A NEW AND VERSATILE SCHEME FOR INDUCTION MOTOR PROTECTION

A partial fulfilment thesis
Submitted for the Award of Degree of
Master of Engineering
in
Power Apparatus & Electric Drives

by

ANAND KUMAR JAIN

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE

CERTIFICATE

Certified that the dissertation entitled "A new & Versatile scheme for induction motor protection" which is being submitted by Shri Anand Kumar Jain in partial fulfilment for the award of the Degree of Master of Engineering in Power Apparatus and Electric Drives of the University of Roorkee is a record of 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 further to certify that he has worked for a period of 8 months from June 1977 to January 1978 for preparing dissertation for Master of Engineering Degree at this University.

(K. L. [illegible])
Lecturer
Deptt. of Electrical Engg.
University of Roorkee
Roorkee

Bharat Gupta
(BHARAT GUPTA)
Lecturer
Deptt. of Electrical Engg.
University of Roork
Roorkee

Place : Roorkee

Dated : Feb 4 , 1978.

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(ANAND KUMAR JAIN)

SYNOPSIS

Common motor circuit protection has consisted of thermal overload to sense motor overcurrent and a short circuit protective device which acts after a catastrophic condition has occurred. While the present scheme provides adequate protection for the most common motor and motor circuit problems.

Common motor and motor circuit problems, the circuit variances that occur and the use of common devices under those conditions are discussed. It has been shown that how a solid state logic approach can sense these circuit variances and results in economy. Further how the application of solid state logic approach results in improved protection, coordination and easy application help to eliminate or minimise loss due to many of these common problems has been discussed.

In addition to thermal and overcurrent protection, impedance starting circuit has been provided to look after jamming problem of induction motor.

The scheme is fabricated and tested for the protection of single phase induction motor and for three phase induction motor a scheme has been suggested. Laboratory results obtained were satisfactory.

At the end the conclusions have been brought out on the superiority of the present scheme over the schemes worked out by others.

CONTENTS

LIST OF SYMBOLS

Symbol	Description
Chapter - I	
I	Full load current
r	Resistance of the winding
Chapter - II	
ΔI	Change in current
Chapter - III	
I	Full load current
t	Duration of the current
Chapter - IV	
K	constant
E	Input Voltage to motor
R	Resistance of winding
[illegible]	Reactance of the winding
e_m	Modulation signal applied to the control input
A_1, A_2, A_3	Different integrated Circuits
Q_1, Q_2	Different Transistors
R	Resistance of circuit marked in Fig. 26
C	Capacitance of circuit marked in Fig. 26
V_o	Integrator input voltage marked in Fig. 26
f	Output frequency of voltage control oscillator.

Symbols used in level detector without hysteresis

A_{vo}	Op amp voltage gain at dc
I_b	Input bias current of op amp
I_{io}	Input offset current of op amp
R_1	Resistor attached to op amp inverting input
R_2	Resistor which established correct current in Z_1 and Z_2
R_f	Feedback resistor which established hysteresis
R_{id}	Differential input resistance of op amp
R_{in}	Input resistance of circuit
R_{out}	Output resistance of circuit
R_p	Part of hysteresis feedback circuit
R_{z1}	Dynamic resistance of zener diode Z_1
R_{z2}	--do-- Z_2
ΔV_1	Portion of hysteresis loop caused by V_{z1}
ΔV_2	--do-- V_{z2}
V_i	Input voltage to circuit
Δvi	Minimum input voltage change which may cause a full output voltage change
$V^{(+)}$	Positive power supply voltage
$V^{(-)}$	Negative power supply voltage
V_{io}	Input offset voltage of op amp
V_L	Lower trip voltage
V_o	Output voltage of circuit

V_{off}	Error in trip voltage due to non-ideal op amp input parameters
V_R	Reference voltage used to establish trip voltages
V_U	Upper trip voltage
V_{z1}	Breakdown voltage of Z_1, plus the forward breakdown voltage of Z_2
V_{z2}	Breakdown voltage of Z_2, plus the forward breakdown voltage of Z_1

Symbols used in Integrator

R_1	Input resistance circuit
C_f	Feedback capacitor
I_f	Feedback capacitor current
v_i	Input voltage to circuit
v_c	Capacitor voltage
v_o	Output voltage of circuit

Symbols used in Level detector without hysteresis

A_{vo}	Op amp voltage gain at dc
I_b	Input bias current of op amp
I_{io}	Input offset current of op amp
R_1	Resistor attached to op amp inverting input
R_2	Resistor which establishes correct current in Z_1 and Z_2
R_{id}	Differential input resistance of op amp
R_{in}	Input resistance of circuit
R_p	Resistor used to nullify the effect of Ib

R_{z1}	Dynamic resistance of zener diode Z_1
R_{z2}	--do-- Z_2
V_1	Input voltage to circuit
$\Delta v1$	Minimum input voltage change which may cause a full output change
$V^{(+)}$	Positive power supply voltage
$V^{(-)}$	Negative power supply voltage
V_{1o}	Input offset voltage of op amp
V_o	Output voltage of circuit
V_{off}	Error in trip voltage due to nonideal op amp input parameters
V_R	Reference voltage used to establish trip point
V_{z1}	Breakdown voltage of Z_1, plus the forward breakdown voltage of Z_2
V_{z2}	Breakdown voltage of Z_2, plus the forward breakdown voltage of Z_1

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CHAPTER - I

INTRODUCTION

An electric motor is the fundamental element of an electric drive. In most of the practical applications the induction motors are widely used and hence the question of their protection is of vital importance and necessity.

1.1 Grouping of problems occuring in A.C. Motors and necessary protectionary measures :

When the problems of underwork, overwork or simply not work in induction motors occur, they lead to loss of production, equipment damage and sometimes catastrophic damage.

Generally the problems can be grouped into following categories which help in defining the nature of the problem.

1.2 Load induced problem :

The problems induced by load may give rise to decrease or increase in power demand of motor. Since input power must be equal to output power hence the net effect is change in power consumed by motor.

Generally, the problems induced by load are

1.2.1 Problem of overload :

An electric motor requires more power if its load is increased. Electric power is the product of current, voltage and power factor but voltage and power factors are relatively constant for a particular power source, number of motors and other loads on the line, therefore the only variable remained is the current to increase the power demanded by a particular motor.

Increase in power results in increase in current drawn by the motor. But there is a limit to which the current can be drawn by the motor, if the former is exceeded, the motor may get damaged because of excessive heating.

Thus, to protect the motor on overloads, need becomes of overcurrent protection. Common method available for this is the thermal overload protection.

1.2.2 Problem of Underload :

This problem may arise at the time of breakage of fan belt or when the motor is being used as a pump and suction gets over. This problem results in mechanical damages to the equipment.

Thus, to protect the motor on underload, need becomes of underload relay. Common method available is broken belt limit switch.

1.2.3 Problem of Jamming :

This problem may come because of blockage of mechanical load or if the bearing freezes up. This problem results in instantaneous increase in current which is approximately 600% locked rotor value(2) and which in turn results into damage of the motor as well as damage to the equipment.

Thus, to protect the motor, there is a need of a relay which can quickly clear from this problem. The common method available is the thermal overload relay which is very slow in operation for this problem.

1.2.4 Long Acceleration Time :

This problem can come when the rotating load has large inertia due to which motor has to carry current, which is approximately 600% locked rotor value(1), for long time and hence it is likely that the motor may get burnt out.

The common method available for this is the thermal overload which is not quite adequate. Hence there is a need of better protection.

1.3 Source Induced Problem :

Sometimes the motor is not able to make use of the incoming power efficiently when the latter is oscillating.

Generally, the problems induced by the source are

1.3.1 Phase Failure :

This problem may arise due to blown out of the fuse in a phase or because of the loose connections. This results in burn out of motor conductors as the one phase current has declined instantaneously. ?

This problem suggests the need of a phase failure relay for protecting the motor.

1.3.2 Over voltage :

This problem comes due to higher line voltage which results lower copper losses but increased magnetic flux which in turn results in higher iron losses (unwanted circulating current). Line voltage modestly above normal reduces the current drawn by the motor, but an additional increase in voltage causes saturation of the iron and a consequent steep rise in current. This rise in current may burn out the motor.

To protect the motor from this problem commonly over voltage relay is used which is an expensive protection. This problem can also be taken care by an overcurrent protection.

1.3.3 Under Voltage :

This problem may come if the source have low t? voltage or line voltage drops particularly at inrush. This problem results in increase in three phase running current (In this case analysis is similar to the case of overload except that here power requirement is constant and the voltage dips at the expense of the current.) which may burn out the motor. Again this problem can be overcome by sensing the increase in current that is by providing an overcurrent protection.

1.3.4 Phase Sequence :

This problem can result in damage to the rotor if motor runs in incorrect phase sequence. Phase sequence relay can be used to protect the motor from this problem.

1.3.5 Unbalanced Voltage :

The problem of unbalanced three phase voltages can result in current unbalance upto fifteen times(2) the voltage unbalances. When a three phase motor is subjected to unbalanced voltages, a negative sequence magnetic field (field opposing motor rotation by producing opposing torque) is established in addition to the existing positive sequence field (field causing the motor to rotate by producing forward torque). Since additional torque is required by the positive sequence field to overcome the torque produced by the negative sequence field, increased line currents will be drawn. Motor overheating will result if the voltage unbalance is great enough. Since motor overheating is a function of increased line current hence overcurrent relay can disconnect the motor from the line. The damage by this problem can be burnt out of the motor. Also motor can be protected by thermal overload relay but it provides only marginal protection.

1.3.6 Voltage Spikes :

Motor failures caused by voltage surges due to lightning, arching faults, switching, fuse blowing etc., are usually extremely difficult to diagnose, although they account for more failures than generally realized. Since thermal heating is not significant or the duration of the heavy current persisting is not large during voltage spikes, overload or overcurrent relay is not called upon to function. Even if relay could act, the inherent drop out time of a starter, coupled with the longer arc duration across the contact (due to the voltage spikes) would most likely allow the motor to feel the full impact of the spike.

Lightening arresters, surge capacitor or a combination of the two can be used to offer good protection. But these are not economical unless such surges are common in the particular area.

1.4 Specific application induced problems :

These problems include conditions that cause the R.M.S. current into the motor to greatly exceed full load current, even when the running current is less than or equal to full load current. The specific applications are :

explain duty cycle

1.4.1 High ON-Off duty cycle :

Jogging or higher production applications need operate motors at speeds below normal. Since motors draw higher than normal current at starting, motors experiencing these duty cycles will be frequently subjected to higher than normal currents. Over current relays will detect these high currents.

Also thermal overload relay can be used to protect the motor from this problem. In this case thermal overload provides good protection.

1.4.2 Rapid Reversing :

In rapid reversing again motor operates at speed below normal. Hence it is exactly the case of High On-Off duty cycle. Therefore same protection can be applied.

1.4.3 Plug reversing :

Again in this case motor operates at speed below normal. Hence the protection applicable to high on-off duty cycle will be applicable for it.

1.5 Load wiring induced problems :

These generally produce damage to the motor controller or cause other conditions such as single phasing of the motor. The most common induced problems are :

1.5.1 Wire insulation problem :

This problem is caused because of the insulation manufacturing defects. The insulation defects result in its breakdown and thereby grounds or shorts. Overload, overcurrent relays do not offer protection against these occurrences. Instantaneous circuit breaker and primary fuses are mostly used to protect the motor from this problem.

1.5.2 Loose connections problem :

This problem may arise because of improper installation and can damage the motor. If this condition comes, fuses, breakers and overload relay can offer some protection.

1.6 Motor induced problems :

The problems induced by the motor are :

1.6.1 Insulation failure

It has already been listed under load wiring induced problem and is one of the primary loss conditions and therefore it is desirable to protect against.

1.6.2 Bearing failure :

Improper lubrication, foreign materials, wear, defective parts, etc., can cause sudden bearing failure within motor.

Overload relay limit the motor damage imposed by increased mechanical 'drag' but can not prevent consequent fault damage.

Combination of impedance starting relay and thermal protection can be a better solution for this.

1.6.3 Vibration :

Bearing failure, insulation flexing, flaking or rubbing, failure of impregnants to secure winding, and damage to other mechanical components may be due to vibration, resulting in shorts or grounds. Motor can only be protected against this defect by proper installation and maintenance.

1.6.4 Blocked Ventilation :

This is also one of the cause of motor failure where thermal protection can be used to protect the motor.

When air passages within the motor become clogged due to lint, dirt, dust and other foreign matter, the natural cooling effect of the motor diminishes. In addition to the obvious increase in winding temperature, increased I^2r losses result from an increase in winding resistance which in turn results the higher temperature. Since in this case incre in line current, so the motor can be protected best from this problem by inherent thermal protection.

Though the easiest and most economical solution to thi problem is proper selection of the motor enclosure coupled wit a periodic cleaning programme. If motors are properly enclosed and periodically cleaned, thermal protection will not be required. But if the condition occurs this protection can serve the purpose.

1.7 Environmental induced problems :

These include :

1.7.1 High ambient temperature :

Since current motor winding resistances by creating heat, it follows that a high ambient temperature will produce the same effect as that by increased current. This means motor life will be reduced in high ambient environments. Thermal protection can offer good protection in such occurrences if sensors are properly applied to components for motor ambient.

1.7.2 High altitude :

The lower air density at high altitudes reduces the cooling effectiveness of the average motor to increase by approximately five per cent for each 100 ft.(2) of elevation.

Thermal protection is the better answer for this problem.

1.7.3 Moisture :

This problem contributes to motor failure in two ways :

(i) should a layer of moisture form on the surface of the insulation, due to higher humidity, temperature change, or direct spray, the insulation surface may become highly conductive and get broken.

(ii) Depending upon the porosity of the insulating material, moisture may be absorbed and cause insulation breakdown over a period of time.

Harmonic relay, leakage relay is the best solution for this problem.

1.7.4 Contaminants which generally result in motor insulation failure over its service period (ageing effects) :

The effect of heat on motor insulation results its deterioration. Motor life is approximately halved for every 10° C(2) rise in temperature.

Overcurrent and thermal relay help to prevent rapid insulation deterioration caused by excessive heat.

The general nature of the problem conditions has been defined. Table 1 gives a ready glance at each problem, the circuit variances from normal that are caused by the problem, ~~the circuit variances from normal that are caused by the problem~~, probable loss if the problem is not detected and protected in time, traditional protective device used, comments on the adequacy of the traditional protective devices to minimize or eliminate the problem and lastly the devices used or suggested for present scheme.

A thermal overload relay and short circuit protective devices, breakers or fuses, to protect against various conditions have to associate traditionally with the motor to be protected. These devices have been chosen for two reasons :

(i) They must be applied (with a few specific exceptions) to comply with the National electrica code (N.E.C.)

(ii) They do a reasonable job of preventing or minimizing loss due to the most common problem conditions when properly applied.

While devices to provide good protection for all of these conditions have been available for years, but their general application has been limited by cost. Generally basic thermal overload relay and short circuit device package are the main applications for these conditions rectification. But what has been felt from the following point of view :

(i) It should be economical enough to apply on even small H.P. motors.

(ii) It should be easily applicable

(iii) coordinate with the short circuit protective device.

Every protection scheme designer should look at these criteria for obtaining a better motor circuit protective devi

Table - 1

For ready reference at a glance

Problem Condition	Typical ~~fails~~ causes	Current Variance	Possible loss	Common protective device	Comments	Device used or suggested for the scheme
Overload	Too much load	Slow increase in 3 ∅ current to something less than 200%	Motor burnt Conductor burn out, short circuit, fire	Thermal overload	Provide adequate and economic protection when properly applied for running protection.	Static over current protection.
Jam	Mechanical load blockage or bearing freeze-up	Instantaneous increase in 3 ∅ current to approx. 600% locked rotor value	Same plus damage to equipment	Thermal overload	Response time may be slower than thermal capacity of "hot" motor	Static impedance starting cum overcurrent protection.
Underload	Broken bolt, shaft or coupling.	Instantaneous decrease in 3 ∅ current to no load value	Mechanical damage to equipment	Broken belt limit switch	Expensive addition of component mounting	Static underload relay (suggested)
Long acceleration time.	High inertia rotating load	600% locked rotor current for long time	Motor burn out, Conductor burn out, short circuit, fire	Thermal overload	Heaters often oversized, providing inadequate running protection	Static impedance starting and ~~over~~ over current protection.
Phase failure	Blown fuse, loose connection.	Instantaneous reduction in 1 ∅ current.	Motor burn out, conductor burn out, short circuit, fire	Phase failure relay	Good protection proper relay expensive addition.	Static phase failure module (suggested)
				Thermal overload	Provide adequate protection if properly applied	

(Table - 1 - Contd.)

Problem Condition	Typical causes	Current Variance	Possible Loss	Common protective Device	Comments	Device used or suggested for these scheme.
Over voltage	Source high	Decrease in ∅ current until motor core reaches saturation and 3 ∅ current increases.	Motor burn-out Conductor burn out, short circuit, fire	Over voltage relay	Good protection expensive condition addition.	Static over voltage relay (suggested)
Under voltage	Source low or line drop particularly at in-rush	Increase in 3 ∅ running current decrease in 3 ∅ starting current	Same	Thermal over load	Adequate protection if running current properly applied.	Overtemperature.
Phase Unbalance	Properly regulated Service or Unbalanced 1 ∅ loads on the same line	Moderate decrease in 1 ∅ current and increase in 2 ∅ currents.	Same	Thermal over load	Marginal protection. Good protection, expensive addition	Over temperature (Negative Sequence Relay)
High on/off duty cycle	Jogging, inching or high production application needs	3 ∅ current greater than full load current due to high percentage of operating time at 6A locked rotor current.	Same	Thermal overload	Adequate protection if properly applied, heaters often oversized resulting in inadequate running protection.	Current and over temperature operating simultaneously.
Rapid reversing	Application requirement	Same	Same	Same	Same	Same
Plug reversing	Same	Same plus time at 6A locked rotor current is increased by braking. time.	Same	Same	Same	Same

Table - 1 (Contd.)

Problem Condition	Typical causes	Current Variance	Current Variance Possible loss	Common Protective Device	Comments	Device used or suggested for the scheme.
Wiring Insulation	Damage at Insulation or Overcurrent condition	Increase in 1 Ø current from modest to short circuit value dependent on line impedence can blow primary fuse and result in phase failure.	Same	Thermal Overload	Poor protection response time generally not adequate	Instantaneous tripping circuit that operating under short circuit condition (static fuse)
				Primary fuses	May have long response time to low ground fault current and produce phase failure when blown.	
				MCB primary breaker	Good fast protection after condition has developed.	
Loose load connection	Improper insulation	Modest decrease in 1 Ø ~~Motor burn out, short circuit fire~~ current followed by loss of 1φ current when connector burns out.	Conductor burn out, Motor 1 Ø Motor burn out, Short circuit fire	-	Fuses, breakers and overload relay offered same protection after condition has developed	Static fuse
Motor insulation failure	Overcurrent due to one of the above	Initial moderate increase in 1 Ø current followed by increase in 1 Ø current to short circuit value.	Motor burn-out conductor burn-out, short circuit, fire	Primary fuses	Have long response time to initial low level ground fault and produces phase failure when blown. Act as back-up device after something go wrong.	Static leakage current relay
				MCB breaker	Good fast protection after condition has developed	

Table - 1 (Contd.)

Problem Condition	Typical causes	Current Variance	Possible Loss	Common Protective Device	Comments	Device used or suggested for the scheme.
Bearing failure	Improper lubrication, vibration.	Instantaneous increase in 3 ϕ current to 600% locked rotor current after bearing freezes	Same	Thermal Overload	Response time to motor stoppage may not be enough to protect 'hot' motor from burnt out or insulation damage	Impedance and over current and thermal relay.
High ambient temperature	Application parameter	Result in motor insulation failure and therefore same current variances as for insulation failure.	Same as motor insulation failure.	Primary fuses, Thermal overload	Same as motor insulation failure, adequate protection if heaters properly applied to compensate for motor ambient.	Overtemperature protection.
				Inherent thermal protection.	Good protection expensive addition.	
Contaminants	Application parameter	Same as motor insulation failure	Same	Proper motor enclosure and insulation system.		Static fuse, harmonic relay
				Same devices as motor insulation failure to contain failure.		

B. Magnetic (Instantaneous) overload Relays :

Instantaneous magnetic overload relays are the same as those with an inverse time characteristic, except they do not have the oil dashpot and piston for retardation. This relay operates instantaneously at a specific value of current and is utilized to limit the current or running torque of a motor to a specific value. Many applications for magnetic instantaneous over-load relays are for use in conjunction with an overload relay with inverse time characteristic.

CHAPTER - II

COMMON PROTECTIVE METHODS IN USE

Overload relays are usually the basic elements providing protection to electric motors.

The definition of overload relay as per NEMA (National Electrical Manufacturers Association) standard IC-1053 is 'An Overload relay is an overcurrent relay which functions at a predetermined value of overcurrent to cause disconnection of the load from the power source'.

2.1 To be more specific, overcurrent protection can be divided into two ranges.

Range 1 (Branch Circuit Protection) :

In this the motor is protected from the faults in which the current increases above 600%. to a maximum of 1300% of the motor full load current.(6) It is necessary to protect the motor, motor controller, and conductors from short circuits and ground faults in any portion of the branch circuit.

2.1.1 The devices which are in common practice are fuses and the instantaneous trip circuit breakers.

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2.2 Range 2 (Motor Overcurrent Protection) :

Experience in motor failures indicates that most of the faults occur at relatively low levels of fault current just above lock rotor values rather than at higher levels. Motor overcurrent protection prevents damage to the motor, motor controller, and conductors due to motor overloading.

Thus by combining these two ranges extensive damage to motors as well as to control equipments can be greatly reduced.

2.2.1 Types of Commercially available overload relays :

Overload relay protection is available for almost all motor applications and knowledge of different types and varieties of overload relays is a necessity for proper motor protection.

2.2.2 Basic types of overload relays :

Overcurrent is the basic cause of almost all motor overheating. The devices designed to protect motors from excessive heating either sense current or the heat. The majori of all overload relays in use today are thermal devices which rely on the line current flowing to a motor for a similar heating effect. To properly protect a motor relays should possess thermal characteristics closely resembling those of the motor.

Fig. 1 is a comparison of the thermal characteristic

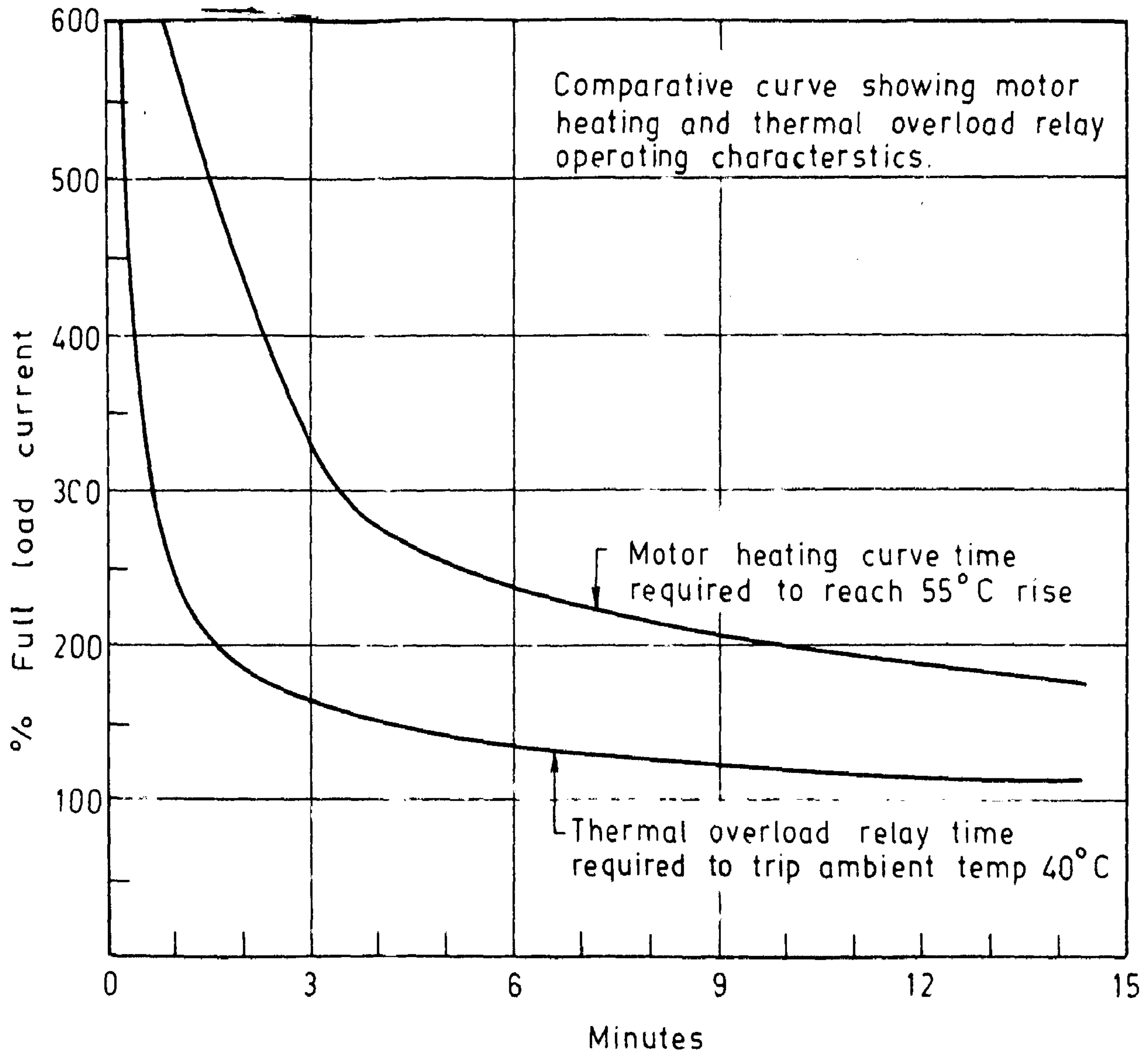


Fig. 1 - Motor heating and overload relay curves

of a typical motor and typical overload relay. These curves(2) show that the overload relay will trip (disconnect the motor from the line) just prior to motor overheating for all values of excessive current. Higher current not only causes motor overheating to take place in a shorter period of time, but also causes earlier tripping of overload relays. These characteristics term replica devices inverse time characteristic relays.

