DESIGN AND FABRICATION OF CONTROLLER FOR MICRO-HYDRO ELECTRIC SYSTEM

A DISSERTATION

Submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(With Specialisation in Measurement & Instrumentation)

By

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CERTIFICATE

CERTIFIED that the dissertation entitled 'DESIGN AND FABRICATION OF CONTROLLER FOR MICRO-HYDRO ELECTRIC SYSTEM', which is being submitted by Mr. Prushottam Datt Kashyap in partial fulfilment for the award of the Degree of Master of Engineering in Electrical Engineering (Measurement and Instrumentation) of the University of Roorkee, Roorkee is a record of the student's own work carried out by him under our supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is to further certify that he has worked for a period of more than 10 months from January 1984 to November 1984 for preparing this dissertation at this University.

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SYNOPSIS

The economic exploitation of hydro power sources of smaller capacities(few KW to 1 MW) is essential for developing isolated power houses to meet the local needs. Such power houses will be particularly useful for hilly areas, where the power transmission cost from the grid will be exorbitant. The foremost problem in the design of micro-hydro plants has been the choice of a proper prime-mover. In the conventional systems the cost of the governing mechanism becomes significant for lower rating turbines.

In recent years, a number of studies have established that pumps can be used in reverse to work as turbines, from few KW to 5000 KW, for heads ranging from 3 mt. to 100 mt. In the absence of any governing mechanism in the prime mover, a load diverter or load controller is required which will divert excess generation to a dummy load, so that voltage and frequency of the power supply can be maintained.

In the present work an electronic controller has been designed which has static switching to divert excess load. The dummy load has been divided into a number of

steps, besides having a continuously variable component. The above arrangement reduces harmonic distortion. The controller has been tested on a laboratory scale micro hydel system of 6 KW.

Chapter 1 of the thesis reviews the literature available on micro hydel schemes. The block schematic and the detailed designing of the control and power circuits have been included in Chapter 2. The fabrication details, preliminary testing of electronic circuits, and final testing on laboratory scale model have been included in Chapter 3. Chapter 4 concludes the test results and includes suggestions for future work.

CONTENTS

CHAPTER 2 : ELECTRONIC CONTROLLER

CHAPTER 1

INTRODUCTION

The first hydroelectric power station in the world started generating electrical power when a 12.5 kw microhydro set was commitioned on Fox River in Apleton, Wisconsin, U.S.A. in 1888. But subsequently as the demand for electrical energy increased with the growth of industry, the emphasis shifted towards larger installations as the cost of generation of electrical power per killowatt decreased. Thus harnessing power from small hydro-power sites was overlooked and many micro/mini/small hydro power stations were disbunded due to high production cost. But the demand for more energy and rise in fossil fuel cost in the early seventies focussed the world wide attention towards harnessing renewable energy sources, foremostamongst them being microhydro.

Hydropower is one of the most attractive source of renewable sources of energy, because of its following merits :

- Renewable source of energy
- Non polluting
- Controlled source of energy as compared to other non-conventional sources like wind power or solar

energy which are intermittent in nature.

- Negligible inundation of land and displacement of community from the development area leading to various social and economical problems
- Less time taken (usually 2 to 4 years) depending on the complexity of the scheme for small scale development
- Utilisation of locally available construction material
- Long life and low operation and maintenance cost and special adaptability to remote control operation
- Fairly constant cost of generation as opposed to increasing cost of fossil -fuel-energy with time
- Possibility of engaging local labour with minimum training for operation as operations can be made simple
- Reliability and flexibility

The microhydro sites are characterised by sparse distribution over a larger area and thus low energy density which evidently indicates higher production cost. But on the other hand, such sites are usually found alongisde consuming centres especially in rural and remote localities. Supply of electrical energy to such remote communities from large central stations may be found uneconomical due to high cost of transmission and distribution. In such cases, development of micro-hydro sites may not only provide basic energy requirements of the remote communities but can also help in augmenting the quality of life.

Inspite of all the above cited merits of micro/mini/small hydro-electric power stations there are several constraints in development of small hydro plants which are as summarised below :

1. High capital cost per killowatt installed
2. Non-availability of equipment in ultra low head (below 3 Mt.) region
3. High cost of controls and management
4. Low utilization (load) factor for decentralised system usually in rural areas

Hence to make small hydropower projects economically viable, it is desirable to reduce :

(a) Construction cost

(b) Standaridisation of hydro-mechanical equipment and civil construction appears necessary for economic viability and reduction in construction period

(c) Standardisation of turbine

(d) Elimination of guide vanes, adoption of induction generators, or ELECTRONIC LOAD CONTROL DEVICES

(e) Harnessing low head falls in irrigation system by standardised designs as source of energy

(f) Higher load factor

The scope of this dissertation is limited to the development of an electronic load control device aimed at reducing the cost of micro hydro electric Units by elemination of conventional governing systems and guide vanes.

1.1 TYPICAL MICROHYDEL SYSTEM

Typically a microhydel generating plant of conventional design includes the following :

1. hydroelectric turbine with flow control mechanism
2. a speed governor

3. a single three-phase alternator with a voltage regulator
4. Gearing or a belt drive to match the operating speeds of turbine and alternator
5. Electrical control equipment

Since the storage of electricity is not possible as yet, the energy generated must be matched to the energy demand. This is done by diverting the flow of water through flow control mechanism and Governor. Thus, allowing the water energy to go waste which can never be recovered. The conventional Governor is a very expensive item and may account for more than 25% of the total cost of small unit.

1.2 THE NEW MICRO HYDRO SYSTEM

The Central Electrical Authority of India has categorised the micro-hydro scheme as the Hydro Electric Scheme with a total installed capacity of 100 KW having individual generating Units with capacities from a few KW to 100 KW.

The new micro hydro system basically work on the constant input-output operation. The turbine works at constant flow and total load on generator is constant, avoiding unacceptable sudden fluctuation in speed, frequency and voltage.

The block diagram of new micro hydel system is shown in Figure 1.

The system utilized simplified turbine (pump as turbine also) operating at constant flow conditions without governors. The Electronic Controller maintains village load as first priority load and diverts surplus power to a by pass loading system. The governor action of Electronic Controller is very fast and can present instability due to very low inertia of the microhydel generation system. Thus the system works as constant output constant speed, constant excitation unit requiring no regulation. With this controller system the total cost of system has reduced in view of following facts :

1. Speed Governor is eliminated effecting substantial reduction in cost of equipment
2. Turbine design is simplified because continuous automatic variation of flow is no longer required
3. Without the need to coordinate the dynamics of Governor rotating machines, and water column, matching the turbine to the site is not critical
4. Surplus electrical power is used to upgrade rural

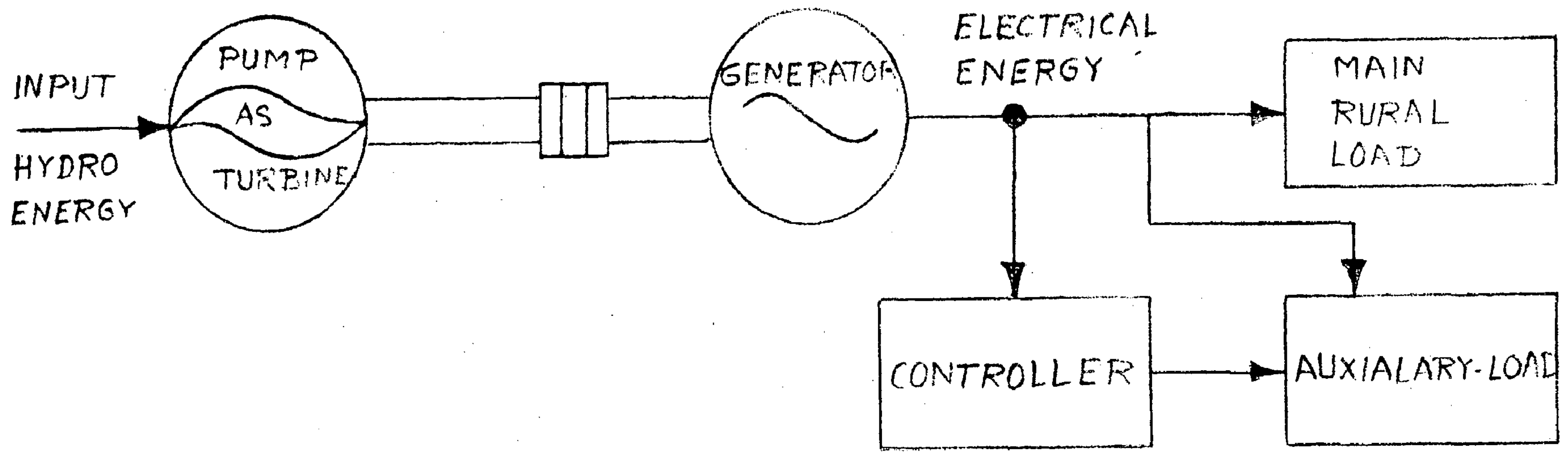

FIG.1 MICRO HYDRO SCHEME

renewables thereby, improving the overall economic viability

5. Maximum available energy is harnessed

1.3 THE CONTROLLER

The controller developed shall perform the following functions :

1. Replace conventional Governors and regulators
2. Act as load divertor to hybrid system
3. Provide stability for low intertia hydro generators in isolated and interconnected systems
4. Perform control/production (overload - under/over voltage)

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1.4 REVIEW OF LITERATURE

For economic exploitation of small hydro sources certain design innovations are necessary. Its importance is further enhanced because it is a renewable source of energy and it has started receiving the attention world over.
One such innovation has been the use of centrifugal pumps as turbine. [1]. Pumps being locally manufactured using local technology and labour meet out the requirements of water turbines for small hydro power projects [2].

Extensive studies made by Worthington pumps [1] have revealed the following features for use of pumps as turbines :

(a) The mechanical operation is smooth and quiet.

(b) The peak efficiency as a turbine is essentially the same as its peak efficiency as a pump at the best efficiency point (BEP).

(c) The head and flow at BEP as a turbine are higher than the corresponding head and flow at BEP as a pump.

(d) The power output as a turbine, is slightly higher than the pump input power at BEP, and

(e) The turbine speed and pump speed at BEP are essentially the same.

U.S. Department of Energy has published a report titled, 'Small hydro plant development program'[2] in 1980 which has examined the two factors in details as given below :

(a) Use of pumps as turbine,

(b) Use of Induction generator in place of synchronous generators

The report includes designs of small hydro plants from 50 KW to 5000 KW for heads ranging from 3 mt. to 100 mts. A total of nine such designs have been compared; one set uses standard turbines coupled to synchronous generators, while the other set uses pumps as turbines coupled to induction generators. The above study establishes that pumps can be picked off the shelf to work as turbines for small hydro plants.

It has been found that pump-generator packages are approximately half the cost of the standard turbo-generator sets, which excludes the civil cost, transmission cost and installation cost. The standard turbogenerator have a plant life of 30 years, while pump sets may generally have plant life of 15 years. Absolute cost benefit ratio have not been worked out, because the civil cost can not be standardised. Some general comments on the use of pump-induction generator set up are as given below :

1) In the pump-generator case elementary types of valves have been used at the inlet side. When there is a fault on the generator, the valve is supposed to close to avoid over speeding on loss of load. However, the generator should be designed to cater for maximum overspeed; which may be as high as 170%. Standard induction generators are designed for 25% overspeed. Hence the manufactureres may have to be approached to suitably modify standard induction generators.

2) The pumps tested in the laboratory for the standard packages showed efficiencies of the order of 80% in the turbine mode, as against the efficiencies of 90% for standard turbo units. However, the pumps may have to be modified extensively; such as modifications in diffusers, propeller blades; hub-nose cones, draft tube etc.

3) As mentioned earlier the pump-generator packages will generally have a plant life of 15 years as compared to 30 years for the standard turbogenerator sets. Hence, the cost advantage of a factor of 2 enjoyed by the pump generator set may reduce considerably in a life-cycle cost analysis.

Squirrel cage induction motors are ideally suited to work as induction generators, as these are very rugged and simple units. In the report only grid operation of small hydro units has been considered, as isolated operation

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Squirrel cage induction motors are ideally suited to work as induction generators, as these are very rugged and simple units. In the report only grid operation of small hydro units has been considered, as isolated operation of induction generators was not considered feasible.

The synchronous generators with electronic load controller are best suited for isolated operation. The electronic load controller has to keep constant load on the generator; for constant head and constant flow. Since the main load or the most priority rural load changes instnataneously, the electronic load controller has to divert surplus power in an auxillary load. The auxilary load has to be at least equal to the generator capacity for continuous operation of the plant. In this dissertation work load controller using triacs has been developed, which further divides the auxillary loads in step load and phase load. The phase loads are for fine control, as the loads can be continuously varied. The A.C. supply to the phase loads varies from 0 to 230 volts. Hence, only heating type of loads can be connected as phase loads. The step loads are switched loads and receive normal mains supply. The step loads can be considered as low priority loads which receives power, whenever excess power is available.

A number of control schemes have been suggested [3,4,5,6]. The block diagram of a control scheme [3,5] which has been implemented on a single phase generator has been shown in Fig. 2 .

