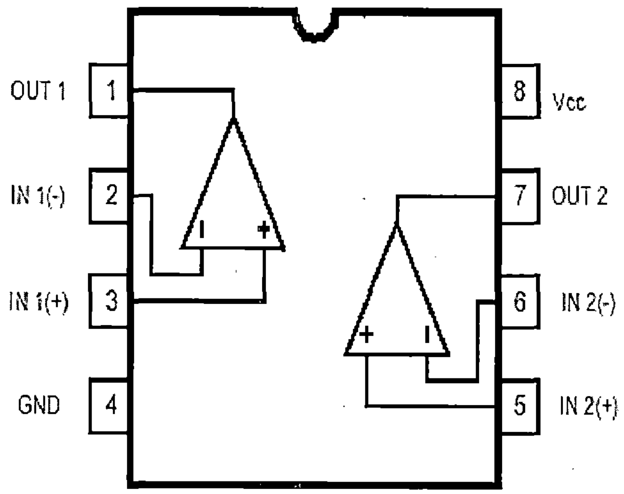


Fig.4.13: Pin Configuration of IC LM 393

Features of LM 393

(a) Single or dual supply operation.

(b) Wide operating supply range (Vcc = 2 V –36 V or +/-1 V to +/- 18 V).

(c) Low supply current drain ICC=0.8 mA

4.4.6 MODULE 6: *Over-voltage Trip Circuit*

This circuit, shown in fig.4.14, is used for the protection of user load from damage being occurred due to over voltage.

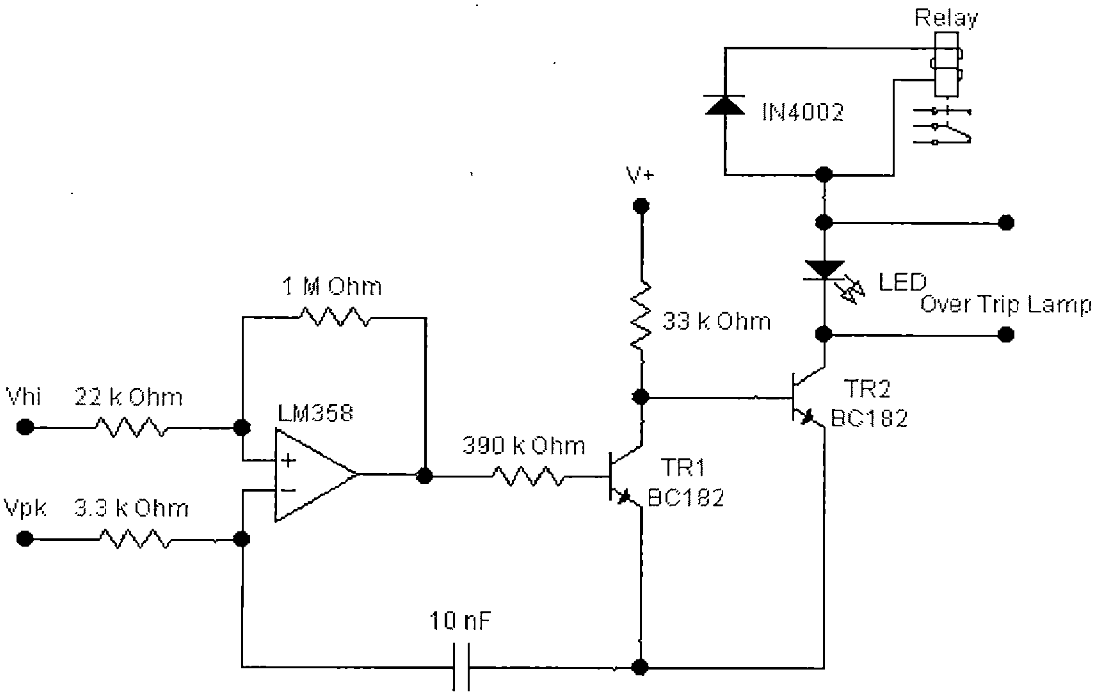


Fig.4.14: Over-volt Trip

As from the comparator circuit as shown in fig. 4.12, this works in the saturation mode, for positive saturation transistor TR1 (i.e. BC 182) gets ON and transistor TR2 (i.e. BC 212) gets OFF while in the negative saturation region TR1 gets OFF and TR2 gets ON which correspond to over voltage case so, relay will trip.

The OP-amp LM 358 is used circuit as a comparator IC. It consists of two independent, high gains, internally frequency-compensated operational amplifier designed specially to operate from single power supply over wider range of voltages. The Pin configuration of IC LM 358 is shown in fig.4.15.

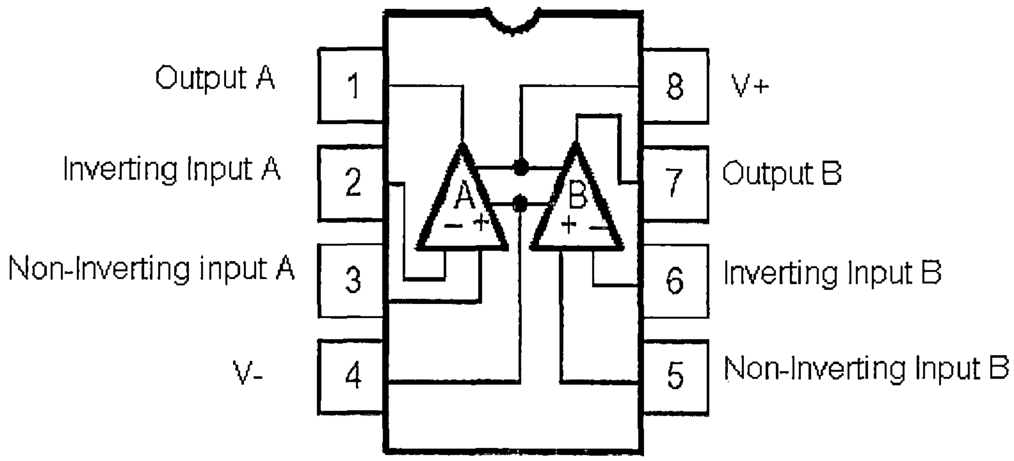


Fig.4.15: Pin configuration of IC LM 358

Features of IC LM358

(a) Internally frequency-compensated for unity gain.

(b) Larger DC voltage gain (100 db).

(c) Wider power supply range: for single supply 3 Vdc to 30 Vdc and for dual supply +/- 1.5 Vdc to +/- 15 Vdc.

(d) Large output voltage (0 Vdc to {V+ 1.5 Vdc})

4.2.7 MODULE 7: *Ballast Short-circuit Trip*

This is also protection circuit using thyristor 2N5060 provides protection from ballast short circuit. In this circuit a comparator is working in saturation i.e. $+V_{sat}$ and $-V_{sat}$ by providing diode after it, a continuous positive gate pulse will be available for the thyristor. Thyristor will trigger and the path through LED, resistance of 2.2 K and thyristor will complete and the LED will start glowing. The Ballast Short-circuit Trip circuit is shown in Fig.4.16.

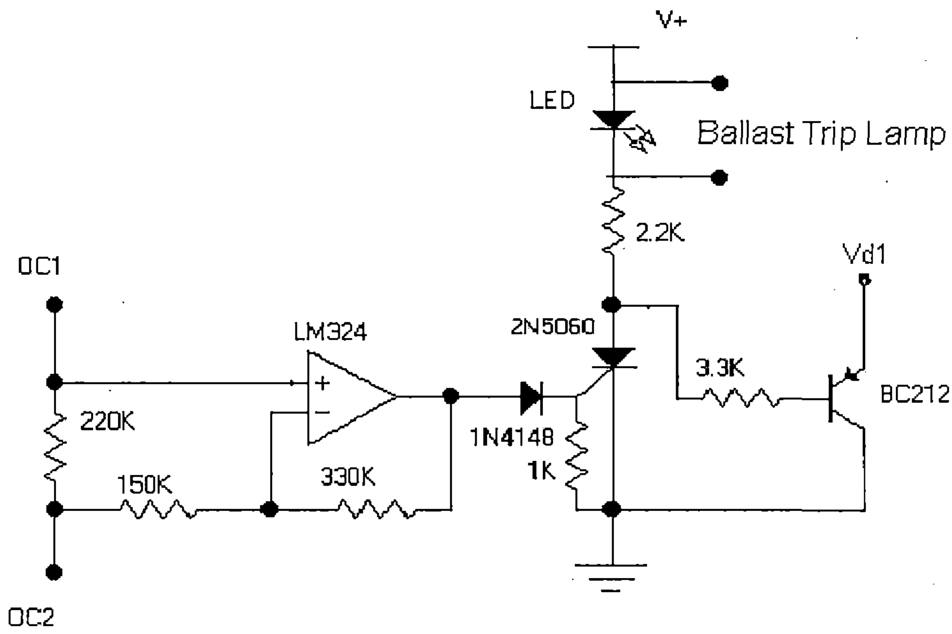


Fig.4.16: Ballast Short-circuit Trip

IMPLEMENTATION OF ELECTRONIC LOAD CONTROLLER USING PROGRAMMABLE LOGIC CONTROLLER (PLC)

5.1 GENERAL

In this part of report, an effort is made to develop the load controller (using Programmable logic controller) for single-phase induction generator powering in stand-alone mode. Using PLC, the possibility of hardware requirement is reduced to greater extent. PLC's are the best suited for the discrete control systems, where the sequence of events is programmed in the form of ladder diagram. The proposed scheme is shown in fig.5.1.