2.2.2(a) Melting alloy :

Melting alloy overload relays (Fig. 2) consist of a heater element, eutectic alloy, alloy pot, ratchet wheel, pawl, spring and contacts. The intensity of heat dissipated by the heater varies directly with the line current and acts upon the eutectic alloy (alloy with a precise low melting point). The spring loaded pawl operates the contacts in such a manner that the contacts are forced open unless the pawl is held in place. This is the function of the ratched wheel, to secure the pawl and thus force the contact closed. Since the shaft of the ratchet wheel is secured by the solidified eutectic alloy, the contact remain in closed position. When the motor draw excessive current for a long enough period of time, the heat dissipated by the heater melt the eutectic alloy, allowing the ratchet wheel to spin. The spring loaded pawl is then free to move, allowing the contacts to open

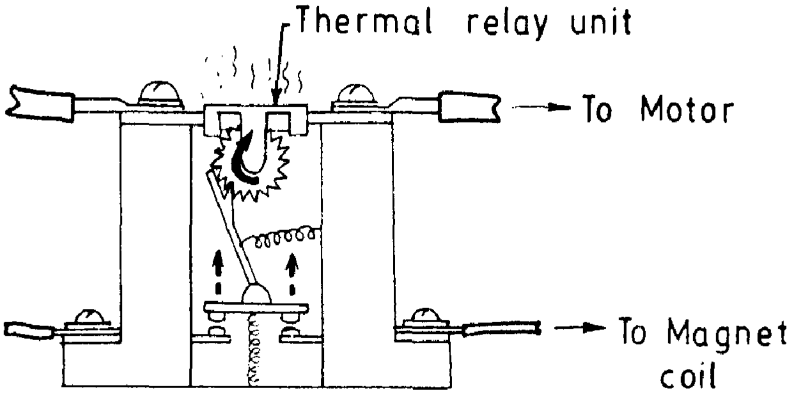


Fig.2 -Melting alloy overload relay

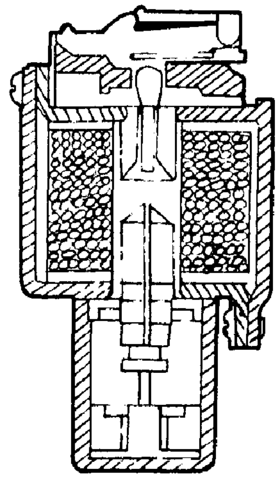


Fig 3 - Typical magnetic overload relay

which, in turn, deenergize the control circuit and drop out the starter. After the alloy has cooled and hardened, the unit can be manually reset.

There are two types of melting alloy overload relays which have been manufactured.

(i) One type combines all the parts in one unit, except the heater, and utilizes a complete range of heaters to provide a wide range of trip currents. With this type of melting alloy unit it is only necessary to select the heater for a particular application.

(ii) The second type of mechanism combines all the forementioned parts except the heater, ratchet wheel, and eutectic alloy, which are combined in a second unit. By combining the heater and eutectic alloy in one unit accuracy is increased. Also, the alloy and heater can be tested and calibrated as a unit, providing additional accuracy. Just as a complete range of heaters is provided for the first type of mechanism, a complete range of this second unit (thermal unit) is provided for the second type of mechanism.

Overload assemblies are also manufactured with contacts which may be replaced without replacing the complete overload block.

2.2.2(b) Bimetallic overload relays :

This type of overload relay also contains a heater which is sensitive to line current. As the line current increases and the heater dissipates more heat, a bimetallic strip is heated instead of a eutectic alloy. This bimetallic strip is designed to flex a predetermined distance when it reaches a specific temperature, a temperature corresponding to the point at which the motor should be disconnected from the line to avoid excessive heating. When the bimetal strip bends this predetermined distance, force is applied to the contact mechanism and the contacts open to disconnect the motor from the line.

As compared to melting alloy overload relays, bimetallic has both advantages and disadvantages. One advantage is that the bimetallic overload relays can be converted from manual reset to automatic and vice-versa by merely moving a spring or leaver. The drawback of this advantage is that overload relays should normally be of the manual reset type to call attention to an overloading motor in order to locate the trouble. It is extremely easy for a busy maintenance man to set an overload relay of this type to automatically reset itself so that he is not to bothered. Then allowing the motor problem to remain unsolved and causing unnecessary motor deterioration. Another danger is the possibility of an overload relay being set to automatically reset itself on a 2-wire control scheme where personnel injury could result from a motor suddenly starting without warning.

The automatic reset feature, however aids in protecting a motor that is

(i) isolated, such as in an oil field where personnel would be required to travel a considerable distance to reset the device or

(ii) controlling equipment such as a refrigerato when it would be more desirable to deterior the motor than have it disconnected from th line unit, personnel are in attendance. Disconnection could result in loss of the refrigerated goods.

The second advantage of bimetallic overload relays is the adjustment of trip point which can be sett from approx. 85% to 115% of the ultimate trip current.(2) Again, this feature have drawbacks. The adjustment is provided to allow a setting more closely corresponding to motor loading and/or rating. Unfortunately, it is no uncommon for maintenance personnel to adjust such a device to a setting higher than allowable for a particular motor in order to prevent periodic tripping. Usually, this periodic tripping should be allowed to take place. Damage to the motor may result if the trip point is set too high. Melting alloy overload relays which are adjustable only by replacing the thermal unit or heater and not by changing the position of the heater prevent such occurrences.

In general, bimetallic overload relays are not as accurate as melting alloy overload relays because of :

(1) Variations in the distance travelled by the bimetal

(2) Variation in the thickness of the bimetal (manufacturing tolerances), and

(3) Variations in the relative positioning of the bimetal and heater.

Whenever automatic reset or adjustment is not required for the particular application melting alloy relays are suggested.

2.2.2(c) Magnetic (Inverse time Characteristic) overload relays :

Magnetic overload relays (Fig. 3) are differentiated from the thermal type of replica overload relay by their principle of operation. These overload relays are merely current sensitive devices with an armature which is attracted by the induced magnetic field as current passes through a coil. The armature actuates the contact mechanism as it

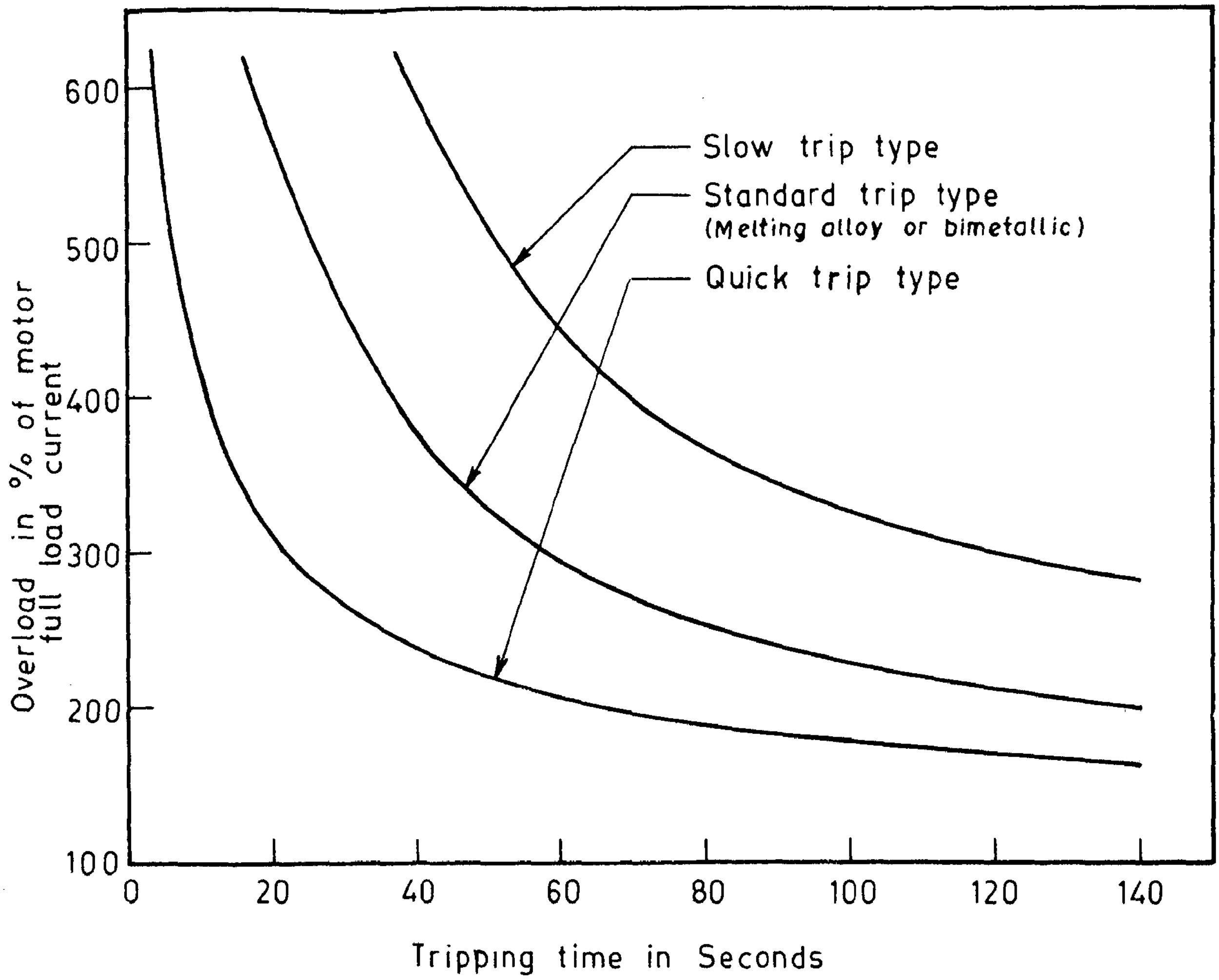


FIG. 4 - Typical inverse time characteristic trip curves for standard, quick and slow trip over load relays.

completes its upward movement. An inverse time characteristic is obtained by attaching a piston to the armature. This piston moves through an oil field chamber (termed as dash pot) and the time delay can be adjusted by opening a number of holes in the piston, thus controlling the rate of oil flow through the piston. Different trip settings (current are obtained by adjusting the initial position of the armature and by selecting the proper coil. Hand or automatic reset is available, with additional advantages being the wide range of trip adjustment, adjustable time delay, repeat accuracy, and the insensitivity to ambient temperatures (when application permits).

2.2.2(d) Special Purpose Overload Relays :

(i) Quick Trip - Standard inverse time characteristic overload relays protect the great majority of motors in use today. However, some applications or types of motors require overload relays which will trip in a shorter period of time fo the same values of line current. Such devices are termed quick trip overload relays and have an inverse time characteristic curve resembling of the standard unit, except the curve is shifted in position (Fig. 4).

Motors which cannot stand excessive currents for as great a time period as standard general purpose motors, those with a locked rotor current much less normal (such as 400 - 450 per cent of full load current)(2), and intermittently rated or short time motors may require quick trip overload relays. In addition to motors requiring quick trip because of inherent design considerations, are many of those applied to hermetically sealed compressor units or submersible pumps. Such motors are artificially cooled by the refrigeration collant or liquid as it passes over, making it possible to operate at 125 - 140 per cent the rating of an equivalent standard motor. With a running current of upto 40% greater than standard motors, the locked rotor current may be only 400 or 450% of the running current. The overload relays should disconnect the motor from the line at this locked rotor current in about the same time period a standard motor is disconnected when drawing 600% running current.

(ii) Slow Trip - High inertia loads require an acceleration period greater than normal during which the motor will draw current approaching locked rotor intensity for approx. 70% of the acceleration time(2), the higher the inertia, the longer the acceleration time. Standard motors can not with withstand this duty. A motor capable of accelerating such a load without incurring damage will probably be disconnected due to mal-tripping if standard overloads are used.

Tripping of overload relays under this type of situation is not limited to the acceleration period but may als occur after the motor reaches running speed and the current has reached to normal. This is a result of the thermal storage characteristic of thermal overloads and this, along with mal-tripping during the acceleration period, will cause to select standard thermal units one size longer than desirable for proper protection. Such a selection will not provide proper running protection, slow trip overload relays should be used. Slow trip overload relays trip after a longer period of time than standard trip units for the same values of line current and have an inverse time characteristic curve resembling that of the standard unit, except that it is shifted in position (See Fig. 4).

Melting alloy and bimetallic overload relays are available in the quick trip and slow trip versions and have the same advantages and disadvantages as previously mentioned for the standard version. Magnetic quick trip and slow trip overload relays are physically the same as the standard version, except for differences in the number of holes opened in the piston and possibly the viscosity of the oil.

2.2.2(c) Ambient Compensated :

Ambient compensated overload relays are probably the most widely misunderstood and, consequently, misapplied version of overload relays. There are number of motor failures that are the result of this misapplication.

Motor and Controller in same ambient :

The heating of motor windings and of thermal overload relays is comprised of two components , (1) The heating effect of the current, and (2) The ambient temperature of the surrounding atmosphere. Since the higher ambient temperatures reducing the maximum current which can flow without incurring overload tripping, has led to misconceptions that ambient compensated overload relays should be used in all high ambients. Such is not the case. The motor will also incur heating from this ambient temperature, and winding life will be halved(2) by approximately every 10° C just as it would from an increase in temperature due to current. Non compensated overload relays, therefore, offer proper protection.

If the ambient temperature is high enough to cause the overload relays to repeatedly disconnect the motor from the line, either a higher grade motor insulation or a larger motor should be used. Ambient compensated overload relays should not be used, nor should longer size non-compensated devices, since decreased motor life will result.

Another misconception is the use of ambient compensated overload relays to adjust for the heating effect of the starter

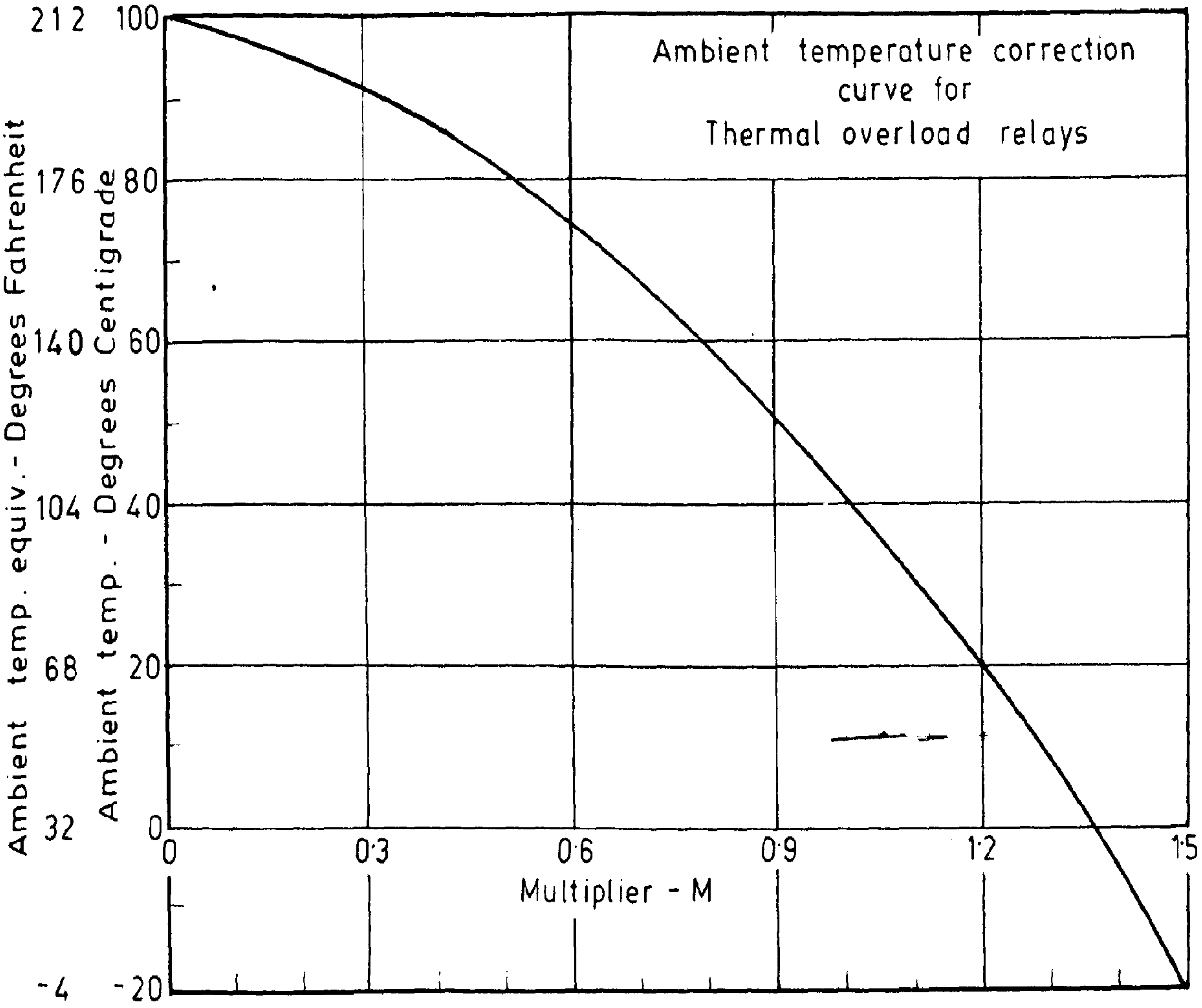


Fig 5 - Ultimate trip current in ambients other than 40°C can be calculated by multiplying ultimate trip current at 40°C by correction factor taken from graph.

or other components in the controller enclosure. Overload relay selection tables allow for this heating effect, and ambient compensated overload relays should not be used for the reasons previously mentioned. Selection tables are available for small, medium and large enclosures with varying amount of electrical components.

Motor and Controller in different ambients (Constant temperature difference)

When the motor and the overload relays are in differ ambients, but the temperature difference between those ambie is relatively constant, noncompensated relays should be utilized. For example a separate motor control centre room or the motor controller being in a different ambient for any reason. For such applications, the selection of the overloa relays must be allowed similar to that shown in Table II or Fig. 5 (Table II shows the selection of overload relays when motor and controller are in different ambients with constant temperature difference). Ambient compensated devices should not be used for the same reasons that apply when the motor and overload relays are located in the same ambient.

Motor and Controller located in different ambients; (Variable temperature difference) :

For the relatively in-frequent application of a moto and its protection located in different ambients and with the

Table - II

Selection of Overload Relays

Motor Service Factor	Type of Motor	Ambient Temp. of Motor same as controller (normal condition),	Ambient temp. of motor 12°C higher than controller	Ambient temperature of motor 12°C less than controller.
1.15 or higher	Continuous duty, open type (Drip proof, etc.) with rated temp. rise of 40° or 60° C *	Select directly from table	Use one size smaller than shown in table.	Use one size larger than shown in table.
1.0	Continuous duty, totally enclosed with rated temperature rise of 50°, 55°, 70° or 75°C *	Use one size smaller than shown in table.	Use two sizes smaller than shown in table.	Select directly from table.
1.0	Intermittent duty (one hour)	Multiply full load current by 0.8, then select directly from table.	Use one size smaller than indicated for normal condition.	Use one size larger than indicated for normal condition.

* Motors built after 1954 may not show a temperature rise rating on name plate - Use service factor as basis for thermal unit selection.

temperature difference between these ambients having a pronounced variation, ambient compensated relays should be used to prevent mal-tripping when the motor ambient is lower and to prevent motor failure when the controller ambient is lower than normal. For example submersible pumps, where the controller is subjected to direct sunlight, or whenever the motor is located indoors and the overload protection outdoors.

Ambient compensated bimetallic overload relays are available for those applications requiring such a device. These devices merely use a compensating bimetal which is sensitive only to the ambient temperature and which drives the movable contacts in a direction opposite to that of the current sensitive bimetals. Magnetic overloads are inherently ambient temperature compensated since the coil on such a device senses only current and is not affected by the ambient temperature. The numerous advantages of a magnetic overload frequently make such a device preferable when ambient compensation is required.

2.2.2(f) <u>Other forms of overload protection</u> :

<u>Time Lag Fuses</u> :

The national electrical code (N.C) permits the use of fuses rated upto 125% of rated current (service factor 1.15, general purpose motors) as running over current devices. These fuses do not offer adequate motor protection since their melting characteristics do not match motor heating characteristics. Selection of a fuse allowing a motor to start will not protect against slight overloads. To protect fractional H.P. motors, time lag fuses have been used widely. Integral H.P. motors are not usually protected by this means.

2.3 Inherent Motor Protection :

Inherent motor protectors are the devices placed inside the motor housing which directly sense the temperature of the motor windings. The devices may be embedded in the winding slots, attached to the end turn of the stator winding, or may be attached to the frame.

In this way devices are responsive not only for conditions of motor overtemperature because of increased motor current but also for conditions of motor overtemperature because of otherwise.

Several types of inherent protectors are available which use different types of sensors to measure the motor winding temperatures. Thermistors or miniature sealed thermostats are most commonly used. Both types may have contacts

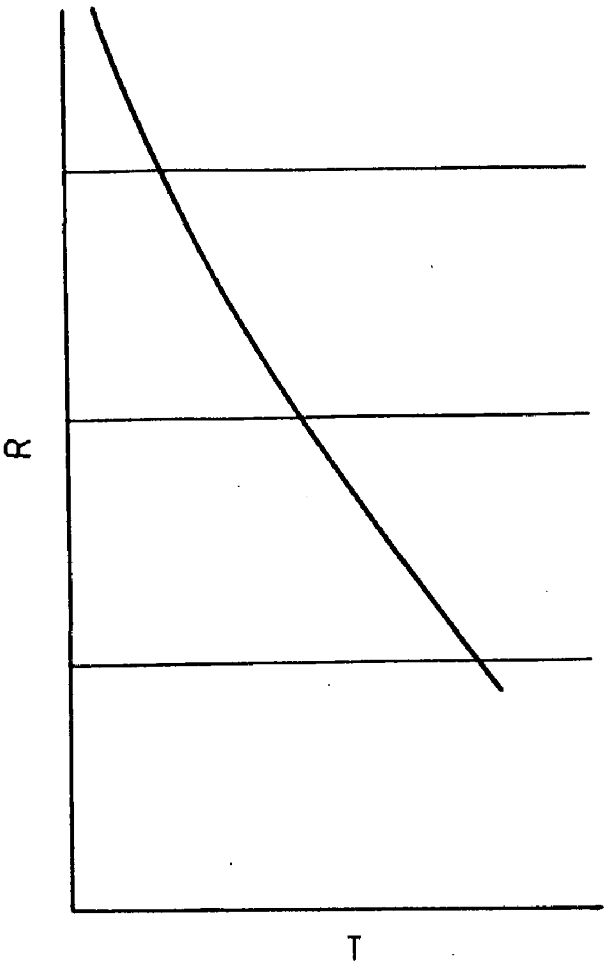


Fig.6 - Characteristic of a NTC thermister

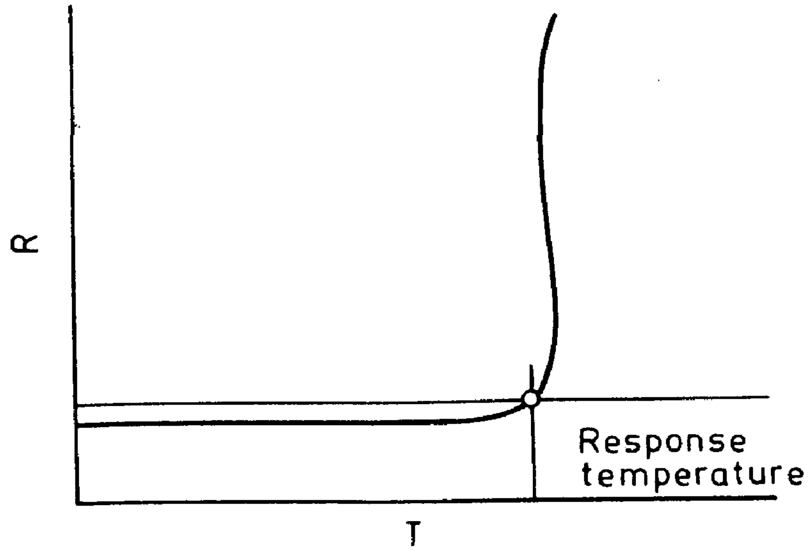


Fig.7 - Characteristic of a PTC thermister

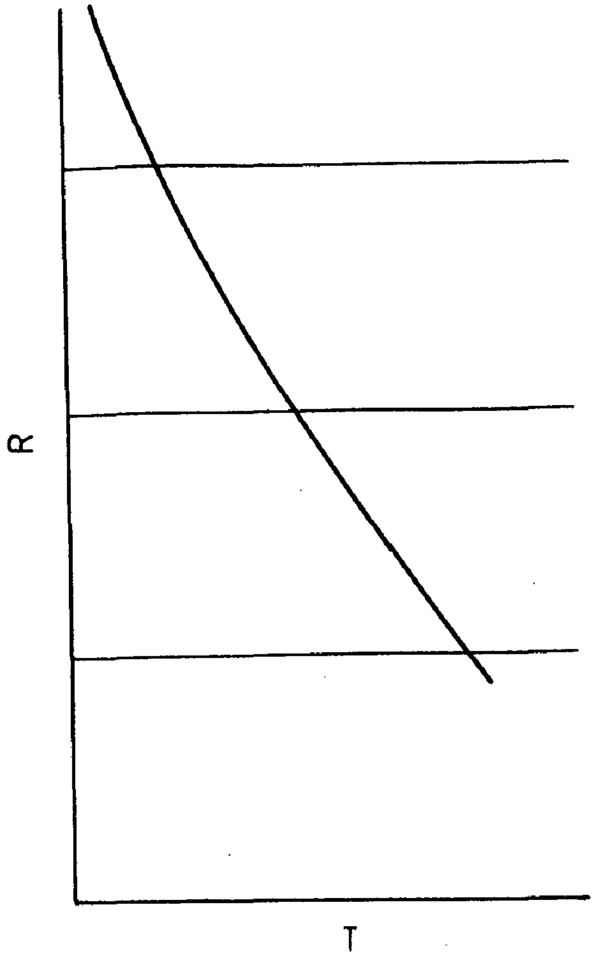


Fig.6 - Characteristic of a NTC thermister

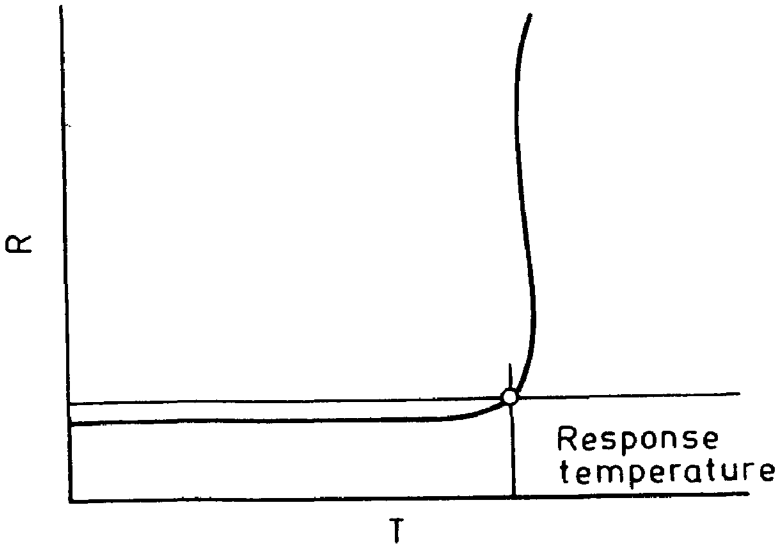


Fig.7 - Characteristic of a PTC thermister

in the control circuit just as conventional overloads or on small motors may be line break devices.

Negative Temperature Coefficient Thermistors :

These are nothing but the semiconductor resistances. The characteristic of it is shown in Fig. 6 which is exponential between resistance and temperature i.e. resistance is reduced by several orders of magnitude as the temperature increases. Before the introduction of positive temperature coefficient thermistor (PTC) NTC was in common use. The first full thermal protection systems built in Europe were developed by Siemens and used NTC.