The frequency control of the generator has been achieved by frequency feed back, which is compared with a frequency reference. The error signal modifies the firing angle of thyristors, connected in a bridge formation. The thyristor bridge rating is equal to the rating of the main load. The voltage control has been achieved by excitation control. (Ref fig 2 a)

In an another control scheme [5] Fig. 2.b , the frequency feedback control switching of 4 nos. of auxillary loads, whose capacities are in the ratio of 1, 2, 4 and 8. In thisway, the auxillary load becomes a 15-step load. For a 3-phase system, three identical load controllers may be used, each comprising of 3 loads in the ratio of 1:2:4. The above three controllers are co-ordinated to obtain 21 step load switching. The above controller keeps the frequency of the generator constant and at the same time maintains phase balance.

The present thesis, in Chapter 2 describes the design of an electronic controller which uses frequency feed back to control a 4-step load, where the loads need not be of definite capacities. The only restriction is that the maximum capacity of any step load be less than the capacity of a continuously variable 'phase load', which is also the part of the auxillarly load. The 'phase load' is controlled by the sum of the frequency error signal and

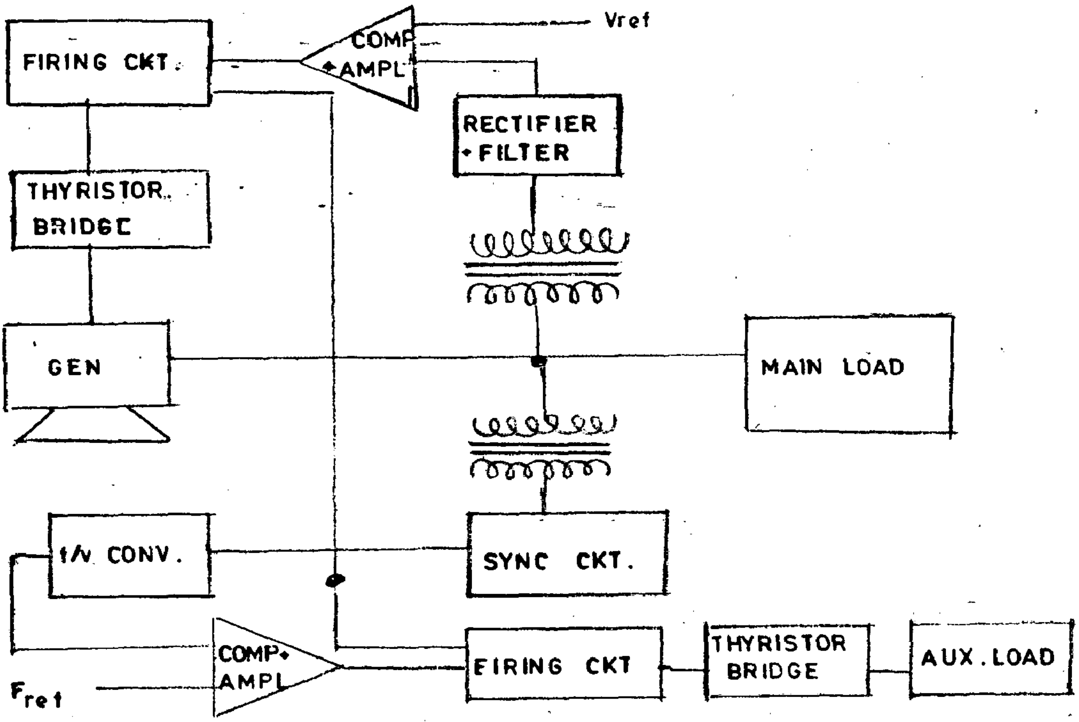


FIG.2a_CONTROLER SCHEME WITH EXCITATION CONTROL

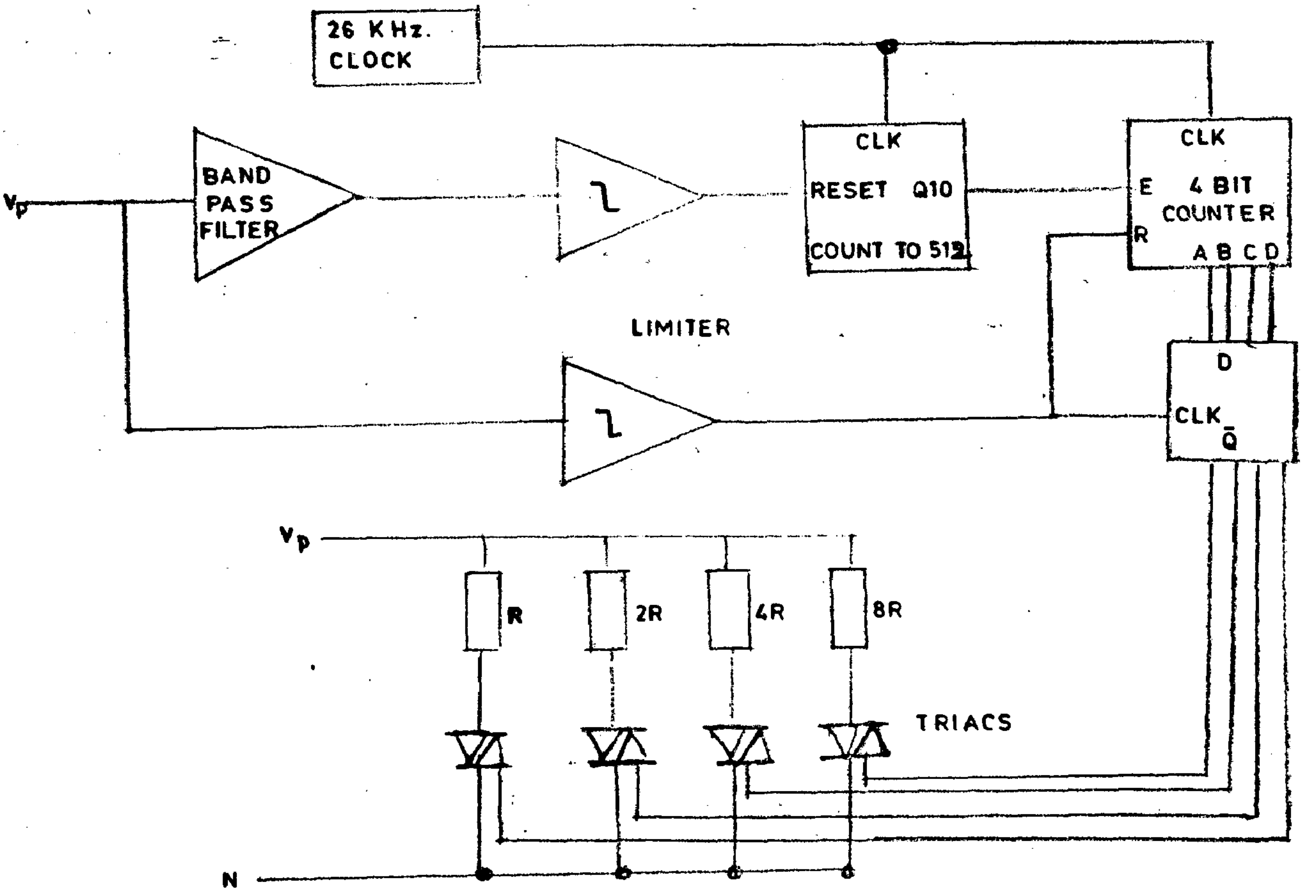


FIG. 2 b - CONTROL SCHEME WITH AUXILLARY LOAD IN THE RATIO OF 1, 2, 4, 8

FIG. 2_ CONTROL SCHEME.

current error signal. It can be seen that low priority useful loads can be connected as 'step loads', provided the maximum current drawn is less than the capacity of 'phase load'. The above controller also takes care of imbalance on generator which is equal to the 'phase load' capacity.

Chapter 3 includes the fabrication details and the test results, when the controller was tried on a 6 KW micro hydel test rig. The controller was tested on resistive loads, for frequency regulation and correction of unbalance in the main load. The controller was also tested for dynamic behaviour for load throw off and sudden application of main load.

Finally, Chapter 4 includes conclusion of the work done and the suggestion for future work.

CHAPTER 2

ELECTRONIC CONTROLLER

An electronic output controller has been developed for diverting the surplus energy, which is the difference between the input energy and the load requirement at any instant to a buffer load system.

The microhydro system design has been made such that the energy out put of the turbine shall not exceed the rated output, which has been achieved by holding the head constant on the turbine by suitable design of the intake system.

The electronic controller thus keeps the electrical load on the generator constant thereby eliminating the need of mechanical or electro-hydraulicgovernor. The performance of the electronic output controller has been tested on a synchronous generator. The electronic controller thus keeps the electrical load on the generator constant thereby eliminating the need of mechanical or electro-hydraulic governor. The performance of the electronic output controller has been tested on a synchronous generator.

2.1 DESIGN CRITERIA

The magnitude of main load (most priority load) on the generator is variable from zero load to full load. The difference in power output available at generator terminals and the main load is diverted to an auxiliary load system (less priority load). This auxillary load should be a variable load so that the surplus power not being utilised in the main load may be transferred to it according to the instantaneous demand. It is necessary, therefore, that auxillary load has a power rating equal to that of the generator power rating. The way to control the magnitude of power flow into the auxillary loading system is by varying the biasing of the grid of a thyristor (by control of firing angle).

The use of tyristors to obtain 0 to 100% variation in auxiliary loads leads to distortion in supply voltage and current wave forms, and harmonic generation for all firing angles being most acute at 90°. At 0° and 180° firing angle, the above mentioned problems are not present. Therefore, practically for all time the above problem will exist if the total variation in auxiliary load is to be taken care through the thyristor firing. These problems may be overcome to a great extent if the capacity of the auxiliary load to be varied by the variation in firing angle is reduced. This can be achieved by providing discrete switched loads together with continuously variable load, so that when the variable load is exhausted or has reached full capacity power can be diverted to the discrete auxiliary load through thyristors firing at 0° crossing. Hence, there should be two types of auxiliary loads :

1. Variable load which may be used as fine control
2. Discrete switched load which may be used as coarse control

The discrete load can be further divided into smaller steps, which can also be assigned a priority for unambiguous operation of the system. For simplicity here the variable auxiliary load has been named as 'phase load' and discrete switched auxiliary loads has been named as 'step loads'.

2.1.1 Selection of Phase Load and Step Load :

For selecting the capacity of the phase and step load the following two points have been considered :

1. The phase load should always be more than the permissible unbalance loading which may occur in the system.
2. The individual step loads should always be less than the phase load. Otherwise, if the step load is more than the phase load the system may oscillate.

2.1.2 Advantages of Phase and Step Load Scheme :

(i) Reduced distortion in voltage and current wave forms, harmonics and radio frequency interference is obtained with the use of phase and step loads.

(ii) Auxilary loads may be used at number of distinct useful destinations.

2.2 CONTROL SCHEME

The control scheme can be divided into three parts broadly :

1. Frequency Control Scheme
2. Current Control Scheme
3. Voltage Control Scheme

2.2.1 Frequency Control Scheme :

In the scheme shown in Fig. 2.1, the frequency is sensed through a step down potential transformer T_4. This system frequency is converted into proportionate voltage by f/V converter and compared with a reference frequency signal in the comparator. If the system frequency is more than 50 C/s the signal Δf will cause increase in auxilary load on the generator, where as if the system frequency is less than

