DEVELOPMENTS IN STATOR WINDING PROTECTION OF LARGE GENERATORS

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(With Specialization in Power Systems Engineering)

By

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APRIL, 1989

DEDICATED

TO

MY PARENTS

CANDIDATE'S DECLARATION

I hereby certify that the work presented in this dissertation entitled **DEVELOPMENTS IN STATOR WINDING PROTECTION OF LARGE GENERATORS** in partial fulfilment of the requirements for the award of the degree of **Master of Engineering (Electrical)** with specialization in POWER SYSTEMS ENGINEERING, UNIVERSITY OF ROORKEE, is an authentic record of my own work carried out during the period October 1988 to April 1989, under the supervision of Dr. H.K. Verma, Professor, Electrical Engineering Department, University of Roorkee.

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

Dated : 23 April 1989

(M.M.S. BHARAJ)
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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Dated : 23 April 1989

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SYNOPSIS

Large size generators form a sizable percentage of system capacity and therefore their availability needs to be ensured at all times by reducing outages. This is possible by a comprehensive reassessment of existing protection and monitoring methods necessitated by operating experience and advances in relay technology. One of the objectives of recent developments is to take corrective action before damage.

A review of the developments in stator winding protection has been carried out during the course of the present work. The developments include digital relays for differential and interturn fault protections, a scheme to safeguard against accidental energization of a generator at standstill and an impedence relay as a back-up protection to external faults. Certain monitoring methods detecting overheating, stator winding deterioration and vibration are also covered which provide adequate warning of faults at the incipient stages.

Protection of the entire winding against earth faults is now considered necessary instead of the usual 90-95% coverage by overvoltage or overcurrent relays. Three methods are available based on subharmonic voltage injection and generator third harmonic voltages. These methods and their comparative performances have been examined here.

Two digital relays, namely a 100% stator earth fault relay and a differential relay have been implemented on a 16-bit microprocessor. An improved logic has been adopted for the protection of stator windings upto the neutral end. The relay uses a current monitoring feature to differentiate between internal and external faults and ensures high speed fault clearance

for all internal faults. The differential relay uses digital filters to eliminate harmonics from the measured current signals. It has a variable bias which ensures high sensitivity on lightest internal faults and high stability on heavy external faults.

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CHAPTER - I

INTRODUCTION

1.1 BACKGROUND

Generators are the most expensive pieces of equipment in any power system. The technical progress made in the design of turbo-generators, coupled with efficient cooling methods, has contributed to a rapid increase in unit size. The size of turbo-generators has steadily increased to a point where a single unit may represent a substantial portion of the system capacity and therefore require most sophisticated protection and monitoring.

Electromechanical relays have been replaced by static relays in order to meet the challenges posed by the large and complex systems. Digital techniques are of late being employed in modern relays. The micro-processor or minicomputer is beginning to have an impact on protective relaying. Initially, work was being done on the use of a single computer for all relaying functions in a station, but, the present view believes in provision of a number of microprocessors dedicated to individual relaying tasks. The steadily decreasing cost of digital hardware is also encouraging the present trend.

Some additional advantages of microprocessor technology over solid-state (hard-wired circuits) technology [29] are :

(a) Ability to implement more complex relaying functions

(b) Greater flexibility of characteristics and settings

(c) Multiple functions in a single package

(d) Self checking capability

(e) Capability to interface with other supervisory and control systems

(f) Supervisory functions for pre-fault, fault and post-fault analysis

(g) Capability of adaptive behaviour

(h) Ability to capture events in memory

1.2 PRESENT WORK

1.2.1 Scope of the Work

The present work is restricted to the protection of stator windings of large generators. The aim is to review the latest developments in stator winding protection.

In keeping with the latest trend of seperate microprocessors dedicated to individual relaying tasks, two relays, namely, a differential relay and a 100% stator earth fault relay, have been implemented on an MC-68000 microprocessor as seperate protective schemes.

1.2.2 Organisation of Thesis

The thesis is organised into seven chapters. The present chapter introduces the subject and summarizes the work.