PTC (Positive temperature) Coefficient Thermistor

In contrast to NTC thermistors, the resistance of PTC elements remains constant upto the critical temperature and then rises very steeply. The characteristic is shown in Fig. 7

PTC thermistors are prepared from barium and strontium titanate ceramic samples fired in the presence of oxygen. The oxygen penetrates the pores of the samples and is absorbed on the crystal surfaces. Above a certain temperature, called the curie temperature, the oxygen attracts electrons from the crystal surface and forms electrical

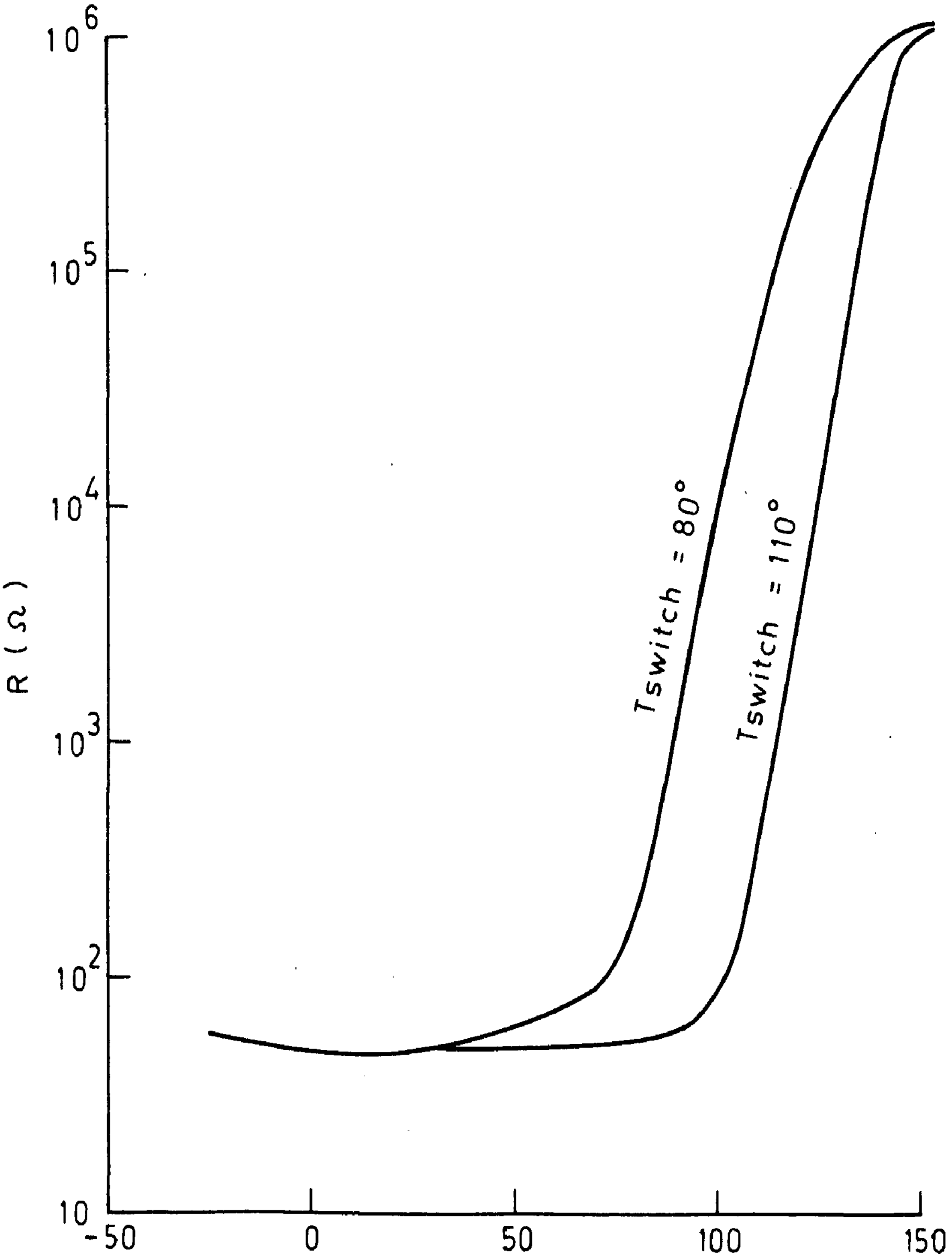


Fig. 8 - Typical characteristic for PTC thermisters

potential barriers, which cause the extra resistance of the thermistor. Below the Curie temperature the crystal has weak negative temperature coefficient (n.t.c.) at highe temperature (100° to 200° C)(3) the electrons captured at the boundaries are librated and a new n.t.c. region occurs. Fig. 8 shows a typical characteristic.

The characteristic of a p.t.c. thermistor is specified by switch temperature, defined as the temperature at which the resistance is twice that at 25° C, and the resistance at two points (a) at 25° C and (b) at a temperature above the switch temperatures.

For motor control work, however, it is only the characteristic above the switch temperature which is of interest, and in practice it is sufficient to state the required operating temperature. The resistance at switch temperature is usually between 100 and 150   and at operatin temperature 300 to 1000   , this represents a temp. differen of 2 to 5 deg C for the usual types of p.t.c. thermistor.(3)

Thermistors are also given a wattage rating or have a dissipation constant quoted. Tentatively, it can be expected that the smaller the thermistor the smaller the thermal time lag will be when the units are used as sensors in a motor winding. Thus for motor protection 0.5 w thermistors with a dissipation constant of about 600 w/deg C in free air are usually used. This places a limit of about 5 V and the voltage that can be applied across the thermistor. Above this voltage there is a tendency for the thermistor to self-heat.

At the present time, PTC thermistors are available(4) for response temperatures between 90 and 130° C with spacing of 10 deg, and also for 170° C. It is intended to extend the range to include elements for temperatures from 60 to 180° C. With these thermistors, it will be possible to use this system for other machine parts as well, such as sleeve bearings whose maximum temperatures mostly vary between 60 and 80° C.

More detailed discussions of p.t.c. thermistor applications and characteristic can be found from the manufacturer's hand book.

The most common thermistor in use at present is the positive temperature coefficient thermistor. Thermistors have been chosen as the most satisfactory temperature sensors for the following reasons :

(1) They have a smaller thermal mass than (say) thermal switches and monitor the temperature more closely by reducing heat transfer, time lag and overshoot to a minimum.

(2) They have a trip point which can be sharply defined and consistently held (Fig. 5)

(3) They are not easily damaged and their trip point cannot be accidently altered during insertion into windings.

(4) They are small in size and shape about 10 mm long, 3 mm wide and 2 mm thick) allow for easy insertion into a machine.

(5) They can be inserted in a machine before the windings are impregnated without being adversely affected.

(6) They fail to safety on open circuit (a reason for using the positive temperature coefficient resistor type of thermistor.)

The standard protection unit utilises three thermistors connected in series to protect a three phase motor against sing phasing and one thermistor to protect a single phase motor.

The sensors are usually installed at the end windings at the top of the drive. It is also possible to install them on the winding surface of a completed motor, although this increases the temperature overshoot during fault. Since thermistors are placed in the immediate proximity of the live winding conductors, they are provided with an insulation which resists the maximum voltage to frame occurring under exacting conditions, e.g. at comparatively high temperatures. In addition to the high temperature resistance and a good thermal conductivity, the mechanical strength of the temperature detectors is of great importance. To prevent damage to the detector insulation e.g. during installation, provision of a particularly high mechanical strength is given special attention when the detectors are manufactured. For this purpose, the detector element and a short section of the connecting leads are covered by a tube of glass fibre, the resulting hollow space being filled with casting resin.

Well curing resins with a good thermal conductivity are used as filling compounds, the properties of which are unaffected by comparatively high temperatures. To prevent hollow spaces from forming when the detectors are filled, the compound is applied under vacuum. The temperature detectors are insulated from adjacent parts for a voltage of 600 V. The test voltage is 5 kV.(4) Thermistors with a switch temp. suitable for a particular motor insulation class are placed one in each phase. Because the resistance characteristic is almost flat below the switch temperature, and steep (typically 15%/deg. C)(3) above it, the thermistors can be connected in series without any dangerous inaccuracies in temperature measurement being introduced. This also provides

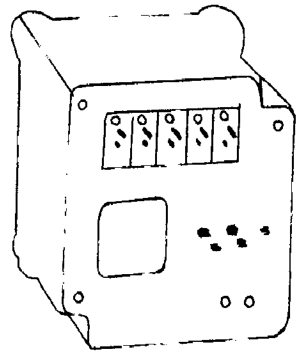


Fig.9 - Tripping unit

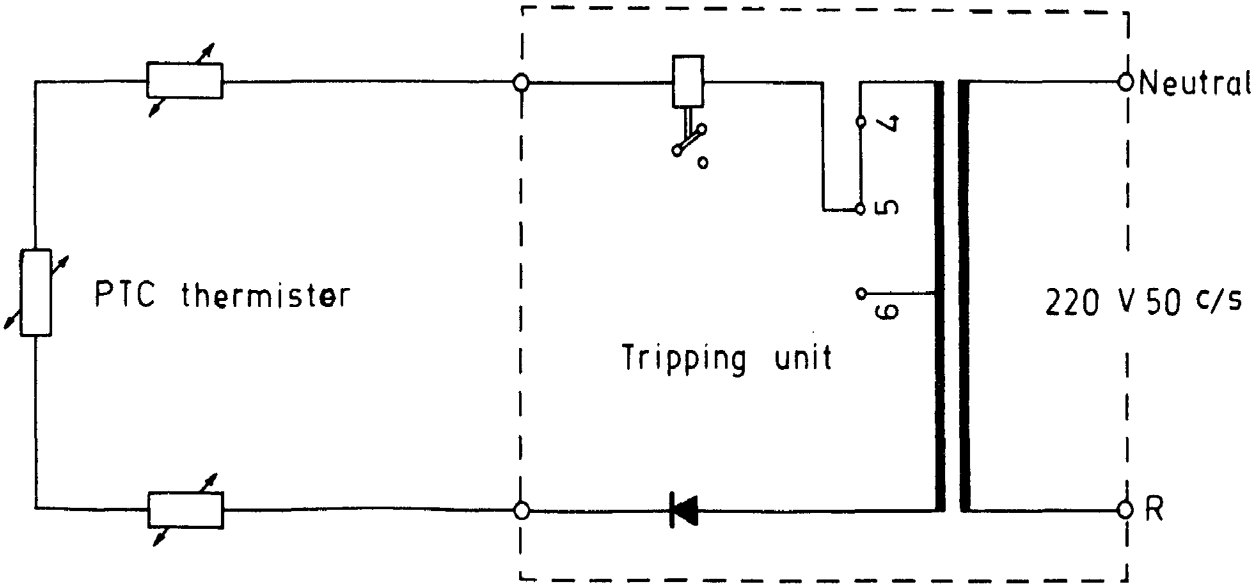


Fig.10 - Basic circuit of a full Thermal Pròtection system.

an automatic tripping if the sensor circuit is interrupted.

2.3.1 Method of Operation :

The detector resistance is evaluated in a tripping unit. (Fig.9). This incorporates a d.c. excited relay whose coil circuit is connected in series with the temperature detectors. The rotary armature of the relay actuates an auxilia switch by means of which the control circuits are operated. The power supply is obtained from a transformer whose primary winding is connected to a 220-V single phase a.c. supply,the secondary feeding a rectifire (Fig.10). The resistance difference resulting if three or six series-connected detectors are used is compensated by varying the secondary voltage. This can be easily be affected on the tripping unit by connecting terminals 4, 5 and 6.

When the rated response temperature is reached at a point where a detector is embedded, the detector resistance increases rapidly. The resulting current drop causes the relay to drop out and the auxiliary switch to be actuated. The control circuit of the motor circuit breaker is thereby interupted and the motor disconnected from the supply. For initiating this process,the resistance rise in one detector is sufficient so that three phase motors in which one phase winding has failed can be reliably protected.

When the detector has cooled down by about 6° C after tripping,(4) the relay is automatically re-energised. The auxiliary switch is changed over and the motor circuit breaker can be reclosed.

The tripping unit can be installed separately from the motor in the control board. It is virtually insensitive to vibration and operates reliably at shocks of the order of ten times the acceleration due to gravity.

Full thermal protection systems using PTC thermistors are primarily employed for low-voltage three phase squirrel cage motors.

2.3.2 Mathematical Model of the Thermistor Response(3)

The ~~effect~~ object of the previous discussion has been to show that application information on two important aspects of thermistor protection has so far been lacking.

(a) Information on the effect of the thermal inertia of the thermistor winding system, and the effectiveness of thermistors installed, for example on the winding surface.

(b) Methods of testing for and evaluating the above.

A series of tests can be carried out on a motor which can be specially rewound with thermistors in and on the windings in order that these aspects could be studied.

If a batch of P.T.C. thermistors are calibrated against temperature before being mounted in the motor and if increasing voltage is applied to say two thermistors from the same batch in order to find how they failed, then the results should be :

(a) The deviation from the manufacturer's curves should be negligible for both the resistance temperature and voltage current characteristic.

(b) Thermistors mounted in motors are most unlikely to be damaged by the motor overheating or by the normal baking of the winding after impregnation, since they can survive a far higher temperature during the tests than winding insulation could survive.

(c) They can be damaged by self-heating caused by excessive voltage. The first stage of failure would be a melted track between the terminals. After this the thermistor characteristic will retain its knee, although the resistance at all temperatures is higher. The final stage would be the cracking of the crystal after which the thermistor will lose its distinctive characteristic but retain some resistance.

The calibrated thermistors can be mounted in the conventional motor, one set of three embedded one per phase, inside the conductor bundle in the end turns (mounted before impregnation) and one set on this outside surface of the motor. The rotor of the motor is locked, and test is made to discover the relation of winding temperature, thermistor temperature, and motor current with respect to time.

The response of the thermistor can be measured with an ultraviolet recorder.

The winding temperature can be calibrated from resistance measurement made immediately before starting and after tripping, using the voltage and current method.

The motor current can be measured with a conventional c.t. ammeter system.

About two series of tests should be carried out, with the motor fed from two phases and three phases respectively. Measure ents with the motor both hot and cold can be performed.

Then, mathematical model of the thermistor response can be developed by analogy with an electrical series resistance capacitance circuit fed by a ramp voltage function. The voltage across the capacitor at time t can be taken to be analogous to the temperature sensed by the thermistors, i.e.

$$T_o + k_1 t = S\,(dT_c/dt) + T_o$$

where k_1 = rate of winding temperature rise

S = thermal time constant of the motor (analogous to RC in the elect. case)

T_c = temperature sensed

T_o = ambient or initial temperature.

The solution to this equation is

$$T_c = k_1 t - Sk_1 + T_o \ (\text{Approx. } \underset{t>>S}{}) \ \ldots \quad (1)$$

k_1 is assumed to vary by the square of the motor current, so that $k_1 = k\,I_1^2$ for conditions within the scope of the experiment, where k becomes a constant for a particular motor, representing the specific rate of winding temperature rise.

When the thermistors are self-heated to a temperature $T_o + T$ and allowed to cool while the surroundings are still at temperature T_o, the cooling characteristic will be

$$T_c = T_{exp}(-\,t/S) + T_o$$

when $t = S/2$

$$T_c = 0.61\,T + T_o$$

It is not necessary to start measuring at the instant the system starts cooling. Consider that measurement starts x seconds after this instant, i.e. at $t = x$

Then $T_2 = T_{exp}[(- x/\theta) - 1/2] + T_o$

$$= 0.61\ T_{exp}\ (- x/\theta) + T_o$$

The eqn. (1) ignores all cooling effects, and is thus applicable only while the motor is heating rapidly.

The expression $k_1 t$ is a measure of the average winding temperature, and $k_2 \theta$ is a measure of the temperature difference between the winding and the thermistors.

The eqn. is reasonably accurate when t is large compared to θ but small compared the thermal time constant of the motor body.

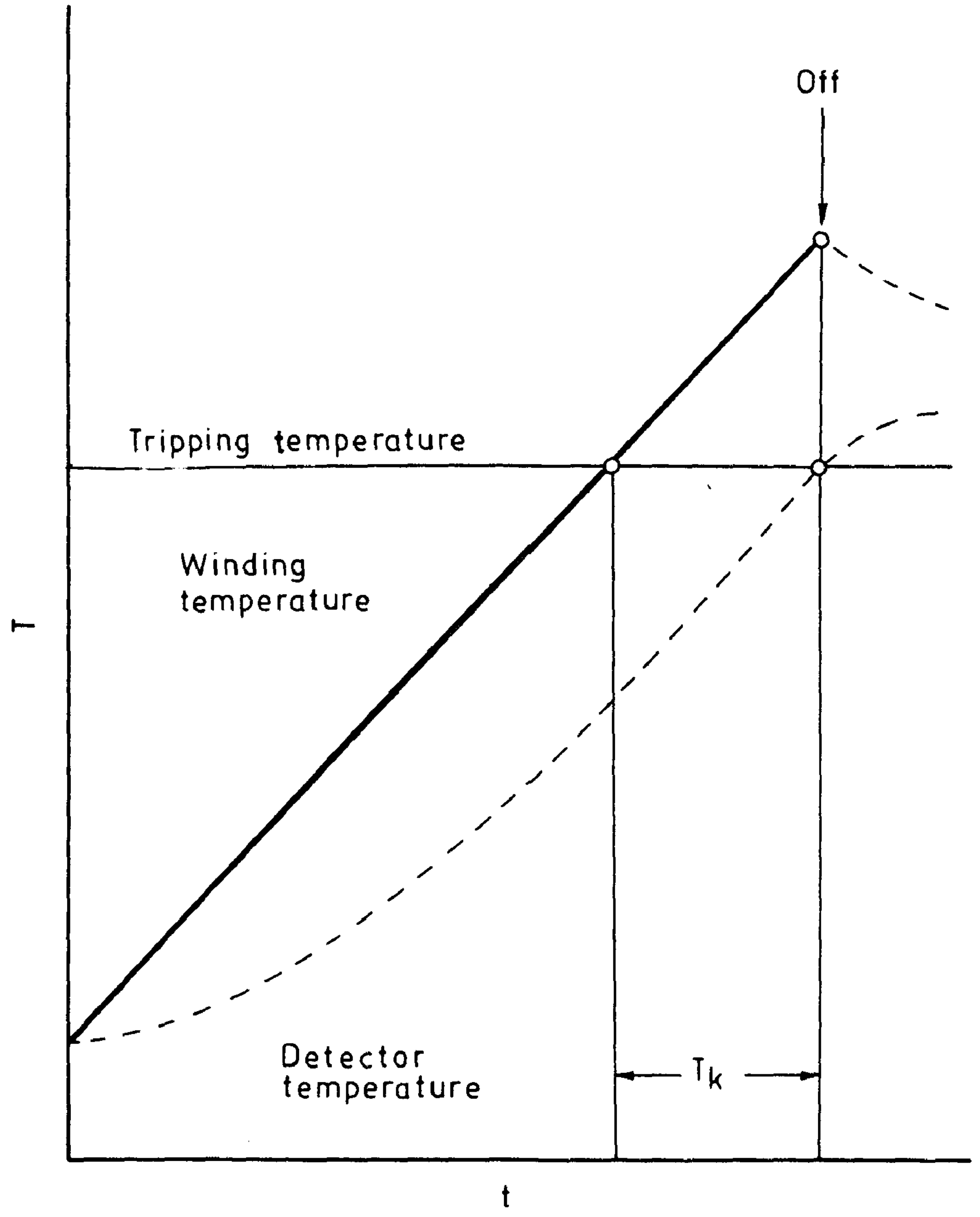
2.3.4 Significance of Thermal Time Constant θ

The θ-value for the internal thermistors should be representative for thermistors in all motors, since the thermal resistance and capacity of the thermistor system should not alter significantly with different motors.

The θ-value of external thermistors can be expected to vary with the size of the motor, since the thermal resistance and capacity of the winding and method of mounting are significant. It seems possible to estimate this effect, on the assumption that the current density in the winding does not vary significantly from motor to motor and that the thermistors are similarly mounted. This assumption have support of (a) Elementary text books on motor design and (b) manufacturer's data that allowable starting time for motor of the same type but different sizes is same.

On this assumption the heat generated per unit volume of the winding will be constant, but the surface area of the winding per unit volume will be in inverse proportion to the current rating and hence the size. If, as in the elementry text books we assume, the cooling effect is linear with temperature (at least in the end turns), then the surface temperature of the winding will increase with increasing motor size. Thus surface mounted thermistors can be expected to react more rapidly with larger motors.

The relation (1) has been derived because the thermal capacity of the temperature detectors and the heat transfer resistance of the insulating layers between the detectors and the copper conductors of the winding causes a delay between the temperature rise in the winding and that in the detectors. Fig. 11



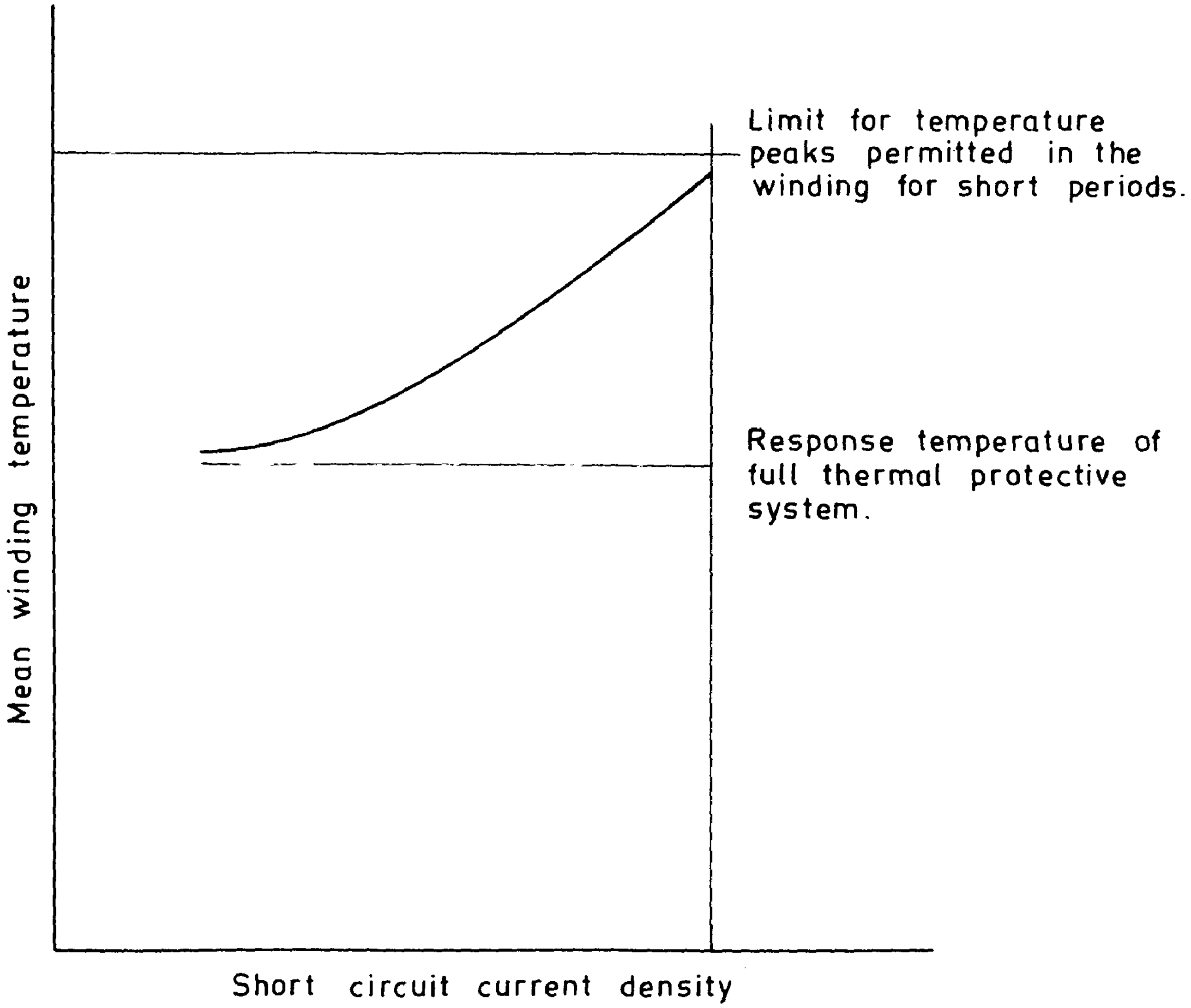
T_k = Coupling time
(time lag of temperature rise between detector and winding.)

Fig.11 – Temperature rise in the stator winding of a 3φ squirrel cage motor with locked rotor. The broken line shows the temperature variation of the PTC thermistor in the winding-up to the moment of tripping through the protection system.

Fig.11 shows the temperature rise in the stator winding of a three phase squirrel-cage motor with locked rotor. The broken line shows the temperature variation of the P.T.C thermistors in the winding upto the moment of tripping through the protection system. T_k = coupling time (time lag of temperature rise between detector and winding).

In case of heavy starting conditions or short-time heavy overloads causing a rapid temperature rise in the winding, for instance, the winding reaches a higher temperature than the temperature detectors. This temperature difference normally varies(4) between 10 and 40 deg. depending on the rate of rise which varies in proportion to the square of the current density.

The severest case of loading of motors could be. If motors of different output ratings and short-circuit current densities fitted with P.T.C thermistors are heated from the cold state under short-circuit conditions until the protection system response. In this condition the curve between mean stator winding temperature and short circuit current density (extrapolated to the tripping instant) will be as shown in Fig.12 . The curve goes upwards i.e. the temperature difference becomes larger, as the short-circuit current density increases.



g.12 - Mean stator winding temperature of a three phase squirrel-cage motor with locked rotor on response of the protection system, shown here as a function of the short circuit current density

To keep the temperature difference small, the volume of the detector and thus its thermal capacity should be reduced to a minimum.

2.4 Installation and Maintenance :

The conventional thermal overload relay is reasonably robust, cheap, reliable, and proven by many years of service. Since it is usually installed together with the motor contactor the installation cost is very small.

Commissioning and routine testing of such a relay consists of checking the time to trip at one or two points on the manufacturer's curve. Some industrial users make this check during commissioning or sample check relays on delivery, but many are satisfied to rely on the maker's factory tests alone. Very few, if any, make systematic routine checks.

The heater coil of the bimetallic element is usually the weakest part of the relay, and is comparatively easily damaged by mechanical forces and short-circuit currents. Because of this, magnetic overloads of the dashpot type are used in severe environments, in spite of their generally poorer characteristics.

In comparison, thermistors are best installed in the motor during manufacture, before the windings are impregnated

It is feasible to mount them on the winding surface, although this will reduce the heat transfer from the windings, increase the thermal inertia of the system and increase the temperature overshoot during faults.

Extra control wires are required between the motor and contactor, irrespective of where the thermistor relay is mounted.

The relay itself is the weakest link in the protective chain, since it usually comprises a small electromagnetic relay and electronic components. However, by reasonable design (e.g. an adequately robust relay suitable for industrial environments, and silicon components) the unit can be made proof against vibration, mechanical damage, and over temperature, and by separating the power and sensing circuits with an isolating transformer, electrical faults can be localised. Moreover, thermistor units are usually arranged to 'poor' their operation at each starter function as distinct from the overload relay which only operates during faults. Thermistor protection equipment can thus be as robust and reliable as the best of the other types of overload relays.