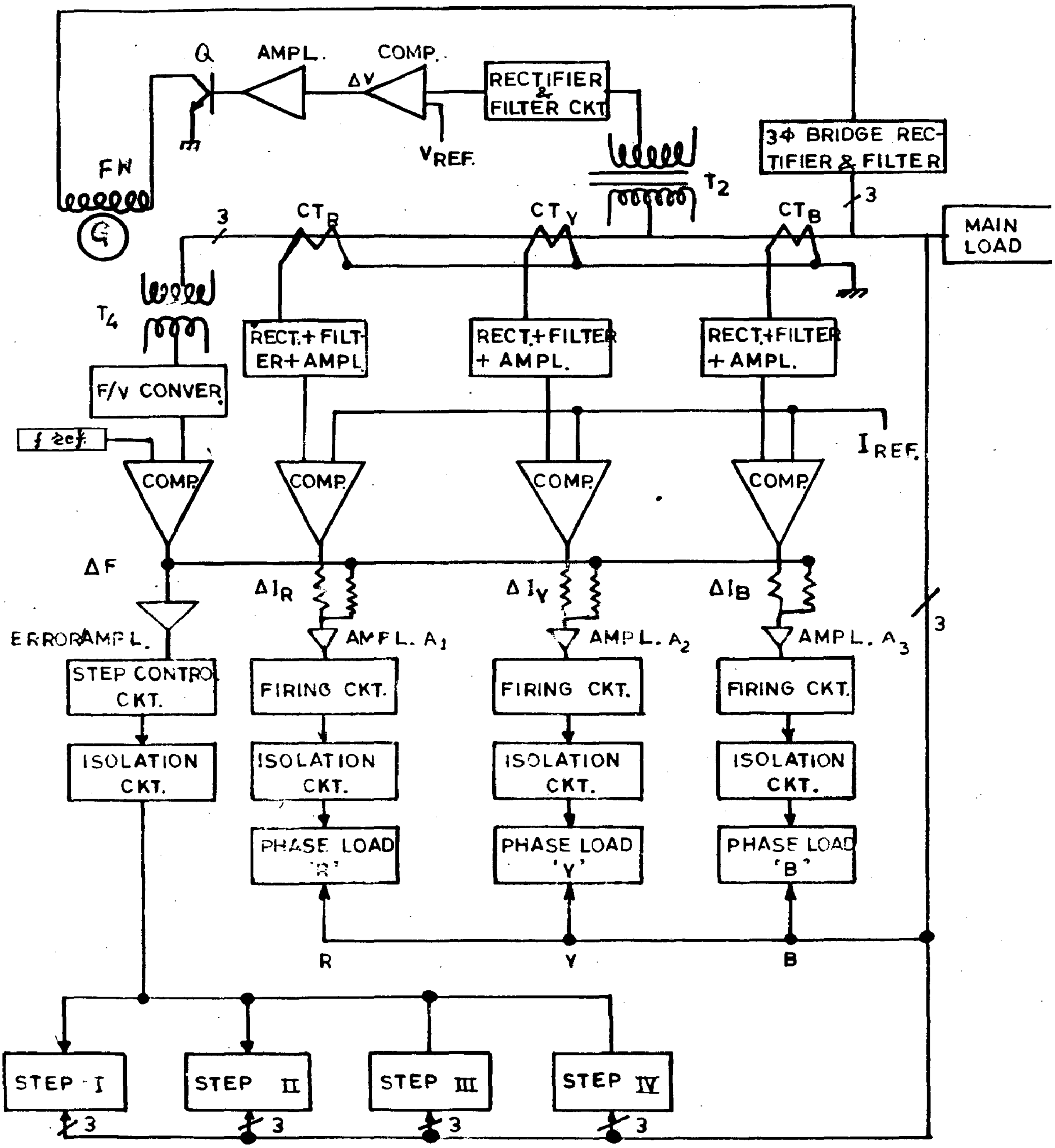


FIG.2·1-CONTROL-SCHEME

the reference 50 C/s, signal Δf will cause reduction in auxilary load on the generator. Thus the system is maintained at constant reference frequency. The increase or decrease of auxillary load can be arranged through the Firing circuits and step control circuits for phase load and step loads respectively.

2.2.2 Current Control Scheme :

It has already been mentioned that the main load on the system is unpredictable. At the same time, it is quite likely that the load in all the three phases may not be balanced. It means that the current in each phase due to unbalanced loading will not be equal. Therefore, to maintain same current in all the three phases i.e. to keep the balanced load on the system it is essential to sense the current in each phase. In this scheme, the current in each phase has been sensed through current transformers CT_R, CT_Y, CT_B. This signal is amplified, rectified and filtered. Then it is compared in a comparator seperately for each phase with a common reference for total load on generator. In this way, the error signals ΔI_R, ΔI_Y and ΔI_B for each of the three phases is obtained. The error signals of a phase act upon the Firing circuits only to keep the current in the respective phase equal to I ref.

Thus the current scheme takes care of the unbalance in the main load by reducing or increasing the phase load individually for each phase.

For the control of Firing circuits of phase load the frequency error signal Δf has been combined with current error signals ΔI_R, ΔI_Y, and ΔI_B in amplifiers A_1, A_2 and A_3 respectively. The combined error signal controls individual Firing circuits for phase load. The ratios of resistors at the input of amplifiers have been chosen so that frequency error signal is more predominant as compared to current error signals. Therefore, phase loads are driven essentially by f. The current error signals merely take care of the unbalance only when Δf is small.

2.2.3 Voltage Control System :

The voltage control scheme may be used to maintain the terminal voltage of the generator. In this scheme the terminal voltage is sensed through a step down potential transformer T_2 which is rectified, filtered and then compared with a reference voltage in the comparator. The error signal ΔV is amplified and used to control the conduction of transistor Q. The d.c. voltage for the field winding may be obtained from the main bus through a 3 phase bridge rectifier circuit as shown in Fig. 2.1.

The voltage control scheme essentially takes care of reactive loading on the generator. When the generator is loaded by inductive load, the output voltage falls more than normal, because of field weakening. Hence, the error signal ΔV will increase conduction of Q, to increase the field current. Similarly, when the loading is capacitive on the generator, the generator voltage increases on loading, which is brought down to normal by reducing the field current.

However, the voltage control scheme has not been used in the controller developed.

2.3 CIRCUIT DETAILS

Essentially the circuits of the Controller developed may be categorised as :

(1) Power circuit

(2) Control circuit

2.3.1 Power Circuit Description :

The power circuit is shown in Fig. 2.2. The output of the generator is connected directly to R, Y, B and N terminals as shown. Capacitor C_1, C_2 and C_3 and inductance L_1, L_2 and L_3 have been used to suppress the rf noise. CT_1, CT_2, CT_3 have been used to sense the current in each phase. Seperate Bus bar foreach phase and for neutral has been used

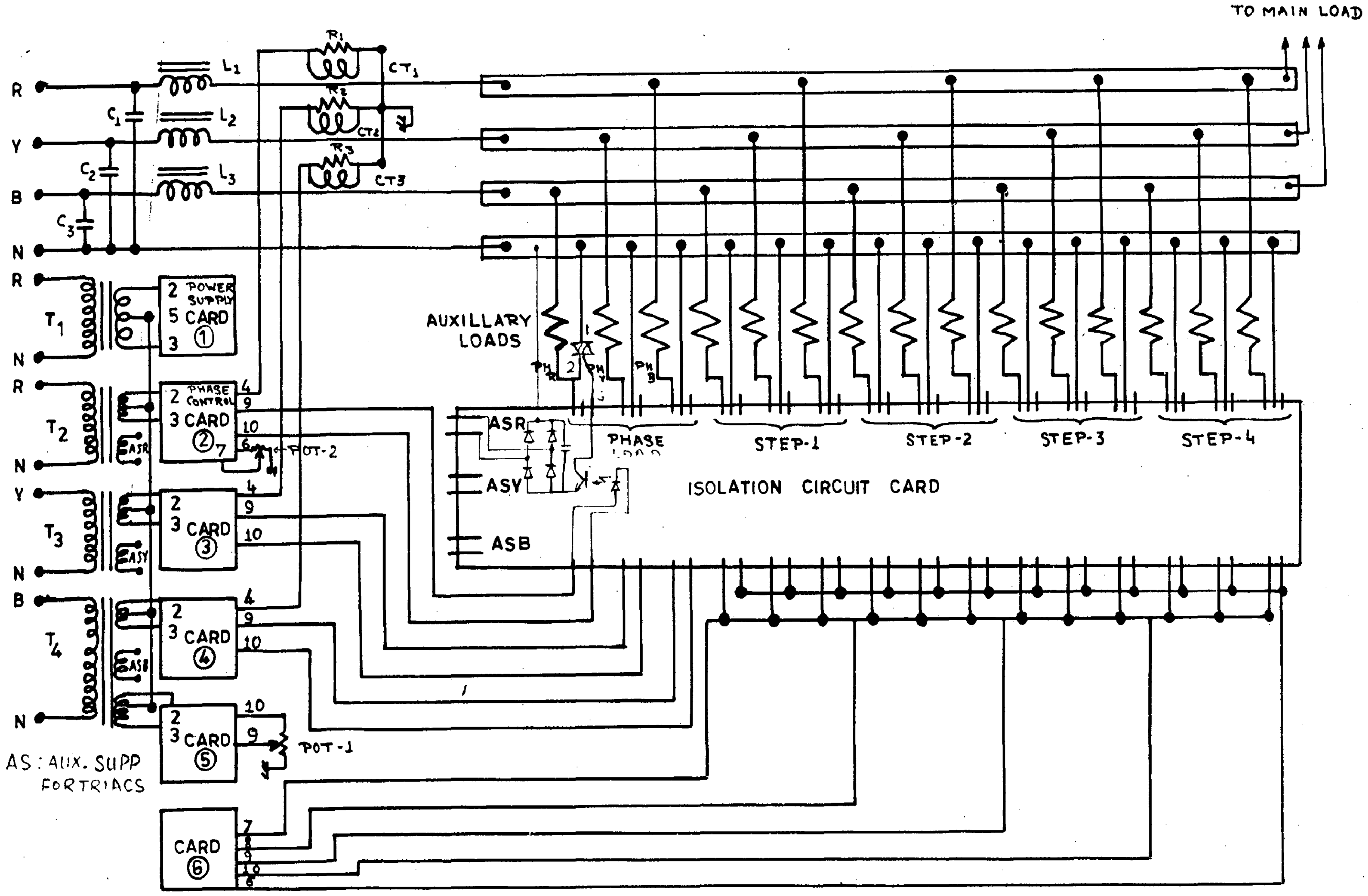


FIG.2·2- POWER CIRCUIT DIAGRAM OF THE CONTROL CABINET to provide the connections to main loads and auxilary loads. Four step down transformers have been used. Transformer T_1 has been used for power supply for the entire electronic circuits. T_2, T_3 and T_4 have been used for synchronizing circuit and to feed the auxilary supply for traic isolation circuit. T_4 has been provided with one extra secondary winding for sensing the frequency of the system. The firing pulses generated in the phase control cards and step control cards are fed to the triacs through optocouplers used for isolation. 15 triacs have been used out of which 3 have been used for phase loads ; one for each phase. The other 12 triacs have been used for four 3-phase step loads.

One of the main problem with triac control is the sudden application of reverse voltage across the triac immediately after it has stopped conduction. This problem is quite serious with highly inductive loads where the current flows for a longer duration in each half cycle for the same firing angle. The high reapplied dv/dt can turn 'ON' the device and so the phase control will be lost. To avoid this maloperation, RC snubber circuit is connected in parallel with traic. This will slow down the rate of change of voltage applied to the triac The snubber circuit recommended as per manufacturers data sheet for the triacs have been used.

2.3.1.1 Design of power circuit :

The Controller is suitable for any size of capacity of synchronous generator under the range of Micro hydel sets. But as the facility available for testing in the lab. is limited to 7.5 KVA, the controller power circuithas been designed for 7.5 KVA sets. Using the same approach, the power circuit for any other capacity can be designed. The control circuit more or less will remain the same.

Selection of current transformer :

Since the controller has been developed for 7.5 KVA sets, the normal full load current will be about 10.5 Amp. Therefore, the current transformers have been selected with the ratio 25:5 having VA burden of 5 VA which were locally available. The secondary of the CTs is shorted by a resistance and the voltage across this resistance will represent the main current. The output of all the three CT's were equalised for the same current by suitably selecting the resistances across each of the CT terminals. While selectingthe resistances connected across CT secondary terminals it was ensured that the VA burden of the CT's does not increase. So as to give the linear output for the required range. The resistance value can be calculated as under :

$$\text{CT Ratio} = \frac{I_p}{I_s}$$

where I_p is the primary current,

I_s is the secondary short circuited current

VA burden of CT : 5 VA

Hence, the maximum value of Resistance may be given by,

$$R = \frac{VA}{(I_s)^2}$$

This limits the value of resistance to 0.2 Ohms. Resistance of value less than 0.2 ohms has been used. The output voltage readings are given in Table 1 and curve shown in Fig. 2.3 gives the linear operation for required range.