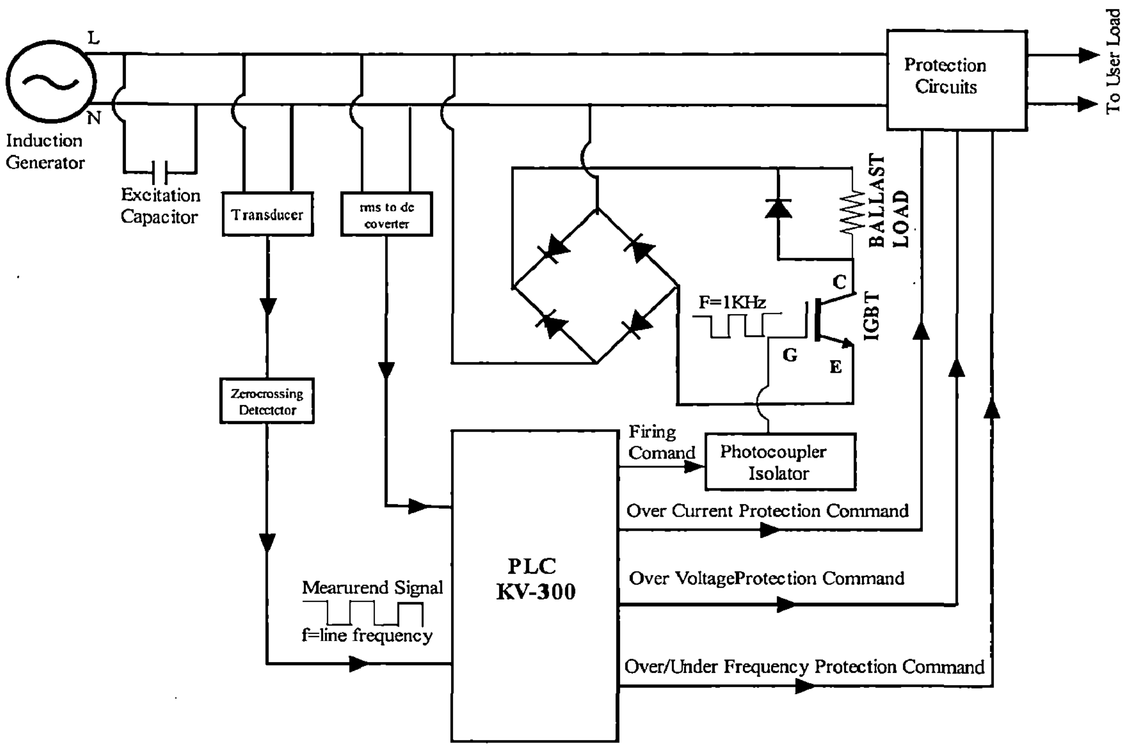


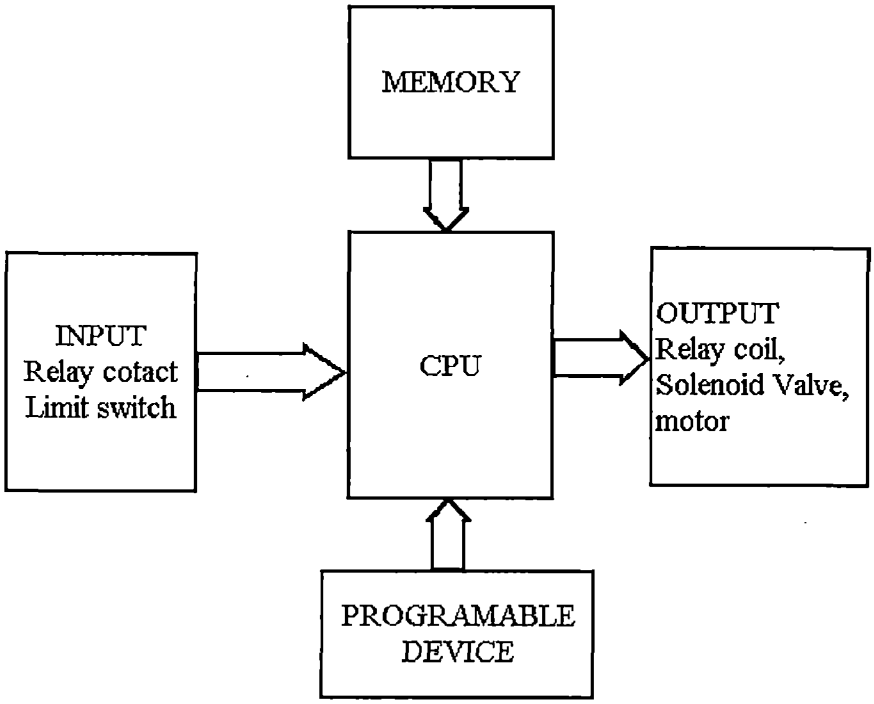
Fig.5.1: Schematic diagram of PLC based Load Controller for Induction Generator

With the use of PLC; the hardware requirement can be reduced greatly for the development of ELC for induction generator. The firing circuit, over-voltage and over-current protection circuits are replaced by a PLC logic relays, timers, counters etc. Without the use of PLC for electronic load controller, hardware are used to sense the generator terminal voltage and compared with the reference voltage. In case of any change in the user load from its normal amount, the duty cycle (i.e. ON/OFF ratio) is also changed according to the error voltage produced from comparison of terminal voltage with the reference voltage, in order to regulate frequency and to maintain the power balance between user load and the ballast loads.

The Electronic Load Controller can be implemented by using PLC. Most of the auxiliary hardware can be dispensed with the use of PLC; the terminal voltage can be fed to KV-AN6 module of PLC through appropriate sensor, which converts the analog input signal to digital data voltage and stored in the KV-300 CPU. This input signal is compared with a reference data stored in the memory of PLC. The error produced by comparison is used to change the duty cycle of firing pulse produced by PLC. In this way PLC can eliminate and reduce the complexity of hardwired circuit.

5.2 DESCRIPTION OF PLC

A simple PLC is a reprogrammable device that has one or more input signals that are conditioned by an input module and one or more output signals that are conditioned by an output module, and a CPU as shown in fig.5.2.



Architecture of PLC

Fig.5.2: Architecture of PLC

The program is the controller is unique in that it is generally written in the form of contacts that logically control the condition of the output coils. This program tends to look exactly like electrical ladder diagrams that are used for traditional hardwired system. The ladder diagram programs are stored in the PLC memory. This diagram looks like a ladder diagram that is used in hardwired system, except that all switches are shown as a set of normally open or normally closed contacts. The controller can have a variety of memory media and can also provide more complex functions such as time delay, counts and sequences. Addition type of controls is generally available to provide motion control, process control and complex mathematical calculations.

5.3. ALGORITHM FOR DEVELOPING A LOAD CONTROLLER USING PLC

(a) Sense/measure the generator terminal voltage and frequency (for providing over/under frequency protection) by PLC's KV-AN6 analog I/O module at the level compatible with PLC. The kV-AN6 converts the analog signal into digital data and stores it in data memory of PLC.

(b) Compare the current value of measured signal with a reference value, which is stored at other memory location.

(c) If error is more than maximum error, provide over-voltage protection and If error is within permissible limit then adjust the duty cycle of firing pulse till error reduced to zero again. Flowchart for developing Load Controller using PLC is shown in Fig.5.3.

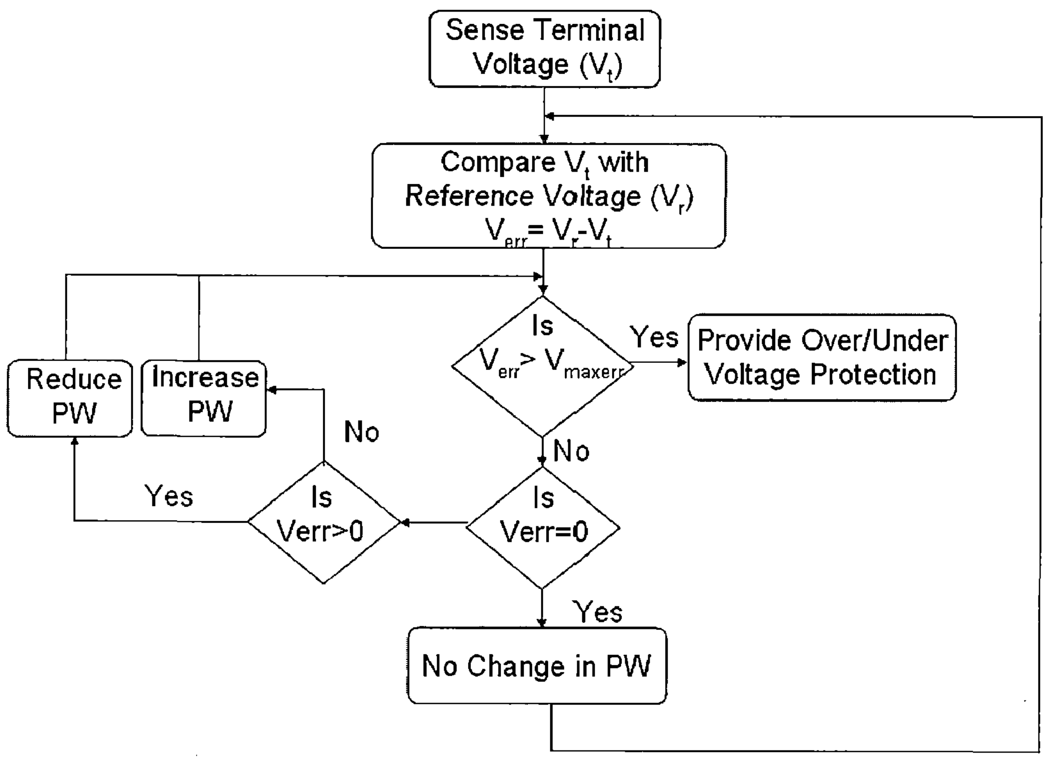


Fig.5.3: Flowchart for developing Load Controller using PLC

5.4 HARDWARE FOR PLC BASED ELECTRONIC LOAD CONTROLLER

5.4.1 RMS to DC converter

This circuit as shown in fig.5.4 gives the dc voltage output proportional to rms value of ac input. This circuit is directly fed by ac input, and output voltage varies as rms value of ac input voltage changes. The output of this circuit is directly fed into analog I/O module (i.e. KV-AN6) of PLC.