2.5 Disadvantages of Thermal Overload Protection :

A thermal overload does not provide adequate protection, against any of the following given conditions because it basically reacts only (1) to the current change, (2) in the 115 to 600% range, (3) to 3 - φ increase, slower on 2-φ increase and (4) with a time delay.

?

All the prob. conditions, except phase sequence, high ambient temperature contaminants, and overvoltage before saturation show a change under the 'variance' column in line current that can be differentiated from normal operating conditions (Table 1 in chapter 1) when change of direction of current +ve or -ve, (2) change of magnitude, (3) one or 3 φ change, and (4) the time interval of the change, are considered.

For instance, examine three of the prob. conditions.(1)

Parameter	Load Jam	Overload	Phase failure
Direction of ΔI	+ve	-Ve	+ve and -ve
Magnitude	600% of full load locked rotor	50 - 60% of full load no load current	173% max. on two phases if running at full load, less if not fully loaded 520% if at locked rotor, 0% on 3rd phase.
Phase change	all 3	all 3	1 -ve 2 +ve
Time interval	Instantaneous	Instantaneous	Instantaneous

In the case of a load jam condition, the time delay can result in 10 or 20 sec of equipment damage or ? burn out of a 'hot' motor before a thermal overload trips.

In the case of underload, the thermal overload will not even sense the condition.

Phase failure may or may not trip the thermal overload, based on motor load and heater application. For instance, a 70% loaded motor would give only 121% of name plate full load on two phases while running. If protected at 125% per NEC, the overload would never trip. Even if running at a full load, the trip time at 125% heater application can run to 10 to 50 m, while the prob. condition had occurred inst.(1)

When we compare these parameters against other prob. conditions, it becomes obvious that to obtain better performance, the motor circuit protective device should intelligibly compare the direction (s), magnitude and phase relations of any change in current and, based on the combination of these three factors, decide to trip inst. or with time delay.

Ease of APPLICATION :

The nature of the thermal overload results in trip curves that make it difficult at best for the motor control application engineer to properly apply and obtain even good motor overload protection when faced with the prob. of

1. wide variance of motor locked rotor withstand times from rating to rating and manufacturer to manufacturer.
2. Special application needs, such as large inertia
3. Wide band heater tables from all control manufacturers

Locked rotor withstandability :

In 1964, westinghouse redesigned its standard heaters to meet the 20-S criteria(1) established by NEMA standards. While this, in general, has proven adequate for locked rotor protection, we still find occasional prob. with some manufacturers motors having withstand time of less than 10 sec.

With this background , a permissible reasonable locked rotor time is to be seen that would not result in significant nuisance application prob. The acceleration time of westinghouse standard motors 1 to 100 hp., assuming a load equal to the inertia of the motor rotor. The results were that 100% accelerated in less than 1 sec. and 98% had locked rotor withstand of 20 sec. or greater while none had locked rotor withstand times under 15 sec.

Another criterion for improved performance was established that the device should permit at least 5 sec. locked rotor time but not more than 10 sec to provide good locked rotor protection and still prevent nuisance field probs.

Special application needs :

For decades, it has been standard practice that increase the heater size if trips occurred due to long acceleration times, high duty cycle, or reversing application but this always results in a decrease in the adequacy of the overload protection for every heater size increased to obtain just a couple more seconds locked rotor time, the running overcurrent protection level is increased approx. 10%. It is not uncommon to find motors with thermal overloads applied that would permit infinite operation at 135 to 140% of full load current.

Conversely, any increase in heater size to permit occasional overloads due to the application need increases the locked rotor trip time by 2 or 3 sec. per step, further compounding the locked rotor withstandability motor burn out prob.

These two conditions are a result of the fact that a larger heater shifts the entire curve, both running and locked rotor ends, rather than just that portion needed to permit motor operation. The curve in Fig. 13 illustrate this point.

The application need suggests that better performance will result if only that portion of the curve required to permit successful operation could be altered.

Wide-band Heater Tables :

Even when locked rotor withstand of the specific motor and duty cycle or acceleration time required for the particular application is known, still does not know if one is providing protection. Suppose there is a class 20 overload heater ~~the-e~~ this means the heater/overload combination must trip in 20 sec. or less at 600% current. Typically, with approx. 7 sec. heater styles between 1 and 135 A, locked rotor trip times very for approx. 12 to 20 sec. If the motor has only 15-sec. withstand capability, the heater may or may not protect. If the load requires 17sec. acceleration time, a given heater may or may not permit acceleration. Unfortunately, it would be required to look at each and every heater curve and factor in manufacture tolerances to make a proper application. This suggests the desirability of a package with a well defined curve that is the same weather the application is a 1 or 125-A load.

Coordination with S.C. Protective Device :

Through destructive testing of motors, it can be found that most motor failures will result in fault current levels in a range of 10 to 20 times motor full load current.

With the long clearing times at low level fault current significant damage can result in all parts of the motor circuit. However, recognizing that any time line current exceeds locked rotor current, something radical is wrong, the objective should be to clear that fault as quickly as possible. The MCP breaker set at greater than locked rotor but less than the 10 X interrupting capacity of the contactor provides this fast response time, minimizing ckt.damage. The overload responds to currents less than or equal to locked rotor, and the MCP responds to currents greater than locked rotor. Coordination of circuit components is always achieved without the need to refer to curves or go through complex calculation.

Uptil now a variety of prob. conditions in the motor circuit have been discussed. The prob in circuit occurs due to changes in :

1. current
2. direction
3. magnitude
4. phase relation

and 5. time

Now it has also been defined that for improved performance in protection as the ability to sense these variances independently and make a decision on when to trip based on what combination occurs.

The criteria for ease of application should be as

1. locked rotor trip time, with minimum of 5 sec, maximum of 1 sec.
2. The ability to conveniently shape the curve to meet special application needs and
3. a well-defined curve that is predictable and consistent regardless of current rating.

The package must be economical enough to justify application on even small h.p. motors.

CHAPTER - III

CONCEPTUAL APPROACH TO MOTOR PROTECTION

Now a days, the integrated circuits find their very wide field of applications. The very fundamental thinking woul be that produces the package to provide performance which count in solving the above said problem in the real world of user applications.

To observe this performance, three elements will have to be required.

(i) A means to sense the line currents and transform them into some reference that can be used by the logic to make a trip decision.

(ii) The logic that looks at these references, makes the decision, and provides a trip signal, and

(iii) An output element that accepts the trip signal and interfaces it to a contact opening sufficient to interupt the contactor coil.

3.1 Problems of Motor Protection :

These have not been finally solved even with the best of the generalised relays available today. Ideally, each relay should be custom built for the particular machine it is protecting. Alternatively, it should have infinitely variable setting with a wide selection of curve shapes, continuously variable sensitivity to negative sequence currents.

To get closer to the ideal service with a practi design, close cooperation must exist between motor and relay manufacturers. Motor manufacturers must give mor accurate and detailed specifications of motor characteristics; heating curves, degree of thermal conductivity between stator windings, cooling characteristics, skin effect factor, hot spot data, etc. When motor users demand this type of information, realizing that the retu on their investment and continuity of service they can expect from these motors depends largely on the protection provided, many advances can be expected further in the effectiveness of motor protective relays.

3.2 The requirements of protected machine on the protective relay

(a) To prevent damage to equipment owing to exter faults (in the case of motors, for example, owing to mechanical overloads).

(b) To limit the extent of the damage during internal faults (insulation failure, for example).

(c) To limit the extent of the disturbance to oth equipment connected to the same supply.

(d) Not to reduce the reliability or availability of the equipment.

It is not economically possible to protect all equipment to this extent against all potential faults. A compromise must be found between the probability and cost of faults and the cost of protection.

Motors are normally provided with a short circuit protection (fuses) ~~and an overload protection~~ (fuses) and an overload protection. The fuses are used primarily to reduce the disturbance to other equipment connected to the same supply, on the assumption that the motor has suffered an internal fault. It is not economically justifiable to try to limit the internal damage to small or medium-sized motors, since almost any winding fault is repaired by completely rewinding the motor. The fuses are sometimes also intended to disconnect the motor in cases of severe overloads, but the overload relay is normally expected to protect for this and all other overload conditions.

The common overload faults (single-phasing, under-voltage, too frequent starting, mechanical overloads, etc.) cause overheating and consequently winding insulation failure. The mechanism of such a failure is not simple. The common insulations (Class A and Class B) are both subject to temperature dependent ageing. As a rule of thumb the insulation life halves(3) for each 8 to 10 deg. C increase in continuous temperature above a certain limit, but is

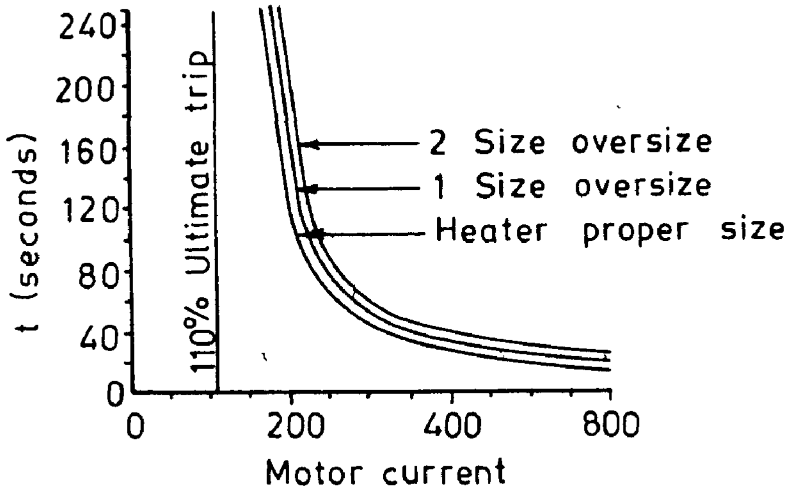


Fig.13

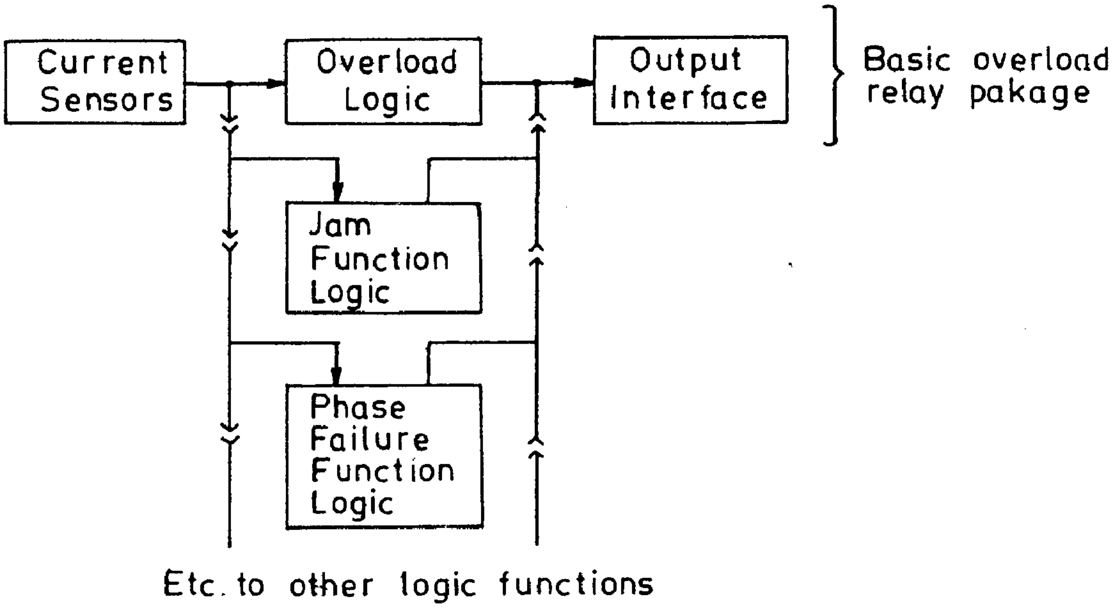


Fig 14

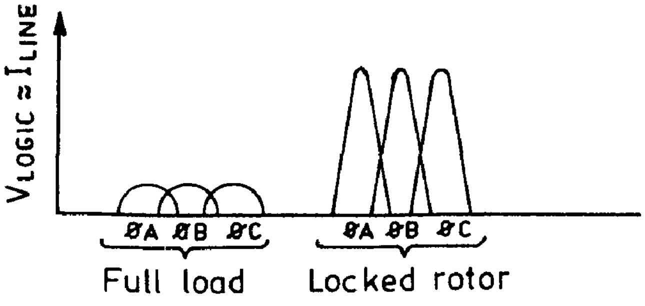


Fig.15 - D.C. logic reference voltage from C.T.

unaffected by transient, moderate overtemperatures. On the other hand, one of the characteristics of the induction motor is that considerable reserve torque is inherently available for emergencies. The ideal overload protection would thus be one which matched the temperature-time characteristics and history of the motor. This is apparently not economically possible, so certain compromises are made.

3.3 Schematic approach to motor protection:

In keeping with the objective of being economical, one thing becomes very obvious. If the circuit could be designed so that the sensors and output were common, approximately 50%(1) could be saved for each trip function required, as opposed to building discrete devices for each function.

This, then, dictates packaging approach. Build a basic overload complete with sensors, output, and overload logic per criteria established, then make the other functions by simple addition to the basic overload, using the same sensors and output. This is shown in the block diagram in Fig. 14

3.3.1 Basic Overload package :

In a molded case, very similar to a 3 pole thermal overload relay block, 3 small C.T's, output contact terminals just like the thermal overload can be packaged. This will mate to the contactor to form a starter which will be little different from a standard starter. The C.T's go through a 3

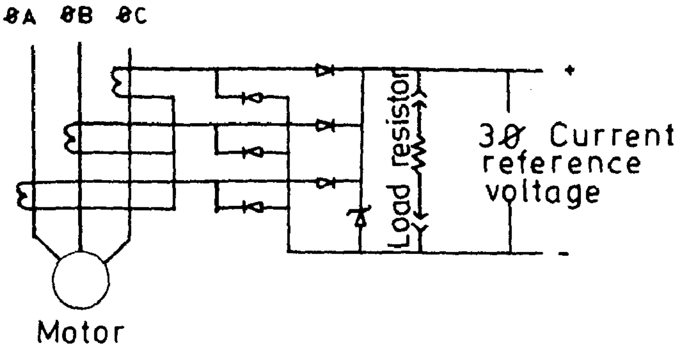


Fig. 16 – Current sensor/reference voltage schematic

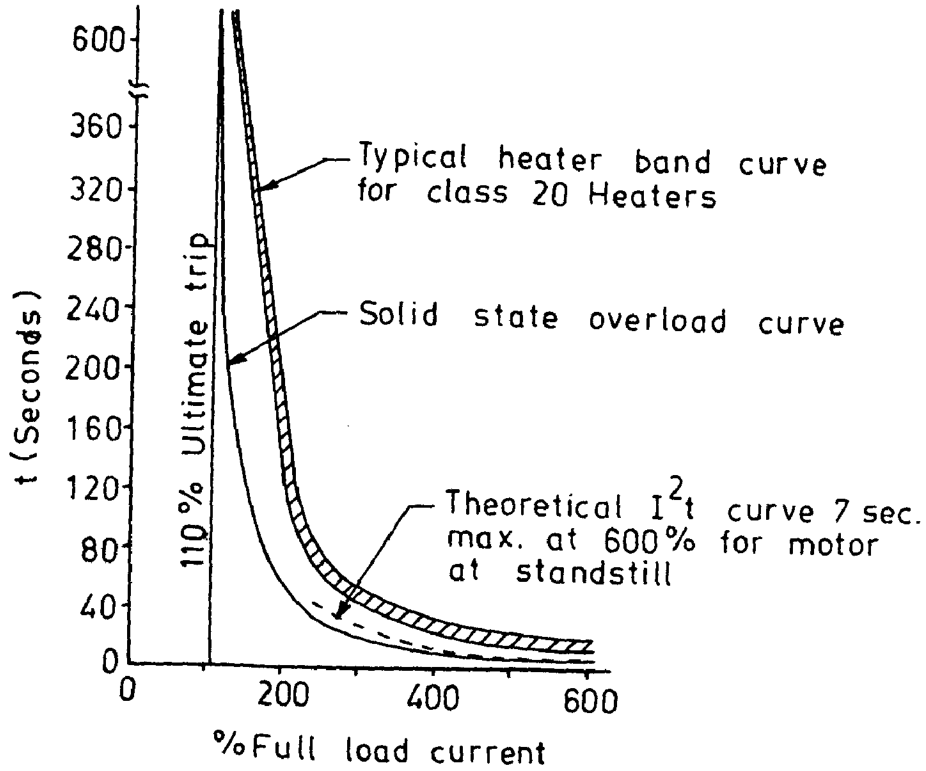


Fig. 17 – Time current curve

phase rectifiers and are loaded across a resistor, providing three voltage reference , one for each phase that is proportionate to the line current on each phase. This logic signal is shown in Fig. 15 . The circuit to achieve this is shown in Fig. 16 .

It can be noted that the load resistor will determine the constant in the relation $V_{ref.} = f(EI\phi)$. The load resistor is shown as a plug in component. This is done to further duplicate the convenience of interchangability with standard overloads. The basic overload carries one style number, and a specific resistor style number is plugged in to determine the current rating needed. This is directly equivalent to placing heaters in a thermal overload, with one minor but important difference.

The resistors from rating to rating have a constant relationship, while heaters change characteristics slightly from material to material for different sizes. This fact plus close tolerances on all components, results in a time current curve which will be a band for a particular range of currents. The designers from here can now know and have confidence in what the curve looks like.

The next step will be to use this logic signal and use the electronic circuits to shape the time current curve to meet the criteria. One can wind up doing following things :

(i) Establishing trip time at 600% locked rotor
(ii) Applying 'heater' for ultimate trip at 110% and,
(iii) Keeping the basic curve below approximately 250% o below starting torque very close to the I^2t curve.

This is based on the fact that the motor will have small heat dissipation at stand still over start time and thermal capacity close to I^2t R where R = constant.

These criteria will result in electronics providing a trip signal based on the typical curve shown in Fig. 17 . For comparison, typical I^2t and thermal overload curves are also shown.

By successfully matching these curves, the basic overload can be completed and will provide improved running over current and lock rotor protection. Next is the designing of special function logic modules which can use the 3 phase voltage reference available and provide a parallel trip signal to the output contact.

The plug-in resistor gives a ready access to the reference voltage. All now needed to do would be to provide an additional access point to the trip signal.

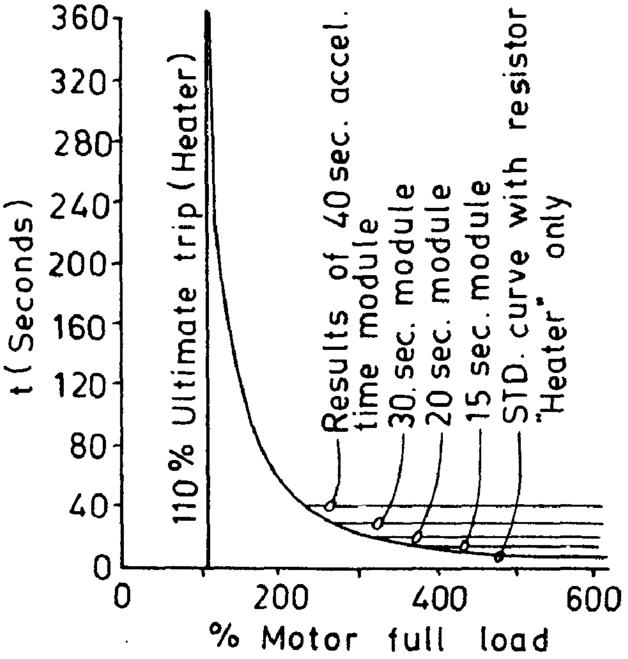


Fig.18 - Long acceleration time module

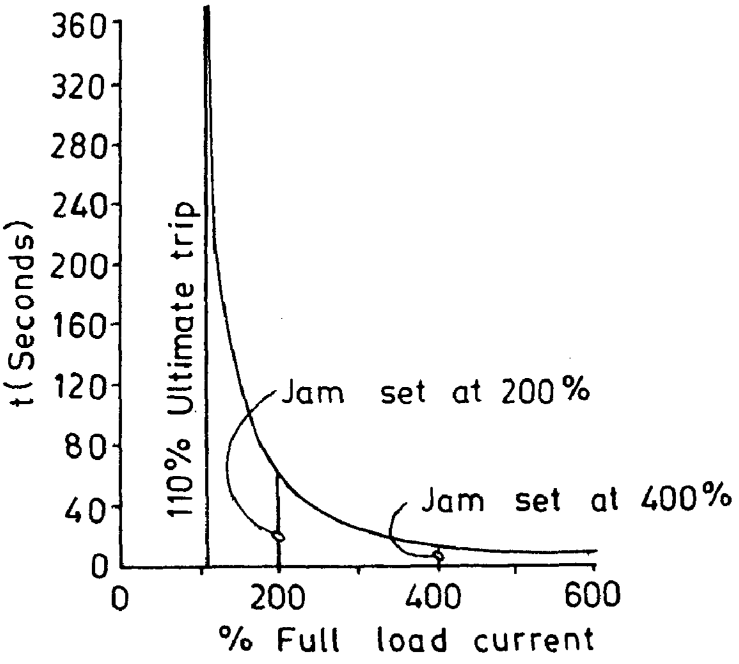


Fig.19 - Effect of jam function module

3.3.2 Long acceleration time module :

A single style number long acceleration time module can be plugged in the base overload. It has a thumbwheel setting that can be adjusted from approximately 10 to 40 second and will result in a multitude of possible curves, as shown in Fig. 18 . This module however, has one significant difference from previous methods to permit long acceleration time, it reverts to the normal overload curve after the permitted acceleration time, providing improved running overload protection. Saturable shunts or dash pot type relays will require the same time current conditions to trip from a running condition as from a starting condition.

3.3.3 Jam function module :

The jam function module provides an instantaneous trip should current exceed a preset value at any time after the motor has accelerated. Its function is shown in Fig.19.

During start, the motor is protected in the region above the jam setting by the standard curve. For running condition below the jam set point, the motor is protected by the standard relay curve. The jam module will operate only when running current exceeds its set point, which is adjustable for any value between 150 and 400%. This unit is often used in material handling applications but also finds applications in such areas as pumping and air handling where

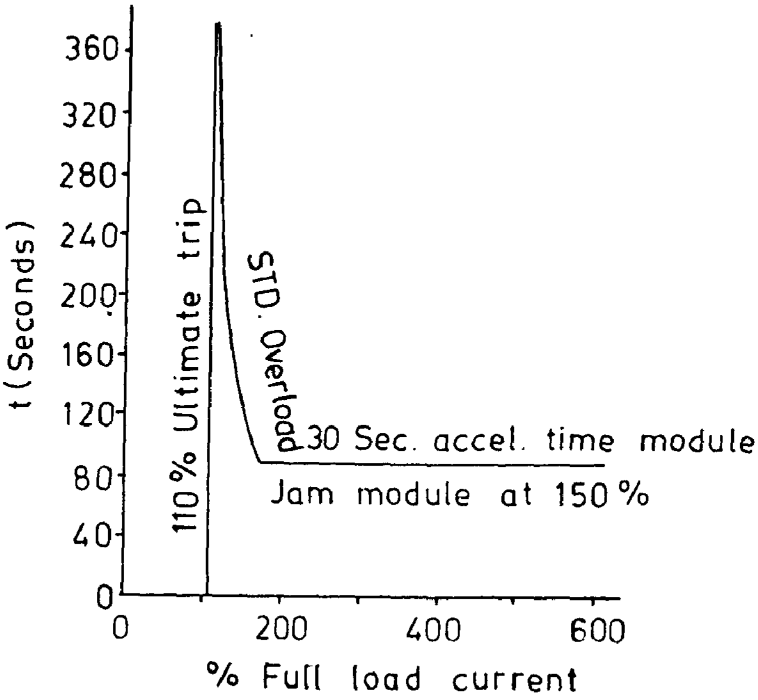

360
320
280
240
200
160
120
80
40
0
t (Seconds)
110 % Ultimate trip
STD. Overload
30 Sec. accel. time module
Jam module at 150 %
0
200
400
600
% Full load current

Fig. 20

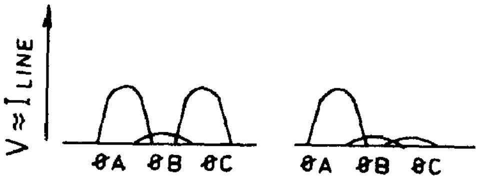

V ≈ I LINE
θA
θB
θC
θA
θB
θC

Fig. 21

any current, say, above 120% or so, indicates something radically wrong, such as a broken impeller, and it is desirable to minimize damage that would occur in the 7 sec(1) required for the overload to trip on locked rotor. Some applications, such as a compressor with long acceleration time, may use both a jam function module and long acceleration time module.

As shown in Fig. 20 , during acceleration the motor would be permitted to operate in the area below and to the left of the standard curve and 30 sec. acceleration curve. After coming to speed, it can operate only in that area to the left of the standard overload and jam curves. This combination permits the long acceleration time required but trips with time delay for operating overloads and instantaneously for current values over the 150% set point of the jam module. If the jam is not used, the motor will lock up for up to 30 sec. doing significant damage.

3.3.4 Phase Failure Module :

This unit looks at the 3 phase voltage reference and provides an instantaneous trip signal should any phases go to current zero. The unit has a 16 ms built-in time delay to permit initial starting when all phases are at current zero.

The reference signals it recognizes as requiring it to operate are shown in Fig. 21 .

Being current sensitive, it is not subject to voltages induced in the motor by remaining phases and as such operates properly without respect to the location of the motor in the distribution system.

Requiring no panel space or wiring as compared to a separate phase failure relay, it is an economical protective package on applications such as pump panels or roof top ventilators when the control is not manned, and due to fuse protection there is likelihood of phase failure protection.

3.3.5 Underload Module :

This module has a dial adjustment that permits setting its pick up value just above the individual motors no-load current. Whenever current fall below this set value (i.e. to No-load value) it provides an output trip signal. When interlocked with other parts of the system, it prevents damage because of a broken belt, shaft, or coupling in one part of the system. It will also provide good protection against pump damage due to loss of suction where the liquid flow is required to keep the pump within safe operating temperatures. In this application, the pick up point would be set slightly above the running current of the motor with the pump running dry.

3.3.6 Phase Sequence Module :

This module must be wired to the primary side of the contact to sense the line phase rotation. If wrong, it provides a trip signal which locks out the contactor and prevents it from picking up. It is most often used in portable equipment when frequent hookups increase the odds of incorrect sequence and damage can result if the motor runs in reverse.

3.4 To protect the motor completely even with best of the relays available is still a problem. A relay with infinitely variable settings and a wide selection of curve shapes is required to protect a motor.

The best application of the relay demands the very cooperation of the motor manufacturers that they must give accurate and detailed specifications of motor characteristics, heating curves, degree of thermal conductivity between stator windings, cooling characteristics, skin effect factor, hot spot data etc.

Advances are still awaited to improve the motor protection relays.

CHAPTER - IV

A NEW SOLID STATE RELAY FOR THE PROTECTION OF INDUSTRIAL MACHINES

4.1 The scheme makes use of solid state devices. Overcurrent and impedence characteristics have been realised by making use of analog/digital circuits. The distinct advantages of high accuracy, high speed of response and considerable reduction in size of the unit have been tried to make use of. The relay has the provision to protect the machine from overtemperatures. The relay can be set to any operating condition depending upon the need of application. The relay has been successfully fabricated and tested in laboratory. The performance in experimentation has been found to be quite satisfactory.