TABLE 1 :

Sl. No.	Generator load current (I_p) in Amp.	CT output across resistance in m Volts
1.	0.7	22.7
2.	1.5	45.1
3.	2.0	69.3
4.	2.8	85.2
5.	3.5	114.0
6.	4.2	132.0
7.	5.0	161.0
8.	5.6	185.0
9.	6.4	208.0
10.	7.1	232.0
11.	7.8	255.0
12.	8.5	278.0
13.	9.3	300.0
14.	10.0	322.0
15.	10.6	344.0
16.	11.4	367.0

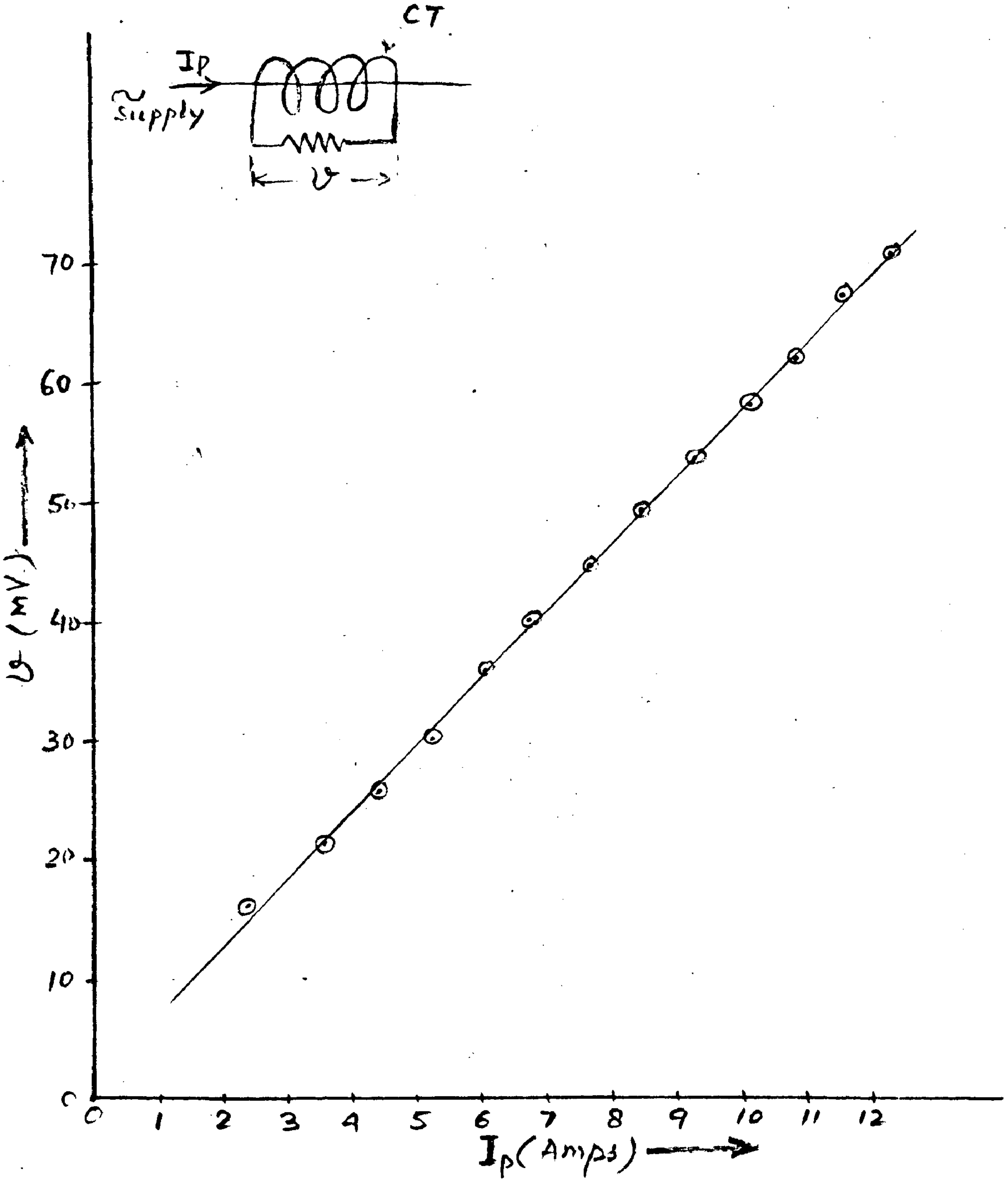


FIG 2·3 TESTING OF CURRENT TRANSFORMER

2.3.1.2 Rating of phase and step load :

The auxilary load has a phase load and four step loads. Phase load has been selected as 750 Watt each phase where as the step load has been selected as 500 Watt each phase. The total auxilary loads thus are given as :

$$\begin{aligned} \text{Auxilary Load} &= (\text{Phase load}) + (\text{Step loads}) \\ &= (750 \times 3) + (500 \times 3 \times 4) \\ &= 2250 + 6000 \\ &= 8250 \text{ watts} \end{aligned}$$

which is more than the capacity of the generator. Hence it can adequately handle the zero main load condition.

2.3.1.3 Selection of traic :

Traics have been used to supply power to the phase and step loads. Phase loads are 750 watts each phase. Therefore, taking the normal phase to neutral voltage as 230 V the load current I may be calculated as :

$$\begin{aligned} I &= \frac{750 \text{ W}}{230 \text{ V}} \\ &= 3.26 \text{ Ampers} \end{aligned}$$

The traic selected has the following specifications :

1.	No. and Make	SC 140 M GE make body isolated
2.	Repeatitive Peak of State voltage at case temperature - 40°C to 100°C	600 V

3.	Max RMS on State current	6.5 Amp.
4.	Max case temperature at rated RMS current	80°C
5.	dv/dt at rated peak off state voltage and case temperature 100°C	100 V/µsec.
6.	Max required d.c. gate current to trigger at Trigger voltage 12 V	50 m Amps
7.	Maximum ON state voltage at 6.5 amps.	1.7 volts

Max. Peak inverse voltage across triac at

$$300 \text{ V main} = 300\sqrt{2}$$

$$= 420 \text{ V}$$

Taking a safety factor of 1.5, PIV rating of traic should be about 600 volts. Triac has to deliver 3.26 amps. Taking a safety factor of 1.5, the triac rms current rating should be 4.8 amps. Hence SC 140 M with a current rating of 6.5 amps. at the case temperature of 80°C is adequate.

2.3.1.4 Heat sink design :

Power dissipation in triacs at 4.8 amps

$$= 4.8 \times (\text{Max. on state voltage})$$

$$= 4.8 \times 1.7$$

$$= 8.16 \text{ watts}$$

Considering maximum ambient temperature	40°C
Case temperature of Traic	80°C

Thermal resistance of triac heat sink should be less than,

$$\frac{80 - 40}{8.16} = 4.9^{\circ}C/W$$

AFCOSET make type 60 NI - series 50 mm length will be edeque for the purpose.

2.3.2 Control Circuit Description and Design :

Functionally the control circuit has been divided into the following individual circuits :

- Power supply
- Phase control
- Frequency control
- Step control

Each of these circuits are discussed in the following sections :

2.3.2.1 Power supply :

A regulated power supply has been designed for the entire control circuit as shown in Fig. 2.4. A centre tap transformer T_1 is used to step down the input voltage to a suitable level. The output a.c. voltage from the secondary of the transformer is rectified through a bridge circuit (diodes D_1 to D_4). Capacitor C_1 and C_2 have been used for filtering the rectified output. Thus unregulated d.c. positive

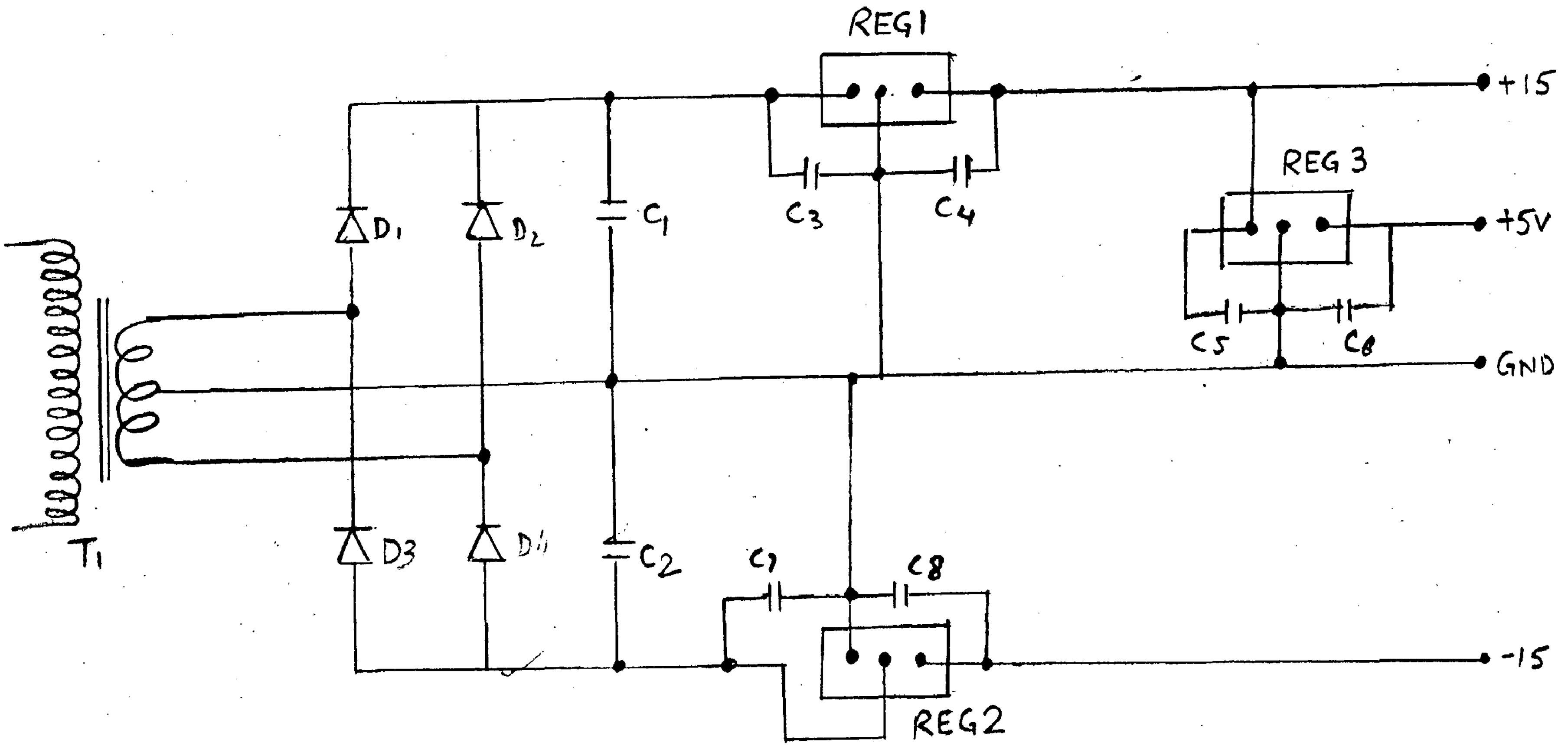


FIG. 2.4 POWER SUPPLY CIRCUIT

and negative with respect to a common ground has been obtained. Three pin regulators REG-1 and REG-2 have been used to get the regulated output of +15 volts and -15 volts respectively. REG-3 has been used to get +5 volts supply. The input to the REG-3 has been taken from the regulated positive d.c. output of REG-1. As recommended by the manufacturers data sheet the capacitors at the input and output of the regulators have been used.

2.3.2.2 Design of power supply :

The power supply designed has the following ratings :

Input voltage	180 - 300 volts
Output voltage	+ 15 volts/400 mA
	- 15 volts/500 mA
	+ 5 volts/100 mA

In the design of a d.c. power supply one has to start from the rating at the input of the regulator and work back the d.c. and a.c. quantities at various points to determine the ratings and design of transformer, rectifier, filter and regulator. The regulators used are 7815 and 7915 for + 15V and - 15Volts respectively. The maximum input limit to the regulators as per manufacturer's data sheet is 35 V.

2.2.2.3 Transformer design :

To find out the normal secondary output voltage of the transformer, let us assume :

V_N Output voltage of transformer secondary at 230V

V_M Output voltage of transformer secondary at 300V

$$V_N = V_M \times \frac{230}{300} \text{ Volts (RMS)} \quad \ldots \quad (1)$$

Capacitor filter has been used. Therefore, neglecting the drop in rectifier circuit we can find out the filter output V_F for the worst condition i.e. at 300 volts.

$$V_F = \sqrt{2}\, V_M \text{ volts} \quad \ldots \quad (2)$$

As the regulator input or the filter output should not exceed 35 volts, therefore, we can work out V_M from Eq.2.

$$V_F = 35 \text{ V}$$

$$V_M = \frac{V_F}{\sqrt{2}}$$

$$= \frac{35}{\sqrt{2}} = 24.7 \text{ volts}$$

From Eq. 1,

$$V_N = 24.7 \times \frac{230}{300}$$

$$= 18.9 \text{ volts}$$

Hence, the transformer secondary output at normal system voltage of 230 volts should not exceed 18.9 volts. Therefore, the secondary output of the transformer has been selected as 18 - 0 - 18 volts at 230 volts.

The minimum generated voltage for which the power supply ensures reliable operation has been taken as 180 V. Calculating again the transformer secondary output at 180 volts mains,

$$V = \frac{18 \times 180}{230}$$

$$= 14.08 \text{ volts} \quad \text{(RMS)}$$

Filter output or the regulator input

$$= 14.08 \times \sqrt{2}$$

$$= 19.92 \text{ Volts}$$

which leaves a drop of 4.9 volts across the regulator. Hence, the power supply will function reliably for mains variation from 180 to 300 volts.

Current rating of the power supply is 500 mA for positive and negative outputs.

Power output of transformer secondary Ps is given by

$$P_s = 500 \times 10^{-3} \times 18 \times 2$$

$$= 18 \text{ watts}$$

Considering 80% efficiency of transformer, input power Pi of the transformer required is given by,

$$Pi = \frac{18}{0.8}$$

$$= 22.5 \text{ watts}$$

The maximum current in the primary of the transformer to meet out the power required as calculated above, will be at minimum voltage, i.e. at 180 V.

$$\text{Primary current} = \frac{22.5}{180}$$

$$= 0.125 \text{ Amps.}$$

Hence the transformer selected shouldhave the following ratings.

Input 180 - 300 Volts/0.125 Amps.

Output 18 - 0 - 18 Volts/500 mAmps.

2.3.2.4 Rectifier design :

Bridge configuration has been used for rectifier circuit, and the power supply has been designed for 500 mA. The maximum diode current, therefore, will be half the load current i.e. 250 mA.

Vp Maximum peak voltage at transformer secondary output at 300 Volts input is given by,

$$V_p = \sqrt{2} \cdot \frac{18 \times 300}{230}$$

$$= 33.2 \text{ Volts}$$

Maximum peak inverse voltage for diode is given by,

$$= 2 V_p$$

$$= 2 \times 33.2$$

$$= 66.4 \text{ Volts}$$

Hence the diode selected should be able to withstand peak inverse voltage of 66.2 V and can deliver current 250 mA.