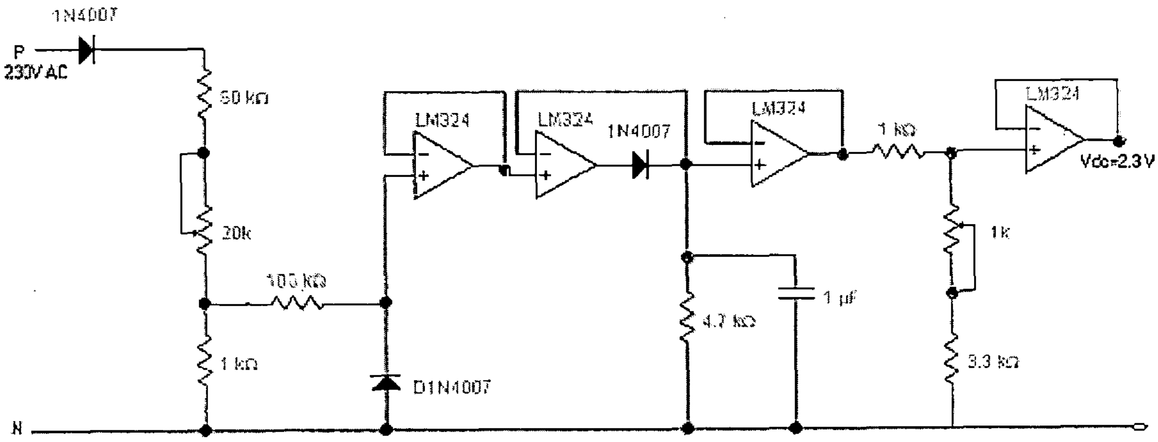


Fig.5.4: RMS to DC converter circuit

5.4.2 Zero-crossing Detector

This circuit as shown in fig.5.5 is used to measure the frequency of Induction Generator output, shown in figure. This circuit uses an Op-Amp IC OP07. A stepped down line voltage is applied to OP07 at inverting terminal with a 10 k Ω carbon resister.

This circuit as shown in fig.5.6 gives a rectangular pulse of frequency same as input signal frequency. Feeding this output pulse to the PLC, the frequency of Induction Generator output can be measured by ITVL instruction. The ITVL instruction of PLC command directly measures the time interval between pulses and this time can be converted into number of pulses per second, in this way line frequency can be measured.

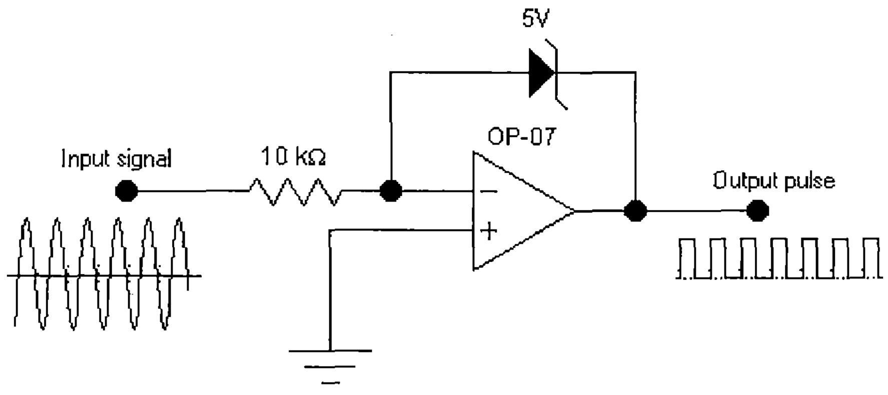


Fig.5.5: Zero-crossing detector circuit

5.4.3 Photo-Coupler Isolator Circuit

This circuit is fabricated around a photo-coupler IC MCT2E, it consists of a light emitting diode and a phototransistor, clamp any high voltage spikes or surges down to the small level. This provides protection to the PLC against switching transients and power supply surges, normally up to 1500 V. This circuit keeps the PLC electrically isolate from external circuit, though the photo-coupler isolator are provided inside the PLC at every input output relay contact, this double protection is adopted to protect PLC from any electrical hazard.

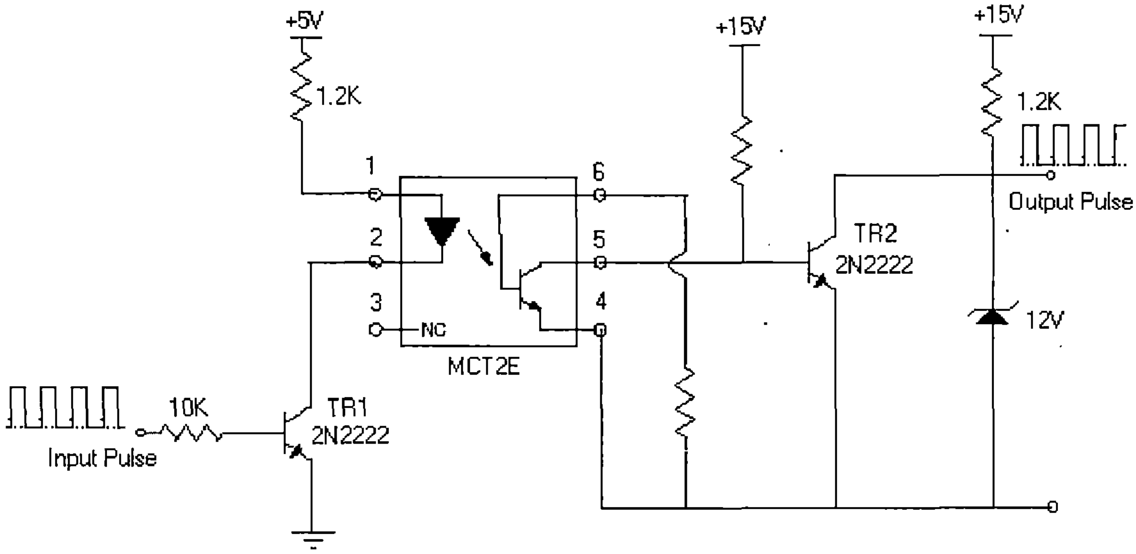


Fig.5.6: Photo-coupler isolator circuit

RESULTS AND CONCLUSION

6.1 RESULTS

All the modules are simulated on Electronic Workbench EDA 5.0 and its results has been obtained. By testing the hardware of all modules, the results, which were obtained by simulation, are matching.

Module 3 (Voltage sensing circuit) gives an output Waveform with constant slope. For 250 V generator output voltage, the output waveform of module 3 are shown in fig. 6.1 and fig.6.2.

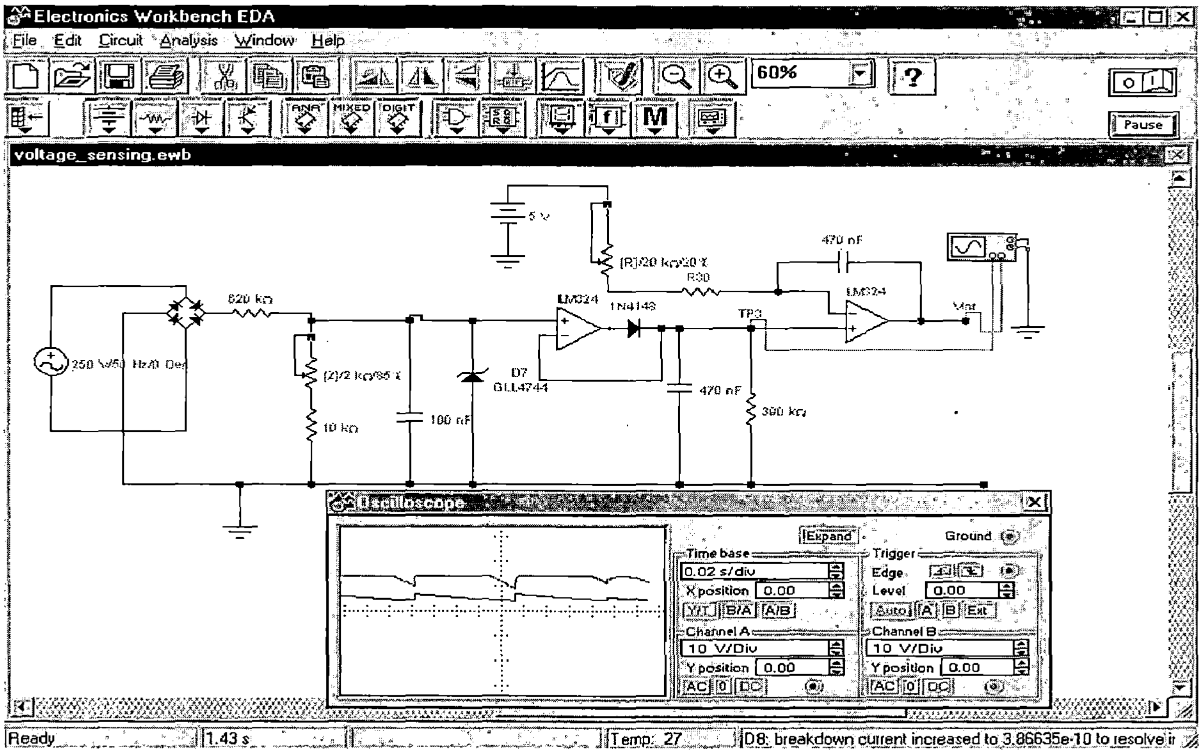


Fig.6.1: waveforms at TP3 and Vint when generator voltage is 250 V.