4.2 Introduction :

The overcurrent relays are used where the minimum fault current exceeds the maximum load current. The relay having characteristic equation $I^2t = k$ is desirable for protection of apparatus against overheating as $I^2t = k$ is also the current versus heating characteristic of most apparatus.

4.2.1 The ordinary Inverse Definite Mean Time (I.D.M.T.) time current curve is not suitable for motor protection. The motor heats according to an I^2t function and good protection is provided by thermal overcurrent relays using bimetallic spiral movements. The slow reset of these relays prevents restarting the motor unit it has cooled. Furthermore, the heat storage

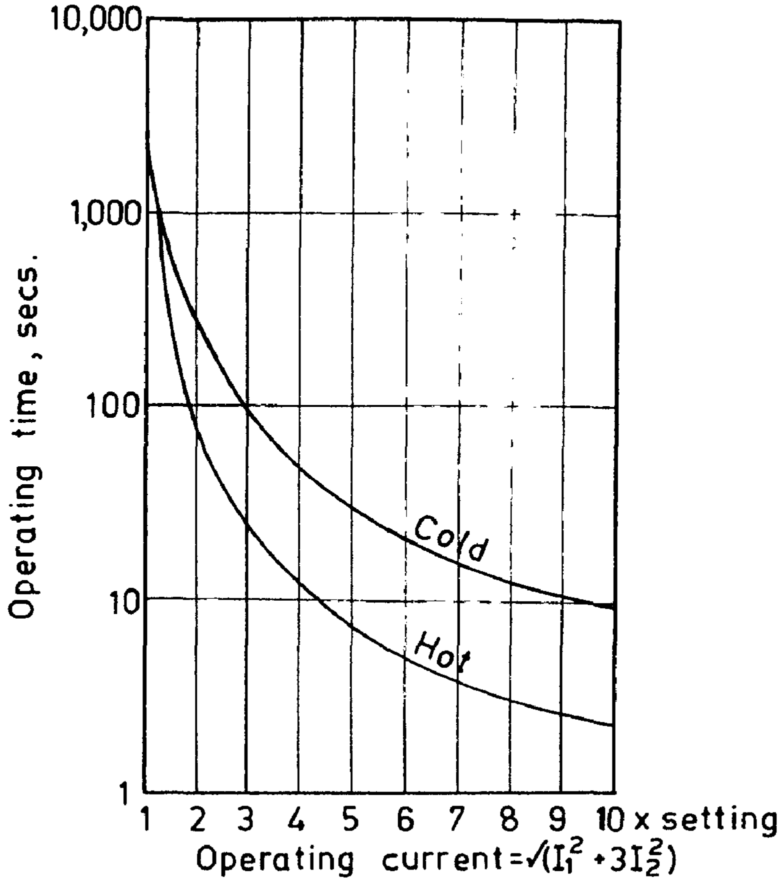


Fig. 22 - I^2t characteristic for motor protection.

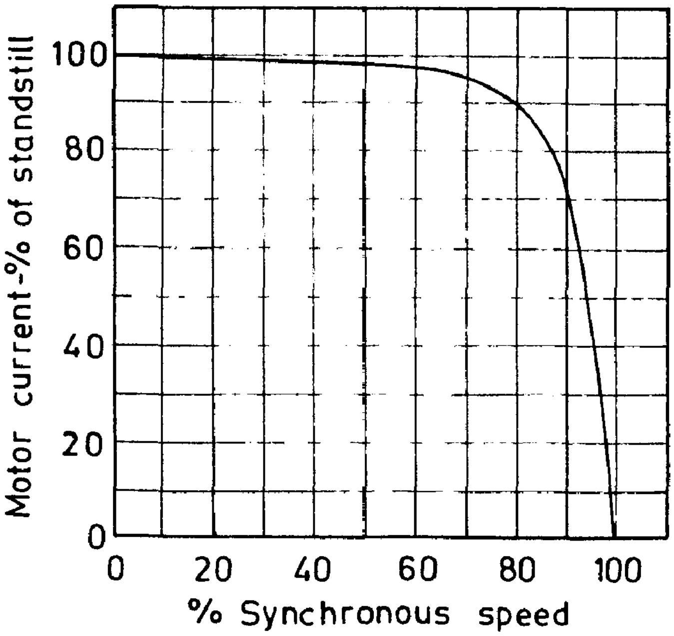


Fig. 23 – Typical motor starting speed - current curve.

property of the relay gives it different hot and cold time current characteristics which correspond to those of the motor (Fig. 22). Superior characteristics can be obtained with a thermistor bridge and a thermal replica device.

In single phase fractional h.p. motors the thermal element usually takes the form of a bimetallic disc which snaps into the operated position above a certain temperature and opens the supply.

The I^2t relays are set(9) to operate on 15% overload with continuously rated motors and upto 40% overload with motors having overload capacity, depending upon the service factor.

When a motor stalls, either due to trouble with the connected load or low voltage, both the stator and rotor windings will be overheated. Some form of protection should be provided to shut the motor down before the locked rotor current persists long enough to cause damage, but it must not shut the motor down during a normal start. It is not always possible to provide adequate locked rotor protection with the overload device without upsetting the overload protection.

The best protection is provided by a thermal device which is only operatable during a stalled condition. Tripping will occur if motor current fails to fall to normal value within the time-current characteristic of the thermal unit. The characteristic curve of the thermal unit is shown in Fig. 22

for starting (cold) and running (hot) conditions. The relay can also be arranged to give restart once after a stall, and to lock out if there is a second stall.

The thermal element also incorporates an indicating device which integrates current during the starting period. The trip setting can be set at a slightly higher value than the indicated value during starting, thus providing the maximum possible protection against a stalled condition.

Overload relays also take care of faults not heavy enough to operate the instantaneous overcurrent relays. Larger motors use temperature detectors.

4.2.2 Motor Currents during starting and stall conditions :

The magnitude and duration of motor starting currents and the magnitude and permissible duration of motor stalling currents are major factors to be considered in the application of overload protection. It is commonly assumed that for machines started direct on line the magnitude of the starting current decreases linearly as the speed of the machine builds up during starting.(19) This in fact does not apply to any machine and for normal designs the starting current remains sensibly constant at the initial stand still value for 80-90%, of the total starting time.

The rotor current of an induction motor corresponding to any value of slip S can be shown to be equal to :

$$I_r = \frac{kS}{\left(\frac{R^2}{S^2} + X^2\right)^{\frac{1}{2}}} \quad \ldots \quad (1)$$

From Eqn. (1) and assuming that the machine reactance is equal to ten times the machine resistance, the starting curve of the machine can be derived as shown in Fig. 23

Eqn. (1) indicates that in the case of motors with low rotor resistance $(R/S)^2$ only becomes large compared with X^2 as the value of slip becomes small. Thus as shown in Fig. 23 the starting current remains substantially equal to the current at stand still until the motor is almost upto normal running speed.

In determining the current and time settings of the overload protection it normally assumed that the motor starting current remains constant and eq ual to the standstill current for whole of the starting period.

4.2.3 Stalling of Motors :

Should a motor stall when running or unable to start due to excessive load it will draw a current from the supply equivalent to the locked rotor current. It is obviously desirable to avoid damage by disconnecting the machine as quickly as possible if this condition arises.

It is not possible on a pure current magnitude basis to distinguish between this condition and a healthy starting condition, the only possible means is to arrange the protective device to disconnect the motor if the current continues for longer than the normal starting time.

The majority of loads are such that the starting time of normal induction motor is under ten seconds while the allowable stall time to avoid excessive deterioration of the motor insulation is in excess of 20 seconds. It is thus relatively easy to discriminate on a time basis between the two conditions.

In the case of motors used for special applications (for example, motors driving high inertia loads) the starting time may be prolonged and the safe allowable stall time becomes nearly equal to the starting time, making the problem of discrimination between the two conditions much more difficult. In these cases, depending on the type of relay used for overload protection, it may be necessary to use a relay especially to protect against stalling condition. whether additional stalling protection is needed in any application depends mainly upon the ratio of the normal starting time to the allowable stall time and the closeness with which the overload relay can be set to match the stalling time-current curve without the possibility of mal operation on a healthy start.

The thermal overload relay, in which a bi-metal spiral in proximity to a heater acts as the contact actuating device, has a fairly high percentage overrun of the order of 45%(13) at six times rated current. If a relay of this type has for instance an operating time of 20 seconds at 6 times rated current, then the maximum starting time of any motor having a starting current of 6 times rated current to which this relay was applied, could not exceed 11 seconds, whilst the motor would remain connected to the supply under stalling conditions for the normal operating time of the relay i.e. 20 seconds.

Due to this large percentage overrun an additional singl phase relay similar to the type described above is sometimes us to provide adequate protection against stalling conditions. When used, this relay is provided with an instantaneous under current relay which disconnects the relay trip circuit when the motor starting current drops to a certain value, usually 3 times rated current. By this means the effect of the overrun on the relay is eliminated and a shorter time setting for stalli conditions is possible.

The above assumes that the motor remains connected to a three phase balanced supply, but the most likely cause of stalling in induction motors is the loss of one phase of the supply due to e.g. to the blowing of a back-up fuse by the inrush current when the motor is first energised. Under this condition the motor would fail to start and would remain stationary with a single phase supply applied to the stator terminals. Also, the motor may stall if one phase becomes open circuit while the motor is running, depending on the load on the machine at time of the open circuit. The actual value of the current drawn by the machine will be less than the three phase stalling current, being equal to 0.866 of this value, however, excessive overheating of parts of the rotor winding is likely to cause.

With a balanced three phase supply applied to the machine a rotating flux is induced into the rotor which causes symmetrical heating of the rotor winding. With unbalanced supply voltages, as in the case of the loss of one phase, there is a pulsating flux induced in the rotor which is the sum of the fluxes due to the positive and negative phase sequence currents; this causes unequal heating of the rotor winding depending on the position of the rotor bars.

Under all those above mentioned conditions the motor is protected by the new suggested relay.

4.3 Principle of Operation :

The principle of operation of the proposed scheme can be explained by, firstly explaining the operating principle of various basic and special electronic circuitry.

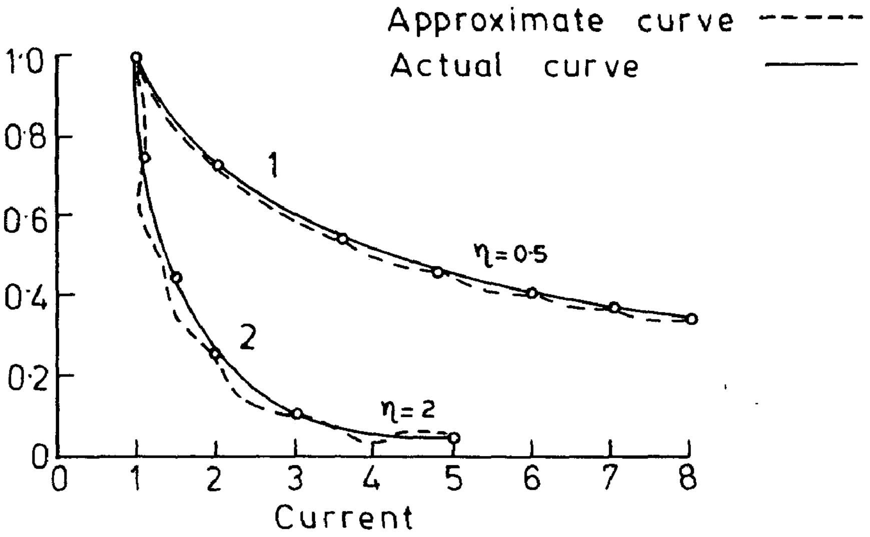
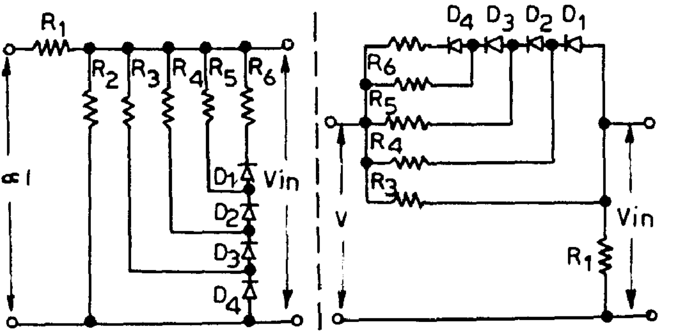


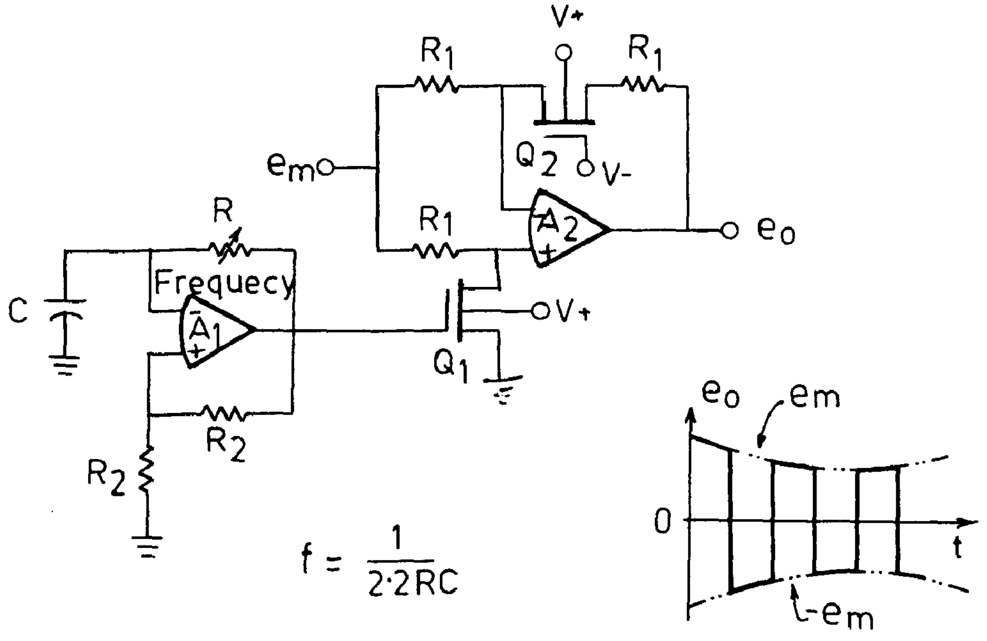
Fig. 24(A) – Current - time characteristic



DIODE FUNCTION GENERATOR FOR η<1
(a)

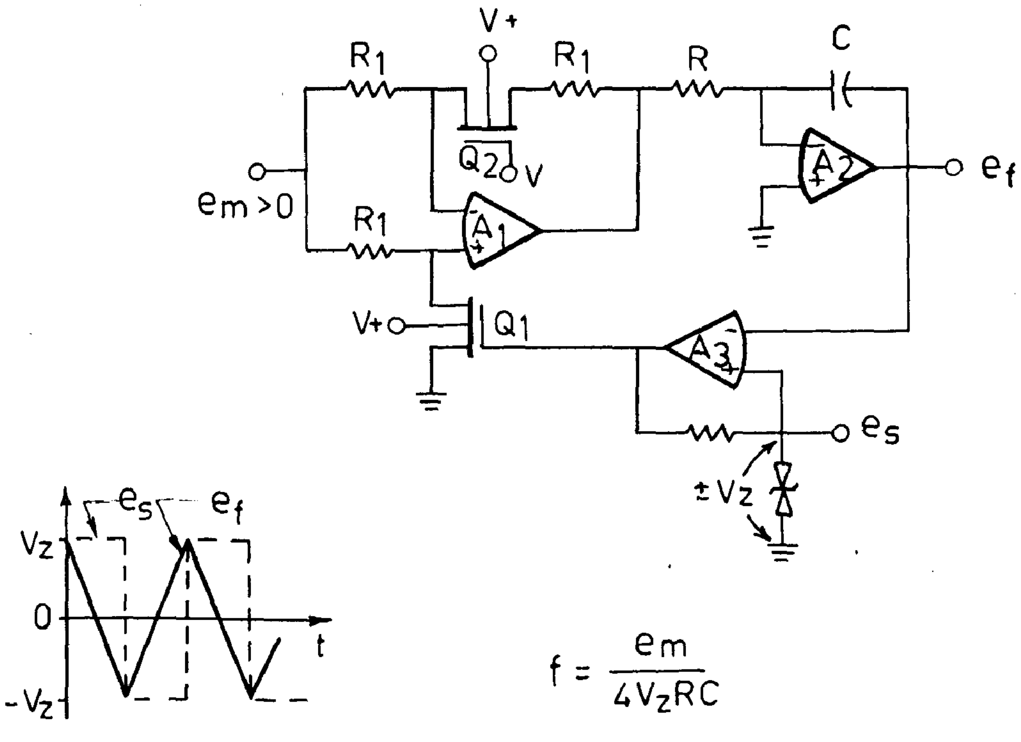
DIODE FUNCTION GENERATOR FOR η>1
(b)

Fig. 24 (B) - Diode function generator



$$f = \frac{1}{2 \cdot 2RC}$$

Fig. 25 – An amplitude-modulated square wave generator



$$f = \frac{e_m}{4V_zRC}$$

Fig. 26 – Voltage control oscillator

4.4 Constituents of Overcurrent Relay :

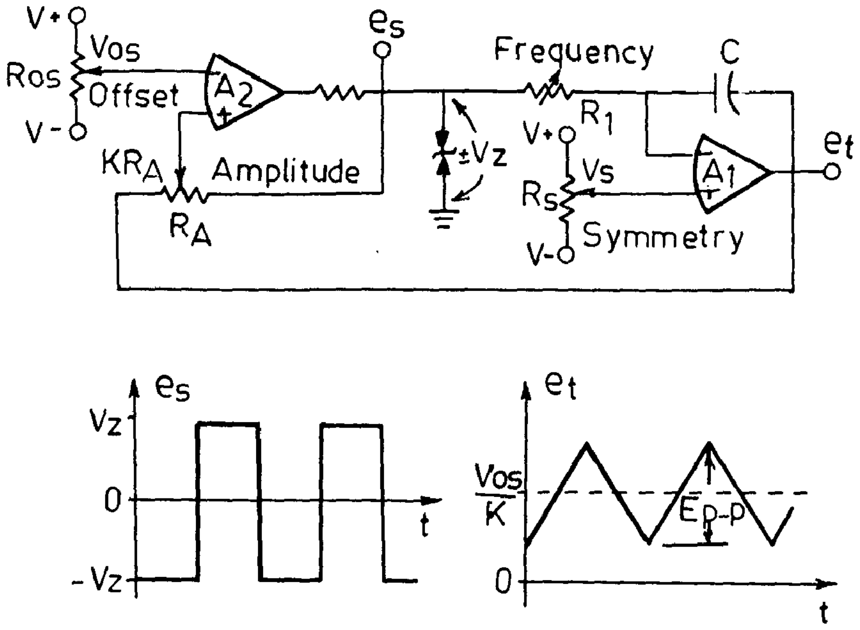
4.4.1 Diode Function Generator :

The time-current characteristics curve has been realised for $n > 1$ (i.e. $n = 2$). Fig. 24A shows the time current characteristic curves (1 & 2) for $n < 1$ (i.e. $n = .5$) and $n > 1$ (i.e. $n = 2$). These characteristics curves (1 & 2) have been realised by making use of diode-function generator shown in Fig. 24B(a) and Fig. 24B(b), respectively. The characteristics have been realised by dividing each curve into 'n'-number of segments of different slopes. The basic principle for $n < 1$ has been explained in references 21, 22 and 23. If the circuit shown in Fig. 24B(b) is used in place of circuit of Fig. 24B(a), the time current curve shifts to match the curve-2 for $n > 1$ as shown by dotted curve.

4.4.2 Voltage Controlled Oscillator :

Voltage Controlled Oscillator can be formed with the aid of the square-wave amplitude modulator as shown in Fig. 25.

Modulation of the amplitude of a square-wave input to an integrator varies the integration time between comparator tr points. By this control over integration time, a frequency modulation is attained with the integrator/comparator configuration, as shown in Fig. 26. The basic generator consists of integrator A_2 and comparator A_3, with operation as described in Fig. 27. Added to the normal



$$S = \frac{V_z - V_s}{V_z + V_s} \qquad E_{p-p} = 2V_z\,(1/K - 1) \qquad f = \frac{V_z^2 - V_s^2}{2E_{p-p} V_z} \cdot \frac{1}{R_f C}$$

Fig. 27 - Comparator feedback around an integrator produces precise square and triangle waveforms that are highly controllable.

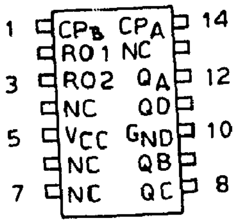
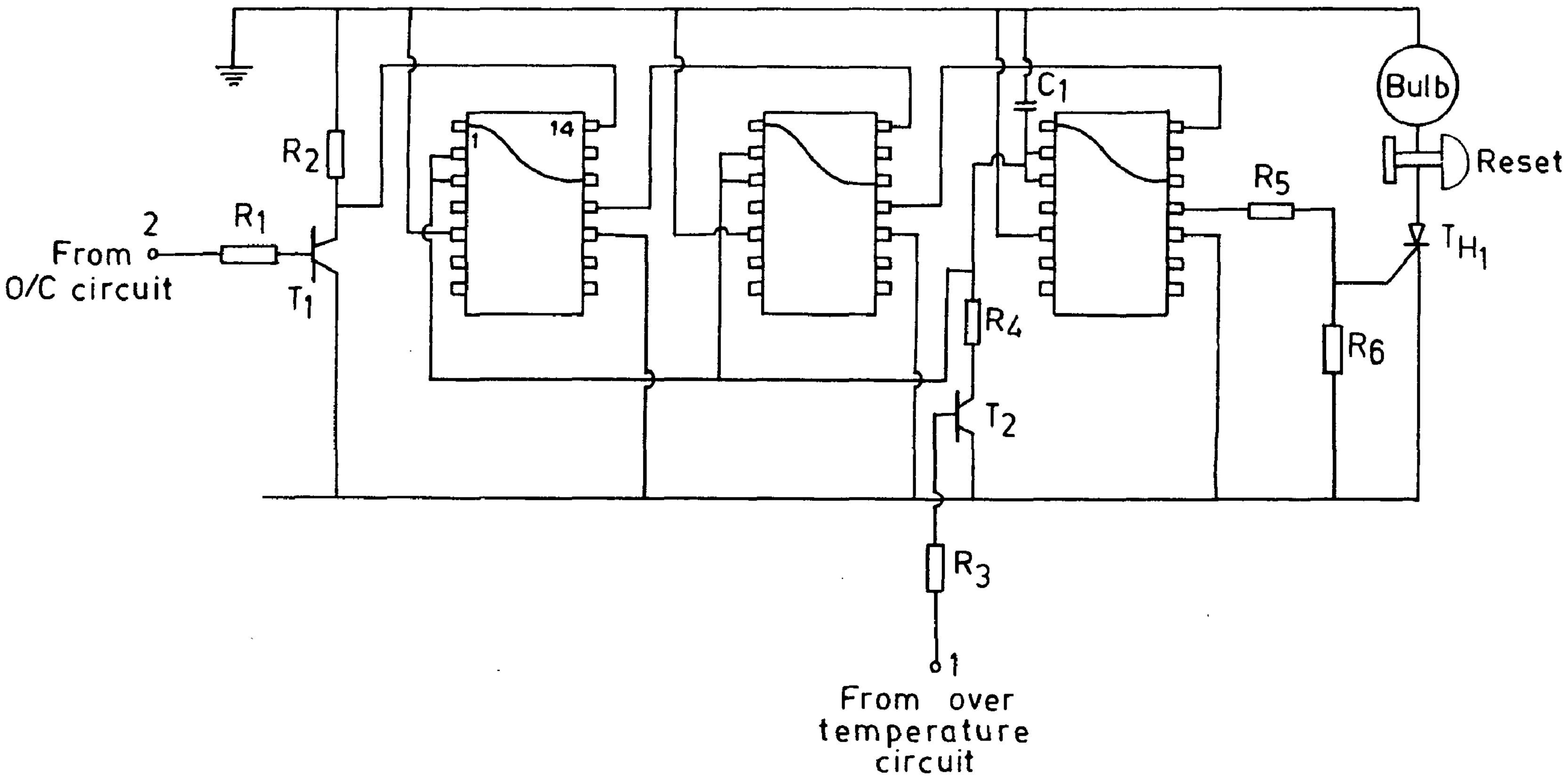


Fig. 28 - I.C. 7493 (Binary counter)



Time delay circuit

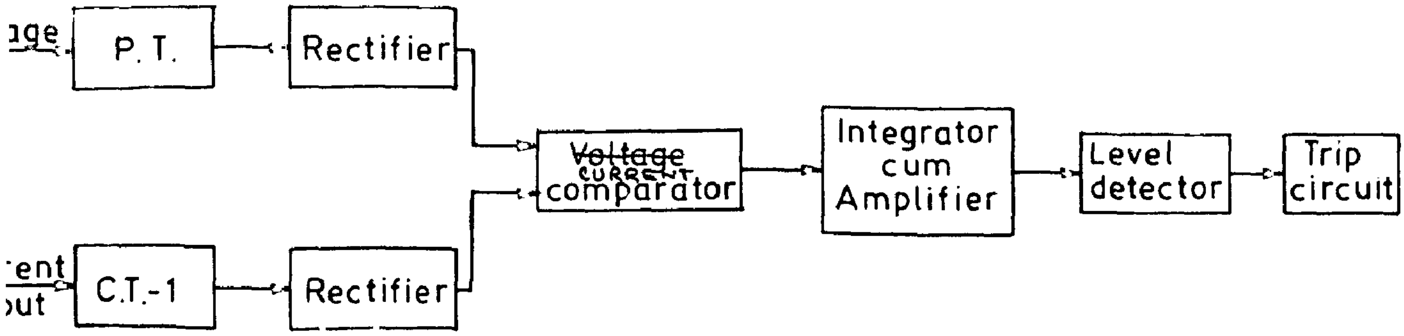
feedback loop is the modulator formed with A_1. The polarity of the gain provided by A_1 to e_m reverses each time the integ output reaches a comparator trip point and causes the comparato to reverse the state of switch S_1. Reversing the state of this switch converts the amplifier configuration from that of an inverter to a follower, and this reverses the polarity of the modulation signal reaching the integrator input. With either gain polarity, e_m controls the magnitude of the integrator inpu voltage and thereby controls frequency by the relationship[27]

$$f = \frac{e_m}{4\ V_Z\ RC}$$

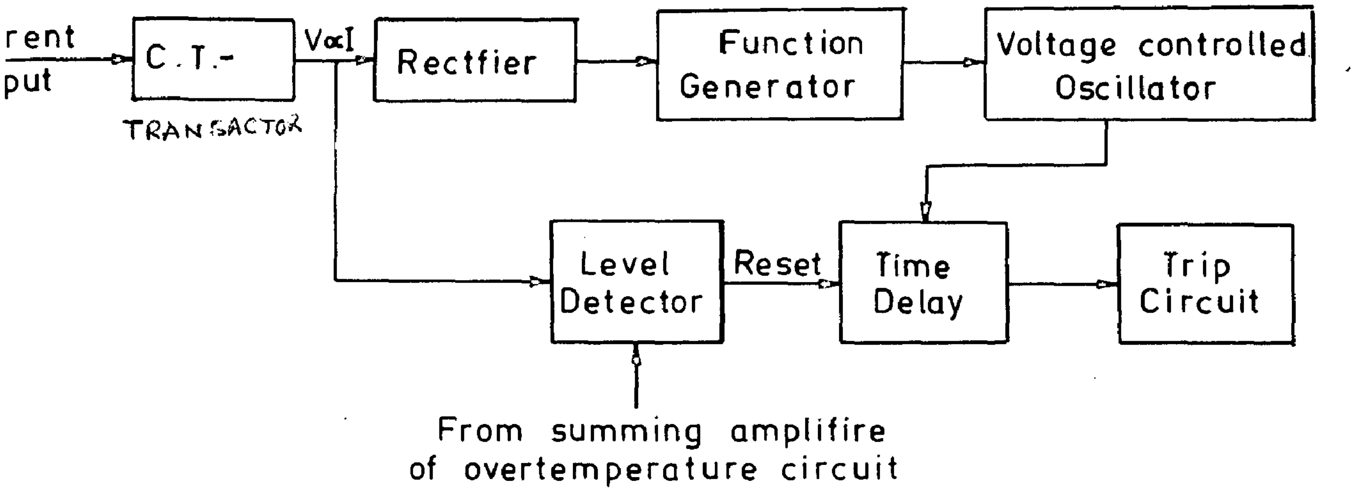
4.4.3 Time Delay Circuit[26] :

The delay has been provided by making use of I.C. 7493 which is a 4-bit binary counter consisting of four master/slave flip-flops which are internally interconnected to provide a divide-by two counter and a divide by eight counter. The counter has a gated direct reset line which inhibits the count inputs and simultaneously returns the four flip-flop outputs to a low level.