Diode IN4002 selected has peak inverse voltage of 100 volts and current rating 1 amp. and hence can serve adequately.

2.3.2.5 Filter design :

For full wave circuits driven by a line frequency of 50 Hz. The time period T is given by :

$$T = \frac{1}{f} = 20 \text{ mSec.}$$

$$\text{Period of half cycle} = \frac{T}{2} = 10 \text{ mSec.}$$

If the discharge time of the capacitor through load is kept more than 10 times of T/2, following approximation[14] may be used for full wave peak rectifieres.

$$\gamma = \frac{0.24}{CR_L}$$

where,

γ is the percentage ripple factor

R_L is load resistance in Ohms

C is capacitance used for filtering in ufd.

Considering the maximum load current 100 mA.

$$R_L = \frac{15}{100 \times 10^{-3}}$$

$$= 150 \text{ Ohms.}$$

Now, if 1000 ufd capacitor is used,

$$r = \frac{0.24}{1000 \times 150 \times 10^{-6}}$$

$$= 1.6\ \%$$

The rippile of the order of 1.6% is sufficiently low and it will be further reduced by the regulator. Hence capacitor of 1000ufd/50V is adequate.

2.3.2.6 Regulator selection :

Three pin regulators 78 and 79 series for positive and negative voltage respectively have been used and are redily available with the following specifications as per manufacturers data sheet.

Sl.No.	Code	Max.Input Voltage V	Max. Output Current Amps.	Output Voltage	Operating Temp. Range
1.	7805	35	0.5	+ 5V	0 to 70 C
2.	7815	35	0.5	+15V	0 to 70 C
3.	7915	-35V	0.5	-15V	0 to 70 C

2.3.2.7 Phase control :

It has been stated earlier, that the phase load is a variable auxillary load which provides fine (smoothly variable) control by using the firing angle α to keep the total load on the generator constant, when the main load changes. The

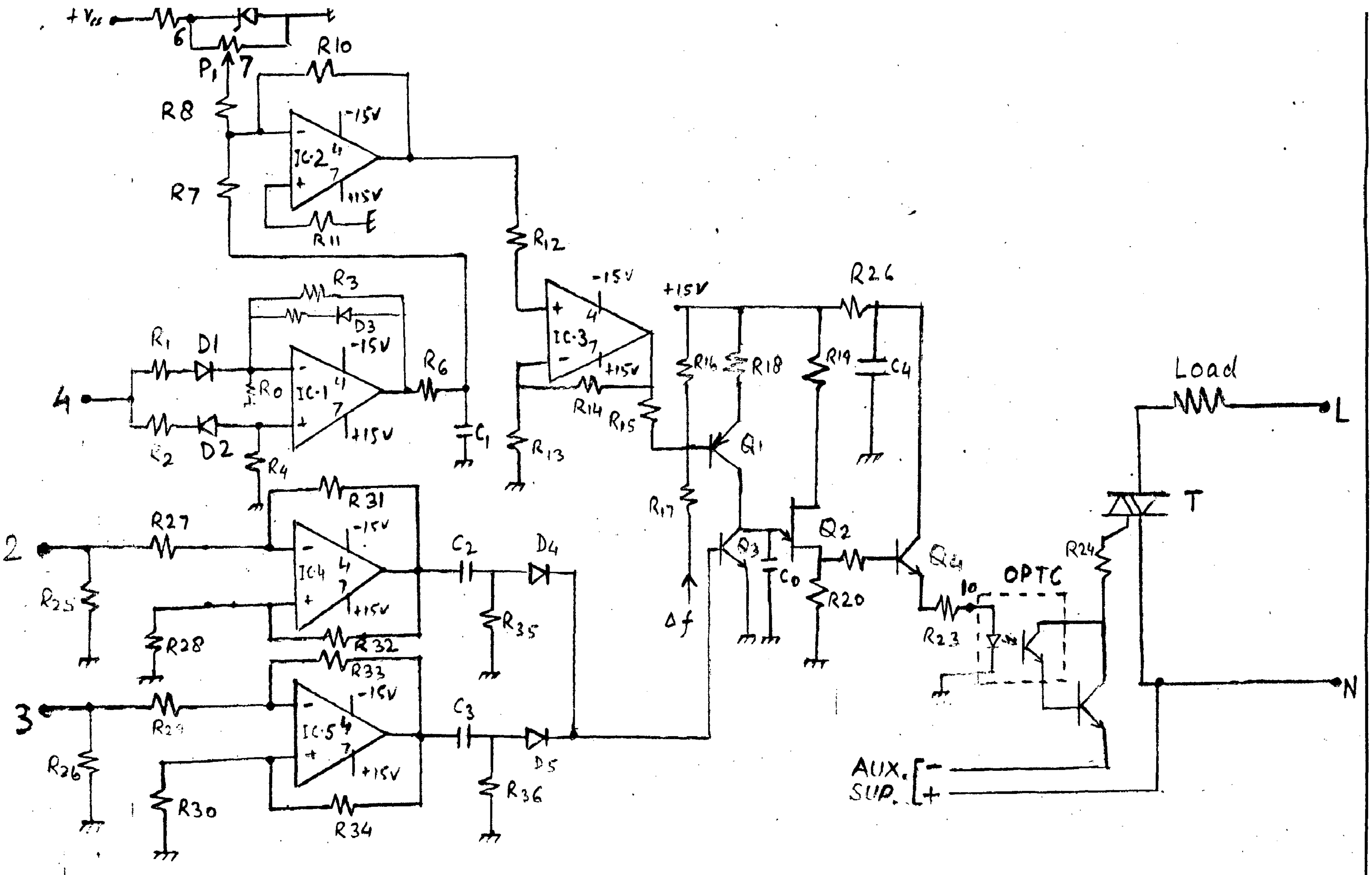


FIG. 2·5 PHASE CONTROL

circuit diagram for phase control is shown in Fig. 2.5. The entire phase control is obtained by the sum of frequency error signal and current error signals.

The load current in each phase is sensed through current transformers (CT). The a.c. output of CT is fed at terminal 4. This AC signal is rectified and amplified by IC-1 and its associated circuitry. For the positive half cycle of the input signal D_1 is forward biased and D_2 is reverse biased where as for negative half cycle D_2 is forward biased and D_1 is reverse biased. Now as D_1 is connected to inverting and D_2 to non-inverting terminal of IC-1, the amplified output will be negative for both the half cycles. Diode D_3 ensures that the output of IC-1 will not go positive. Averaging of this output signal is obtained by connecting R_6 and C_1 as shown. The wave shapes are shown in Fig. 2.6. Thus a negative d.c. voltage signal proportional to the load current is obtained.

This negative d.c. signal is compared with a positive reference in a comparator (IC-2). Error signal ΔV, is the difference between the reference current and actual current signals.

The error signal ΔV is amplified by a non-inverting amplifier (IC-3). If the load current is less than the

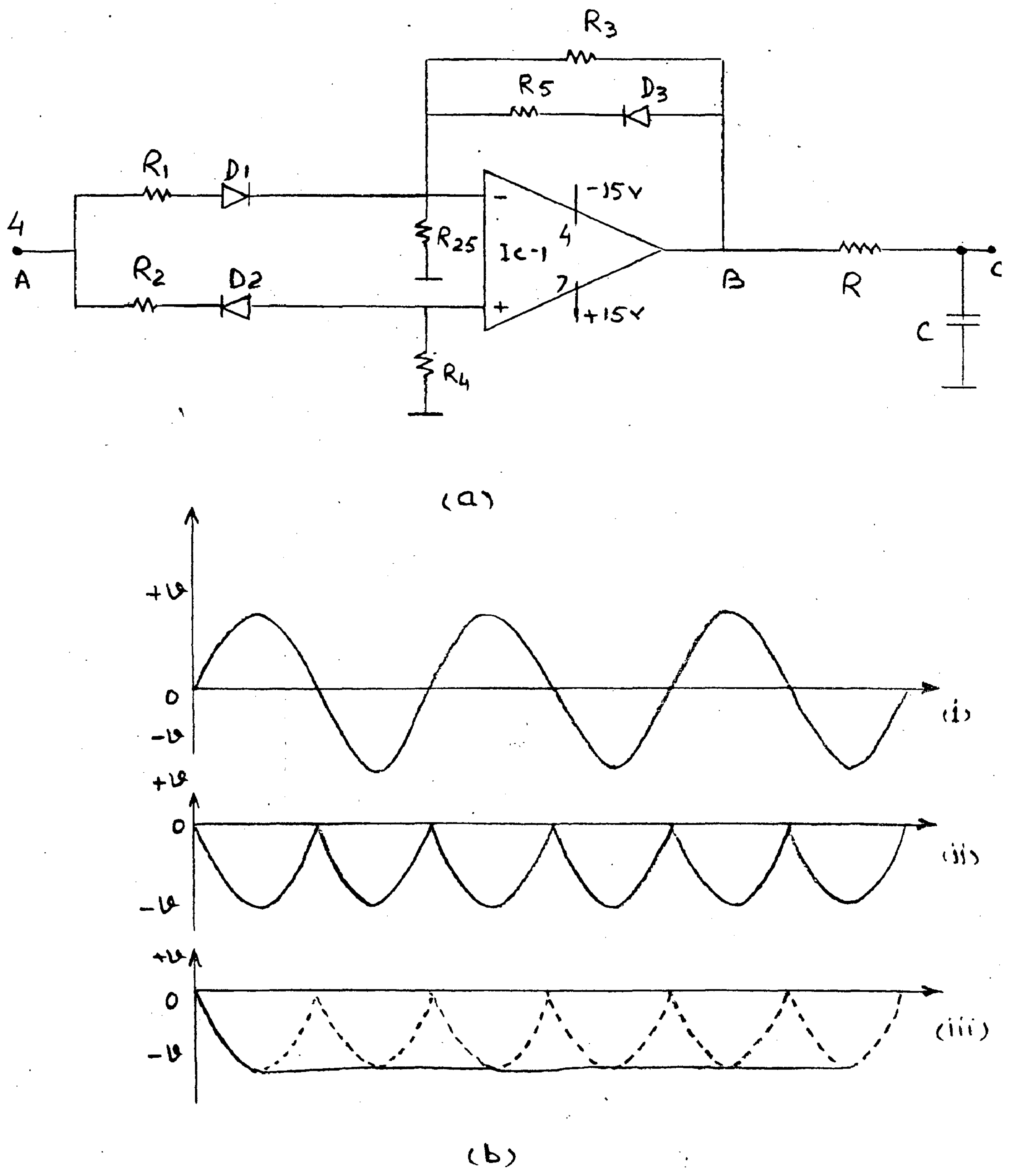


FIG. 2·6 (a) CIRCUIT DIAGRAM FOR CURRENT SIGNAL AMPL.

(b) WAVE FORMS (i) A - INPUT

(ii) B - AMPLIFIER OUT PUT

(iii) C - RAFED OUT PUT VOLTAGE

reference current the amplified error signal is negative and if load current becomes more than the reference the amplified error signal goes positive.

$$V_{c1} = K_1(I_{PH} - I_{Ref}) \quad \ldots \quad (1)$$

where V_{c1} is the voltage which controls the firing circuit due to current feed back.

I_{pH} is the phase current of generator

I_{Ref} is the reference current

K_1 is the net gain of IC-1 and IC-3.

The frequency error signal from the frequency control card is added to the output of IC-3 and the sum of both the error signals (current error signal and frequency error signal) is fed to the firing circuit.

$$V_{c2} = K_2 (f_{ref} - fg) \quad \ldots \quad (2)$$

where, V_{c2} is the control signal from frequency card (explained in the next section)

f_{ref} is the frequency reference

fg is generator frequency

K_2 is the gain of frequency card

Signals V_{c1} and V_{c2} have been summed in the ratio given as below :

reference current the amplified error signal is negative and if load current becomes more than the reference the amplified error signal goes positive.

$$V_{c1} = K_1(I_{PH} - I_{Ref}) \quad \ldots \quad (1)$$

where V_{c1} is the voltage which controls the firing circuit due to current feed back.

I_{pH} is the phase current of generator

I_{Ref} is the reference current

K_1 is the net gain of IC-1 and IC-3.