Chapter-II reviews the conventional methods and schemes of stator winding protection and also covers recent developments in these types of protection.

Chapter-III covers the available methods of providing earth fault protection to the complete stator winding upto the neutral end (100% stator earth fault protection). A new digital relay for this type of protection has been developed during the course of [illegible] work. The details of the implementation are covered in Chapter [illegible].

Chapter-IV highlights the monitoring methods used to detect a fault in the stator windings at the incipient stage itself.

Chapter-VI discusses the implementation details of a differential relay employing a variable bias feature. This relay is based on a 16-bit microprocessor MC-68000 like the other relay described in Chapter-V.

Chapter-VII brings out the conclusions based on the present study and practical implementation of two protection functions. Scope for further work has also been suggested.

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CHAPTER - II

DEVELOPMENTS IN CONVENTIONAL TYPES OF STATOR WINDING PROTECTION

2.1 GENERAL

Conventional protection methods for protection of stator windings are still being used extensively, but, with the increase in the size of generators and the advances in relay technology, these methods are constantly under review resulting in improvements in them and addition of new schemes to ensure better and more comprehensive protection.

Stator winding faults involve the main current carrying conductors and must therefore be cleared quickly from the power system by a complete shutdown of the generator. The faults may be those to earth, between phases or between turns of a phase. The danger from these faults is the possibility of damage to the laminations of the stator core and stator windings due to heat generated at the point of fault leading to a costly and lengthy process of repair.

The conventional methods of protecting stator windings, alongwith improvements and trends, are covered in this chapter.

2.2 DIFFERENTIAL PROTECTION

Differential protection is used to detect stator winding faults in generators [17]. For conventional differential protection, currents on either side of the protected equipment are reduced to low levels by current-transformers and are compared in a differential relay. When a fault occurs outside the protected zone, currents on both sides of the protected zone are equal. These equal currents circulate in the secondary wirings of CTs, bypassing the operating coil of the relay. A fault located inside the protected zone is fed from either one or both sides producing a difference current which flows in the operating coil. If the difference current exceeds a set percentage of the current flowing through the protected equipment the relay operates.

In case of faults outside the protected zone, current transformer mismatches may cause difference currents to be produced. These currents must not cause the operation of the relay. In modern relays this is avoided by increasing the relay pick-up current with increased through currents. A differential relay should not operate in spite of one or more current transformers saturating during external faults. Current transformer saturation was generally seen in case of electromagnetic relays. But, with static and digital relays, CT saturation during external faults is less likely because of a much lower burden.

Three approaches are reported in the literature on digital relaying for generator differential protection. One approach is based on comparison of instantaneous values of the differential current and through current [26]. After successive comparisons confirm a fault, tripping is obtained. The analogue hardware used in this case is extensive. In the other approach the fundamental components of the differential and through currents are extracted using cross correlation technique and compared to detect a fault [15]. The algorithm used for extraction of fundamental components is quite complex for a microprocessor implementation. Both schemes use a fixed bias characteristic.

The third scheme incorporates a variable-bias characteristic of the type shown in Fig. 2.1, stored as a look-up table in the memory [33]. The variable bias ensures high sensitivity of the relay for light internal faults and stability on heavy external faults. The relay computes the average values of rectified differential current Id(av) and rectified through