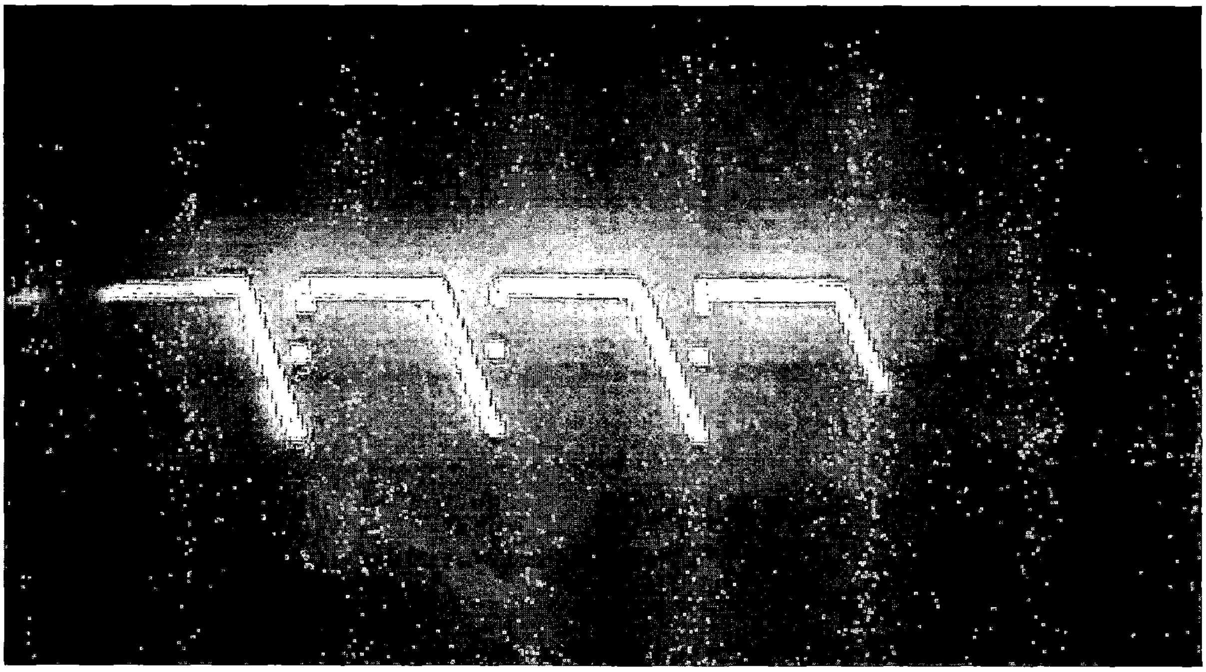


Fig.6.2: Output of Voltage sensing Circuit at 250 V ac.

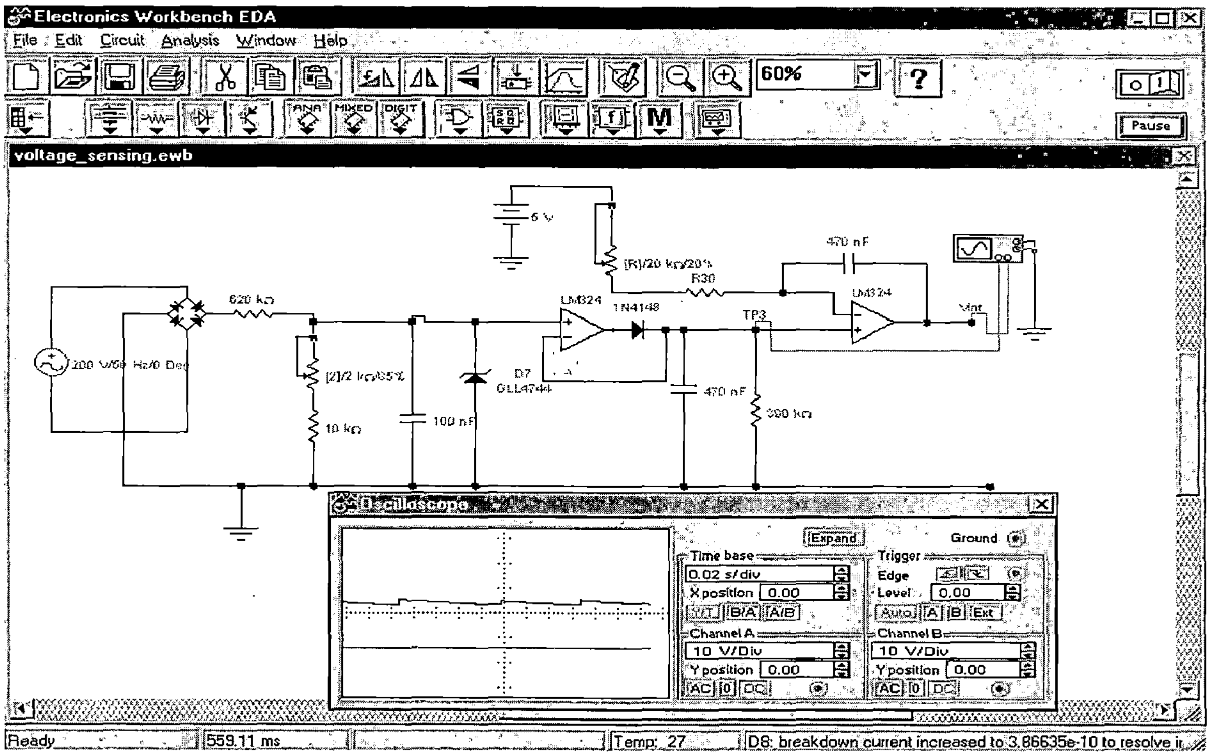


Fig.6.3: waveforms at TP3 and Vint when generator voltage is 200 V

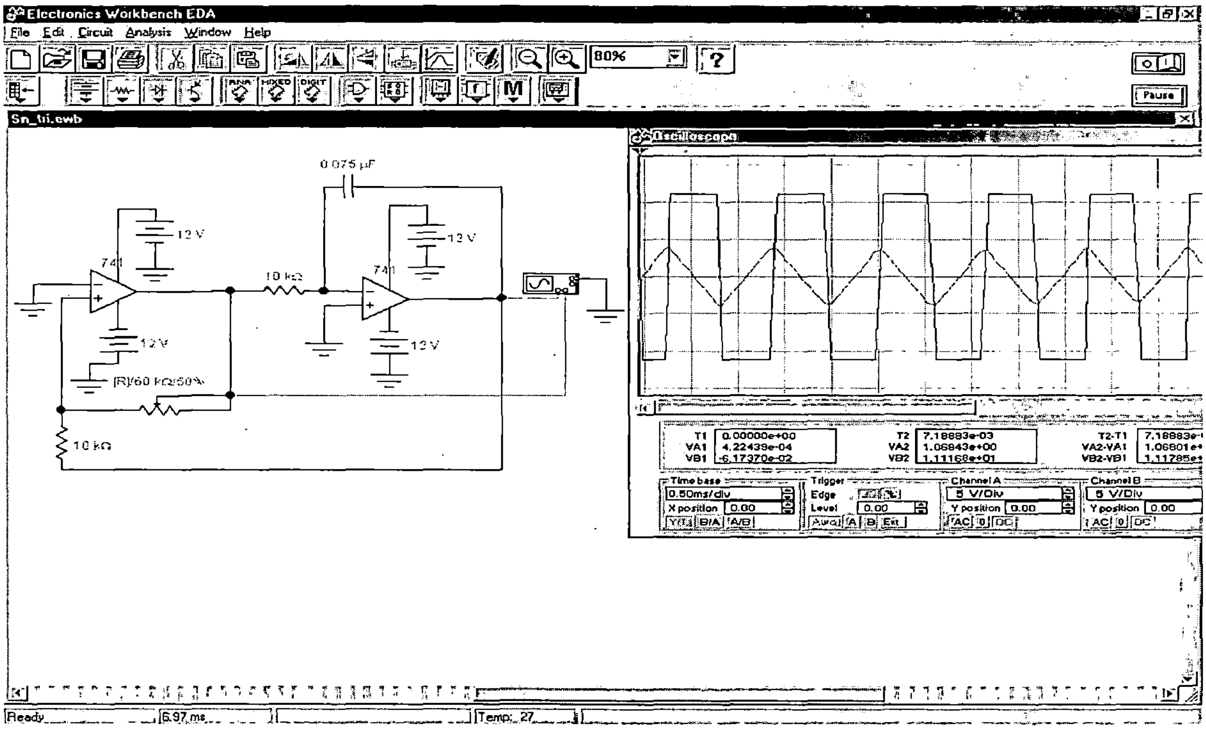


Fig.6.4. The simulated results of module4 (Triangular Waveform generator)

Module 4 (Triangular Pulse Generator Circuit) gives the triangular waveform of frequency of 1 kHz having peak-to-peak voltage of 8 V. The output of module 4 is shown in fig.6.4 and fig. 6.5.