The frequency error signal from the frequency control card is added to the output of IC-3 and the sum of both the error signals (current error signal and frequency error signal) is fed to the firing circuit.

$$V_{c2} = K_2 (f_{ref} - fg) \quad \ldots \quad (2)$$

where, V_{c2} is the control signal from frequency card (explained in the next section)

f_{ref} is the frequency reference

fg is generator frequency

K_2 is the gain of frequency card

Signals V_{c1} and V_{c2} have been summed in the ratio given as below :

$$\frac{V_{c1}}{V_{c2}} = \frac{R_y}{R_x} \quad [R_y \Rightarrow R_{15} , R_x \Rightarrow R_{17} \text{ Ref Fig. } 2.5]$$

$$= \alpha \qquad (\alpha < 1 \text{ in the present case})$$

$$V_c = \alpha V_{c1} + V_{c2} \qquad \ldots \qquad (3)$$

Here V_c is the total control voltage for the firing circuit substituting for V_{c1} and V_{c2} from Eq. 1 and 2.

$$V_c = \alpha K_1(I_{PH} - I_{vf}) + K_2(f_{ref} - fg)$$

$$= \alpha K_1 \quad (I_{PH} - I_{Ref}) + \frac{K_2}{K_1}(f_{ref} - fg)$$

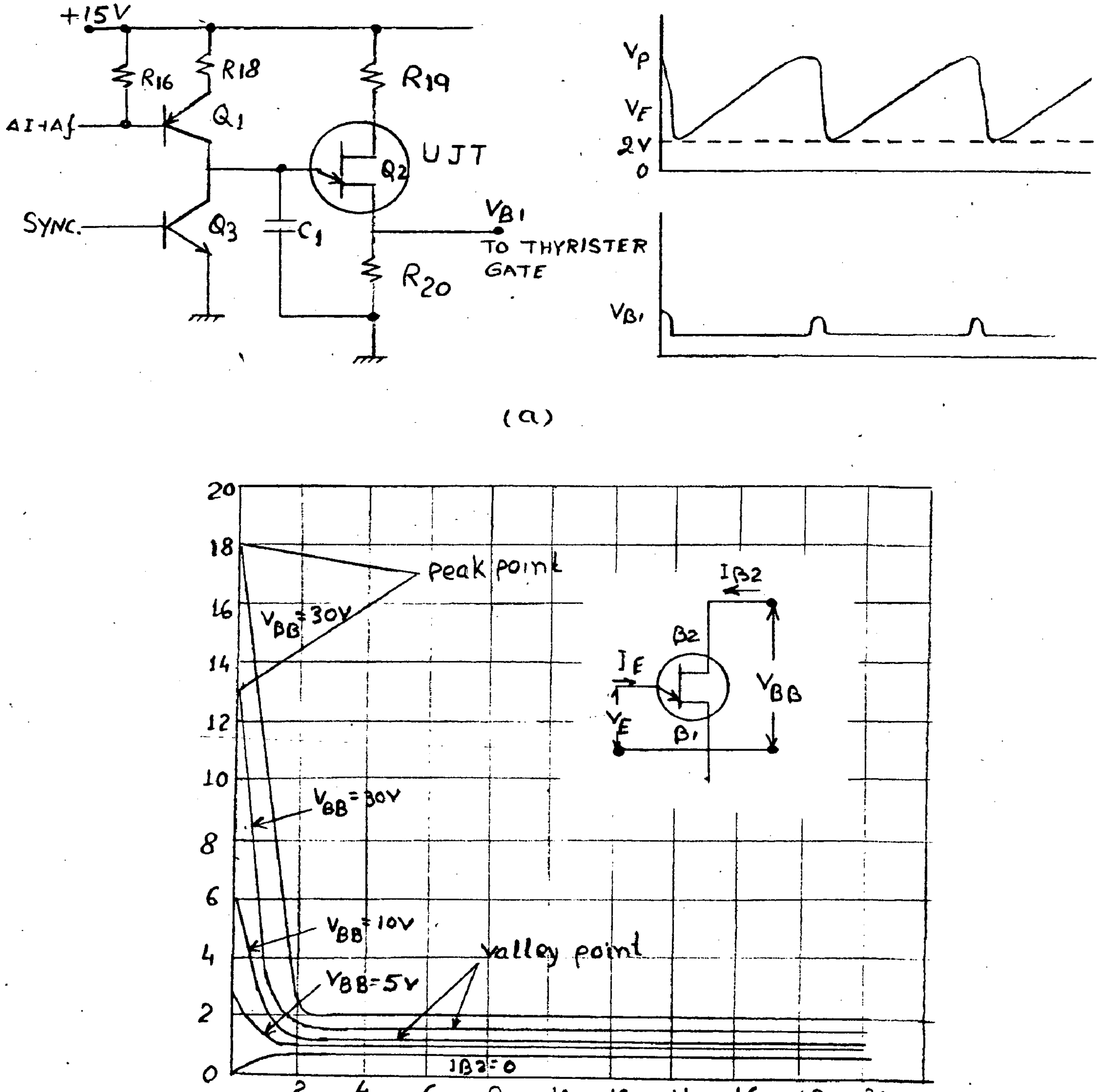
$$= \alpha K_1 \quad (I_{PH}-I_{Ref}) + \beta (f_{ref} - fg) \quad (4)$$

where

$$\beta = \frac{K_2}{K_1}$$

In the present circuit frequency error signal is predominent as the frequency is the main parameter which is intended to be controlled, while current feed back is essentially for balancing the load on generator.

The firing circuit shown in Fig. 2.7 consists of a current source Q_1, a synchronizing transistor Q_3 and UJT (Q_2) being used as relexation oscillator. When the sum of the error signal is less than 15 V, Q_1 conducts and capacitor



(a)

(b)

FIG. 2·7 (a) UJT AS RELAXATION OSCILLATOR TRIGGER CIRCUIT WITH WAVE FOR

(b) UJT 2N2646 SYMBOL AND EMITTER INPUT CHARACTERISTIC

C_1 is charged through R_{18} untill the emitter voltage of Q_2 reaches V_p at which the UJT turns 'ON' and discharges C_1 through R_{20}. When the emitter voltage reaches a value of 2 volts, the emitter ceases to conduct and UJT turns 'OFF' This cycle is repeated and the output pulse of UJT are used for firing the triac. An optocoupler MCT_2 has been used to isolate the electronic control circuit from supply mains in the firing circuit.

Transistor Q_3 used for synchronizing enables the changing of C_1 to start from zero crossing in each half cycle. Thus the duty cycle of the triac is maintained same in both half cycles of the supply frequency.

IC-4, IC-5 and the associated circuitry generates the synchronizing pulses for Q_3 (Ref. Fig. 2.8). IC-4 and IC-5 have been wired as high gain inverting amplifiers with sufficient hysterises to take care of distortion at zero crossing points in the a.c. supply from generator. A.C. supply from the synchronising transformer is fed to the inverting inputs of IC-4 and IC-5. The output of both the comparators are square pulses with a 180° phase difference. These outputs are differentiated by C_2, R_{35} and C_3, R_{36} Thus, for every zero crossing spikes are generated. Diode D_4 and D_5 pass the positive spikes and blocks negative spikes. Now the positive spikes of both are summed and

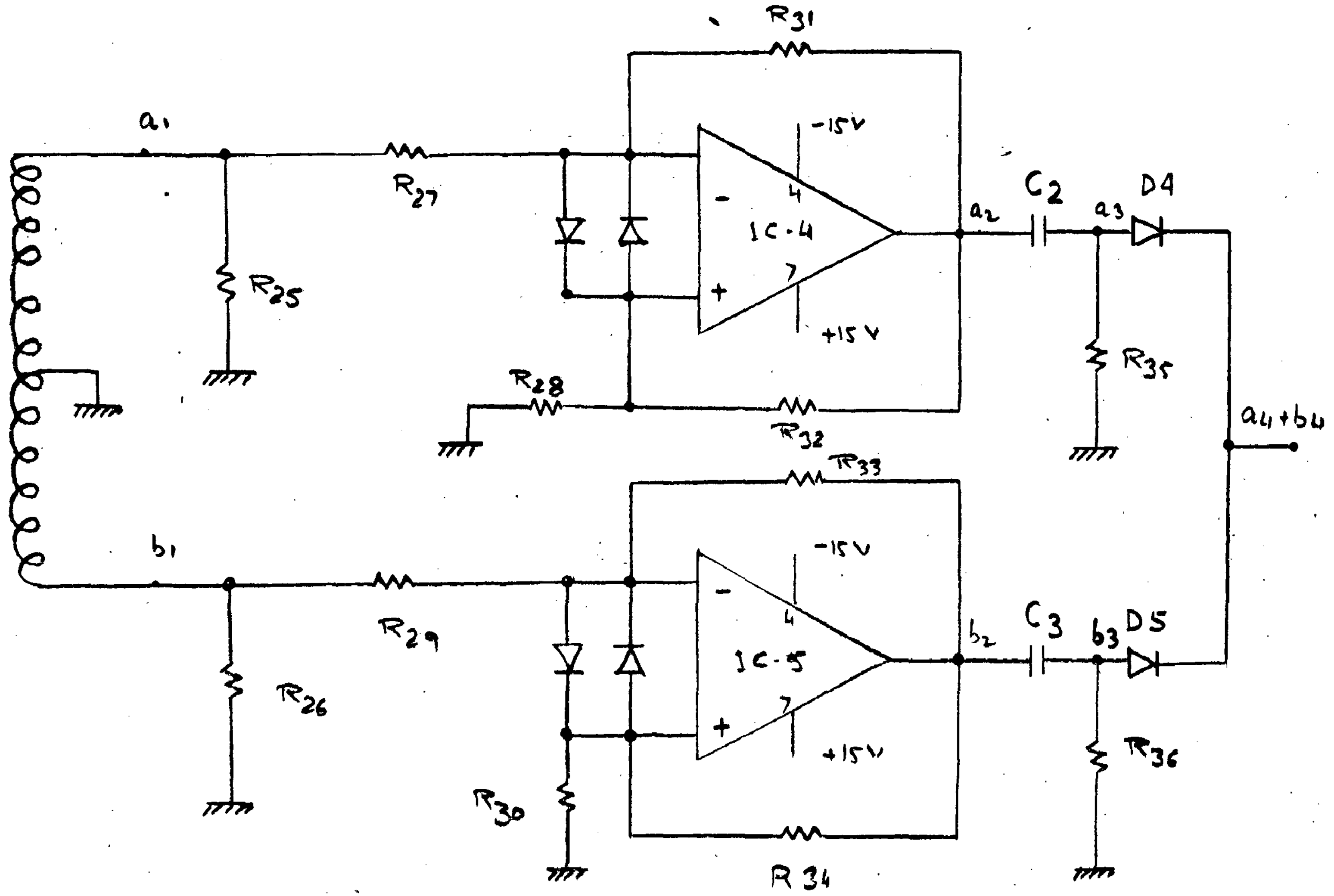


FIG 2.8 SYNCHRONIZING CIRCUIT

thus positive spikes for zero crossings are obtained which is used as synchronising pulses for transistor Q_3. Fig. 2.9 shows the wave forms at different stages. The label a - represents different stages of IC-4 where as b - represents different stages of IC-5.

2.3.2.8 Design of amplifier and rectifier circuit for current (IC-1) : (Ref. FIG 2.5)

Let the reference signal value in comparator (IC-2) be V_{ref}. After amplification and averaging the signal output V_{dc} should be equal to V_{ref} at full load current.

Also,

$$V_{dc} = \frac{2\sqrt{2}\ A\ V_{in}}{\pi} \qquad \ldots \qquad (1)$$

where,

V_{in} is rms input signal from CT
A is gain of IC-1 circuit

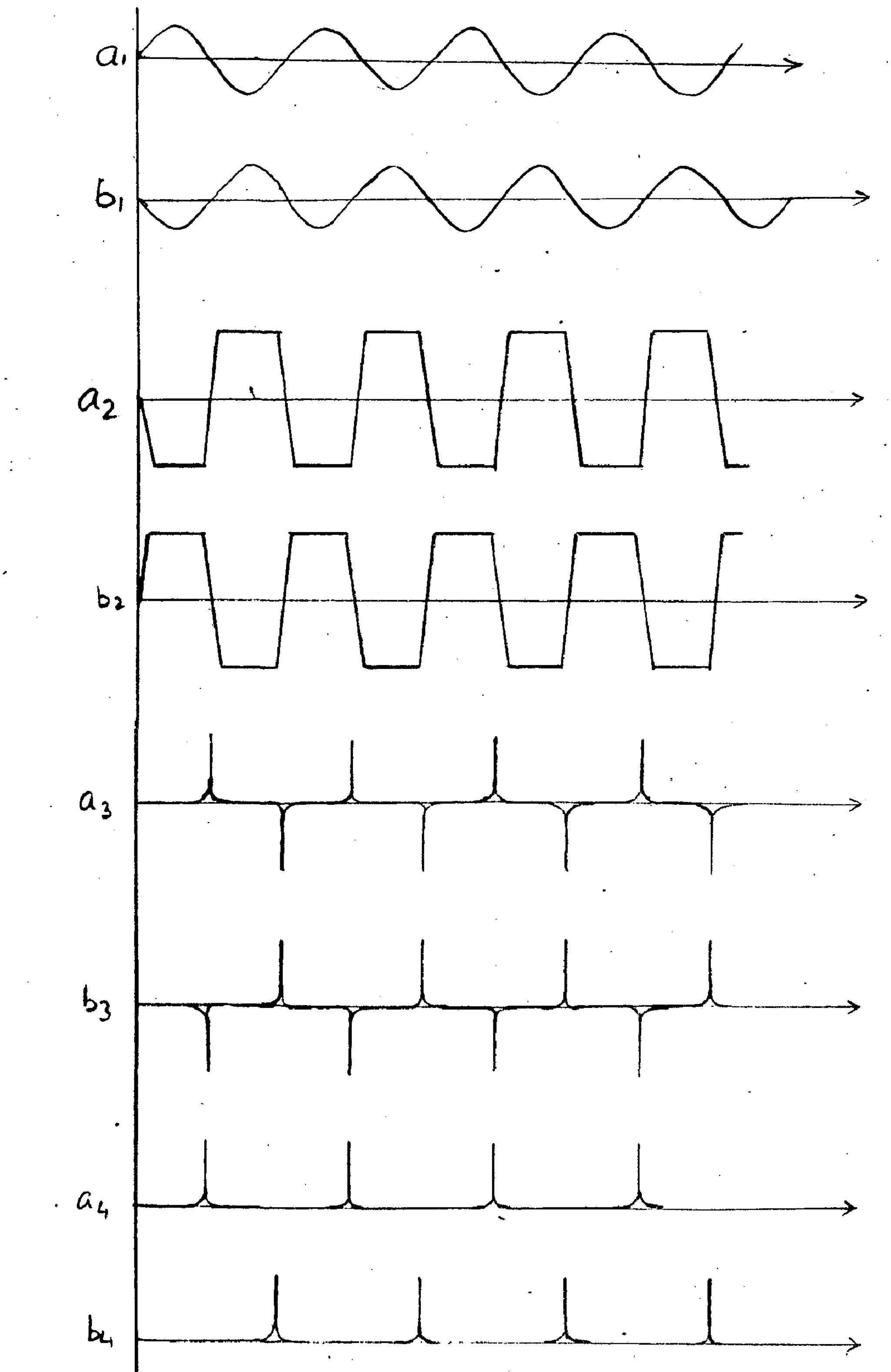
From equation 1,

$$A = \frac{V_{dc} \times \pi}{2\sqrt{2}\ V_{in}}$$

$$= 1.1\ \frac{V_{dc}}{V_{in}} \qquad \ldots \qquad (2)$$

From Fig. 2.3 , the CT secondary voltage across R for full load current of 10.5 amps. is 0.340 volts.