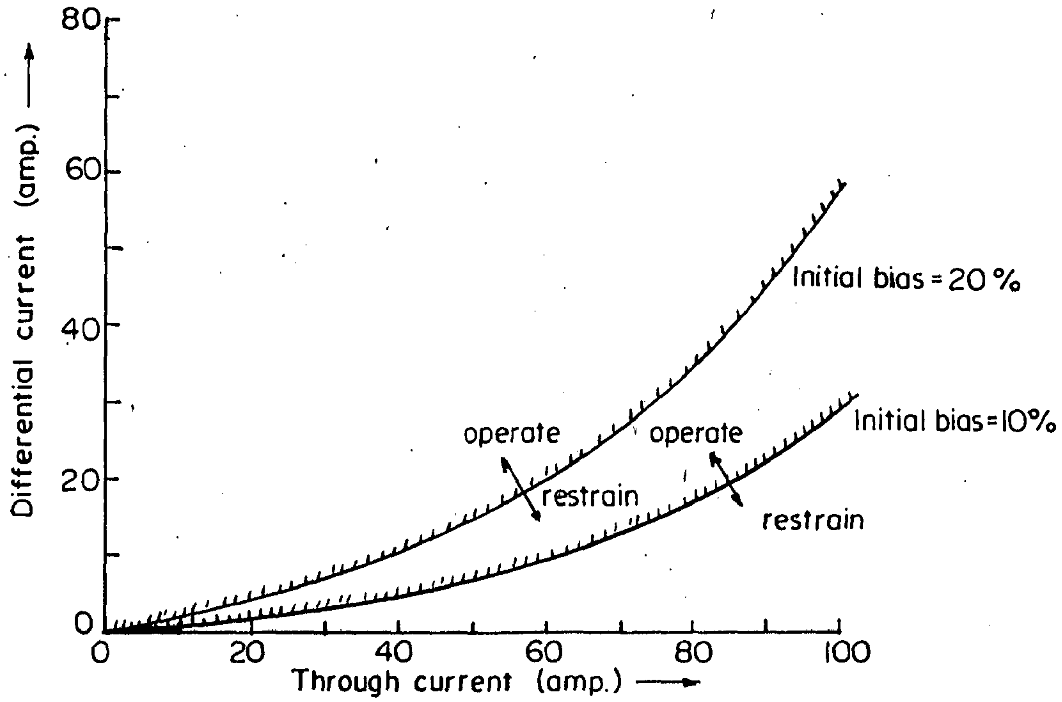

FIG.2.1 VARIABLE BIAS CHARACTERISTICS [33]

current It(av) over half cycle windows. Id(av) is compared with a minimum differential current setting Ido, and if the former is found to be more than or equal to the latter, operating differential current Id(op) corresponding to It(av) is obtained from the non-linear bias characteristic stored as a look-up table. The relay operation on severe internal faults occurs in less than a millisecond and on lightest faults in half a cycle. Due to the high speed of operation, the faults can be detected before CT saturation.

2.3 STATOR EARTH FAULT PROTECTION

Stator earth fault protection in large generators is provided either by overcurrent or overvoltage relays. In important generators, at times, even both are provided wherein one serves as a back-up to the other.

Normally large generators are grounded through a distribution transformer with a resistance loaded secondary in order to reduce the maximum fault current during a phase to earth fault below damaging levels [16]. The overcurrent relays are supplied current by a current transformer connected in series with the secondary resistor while the overvoltage relay may use voltage transformers to sense the voltage across the secondary resistor.

Griffin and Pope have suggested that each unit connected generator be protected with one Primary overcurrent ground relay and two Secondary overcurrent ground relays (one for each breaker connecting the generator to the transmission line)[12]. The coils of all three relays (Fig. 2.2) are connected in series so that each receives the same current. The Primary overcurrent relay is provided with an instantaneous overcurrent unit to provide high speed clearance of ground faults in the transformer delta windings, 50 to 70 percent of generator windings from the terminal end,