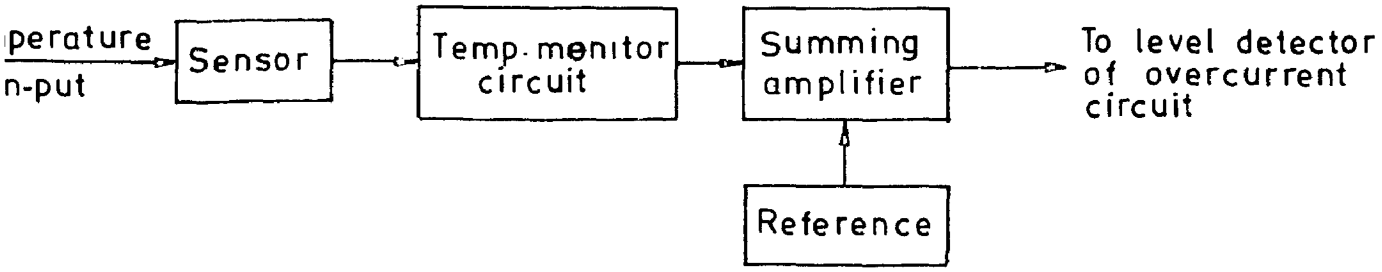
The I.C. 7493 has been used as a 4-bit ripple through counter for which Q_A has been connected externally to input $\overline{CP}_B$ The input count pulses are applied to input $\overline{CP}_A$. A division of 16 has been performed by selecting Q_D as output. The I.C. 7493 is shown in Fig. [illegible].



Impedence starting



Over current and time delay



Over temperature

Fig. 29 – Block diagram of the different circuits

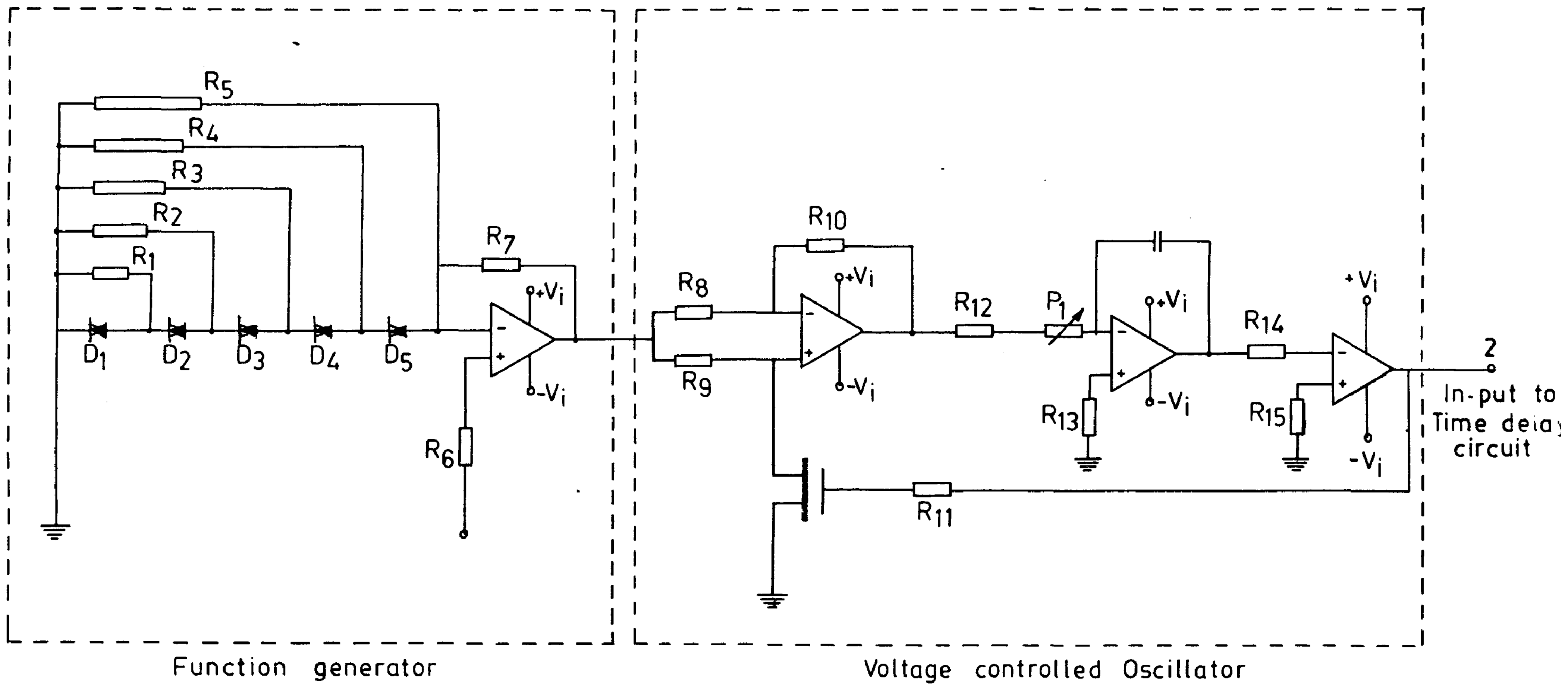


Fig.30 – Over current relay circuit

It is to be noted that :

(i) Output Q_A connected to input $\overline{CP}_B$

(ii) To reset all outputs to 'LOW' level both $R_{0(1)}$ and $R_{0(2)}$ inputs must be at 'HIGH' level.

(iii) Either (or both) reset inputs $R_0(1)$ and $R_0(2)$ must be at a 'LOW' level to count.

4.4.4 The current signal is fed to the transductor unit which converts it into a proportional voltage signal. This voltage signal at the output of the transductor is fed to the function generator which decides the operating characteristics of the relay. The output voltage of the function generator is fed to the voltage controlled Oscillator (described earlier) to convert it into a proportional frequency signal.

Frequency signal is fed to the delay circuit which is a divide by N counter (where N is an integer and equals to 16 x 16 x 16 as three binary counters have been used in cascade). The operation of the delay circuit depends on the resetting signal derived from the summing amplifier (described in the later sections). The output of the delay circuit actuates the tripping device. The operation of the overcurrent relay is also illustrative from the block diagram and circuit diagram, (Fig. 29 & Fig. 30).

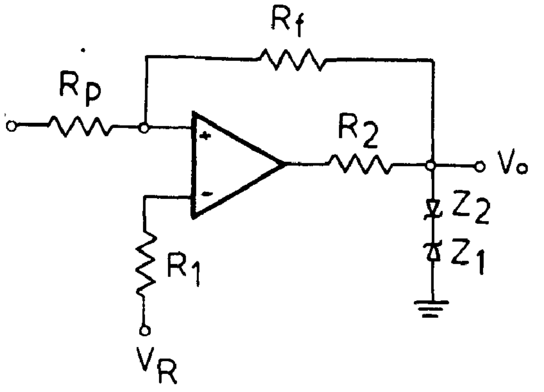


Fig.31

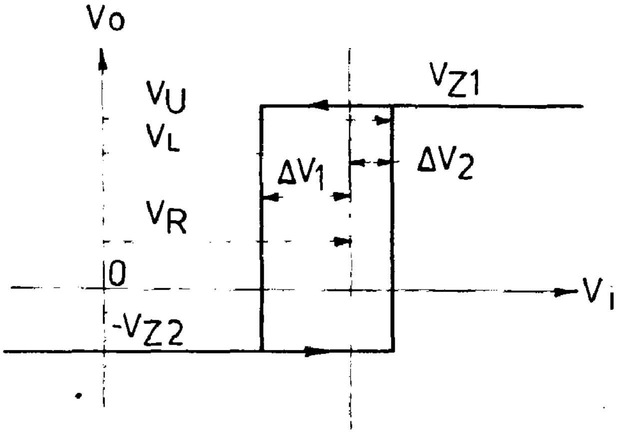


Fig.32

Fig.31& 32- Noninverting level detector with hysteresis(31) and its transfer function (32)

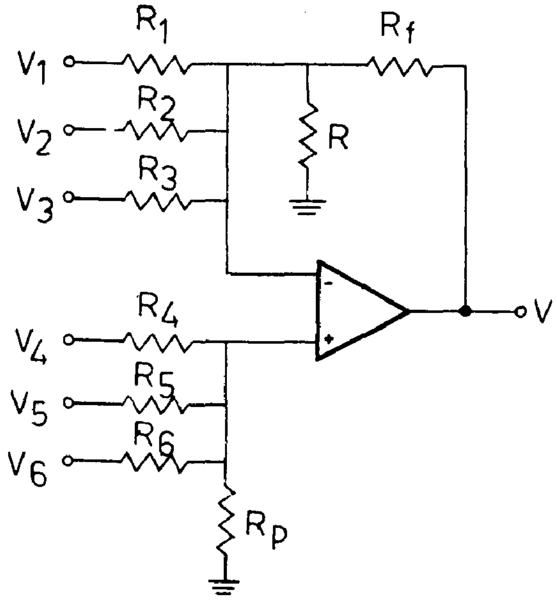


Fig. 33 - Summing amplifier for addition and subtraction

4.5 Constituents of temperatures sensitive device

4.5.1 Level detector with hysteresis using temperature dependent resistance of diode (Non inverting)(10)

A level detector with hysteresis is the most versatile and useful of the comparator circuits. It can be designed to change output states whenever the input voltage passes through any selected reference voltage. The noise immunity can be tailored to each application by choosing the amount of hysteresis. The absolute voltages of the two output states are selected by using two appropriate zener diodes.

Fig. 31 shows the non-inverting level detector with hysteresis and its transfer function is shown in Fig. 32. The level tetector determines if an input voltage V_1 is above or be below a reference voltage V_R. In response to this determination, the output voltage will assume one of two possible states. Referring to Fig. 32 the output voltage states are $+V_{z1}$ if $V_1 > (V_R R_f - R_p V_{z2})/(R_p + R_f)$ and $-V_{z2}$ if $V_1 < (V_R R_f + R_p V_{z1})/(R_p + R_f)$. The actual reference voltage is therefore $V_R R_f/(R_p + R_f)$ instead of V_R.

The hysteresis voltage below V_R is

$$\triangle V_1 = \frac{R_p V_{z1}}{R_p + R_f}$$

and the hysteresis voltage above V_R is

$$\triangle V_2 = \frac{R_p V_{z2}}{R_p + R_f}$$

The two trip points are therefore approximately $V_R + \Delta V_2$ and $V_R - \Delta V_1$.

DESIGN EQUATIONS

Eq. No.	Description	Equation
1	Value of positive output voltage	$v_o = V_{z1}$
2	Value of negative output voltage	$v_o = -V_{z2}$
3	Upper trip voltage for v_1 assuming ideal op amp parameters and square zener characteristics	INVERTING (NON.) $V_u = \frac{V_R(R_p + R_f) + R_pV_{z2}}{R_f}$
4	Lower trip voltage --do--	NONINVERTING $V_l = \frac{V_R(R_p + R_f) - R_pV_{z1}}{R_f}$
5	Width of hysteresis loop	$\Delta V_1 + \Delta V_2 = \frac{(V_{z1}+V_{z2})R_p}{R_p + R_f}$
6	Maximum error in input trip point due to op amp input errors if $R_1 = R_pR_f/(R_p + R_f)$	$V_{off} = \pm(V_{io} + I_{io}R_1)$
7	Maximum error in input trip point due to op amp input errors if $R_1 \neq R_pR_f/(R_p + R_f)$	$V_{off} = \pm\left(V_{io} + I_b\left\lvert R_1 - \frac{R_pR_f}{R_p+R_f}\right\rvert\right)$
8	Minimum change in v_1 required to provide full magnitude output change of state	$\Delta v_1 \approx 0$ since positive feedback makes forward gain approach ∞

9	Optimum R_1 if effects of V_{io} and I_b over temperature are to be minimized	$R_1 = \frac{\Delta V_{io}/\Delta T}{\Delta I_b/\Delta T}$
10	Input resistance of circuit	NONINVERTING $R_{in} \approx R_p + \frac{R_f R_{id}}{R_f + R_{id}}$
11	Output resistance of circuit	$R_{out} \approx R_{o1}$ (positive output) or R_{o2} (negative output)
12	Optimum size relationship between R_1 and R_p (It is best to leave R_1 adjustable)	$R_1 = \frac{R_p R_f}{R_p + R_f}$

4.5.2 Summing Amplifier

The negative feedback used in the basic inverting and non-inverting amplifier circuits tends to arrive the two op amp input terminals to the same voltage. This makes summation of current at both input terminals possible without interaction between input branches, (Fig. 33). Thus, one op amp can be used for both addition and subtraction of a large number of voltages. These may be dc or ac voltages or (both).

This circuit must be designed in the following sequence:

1. Select the value of the feedback resistor R_f. Its maximum size is determined by the allowable output voltage

offset using $V_c = \pm I_{io}R_f$, where I_{io} is the op amp input offset current.

2. Select resistors R_1 through R_6 as if all input signals were to be inverted.

3. Calculate the parallel value of R_1, R_2, R_3 and R_f. Call this R_A.

4. Calculate the parallel value of R_4, R_5 and R_6. Call this R_B.

5. If $R_A > R_B$ do not use R_p chose R_n such that $R_A = R_B$, where R_n is now included in the parallel-resistance calculation of R_A.

6. If $R_B > R_A$, do not use R_n chose R_p such that $R_A = R_B$, where R_p is now included in the parallel resistance calculation for R_B.

DESIGN EQUATIONS

Eq. No.	Description	Equation
1	Output voltage of circuit	$v_o = A_1v_1 + A_2v_2 + A_3v_3 + A_4v_4 + A_5v_5 + A_6v_6$
2	Voltage gain for inverting input voltages (v_1, v_2 & v_3)	$A_1 = v_o/v_1 = -R_f/R_1$ $A_2 = v_o/v_2 = -R_f/R_2$ etc.

3	Voltage gain for noninverting input voltages (v_4, v_5 and v_6)	$A_4 = \frac{R_c}{R_c + R_4}(1 + \frac{R_f}{R_x})$ where R_c = parallel resistance of R_5, R_6 and R_p R_x = parallel resistance of R_1, R_2 R_3 and R_n. $A_5 = \frac{R_D}{R_D+R_5}(1 + \frac{R_f}{R_x})$ where R_D = parallel resistance of R_4, R_6 and R_p. etc.
4	Output offset voltage due to input offset current	$V_o = \pm I_{io} R_f$
5	Output offset voltage due to input offset voltage	$V_o = \pm V_{io}(1 + \frac{R_f}{R_x})$

The output of the summer is '$\Delta C \omega$' and goes to the resetting terminal of the time delay circuit. The presence of the signal determines the operation of the time delay circuit.

Because of this interfacing between the temperature sensing and overcurrent devices the coordinated operation for overcurrent and overrun of the machine is obtained of the relay

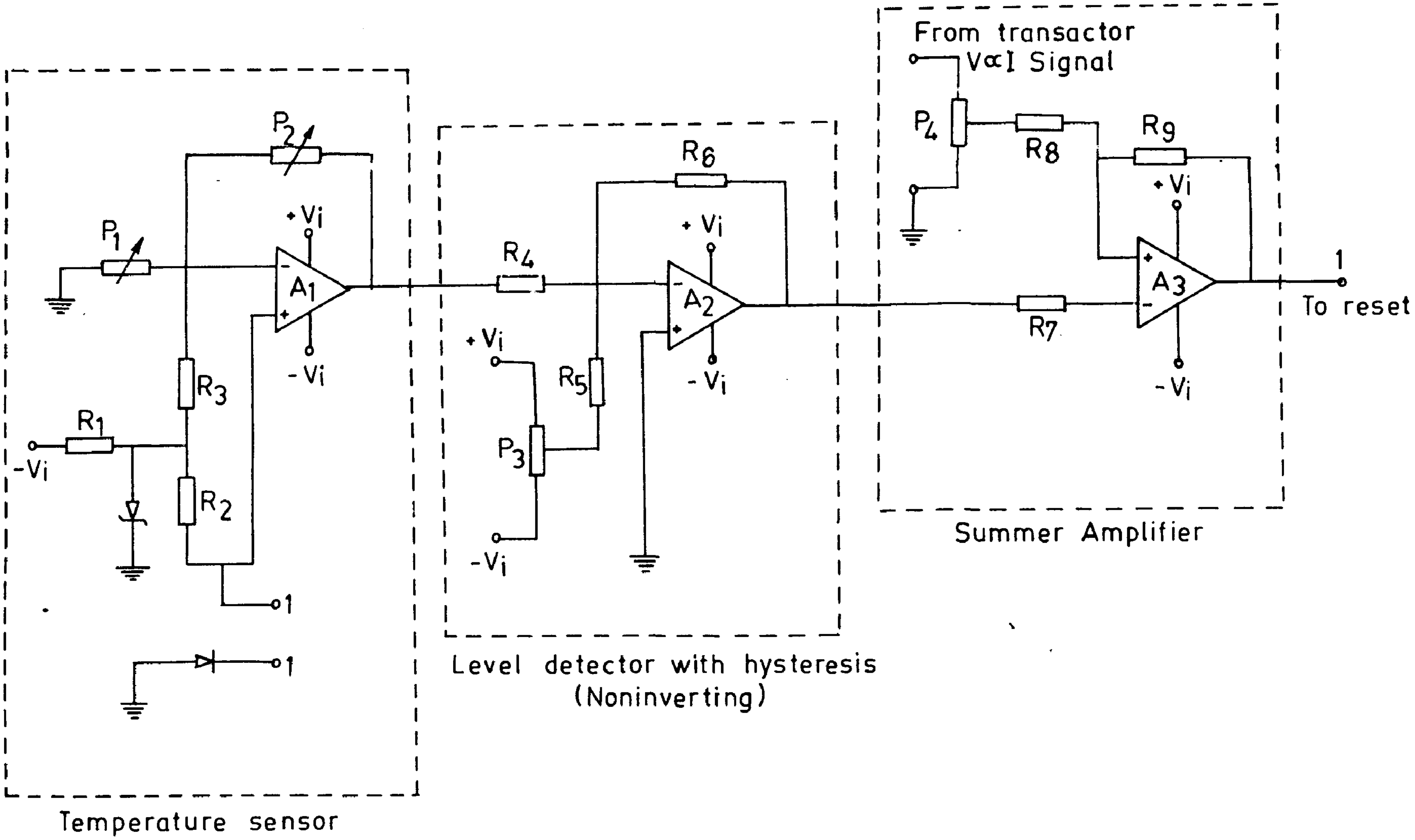


Fig. 34—Over temperature circuit

This coordinated operation between overcurrent and over run has been discussed in Chapter 4.2.

4.5.3 A temperature sensitive diode has been used as the temperature sensing device. The resistance of the diode changes with the temperature. The diode in context is connected in the reference circuit of the amplifier. The output of the amplifier is the function of the resistance of temperature dependent diode and is fed to the level detector with hysteresis (described earlier). The output of the level detector only appears when the input has exceeded the set reference of the level detector. The output of the level detector is fed to the summing amplifier. Another input to the summing junction is the voltage signal proportional to the current from the transactor. The output of the summer goes to the resetting terminals of the delay circuit which is 'LOW' for the operation of binary counters. The operation of the thermal protection relay is also illustrative ~~for~~ from the diagram of Fig. 34.

4.6 Constituents of the Locked Rotor Protective Unit :

4.6.1 Current circulating amplitude comparator used as impedance measuring unit[8]

Fig. 35 shows how two currents can be compared in magnitude only using rectifiers. The current comparator is usually the more practical because the rectifiers provide a limiting action so that :

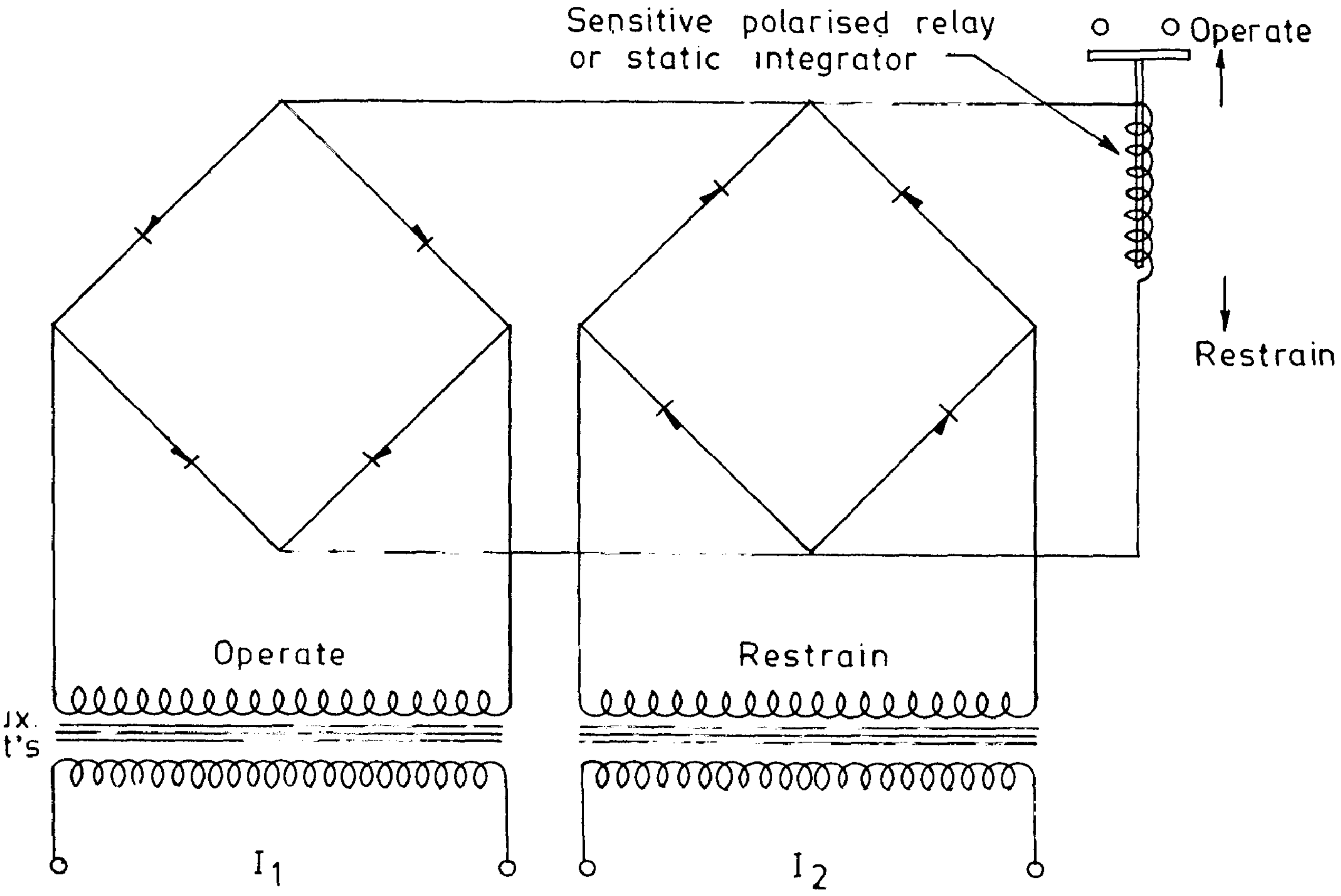
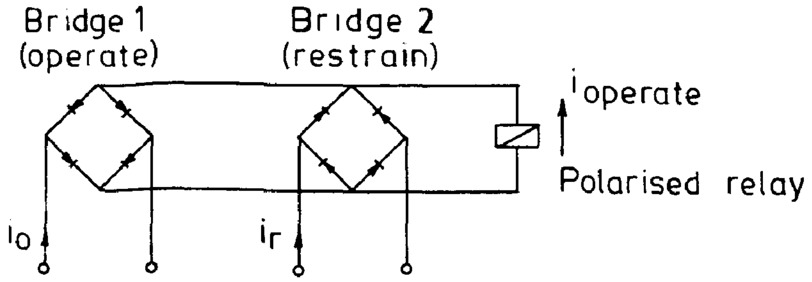
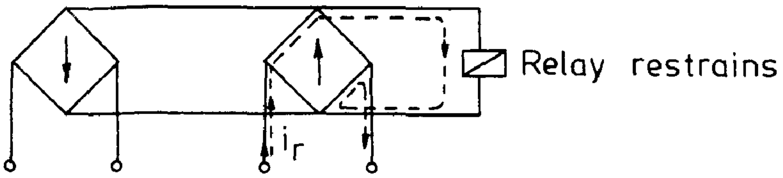


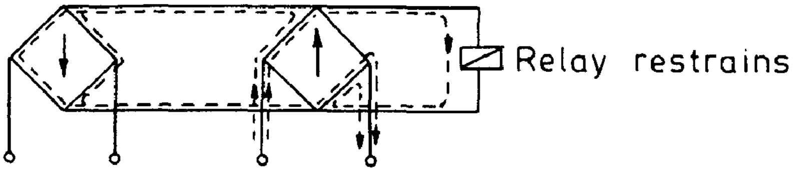
Fig. 35 – Circulating current amplitude comparator



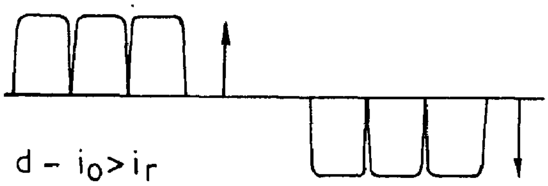
a - General arrangement



b - Current distribution when $i_o = 0$ and i_r is small

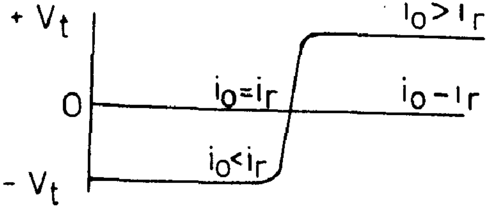


c Current distribution when $i_o = 0$ and i_r is large



d - $i_o > i_r$

e - $i_o < i_r$



f - Ideal rectifier bridge characteristic

Fig. 36 - Operation of circulating current amplitude comparator

(a) The relay can be made very sensitive

(b) The voltage across the rectifier bridge remains substantially constant (Fig. 36 f)

and hence the rectifiers and ~~the~~ the sensitive relay are protected at high currents.