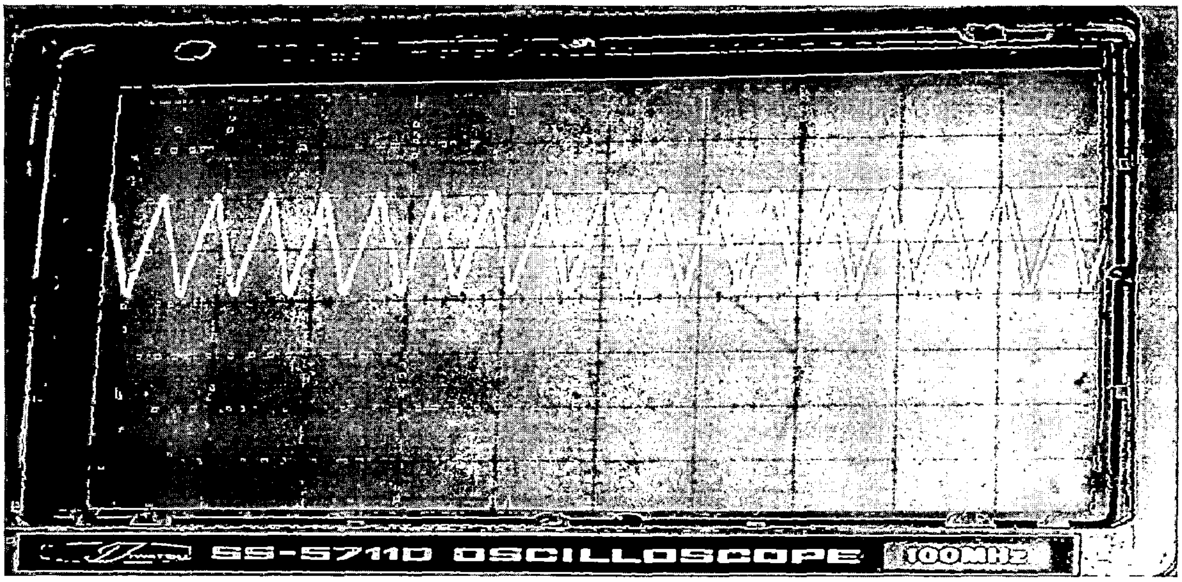


Fig.6.5: Output of Triangular Wave Pulse Generator Circuit

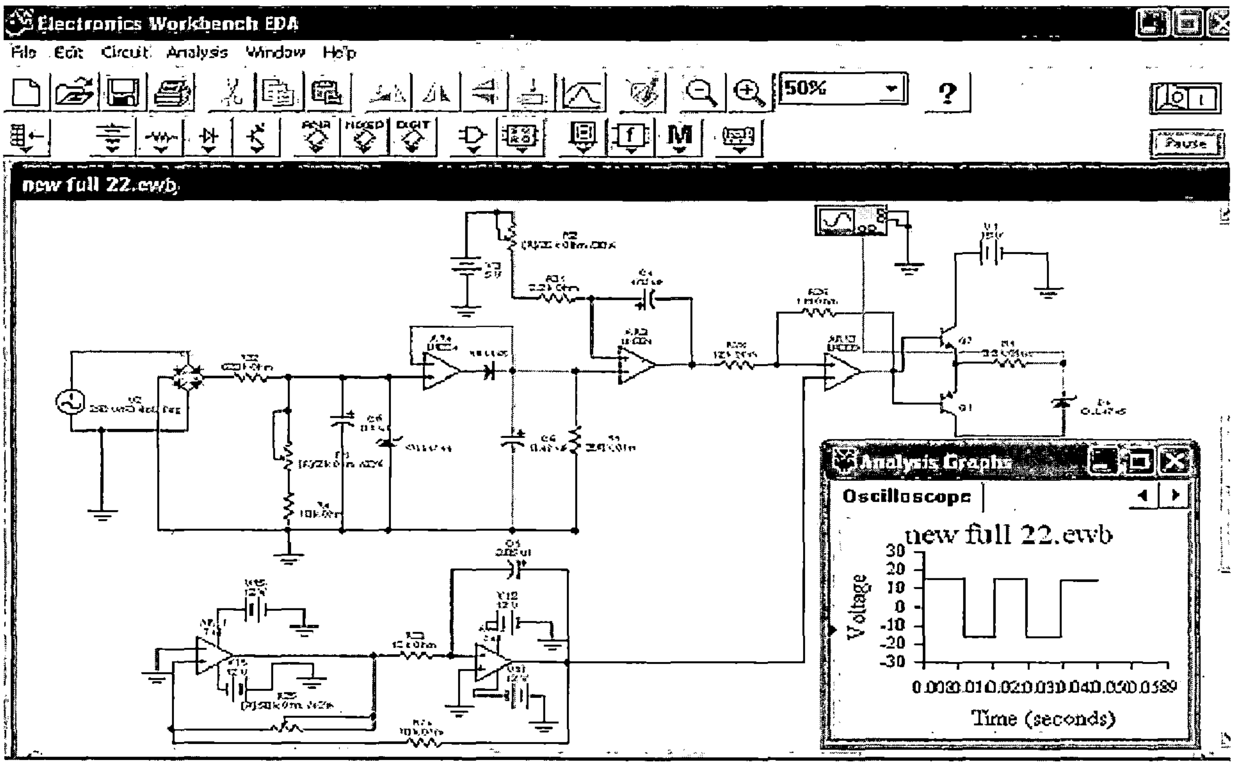


Fig.6.6: The simulated Result of module5 (Comparator/Transistor Drive)

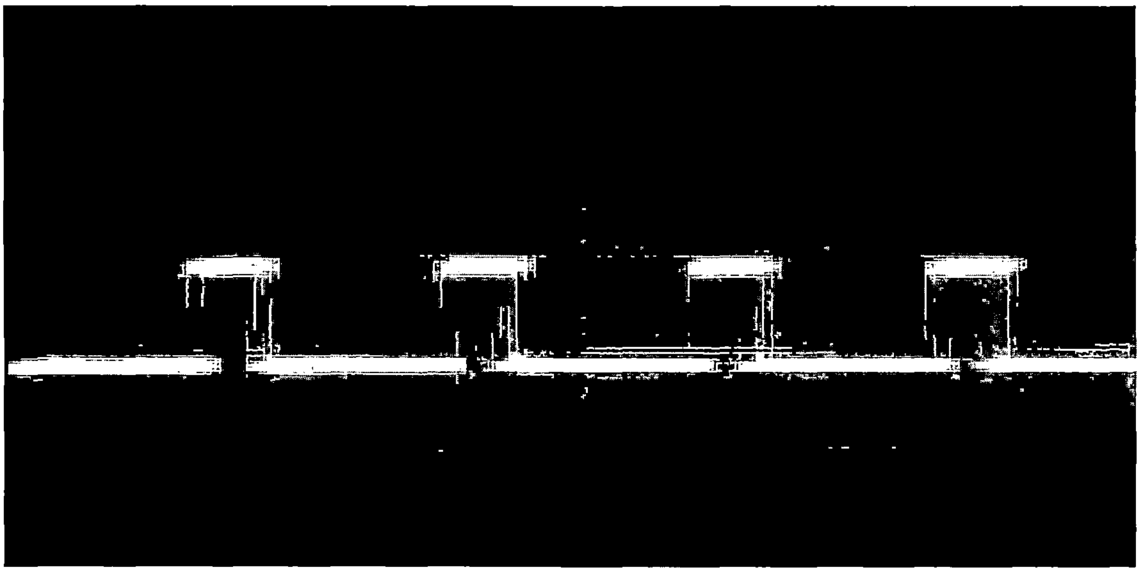


Fig.6.7: Output of Comparator Circuit/IGBT Gate Drive Circuit

Module 5 (comparator/IGBT Gate Drive circuit) gives the output of modulated waveform corresponding to 250 V ac as shown in fig.6.6 and fig.6.7.

6.2 CONCLUSION

The hardware for Electronic Load Controller has been developed. The controller is made especially for single-phase induction generator powering resistive type load in stand-alone configuration. This ELC with suitable excitation capacitor will be highly beneficial to provide regulated voltage and frequency to the isolated load using induction motor as single-phase generator, where the electric supply is not available from local or national grid.

This ELC is a simple and low cost solution for using induction machine as stand-alone generator in micro-hydro schemes. This may feed single-phase load of rating below 3 kW. For feeding power to heavy loads it can be further modified by replacing the switching device of a controller with the higher rating switching device such as IGBT or MOSFET along with suitable heat sink.

The PLC based Load Controller may be an uneconomic approach for small or single user, but it is best suited to provide the control and protection features through software with minimum hardware requirement.

It is concluded that by using PLC for Controlling Load can be easily done by just writing the ladder program of scheme into the PLC memory and giving input/output connections. This eliminates the tedious task of using large number of relays and their interconnection. Modifications can be easily done in the control scheme by making suitable changes in the ladder diagrams; this way, with PLC the external hardware requirement are reduced to minimum extent. This is very useful, as minor changes are usually required at site the time of installation and commissioning.

6.3 SCOPE FOR FUTURE WORK

An Electronic Load Controller for feeding a three-phase load can be developed with hardwired logic as well as with software using Programmable Logic Controller. The reactive power (i.e. power factor) can also be controlled by replacing the diode bridge rectifier with controlled rectifier (i.e. four diodes are replaced with thyristors) in the main power circuit of controller, this scheme is suitable when reactive load is connected to induction generator as main load. The phase angle of bridge can be adjusted to absorb any reactive power not needed by system. With only a bridge the amount of real power absorbed is dependent on the reactive power level. The chopper (i.e. IGBT) is needed to decouple the control between real and reactive power. The chopper is synchronized to conduction period of the bridge, is operated with multiple chopping during each conduction period. Synchronization and multiple chopping can reduce voltage distortion.

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Appendix - A

VARIOUS PHOTOGRAPHS OF DEVELOPED ELC

The PCB maps for different modules used in Electronic Load Controller are given below.