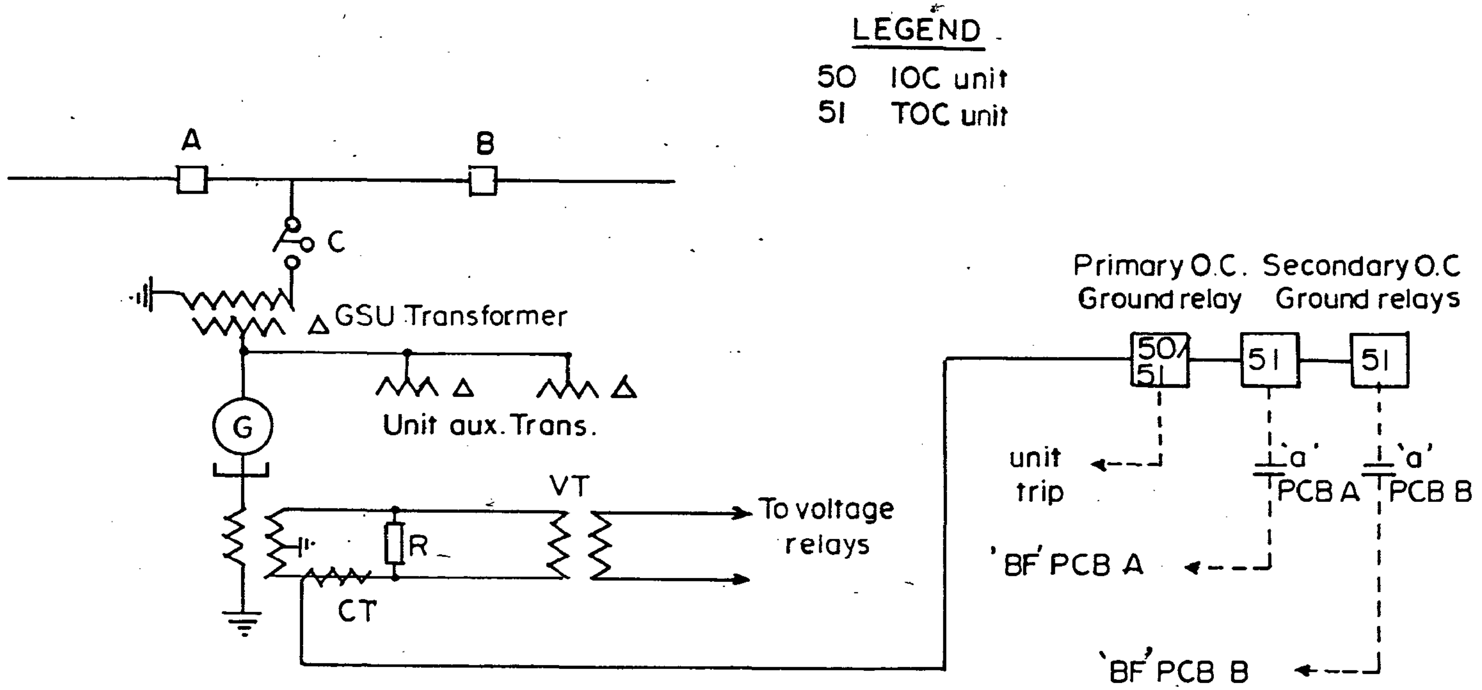

FIG.2.2 OVER CURRENT EARTH FAULT PROTECTION.[12]

and the low-voltage bus-work connected to the generator. This unit is valuable in limiting damage in case of a simultaneous ground fault on two different phases. A time overcurrent unit is also provided with a lower currrent setting in order to protect the remaining winding except the last 8-10 percent near the neutral.

This time overcurrent unit allows a time delay so as to prevent incorrect operation of the relay for faults on the high voltage side of the step-up transformer. A fault on the high voltage side may cause a voltage shift at the generator neutral. A typical calculation is given at Appendix 'A'. The secondary overcurrent relays are provided in order to protect against failure of the generator power circuit breakers to trip.

The operation of the over voltage ground relay and other schemes providing 100 percent coverage of the stator windings on earth faults are covered in Chapter-III.

2.4 INTERTURN FAULT PROTECTION

Generally no separate interturn fault protection is provided in large units due to the constraints in generator construction. It is assumed that interturn faults would quickly involve the earth via the stator core and then be tripped by earth fault protection [5, 25]. This assumption may not hold good for large generators having a number of turns per slot, specially if the interturn fault takes place in the end turn area. Therefore, some interturn fault protection seems necessary for large generators to prevent excessive damage to the insulation.

Buttrey et.al.[8] have proposed the use of a high impedance relay across two cross-connected current transformers, one on each winding.