$$V_{ref} = V_{dc} = 5 \text{ Volts}$$



IG 2·9 WAVE FORM AT DIFFERENT STAGES OF SYNCHRONISING CIRCUIT

From Eqn. 2,

$$A = 1.1 \frac{5}{.34}$$

$$= 16.17$$

Hence, the gain of IC-1 has been taken as 15. Further, the amplifier and rectifier circuit should have equal gain for the positive and negative half of the cycles.

The effective circuit for positive half and negative half is shown in Fig.2.9.A.

For positive half cycle :

$$\text{Gain} = \frac{R_3}{R_1} \qquad \ldots \qquad (3)$$

For negative half cycle :

$$\text{Gain} = \frac{R_3}{R_0} + 1 \qquad \ldots \qquad (4)$$

For equal gains for both half cycles

$$\frac{R_3}{R_1} = \frac{R_3}{R_0} + 1 = 15 \qquad \ldots \qquad (5)$$

(15 is the selected gain value)

$$R_3 = 15\ R_1$$

$$= 14\ R_0$$

If the value of R_1 selected is 10 K.

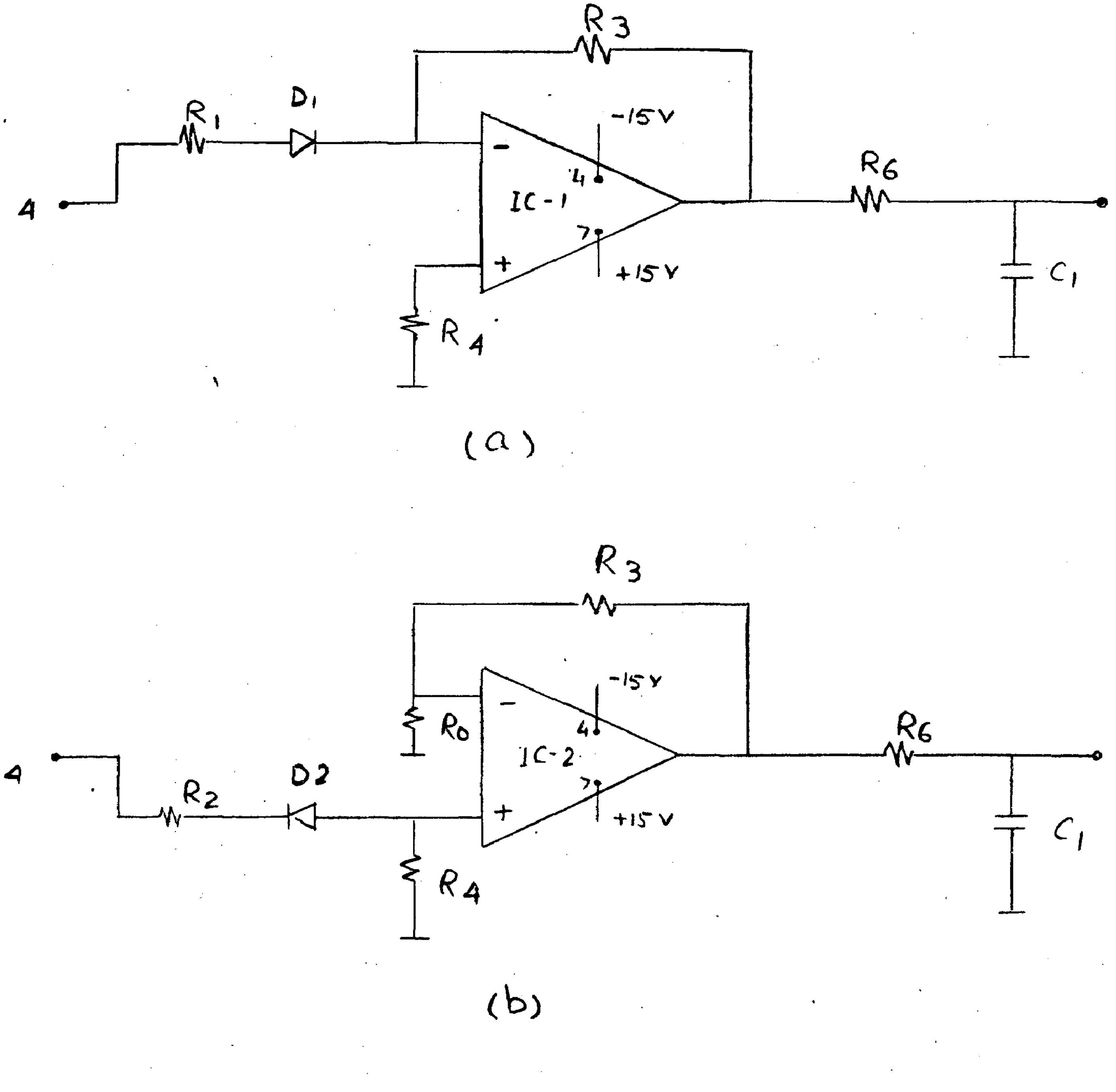


FIG. 2·9. A (a) EFFECTIVE CURCUIT FOR POSITIVE HALF CYCLE.
(b) EFFECTIVE CURCUIT FOR NEGATIVE HALF CYCLE

R_3 = 150 K

R_0 = 10.7 K nearest available value 10K.

The value of R_4 selected is $R_3 \parallel R_0$

= 9.375 KΩ nearest available value 10K

The value of R_2 is to be choosen sufficiently lower than R_4 so that signal attenuation is minimum across R_2. Hence the value of R_2 chosen is 1 K.

For averaging the out put of IC-1, R_6, C_1 has been used. The averaging time constant has been chosen to be greater than 10 times the input signal frequency. In our case, the input frequency for averaging signal Input is 100 C/s i.e. have a time period of 10 mS. Therefore, the value of R_6, C_1 has been taken as given below :

R_6 = 2.2 K

C_1 = 100 u Fd/25V

2.3.2.9 Design of comparator circuit (IC-2 and error amplifier (IC-3) : [REF. FIG. 2.5]

The comparator circuit (IC-2) is a inverting amplifier having unity gain. Averaged output of IC-1 and the reference signal has been given to the inverting terminal of IC-2 through resistances R_7 and R_8 respectively. Resistance R_{10} is connected in feed back loop.

High value of R_7 has been chosen to draw very nominal current from the IC-1 being unity gain amplifier,

$$R_7 = R_8 = R_{10} = 470\ K$$

R_{11} is the parallel combination of R_7 and R_{10}.

$$= 235\ K\ Ohms\ (used\ value\ 220\ K)$$

The error amplifier is a simple non-inverting amplifier having gain of 23. R_{12} = 10 KOhm, R_{13} = 1 KOhm and R_{14} is 22 KOhms.

2.3.2.10 Design of firing circuit :

As per manufacturers data sheet the intrinsic stand off ratio η for 2N2646 lies between 0.51 to 0.86.

Taking n = 0.6 emitter peak point voltage V_p can be calculated given below :

$$V_p = n\ V_{cc} \qquad \ldots \qquad (6)$$

$$= .6 \times 15$$

$$= 9\ volts$$

Hence the current required for charging the capacitor C_D (0.1 ufd) may be found out by,

$$i.\ \Delta t = C_D\ .\ \Delta V \qquad \ldots \qquad (7)$$

where,

i is the changing current

t is the timerequired for changing C_D to 9 V

C_D is capacitor to be charged.

Taking charging time T sufficiently low say as 0.5 m Sec.

From Eq. 7,

$$i \times 0.5 \times 10^{-3} = 0.1 \times 10^{-6} \times 9$$

$$i = 1.8 \text{ m Amps.}$$

This current will be drawn through R_{18}. Allowing V_{CE} = 2 Volts, the voltage drop in R_{18} is required to be,

$$V_{cc} - 2 - V_p = 4 \text{ Volts}$$

$$R_{18} = \frac{4}{1.8 \text{ mA}}$$

$$= 2.2 \text{ KOhm.}$$

As per manufacturers data sheet normal forward current for optocoupler diode is 10 mAmp. max. forward voltage is about 1.2 V. The value of $R_{23} + R_{26}$ can be calculated as under :

$$R_{23} + R_{26} = \frac{V_{cc}}{10 \text{ mA}}$$

$$= 1.5 \text{ K} \qquad (V_{cc} = 15 \text{ V})$$

Hence, the value selected are R_{23}(560 Ohms), R_{26} (1 K) The value of decoupling capacitor will depend upon the time constant of the UJT pulse out put which is given by $R_{20}C_D$.

For selecting the value of C_4

$R_{26} \cdot C_4 > 10 \cdot R_{20} \cdot C_1$

C_4 selected 22 ufd.

(time constant of decoupling capacitor should be greater than 10 times the time of UJT pulse output)

2.3.2.11 Design of synchronising circuit (IC-4 and IC-5) : [REF. FIG. 2.5]

IC-4 and IC-5 have been used as inverting amplifier with high gain (47) with hysterisis as calculated below :

$$= \frac{V_{cc} \times R_{30}}{R_{34}}$$

$$= \frac{15 \times 4.7}{470}$$

$$= .15 \text{ Volts}$$

which means the comparators will take care the input noise of 0.3 volts amplitude. The value for comparator circuit are R_{27} and R_{29} (10 K), R_{31}, R_{32}, R_{33}, R_{34} (470 K), R_{25}, R_{26} (47 K) and R_{28}, R_{30} (4.7 K).

For differentiating the time constant has been taken less one tenth of the input frequency time constant. It has been kept as 40 usec taking the value of R_{35}, R_{36} (10K) and C_2, C_3 (0.04 ufd).