1. ***Top layer (Silk, Pads and Text) of module1 (Power circuit):***

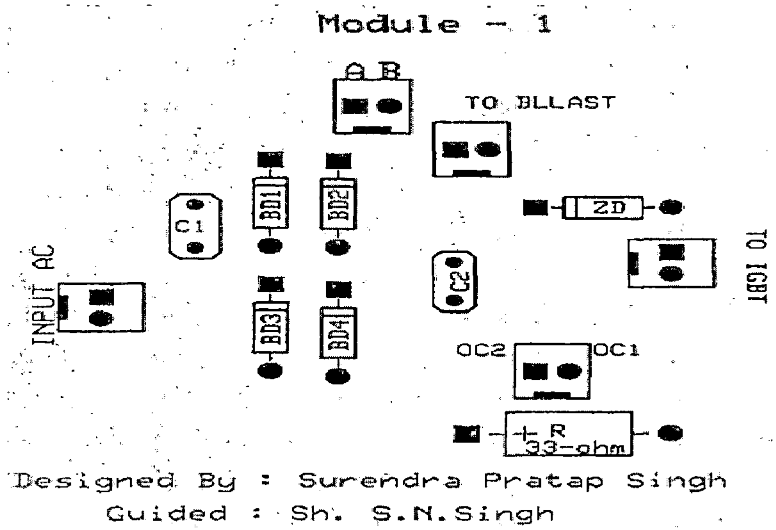

Fig.A-1: Component layout and top screen for the PCB of module 1.

2. ***Bottom copper layer of module 1***

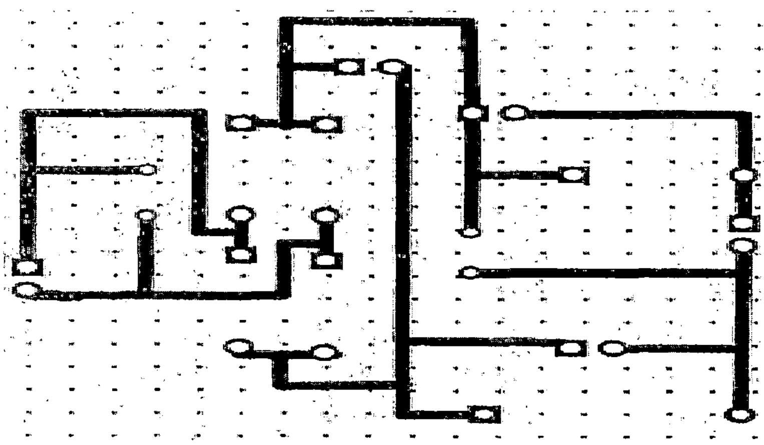

Fig.A-2: An actual size, single side PCB for module 1.

3. ***Top layer (Silk, Pads and Text) of module 2 (Voltage reference and supply circuit):***

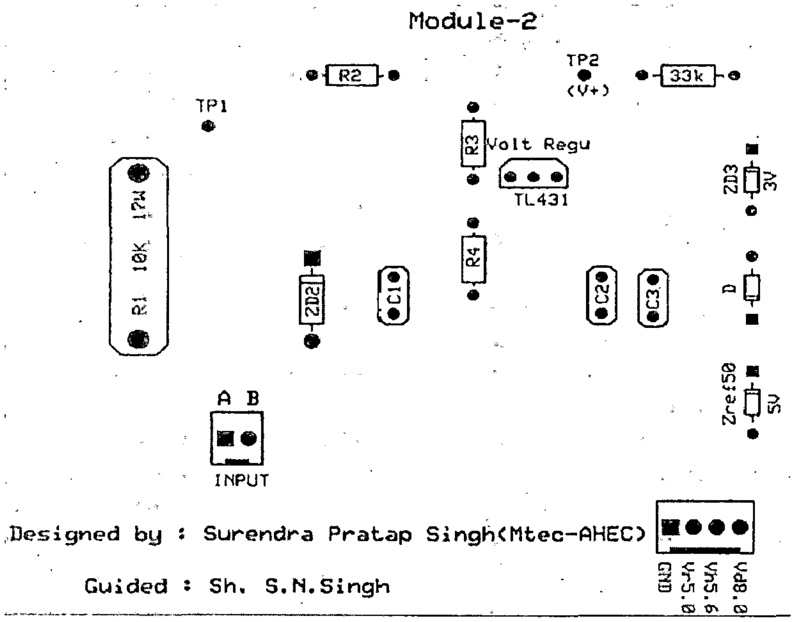

Fig.A-3: Component layout and top screen for the PCB of module 2.

4. ***Bottom copper layer of module 2***

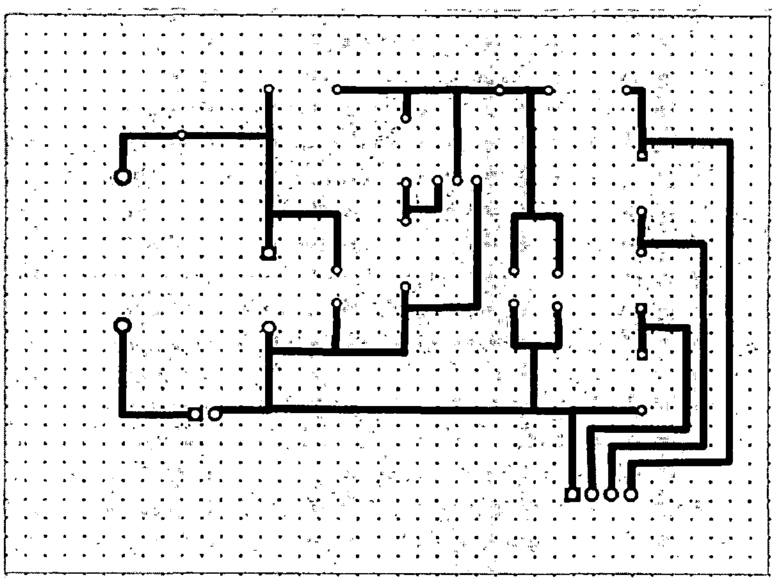

Fig.A-4: An actual size, single side PCB for module 2.

5. ***Top layer (Silk, Pads and Text) of module 3 (Voltage sensing circuit):***

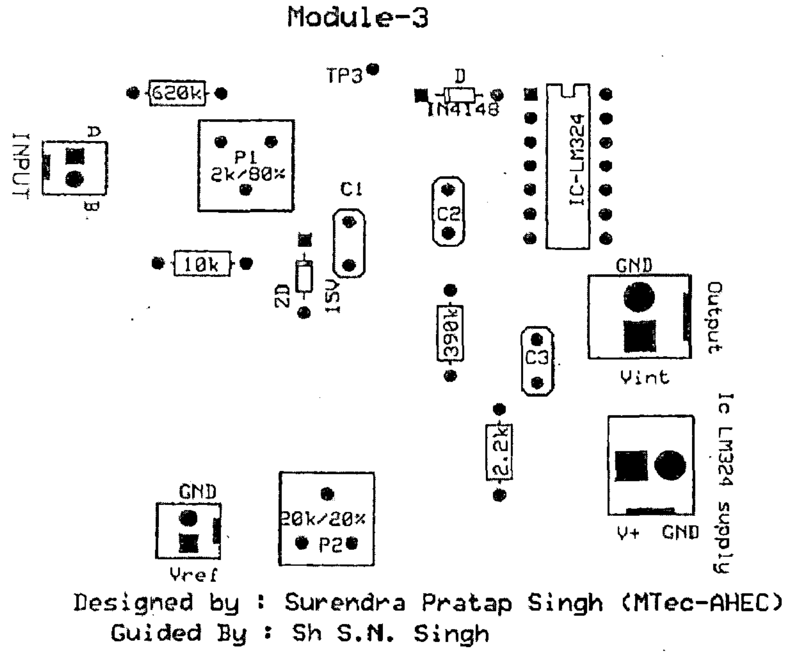

Fig.A-5: Component layout and top screen for the PCB of module 3.

6. ***Bottom copper layer of module 3:***

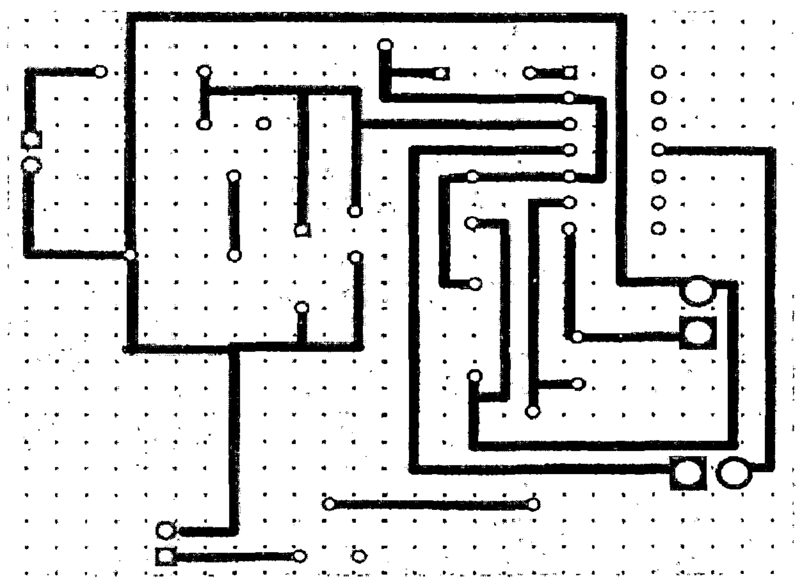

Fig.A-6: An actual size, single side PCB for module 3.