The operation of the circulating current bridge is as follows. Normally the restraining current preponderates and current flows in the winding of the polarised relay in the blocking direction. Small values of i_r will cause a current to flow in the output relay in the blocking direction, as in Fig. 36 the voltage drop, $-V$, across the relay serves as a bias in the forward direction of bridge 1. If i_r is increased further, the voltage drop across the relay will rise to a value $-V_t$, the threshold or toe voltage of bridge 1, and it will conduct (Fig. 36 c). The current through the relay consists of fairly flat-topped half-waves corresponding to the case of $i_o < i_r$, as in Fig. 36(c).

The reverse is true if i_o flows alone; the voltage drop across the relay will now be V and this will bias the restraint rectifier in its forward direction. When the voltage drop across the relay attains the value V_t, corresponding to the threshold voltage of the rectifiers in series, the surplus current from bridge 1 is spilled through bridge 2. This corresponds to the case of $i_o > i_r$ in Fig. 36(d).

When both bridges are energised simultaneously the relay is responsive to small differences between i_o and i_r without requiring a very sensitive output relay. The composite characteristic for the relay is shown ideally in Fig. 36(f).

From the foregoing it can be seen that the current in the relay is a function of the difference between i_o and i_r. Owing to the non-linear resistance of the rectifiers, the current through the relay is limited to a fixed maximum value (Fig. 36 f), and the rest of the surplus flows through a rectifier bridge with the smaller current. The voltage across the comparator cannot exceed twice the forward drop (toe voltage) in one of the rectifiers, which is about 0.6 for silicon. The maximum current that can flow in the relay is the saturating voltage of the rectifier V_s divided by the relay coil resistance.

The linearity of the output characteristic can be improved by the use of different semiconductors in the two bridges, such as germanium in the operating bridge and silicon in the restraining bridge.

4.6.2 Integrator :

An ideal integrator produces an output voltage which is porportional to the integral of the input voltage. In other words, the output is proportional to the product of the amplitud and duration of the input. The integrator performs this mathematical operation on an instantaneous basis, producing an output

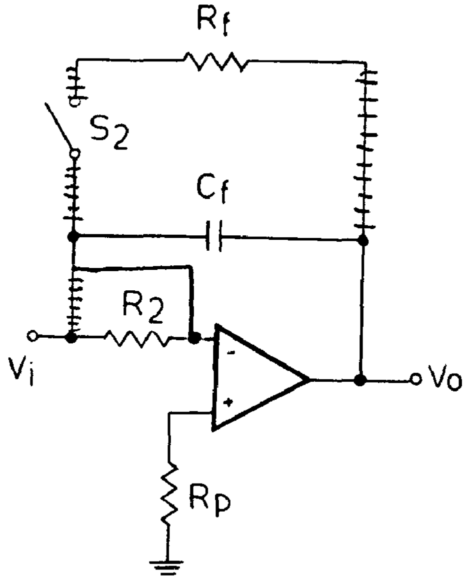
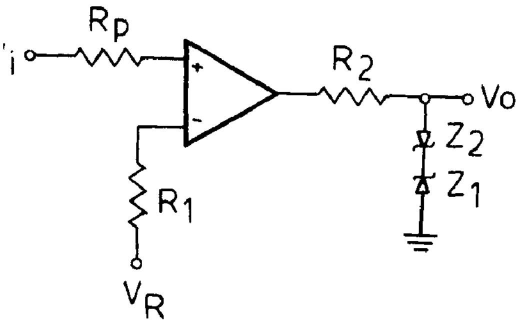
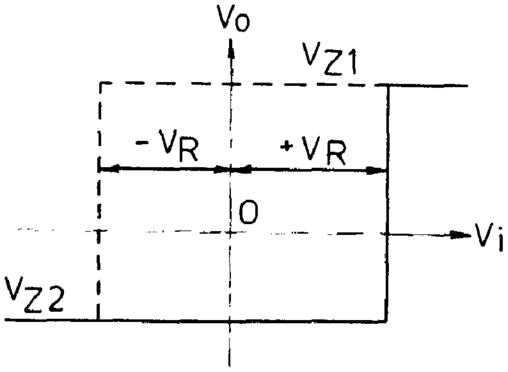


Fig. 37- Integrator



(A)



(B)

Fig. 38 - Noninverting level detector (A) and its transfer function (B)

proportional to the sum of the products of instantaneous voltages and vanishingly small increments of time. The result is an output exactly proportional to the area under a waveform.

The circuit shown in Fig. 37 performs integration by using an op amp to force the same current through both R_1 and C_f. The voltage across the feedback capacitor is related to capacitor current by

$$v_o = - \frac{1}{C_f} \int i_f \, d_t$$

since the circuit causes i_f to equal the input current $(i_i = v_i/R_1)$.

$$v_c = v_o = - \frac{1}{R_1 C_f} \int v_i d_t$$

The gain of the circuit is given by $-1/R_1 C_f$. Thus the output voltage will change by $-1/R_1 C_f$ volts per second for each volt of input.

4.6.3 Level Detector without Hysteresis (Non-inverting)

The operation of this circuit is similar to that of the zero-crossing detector except that the resistor (R_1 or R_p) which is normally grounded is returned to a reference voltage V_R. This change makes the output voltage change states whenever the input voltage passes through V_R rather than zero. V_R can be positive or negative, or it may be a variable which varies according to some system function.

evel detector determines if an input voltage is less than a reference voltage. In response to ination, the level detector output voltage can y two possible states. The output assumes the tate V_{z1} if $V_1 > V_R$ and the negative state $V_1 < V_R$. (Fig. 38A) shows the non-inverting level ircuit and Fig. 38B indicates several of the ransfer functions. V_R can be positive, negative e. The two output voltage levels are determined and V_{z2}. Bias errors are reduced by incorpora-

[illegible]

Description	Equation
voltage when $v_1 < V_H$ ng ideal op amp para- and square zener teristics	NONINVERTING $v_o = -V_{z2}$
voltage when $v_i > V_H$, ng ideal op amp para- and square zener teristics	NONINVERTING $v_o = V_{z1}$

3.	Maximum deviation from V_R of v_i trip point considering of amp input parameters and $R_1 = R_p$	$V_{off} = \pm (V_{io} + I_{io}R_1)$
4.	Maximum deviation from V_R of v_i trip point considering of amp input parameters and $R_1 \neq R_p$	$V_{off} = \pm \left[V_{io} + I_b \lvert (R_1 - R_p) \rvert \right]$
5.	Minimum change in v_i required to provide full-magnitude output change of state	$\Delta v_i(\min) = \frac{V_{z1} + V_{z2}}{A_{vo}}$
6.	Optimum source resistance R_1 if effects of changes in V_{io} and I_b with temperature are to be minimized	$R_1 = \frac{\Delta V_{io}/\Delta T}{\Delta I_b/\Delta T}$
7.	Input resistance of circuit	$R_{in} = R_1 + R_p + R_{id}$
8.	Output resistance of circuit	$R_{out} = R_{z1}$ (positive output or R_{z2} (negative output
9.	Optimum size for R_2	R_2 is chosen to provide the recommended bias current through the zener diodes

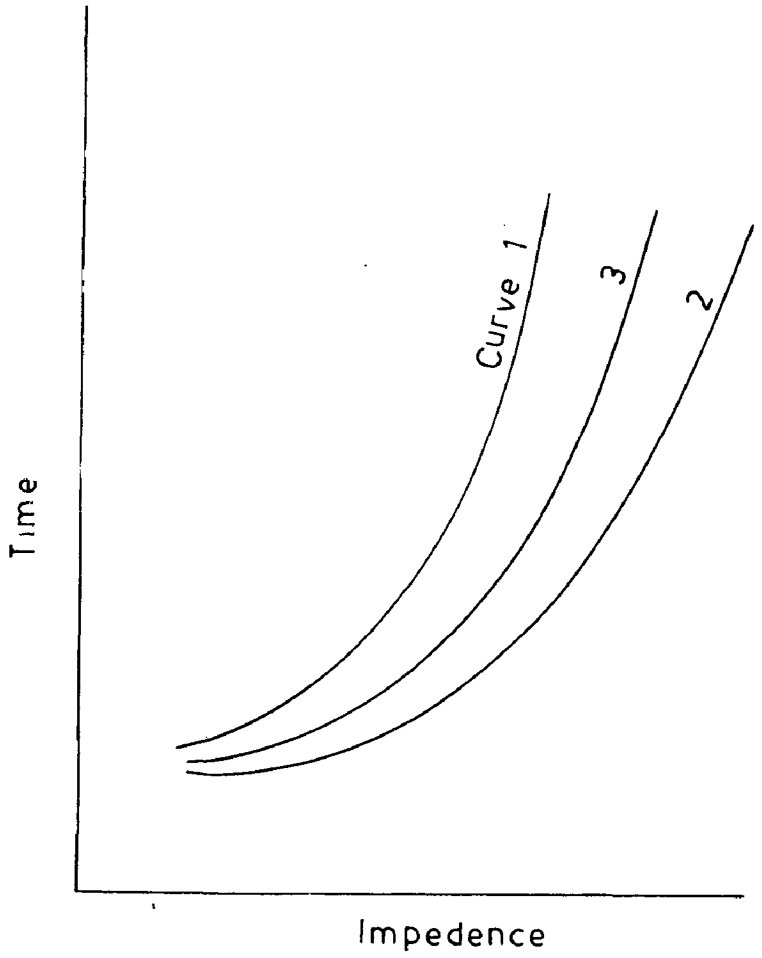


Fig. 39 - Typical characteristic of impedence starting relay and motor

4.6.4 Operation of the Impedance Starting Circuit :

The two current signal one from the CT-1 and another from the P.T. are compared by the current circulating comparator which has been explained earlier. This compared current output is integrated and amplified which then goes to the level detector. The level detector decides the tripping signal and in turn trips the circuit. The delay in the tripping signal is decided by the reference of level detector.

The tripping signal can be controlled by controlling the voltage signal. Further it can be controlled by the input signal to the integrator.

The operation of the relay can be explained with the blockage of motor. The motor may get locked under two conditions (given below). As per the discussion in Chapter II it is known that motor should be protected within 10 seconds after full starting time and there should be a definite delay to prevent the operation of the relay during starting so as to attain the motor a steady speed.

In Fig. 39/curve 1 and 2 are the the typical characteristics of relay and the curve 3 shows the typical characteristic of the motor.

Condition (i) : Motor blocks after steady state speed. The relay will not operate during starting because a definite

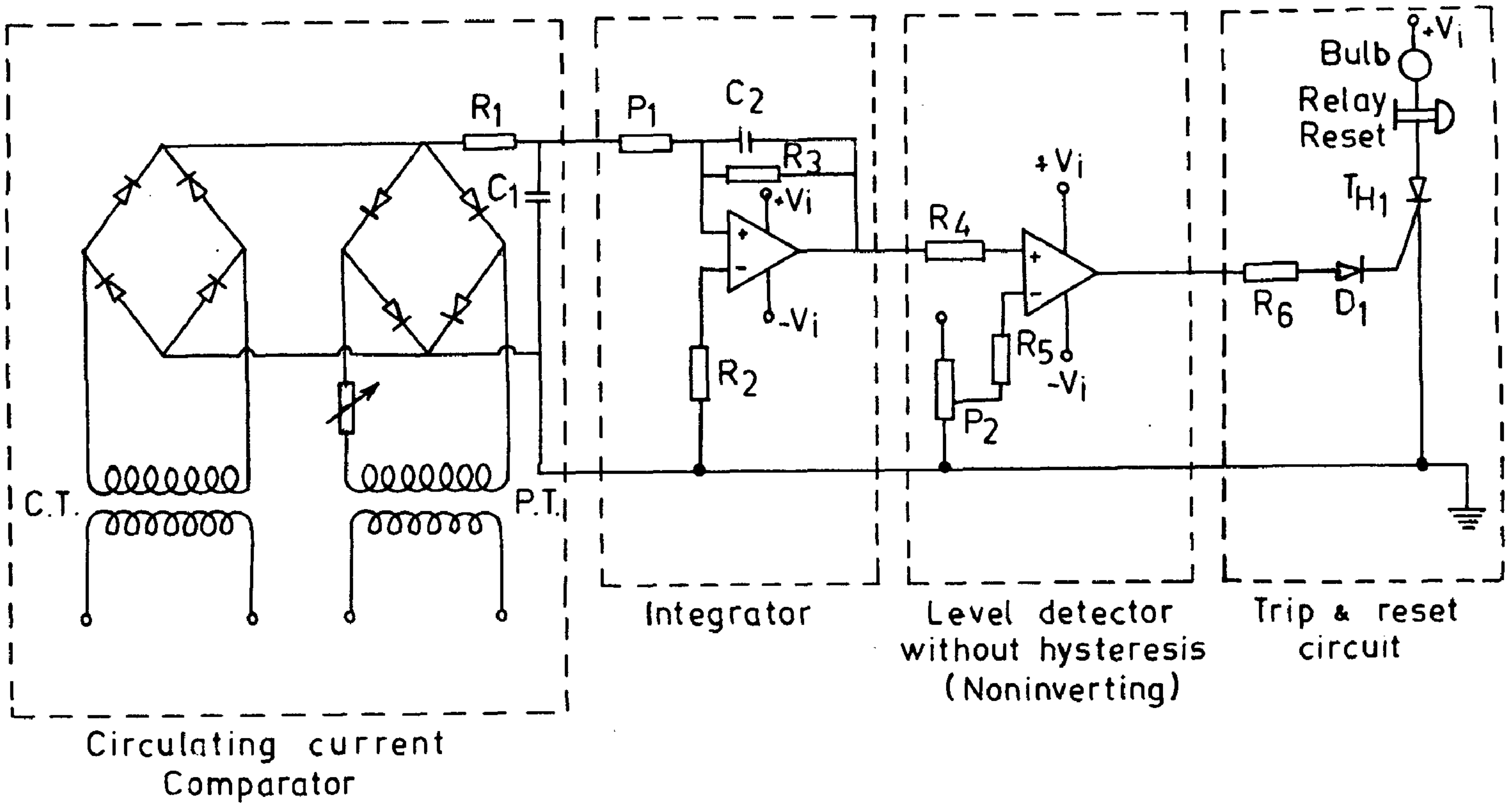


Fig.40 – Impedence starting circuit

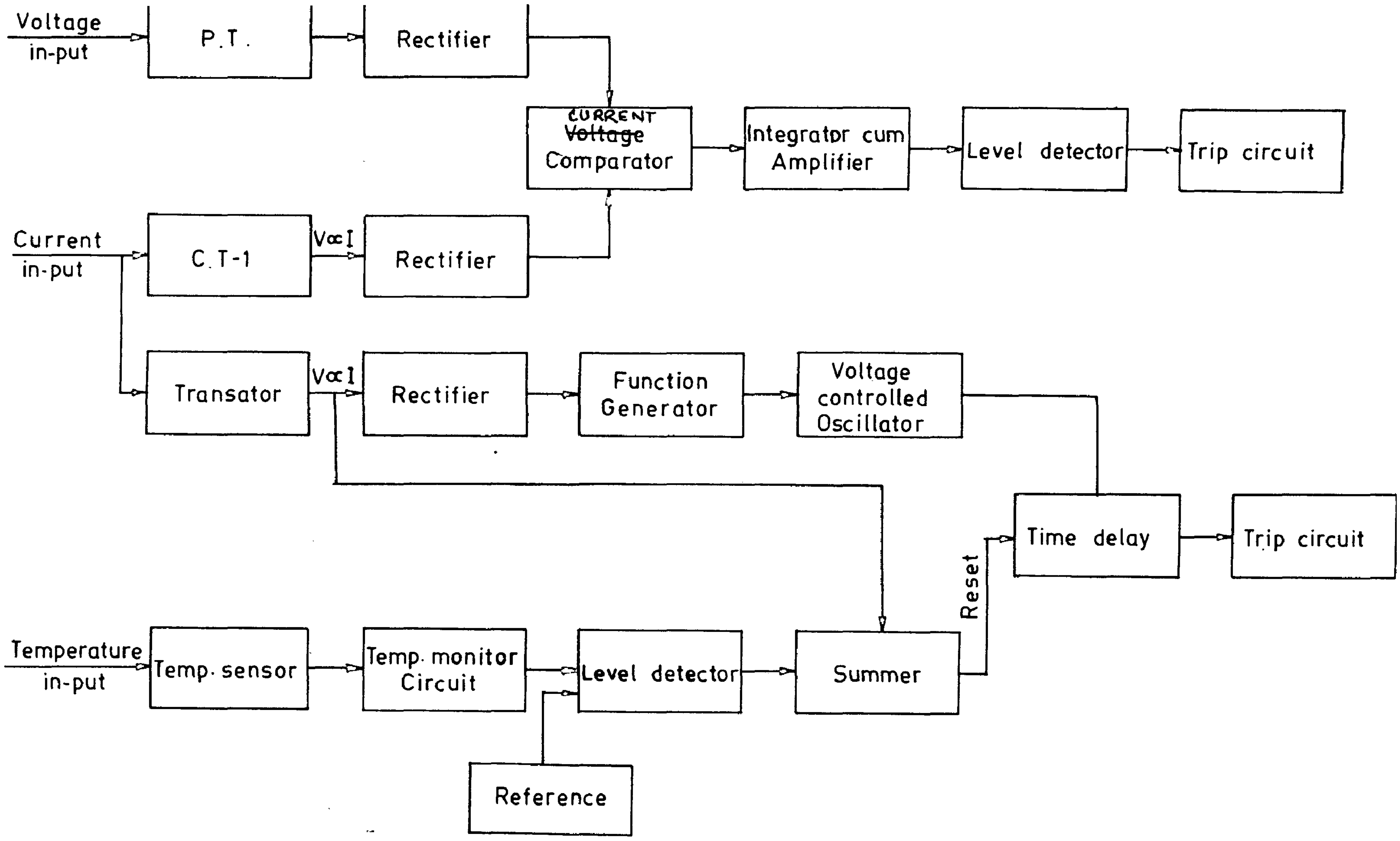


Fig. 41 – Complete block diagram of the proposed scheme

delay has been provided so as to pass the period of starting. If the motor blocks its impedance will fall rapidly i.e. the current will increase about 6 times that of full load and because of circulating current comparator circuit a tripping signal will be produced to trip the relay. The operation of the relay will be decided in less than 10 seconds.

Condition (ii) : Motor blocks during starting :

If the motor blocks during starting, the impedance falls and current becomes about 6 times to that of full load and the operation of the relay is similar to that explained above.

The provision is there to vary the delay as required depending upon different inertia of the motor and further in cases where the motor has to operate at various loads.

Hence the impedance starting relay curve can be given the shape as per the requirement.

The operation of the impedance starting relay is also illustrative from the Fig. 40.

4.7 The block diagram of the complete proposed scheme is presented in Fig. 41.

Thus the proposed scheme presents a new era of improved performance motor and motor circuit protection, improved performance in the basic overload function with superior characteristic to meet the needs of today's motor applications, and packaging that is easier for the application engineer to protect his standard motors and modify the trip function to meet a variety of special application needs.

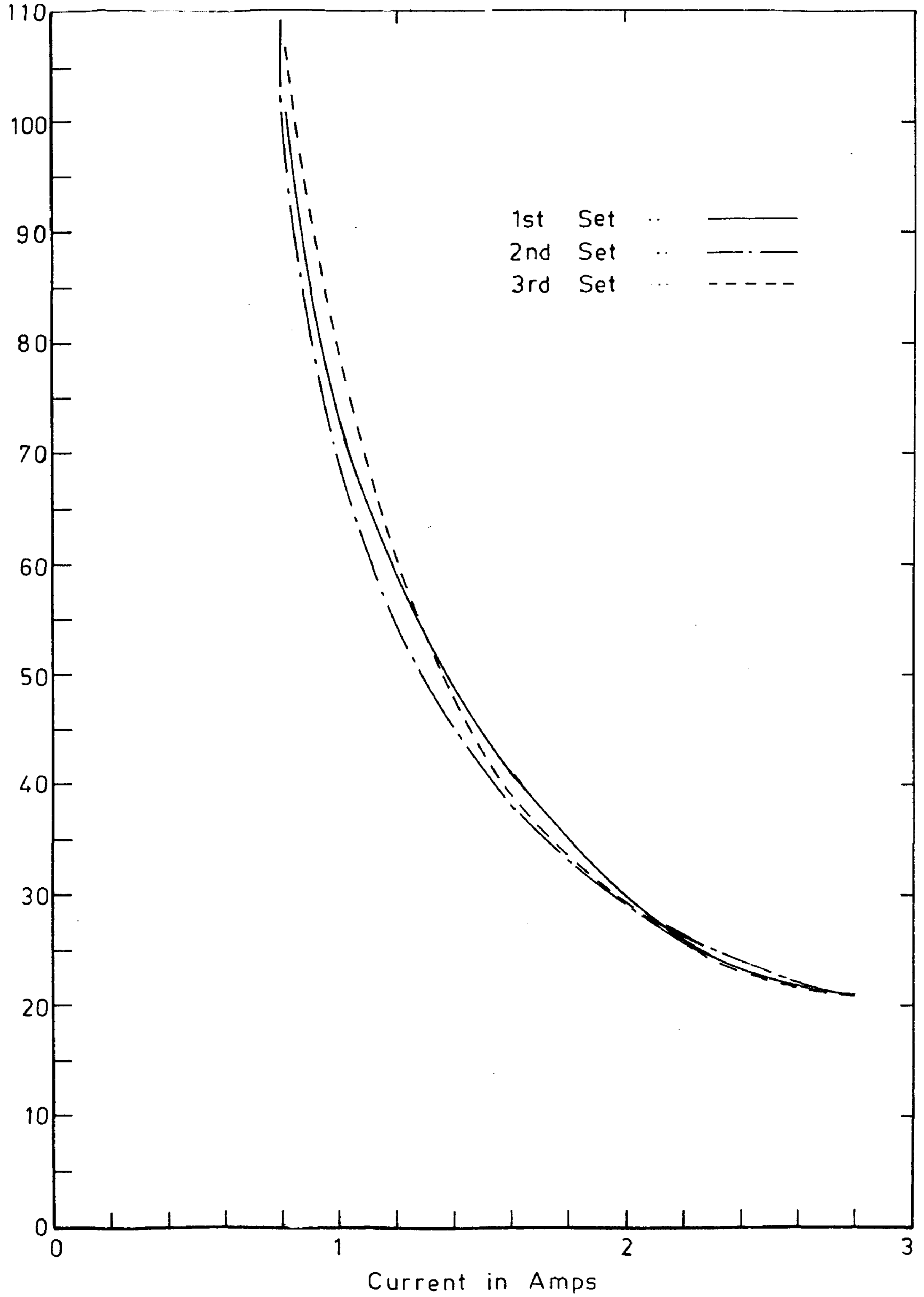
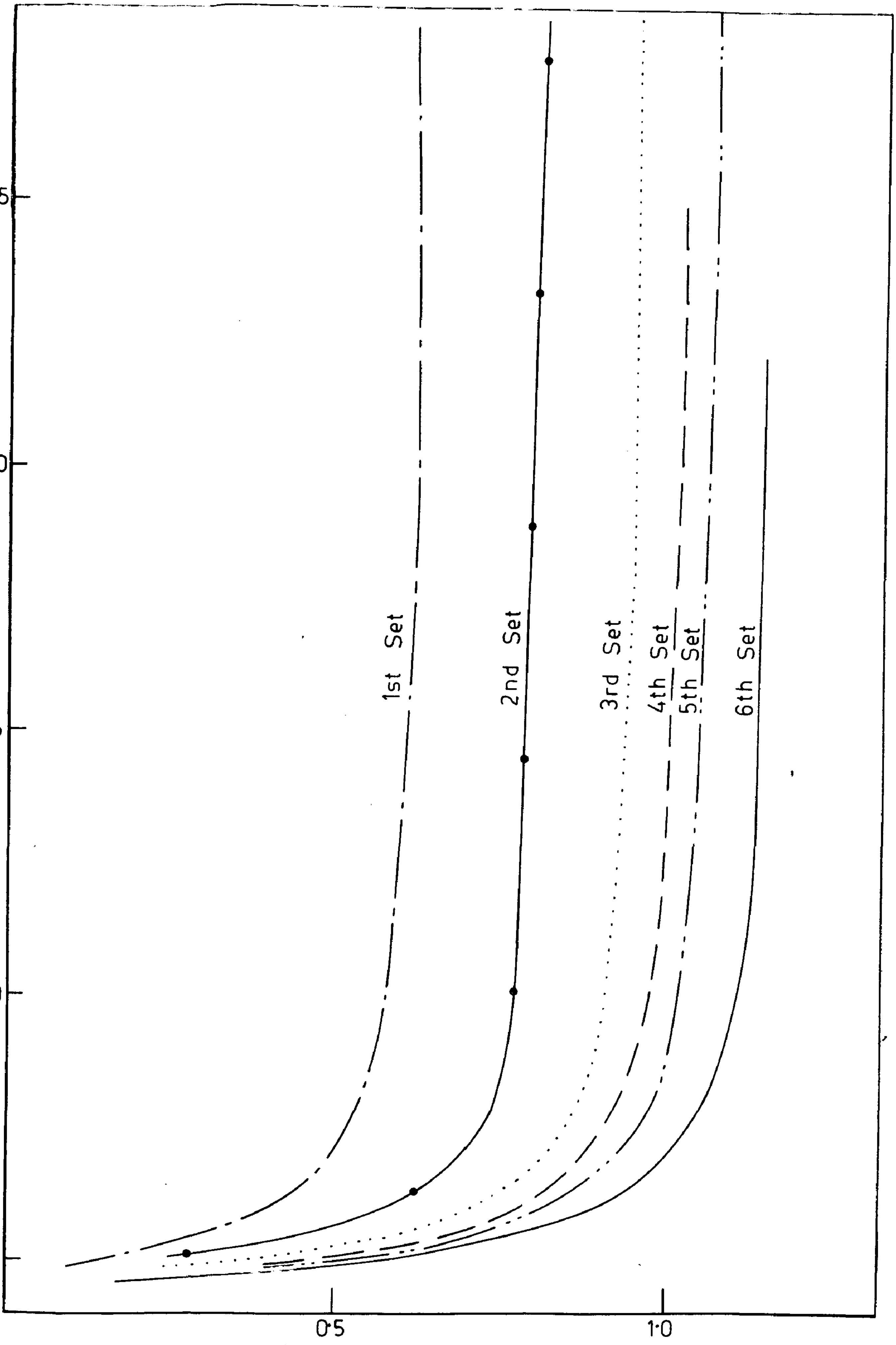


Fig 42 – Over current relay characteristic



43 – Impedence starting relay characteristic. In-put 220 V.A.C.