2.3.2.12 Frequency control :

Circuit diagram for frequency control is shown in

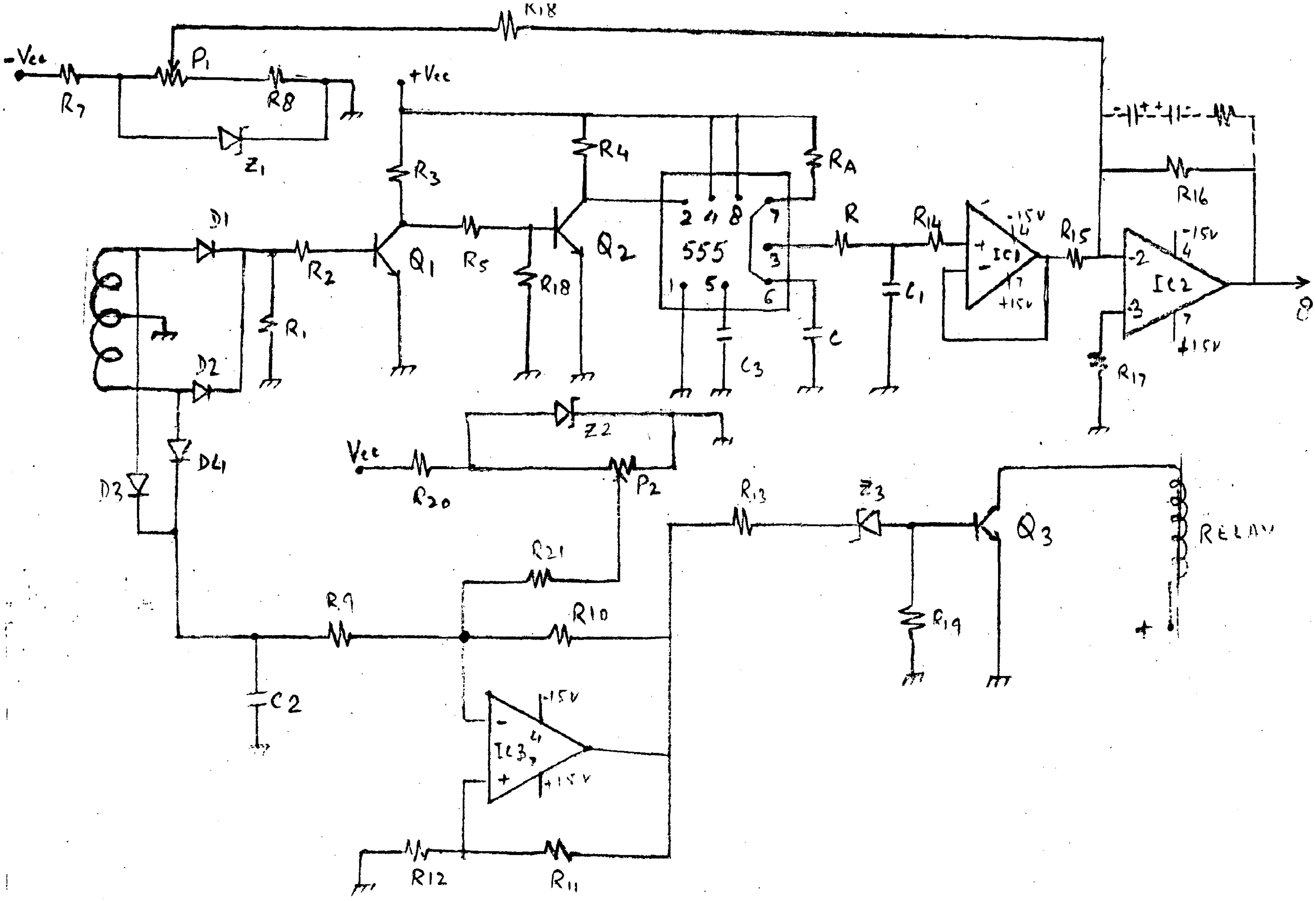


FIG. 2·10 - FREQUENCY CONTROL CIRCUIT

Fig. 2.10. First the frequency of the system is sensed. The output of the transformer is fed to triggering circuit, so as to obtain pulses for IC-555 at each zero crossing of AC supply. The triggering circuit is shown in Fig. 2.11 with wave forms. The rectified d.c. when fed to the base of transistor Q_1, the positive pulses at its collector is obtained. These pulses are given to the base of Q_2 which conducts only for the duration for which Q_1 does not conduct. Thus at the collector of Q_2 inverted, pulses are obtained, which are used for triggering IC-555, which works as frequency to voltage converter.

2.3.2.12 Frequency to voltage conversion :

Timer 555 has been used to convert the frequency into voltage. It has been used in monostable multivibrator mode. The circuit diagram is shown in Fig. 2.12(a) when a negative going pulse is applied to pin No. 2, output at pin No. 3 goes high and terminal 7 removes the short circuit from capacitor c. The voltage across c rises at a rate determined by R_A and c. When the capacitor voltage reaches 2/3 V_{cc} comparator 1 in Fig. 2.12(b) (functional diagram of timer 555) switches from high to low . The input and output wave forms are shown. The output is high for a time given by,

$$T_{high} = 1.1\ R_A \cdot c$$

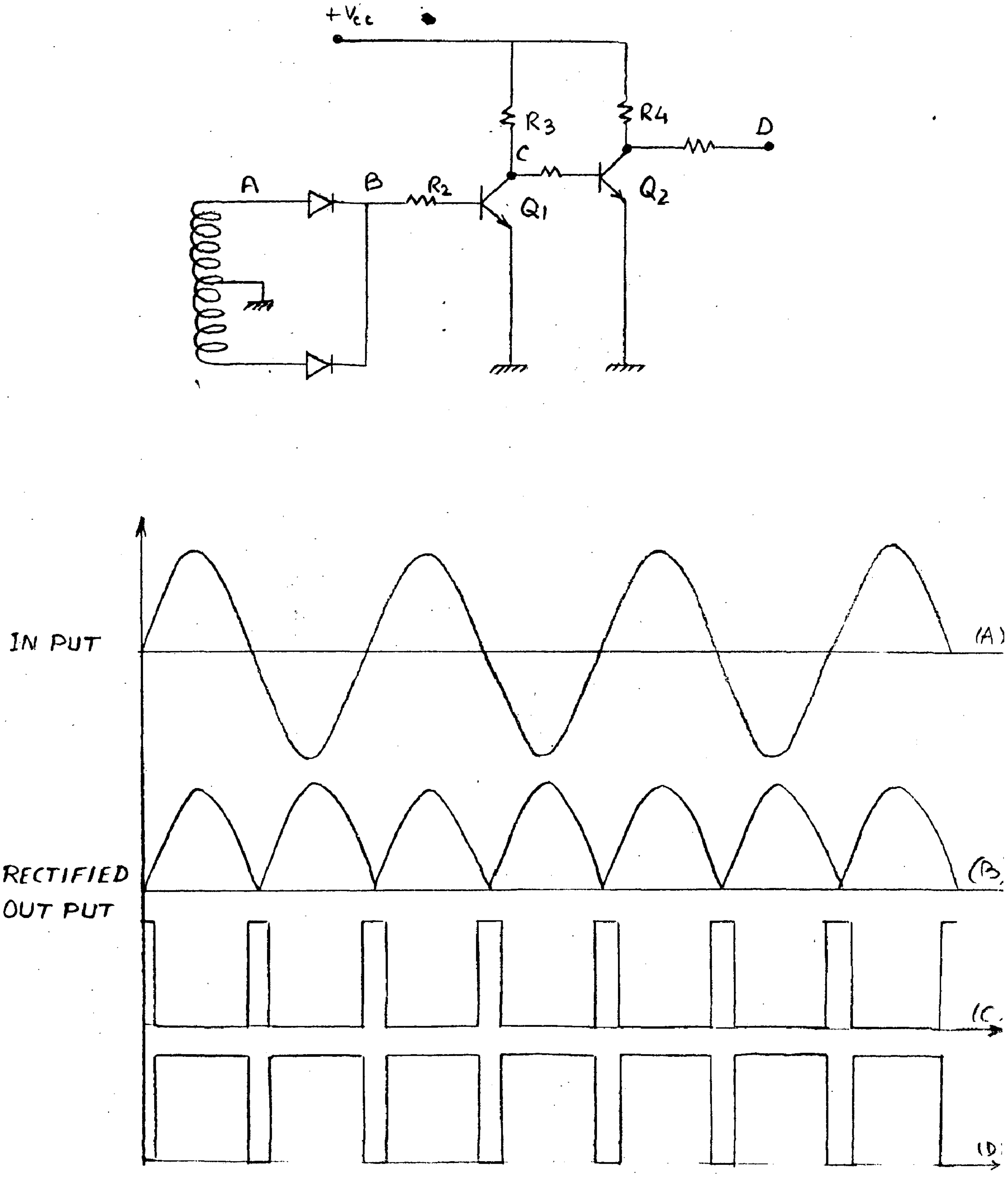


FIG. 2·11 TRIGGERING CIRCUIT FOR IC 555 WITH WAVE FORM.

The value of resistance (R_A), and capacitance (C) is selected in such a way that the time period for the output to be high should be less than the time period of the input pulse. The average d.c. value of the output is obtained by simple R. C circuit and may be given as,

$$V_{av} = \frac{V_o \cdot T_{high}}{T/2}$$

where V_o is the amplitude of IC 555 output, and T_{high} is the 'ON' state period and T is the time period of the input pulse.

Substituting for T_{high} from Eq. 1 in Eq. 2,

$$V_{av} = \frac{V_o \times 1.1\, R_A\, C \times 2}{T} \quad \ldots \quad (2)$$

$$= 2.2\, R_A\, C\, V_o\, f$$

$$V_{av} = K\, f \quad \ldots \quad (3)$$

where K is a constant and is given as below,

$$K = 2.2\, R_A\, C\, Vo$$

The above result shows that the average output voltage of IC 555 is directly proportional to the input frequency.

The output voltage of frequency to voltage converter is first given to voltage follower having IC_1 and then compared in the comparator with a reference voltage. The reason for using voltage follower circuit is that it draws

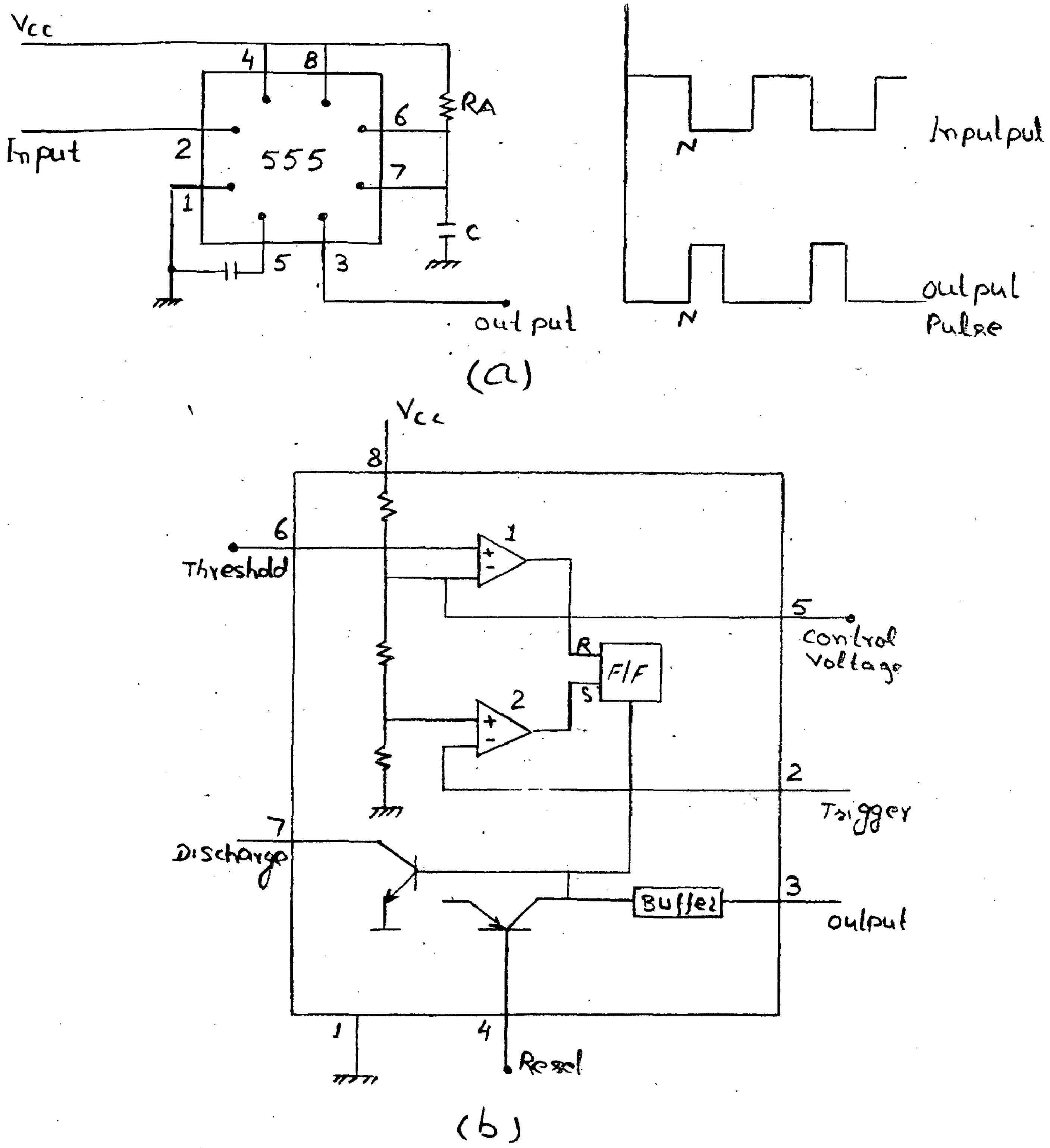


FIG. 2.12

(a) CIRCUIT DIAGRAM FOR MONOSTABLE OPERATION OF 555 WITH WAVE FORMS.

(b). FUNCTIONAL DIAGRAME OF IC 555

negligible current from the source as it has high input impedance. Since the signal is positive, therefore, the negative reference has been used. The algebraic sum of the reference and input signal i.e. the error signal is amplified. Now it can be concluded that if the system frequency is higher than the reference frequency the algebraic sum will be positive and the output of the comparator will be negative and vice versa. The amplified error signal V_{c2} is fed to phase control as well as to step control as shall be discussed in latter sections. Here V_{c2} is given as below :

$$V_{c2} = K_2 (f_{ref} - fg)$$

2.3.2.14 Over voltage protection :

The frequency control card also has an over voltage protection circuit. The a.c. voltage from the step down transformer is rectified and compared with a reference voltage. The output of comparator drives a relay circuits consisting of Q_3 and associated circuitry. When a.c. voltage exceeds the reference the comparator output goes negative. The zener z_1 goes into conduction which also causes the conduction of transistor Q_3 which may drive the relay to close the water input to the turbine or may be connected to an alarm system.