7. ***Top layer (Silk, Pads and Text) of module4 (Triangular waveform generator):***

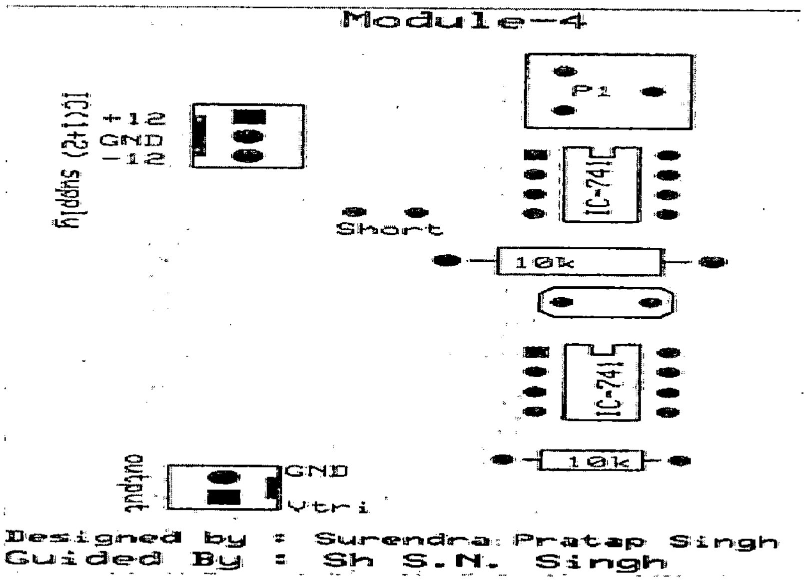

Fig.A-7: Component layout and top screen for the PCB for module 4.

8. ***Bottom copper layer of module 4:***

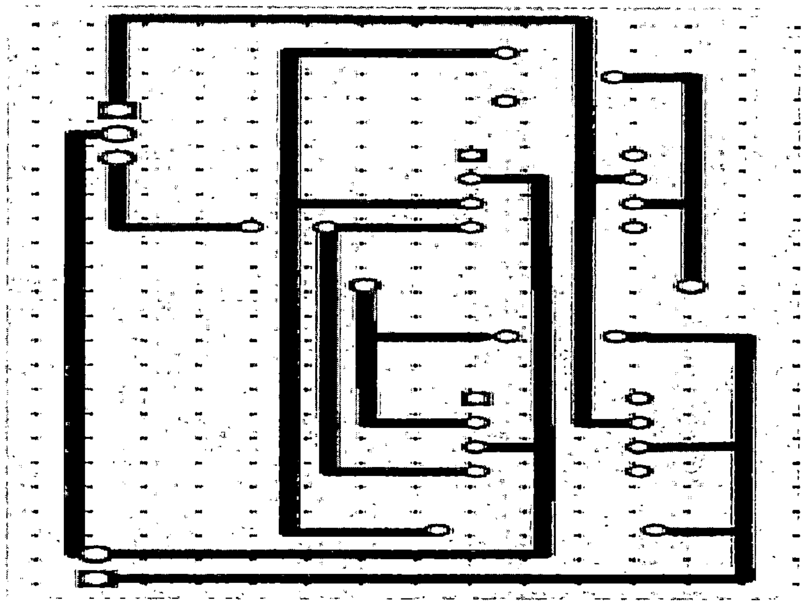

Fig.A-8: An actual size, single side PCB for module 4.

9. ***Top layer (Silk, Pads and Text) of module 5 (Comparator/IGBT gate driver circuit):***

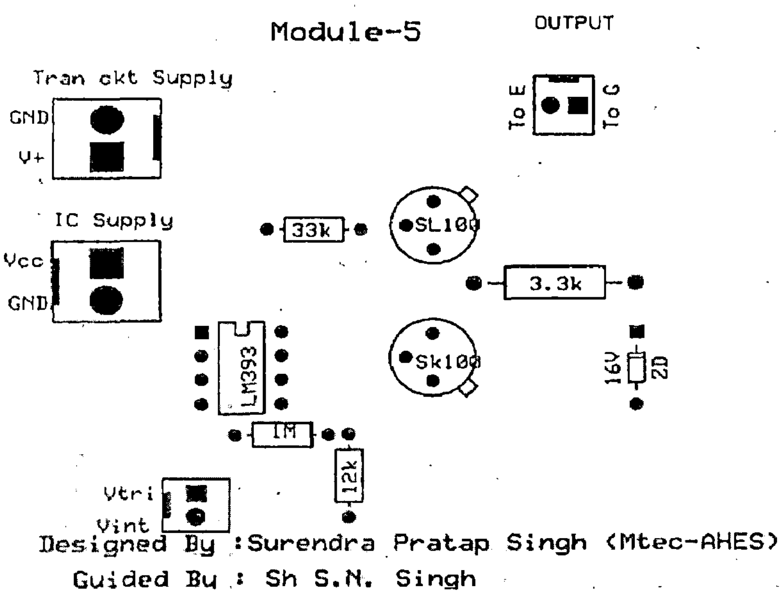

Fig.A-9: Component layout and top screen for the PCB for module 5.

10. ***Bottom copper layer of module 5:***

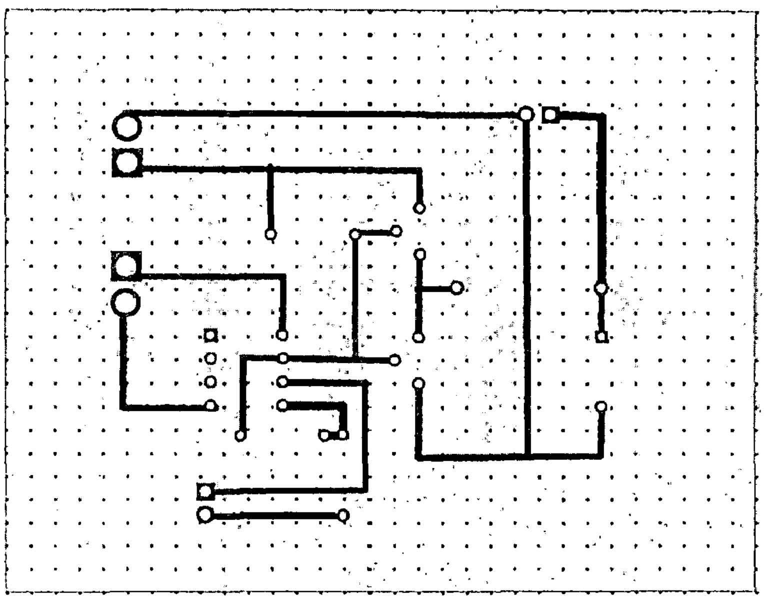

Fig.A-10: An actual size, single side PCB for module 5.