CHAPTER - V

PERFORMANCE AND EXPERIMENTAL SET UP OF THE DESIGNED RELAY

The relay has been tested by simulating all the conditions for an induction motor fault. The performance was found to be quite satisfactory. The time and current and the time and 1/I (which is taken proportional to the impedance) have been shown in Fig. 42+ 43. The relay can be set for any operating conditions by making use of the facilities provided on the relay. The relay characteristics and the experimental set up with the help of the characteristics drawings and the photographs is in brief explained below :

5.1 The Relay Characteristics as obtained experimentally

5.1.1 Overcurrent Characteristic

The overcurrent characteristic of the relay is shown in Fig. 42, which shows that depending upon the inertia load of the relay the starting time of operation of the relay can be varied with the help of the overcurrent setting pot of the relay. The minimum time taken by the relay in operation is almost definite for all settings.

5.1.2 Impedance Starting Characteristic

This characteristic is shown in Fig. 43. The minimum time taken by the relay for operation is about 5 seconds at current about 2.6 A for all setting of the relay. The 2.6 A can be selected as 6 times approximately of full load current by selecting the main C.T. with suitable ratio. Again it is clear from the characteristic that the starting time of the relay can be adjusted by making use of impedance setting pot of the relay. The variation in the intentional delay in operation of the relay is required to suit the relay for applications under various/service conditions and the relay can be matched with the characteristic of machine provided by the motor manufacturers.

5.1.3 Over Temperature Relay

A temperature sensitive diode the resistance of which varies with the temperature has been used for sensing the temperature of the machine. The mounting of the diode in the motor to sense the correct temperature will be similar to the mounting of thermistor as explained earlier. The time of operation of the relay due to temperature depends upon the reference ~~saving~~ setting and the current drawn by the motor jointly. The time of operation of over temperature relay can be adjusted by the over temperature pot.

5.2 Description of the Experimental Set up

Photograph 1 shows the complete front view of the induction motor protective relay. This protection has main , two independent relays, one for impedance starting and another for joint operation on over current and over temperature i.e. over run ~~current~~. Similarly, there are two different indication of the level detector as to change the delay in operation of the impedance starting relay.

The planning of the impedance starting relay plate is shown in photograph 6.

Photograph 7 shows the top view of the temperature sensor plate.

The planning of the temperature sensor plate is shown in Photograph 8. The preset shown can be used to change the reference of the summing amplifier, to change the operation time of the relay.

Photograph 9 shows the top view of the function generator along with the voltage control oscillator. The preset shown can be used to change the reference frequency of the voltage control oscillator and hence the time of operation of the relay.

The planning of the function generator and the voltage control oscillator plate is shown in Photograph 10.

Photograph 11 shows the waveforms obtained from the voltage control oscillator. The operation of voltage control oscillator has been already explained.

Photograph 12 shows the top view of the time delay plate. Photograph 13 shows the planning of the time delay plate. Photograph 14 shows the complete experimental set up of relay.

CHAPTER - VI

CONCLUSION

The successful operation of the relay under all simulated conditions has been observed. To have the perfect and sound application of the relay the machine operating characteristics should in detail be available with the application engineer. With the help of the proposed relay the efficient and optimum use of machine is possible by continuous monitoring the operating conditions of the machine by adjusting the load limits on the machine. All advantages of analog and digital circuits of high speed of response and accuracy have been derived in the scheme. Relay finds its application with all induction machines and variable service conditions of the machine by suitably adjusting the relay characteristic to match with the motor characteristic. The protective scheme can be extended for ~~thethree~~ the three phase application by making use of a summation transforme

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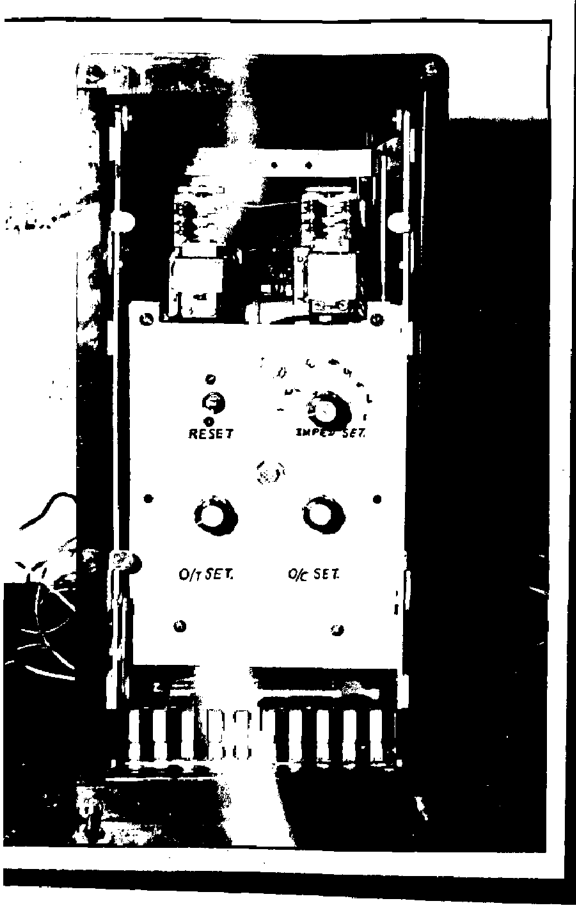
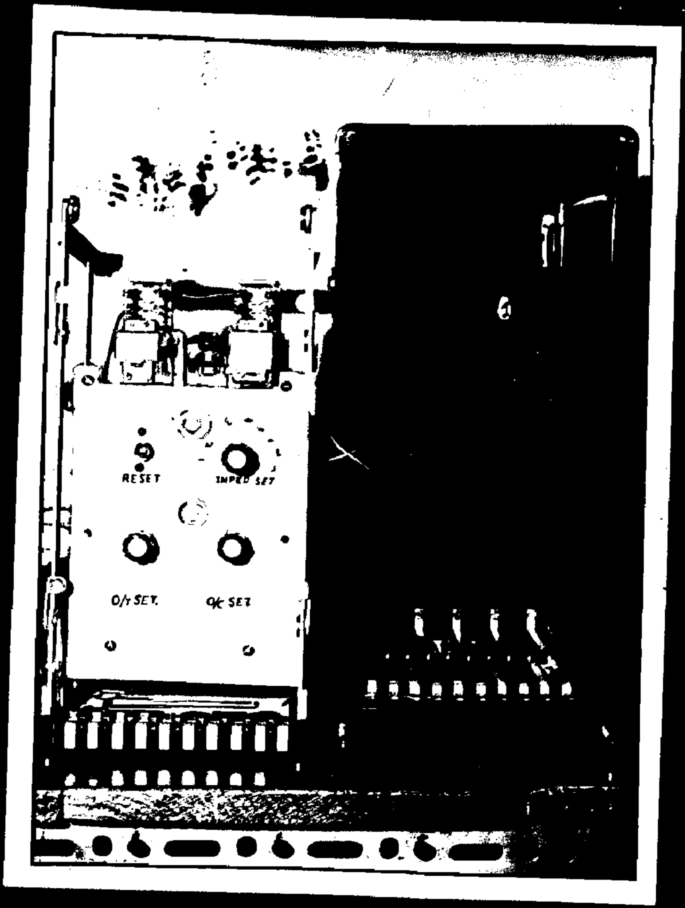


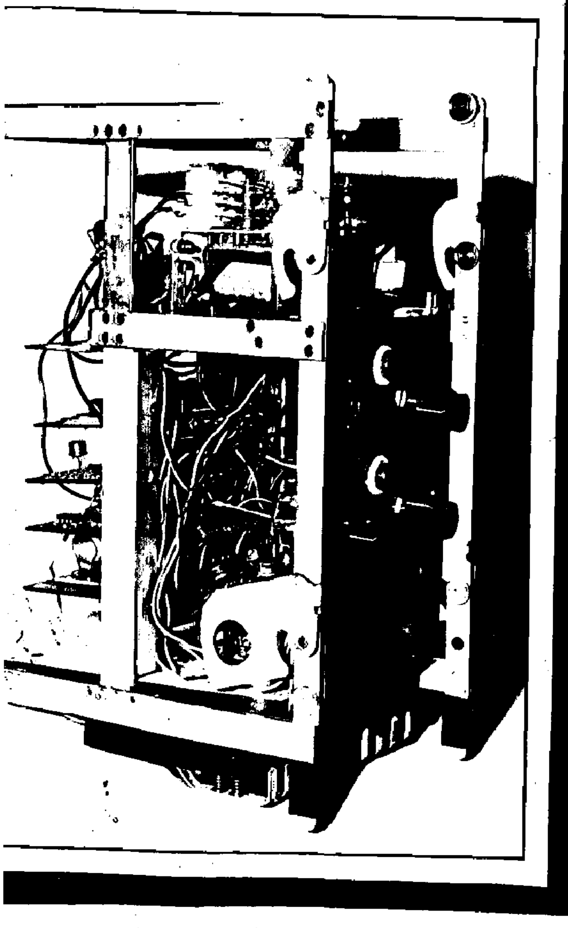
Photograph - 1

ction motor protection relay



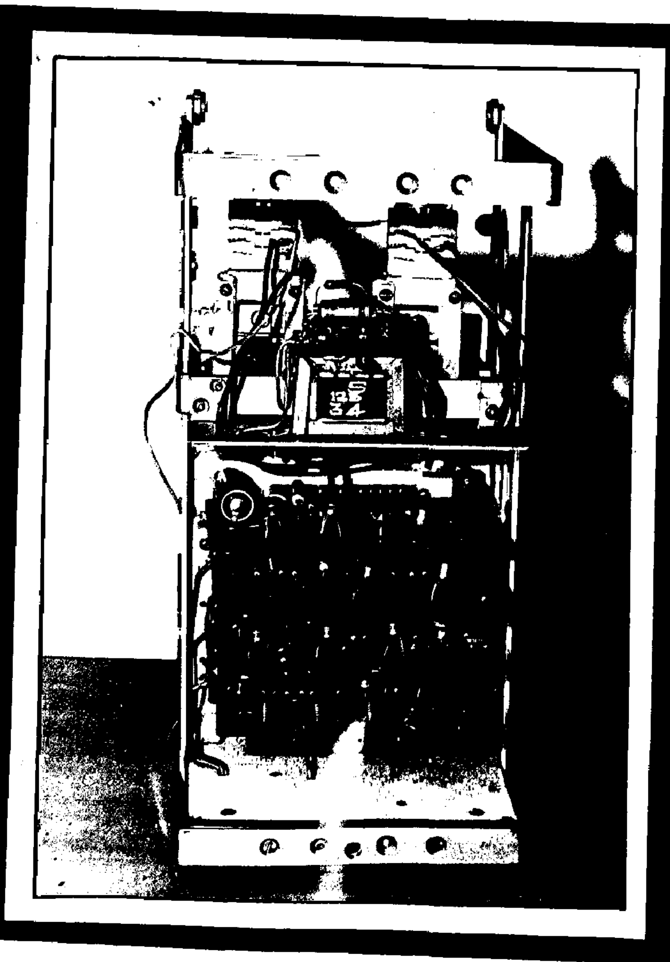
Photograph - 2

Relay with its outer casing



Photograph - 3

ide view of the relay



Photograph - 4

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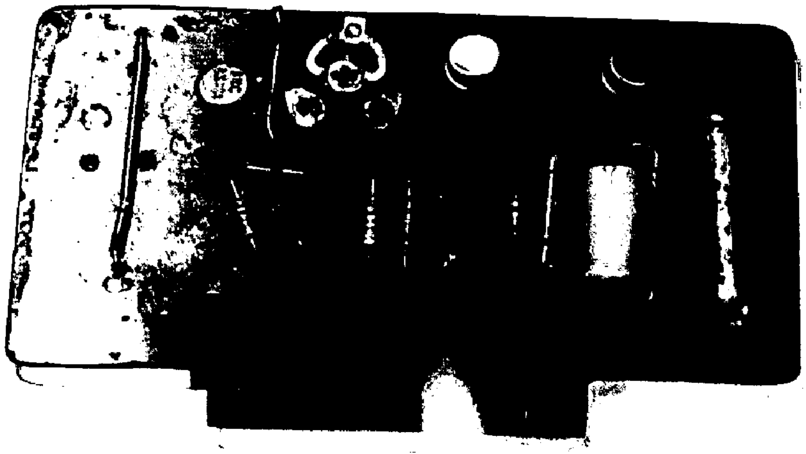
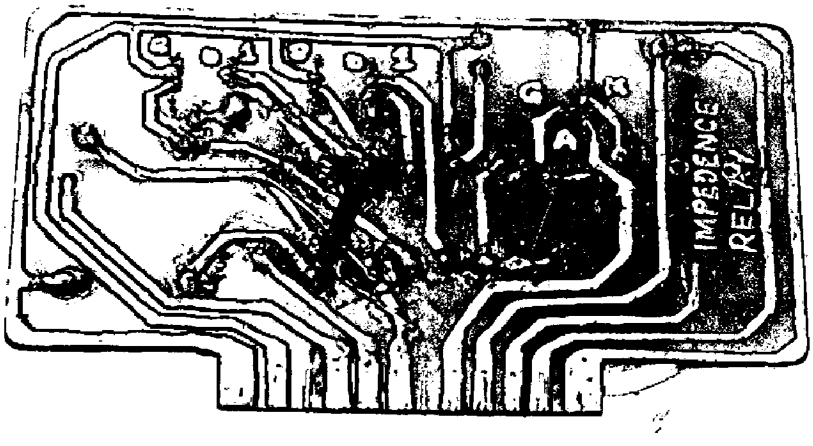


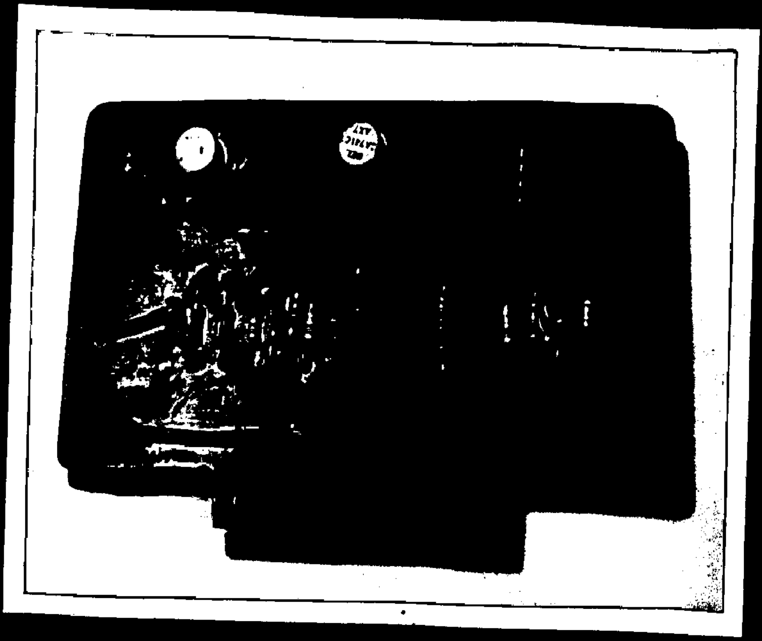
Photograph - 5

Top view of the impedence
of rting plate



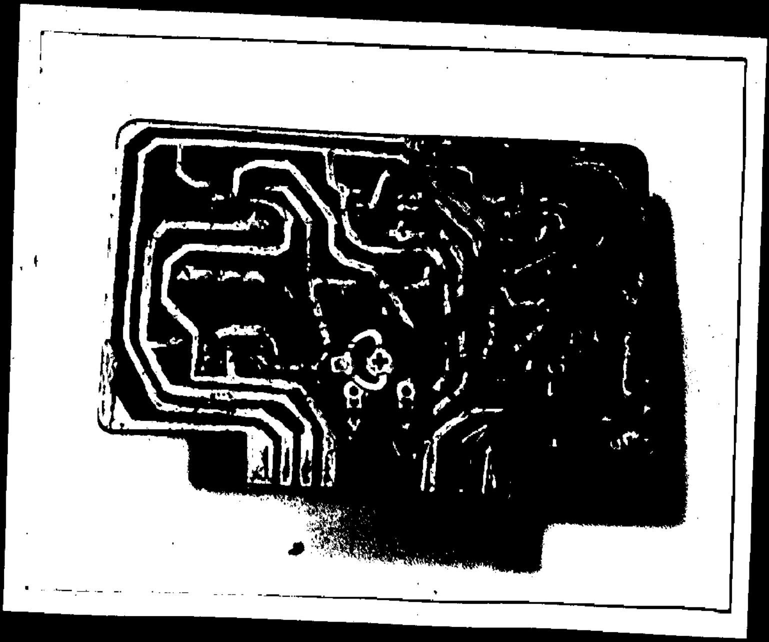
Photograph - 6

Planning of the impedence



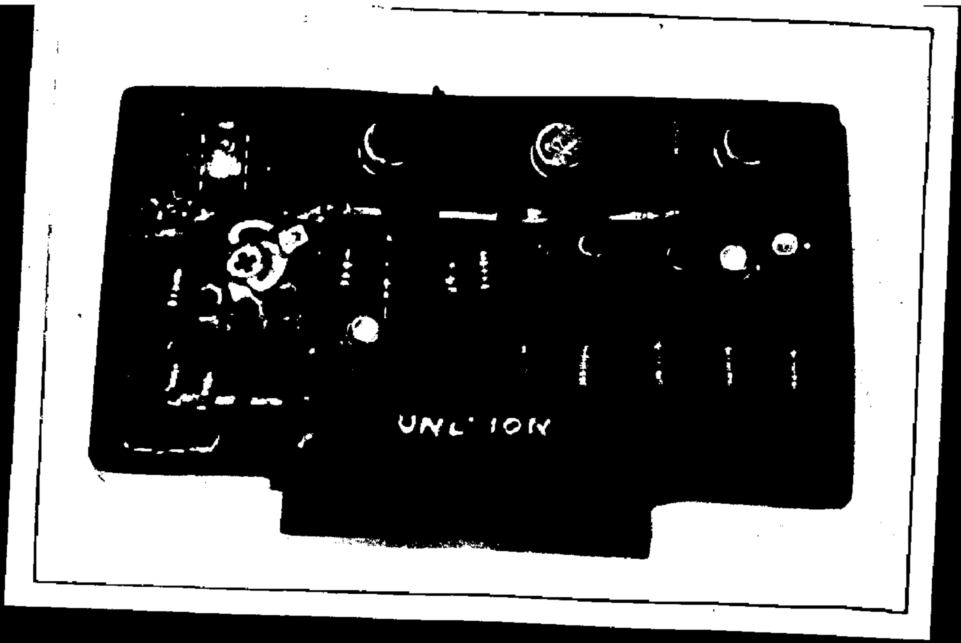
Photograph - 7

Top view of the Temperature Sensor plate



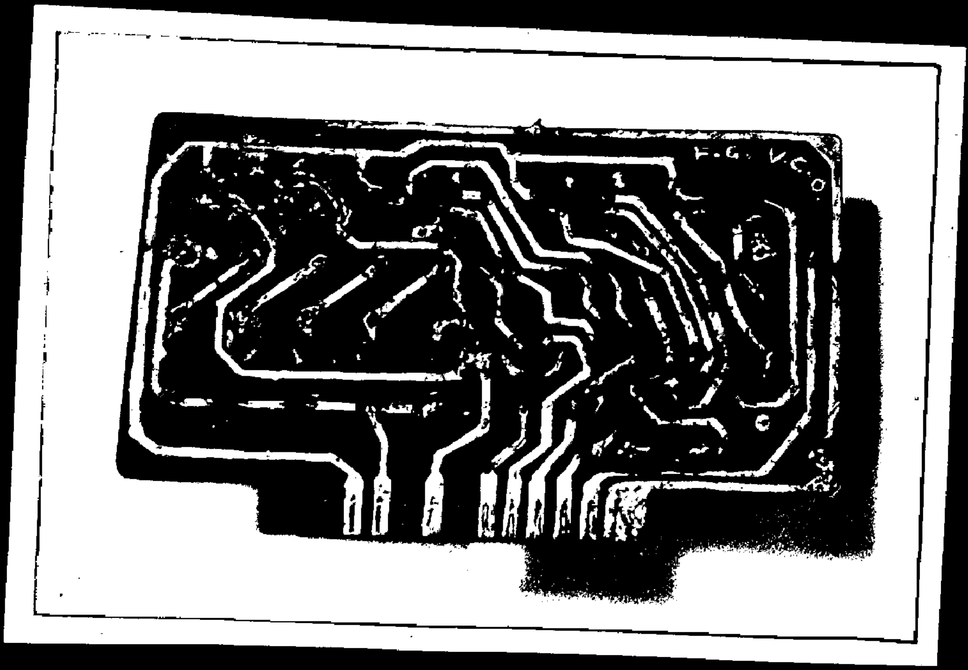
Photograph - 8

Planning of the temperature Sensor plate



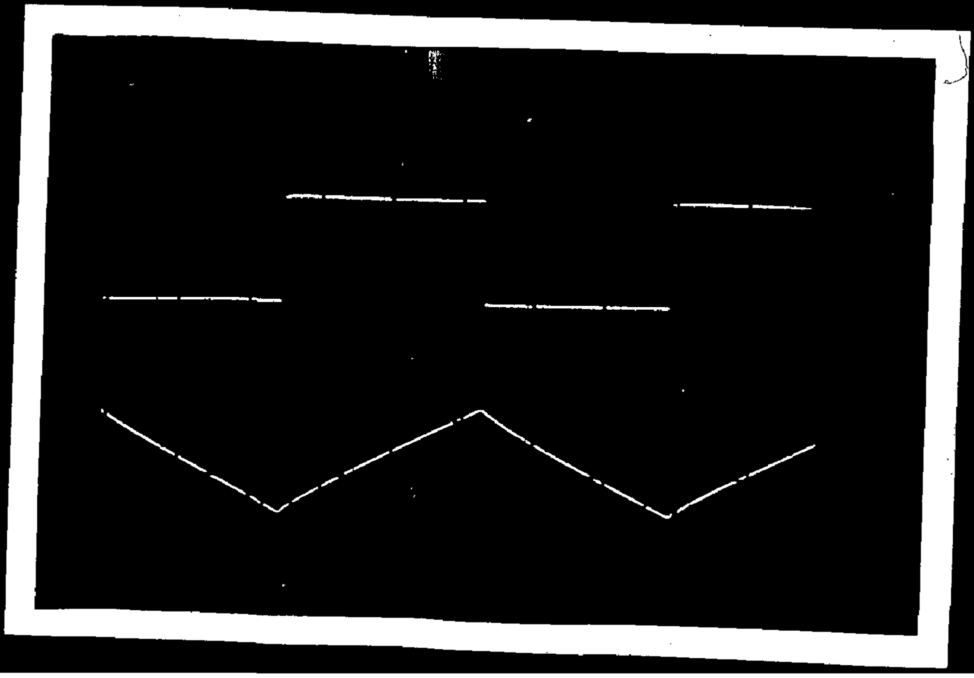
Photograph - 9

Top view of the
voltage control
oscillator plat



Photograph - 10

Planning of the
voltage control
oscillator plate



Photograph - 11

Waveform of the
voltage control
oscillator

Photograph - 1

Top view of the
time delay plat

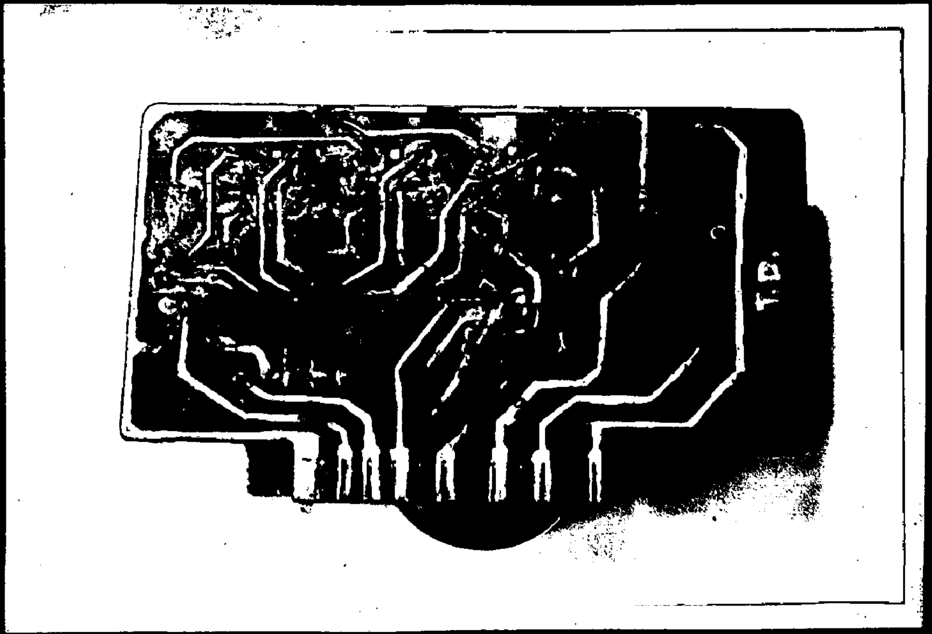
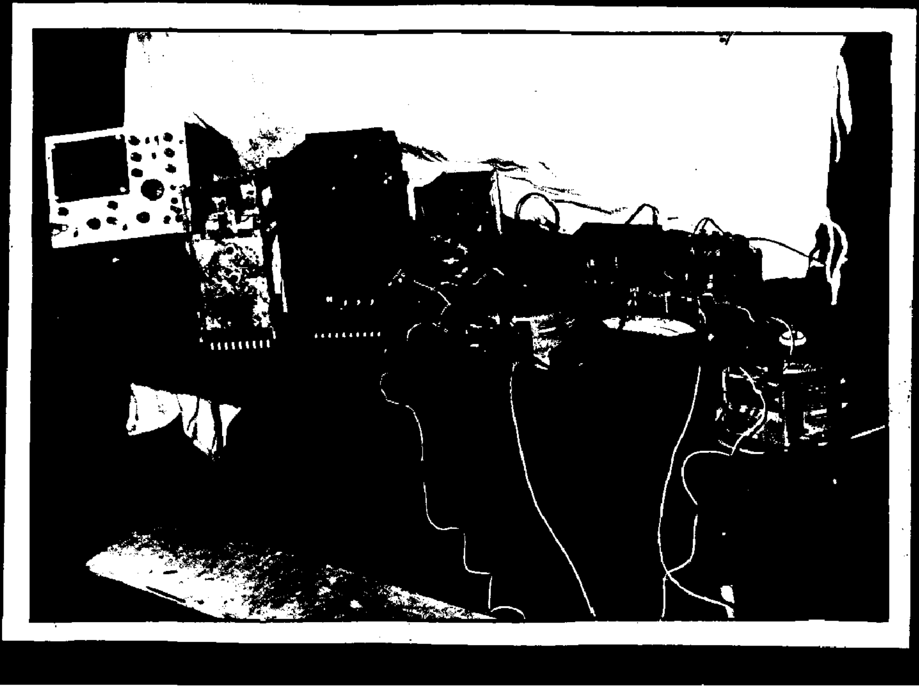


Photo - 13

Planning of the
time delay plat



Photograph - 14

Experimental set
up of relay.