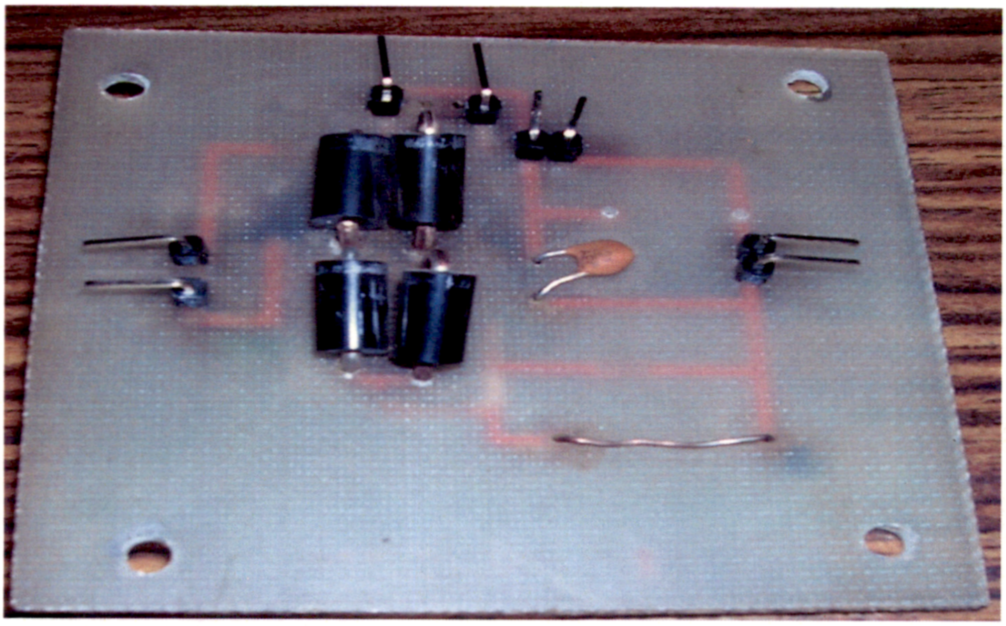

Fig.A-11: Power Circuit for Switching the Ballast Load

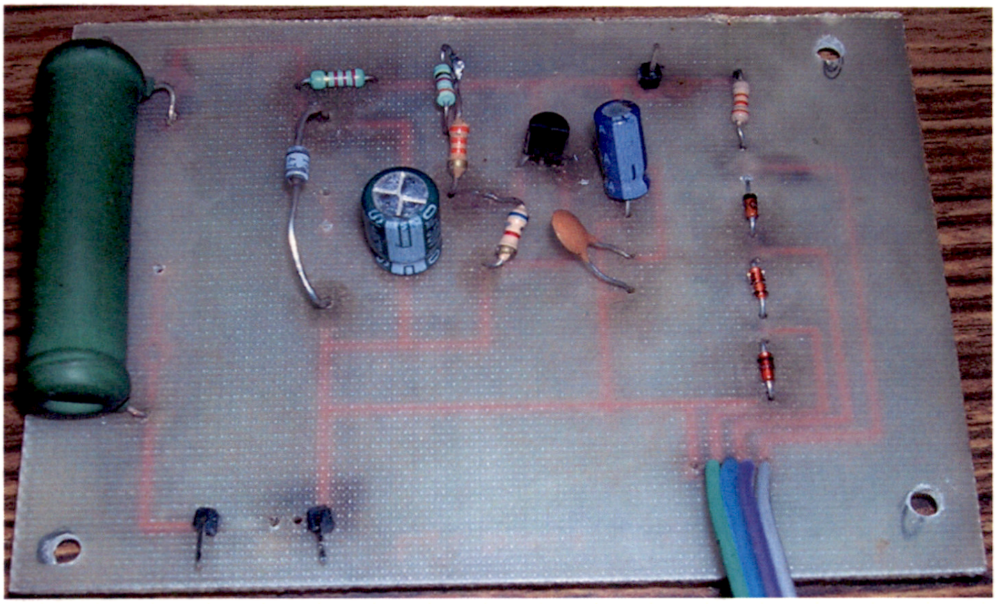

Fig.A-12: Power Supply and Voltage Reference Circuit

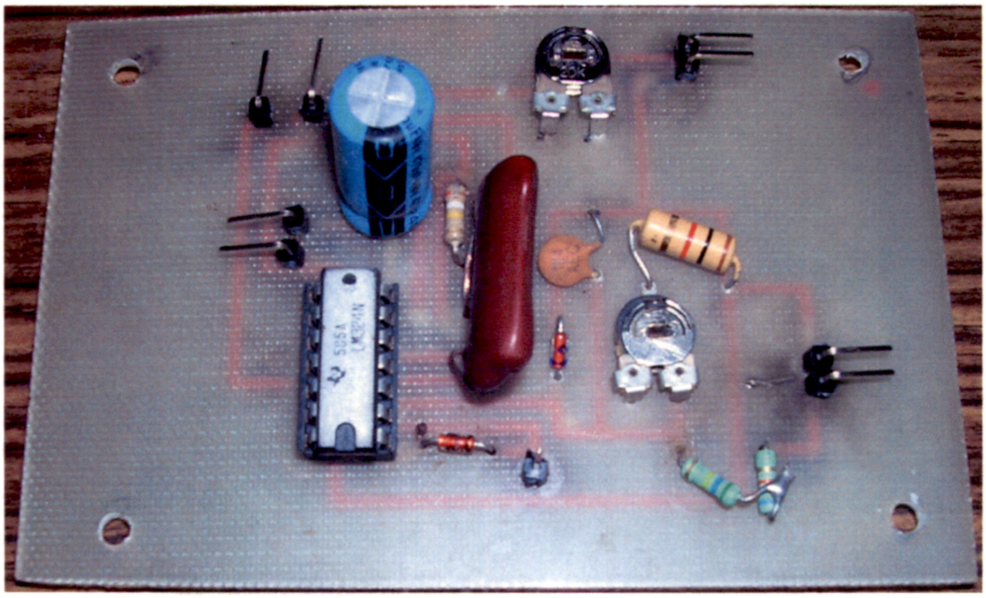

Fig.A-13: Voltage Sensing Circuit

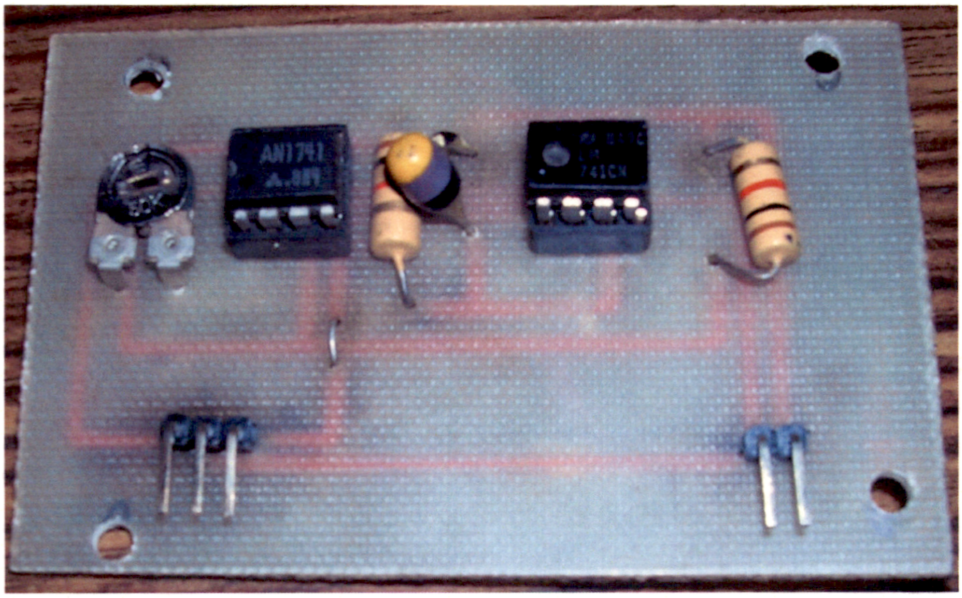

Fig.A-14: Triangular Wave Pulse Generator Circuit

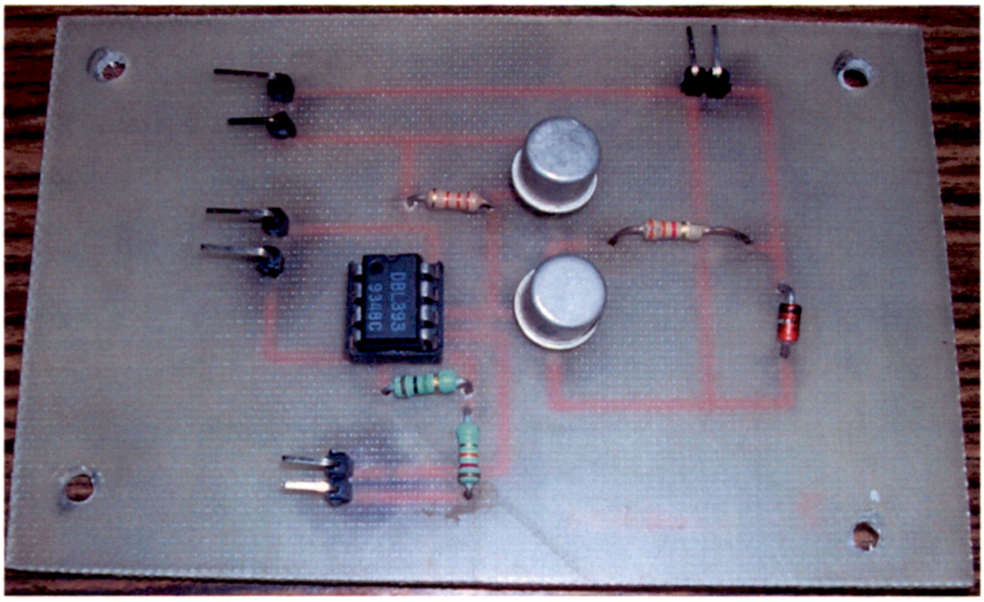

Fig.A-15: Comparator Circuit/IGBT Gate Drive Circuit

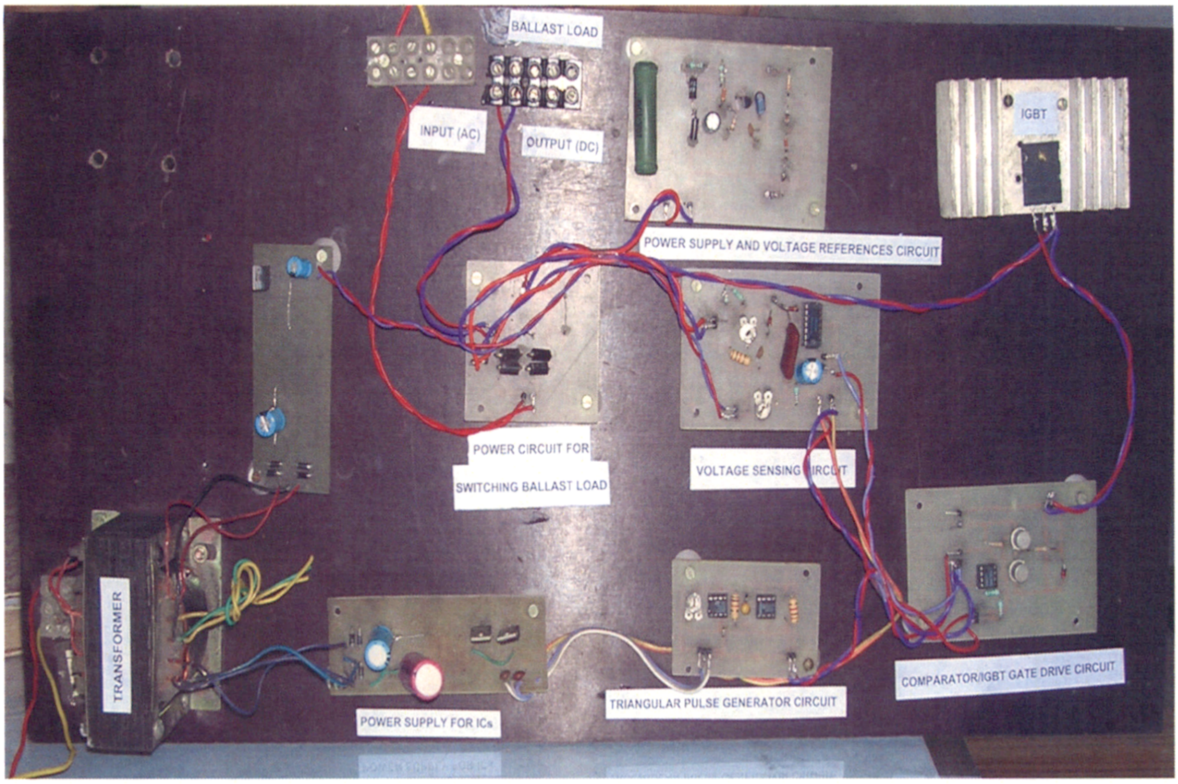

Fig.A-16: Assembly of ELC