The protection relies on the fact that a short circuited turn on the stator winding results in an imbalance of voltage between the individual phase windings which circulates a current between them. The relay is tuned to 50 Hz to eliminate dc offset and transient harmonics.

Verma and Chhajta [32] propose a microprocessor based relay that detects interturn short circuits by extracting the second harmonic component in the field circuit. Any asymmetry in the armature currents of a synchronous generator causes second harmonic currents to flow in the field circuit. The direction of flow of negative sequence power is used to discriminate between internal and external asymmetrical faults. For internal asymmetrical faults, the negative sequence power flows from the machine into the system and for external faults from the system into the machine. The high frequencies are eliminated by using analogue filters. The field current may be assumed to be given by

$$I_f = I_{dc} + I_2 \text{ Sin } 2wt \quad (1)$$

$$I_f' = 2w\, I_2 \text{ Cos } 2wt \quad (2)$$

$$I_f'' = -4w^2\, I_2 \text{ Sin } 2wt \quad (3)$$

$$I_2 2 = (I_f' / 2w)^2 + (I_f'' / 4w^2)^2 \quad (4)$$

Using the central difference technique, the first and second derivatives of I_f at the k^{th} sampling instant are obtained as

$$I_f' = (I_{k+1} - I_{k-1}) / 2h \quad (5)$$

$$I_f'' = (I_{k+1} - 2I_k + I_{k-1}) / h^2 \quad (6)$$

I_2 is calculated by the microprocessor using equations (5), (6) and (4), and compared with the threshold value. A trip signal is obtained after I_2 exceeds the threshold for four consecutive sampling periods to obviate the possibility of false tripping on a transient.

Presently, work is goingon on the possibility of detecting the shorted-turn condition in the incipient stage itself by using a gas sample analysis for detecting ionised particles in the hydrogen coolant. Refer section 4.2, for details.

2.5 BACKUP PROTECTION TO EXTERNAL FAULTS [2]

Time-lag overcurrent protection has been used as a back-up protection on sustained external faults. The overcurrent relays are energized by current transformers at the line end of the machine. Operation on stator faults is due to current fed back from the system. These relays are always delayed, with a time setting of 1 to 10 seconds. A definite time lag or an inverse time characteristic may be used. The actual time setting and the choice of the time characteristic is determined by the overcurrent relays in the external network for which selective tripping is required. A current setting of about 1.5 times the rated current is usually selected. The actual value however, depends on the magnitude of the available short-circuit current, which is directly related to the type and overload capacity of the AVR system.

In case of purely static excitation system, which receives its magnetising power directly from the generator terminal via a 3-phase step down distribution transformer and high current thyristors, the magnitude of sustained 3-phase short circuit current depends on the generator terminal voltage. With nearby 3-phase faults, the generator terminal voltage will be small and the fault current may therefore fall below the setting of the overcurrent relay within a few seconds.

In order to provide a back-up protection which is independent of the overload characteristic offered by the AVR, an impedance relay (voltage restrained overcurrent relay) is used. At rated generator voltage it works as a definite time-lag overcurrent relay. However, at reduced voltages the current required for operation will be similarly reduced, i.e. the relay will operate when the actual fault impedance drops below the pick-up value.

2.6 THERMAL OVERLOAD PROTECTION

Overloads between 1 to 1.5 times the rated current are not normally detected by the overcurrent protection. Sustained overloads within this range are usually supervised by temperature elements embedded at various points in the stator slots [2, 18]. The temperature monitoring system is used to provide an alarm at low temperatures and tripping at high temperatures.

2.7 PROTECTION AGAINST INADVERTENT ENERGIZATION

Inadvertent energization of a large synchronous generator results when the unit is at standstill, or on its turning gear, and is energized from the power system through some operator's mistake and/or an equipment malfunction [17, 18]. Generators are sometimes protected for this condition by relays that are provided for protection during low frequency operation.

Most systems, which protect generators during normal (synchronized) operation, are insensitive to the frequency of currents and voltages. They do not protect generators from faults during start-up because the frequency

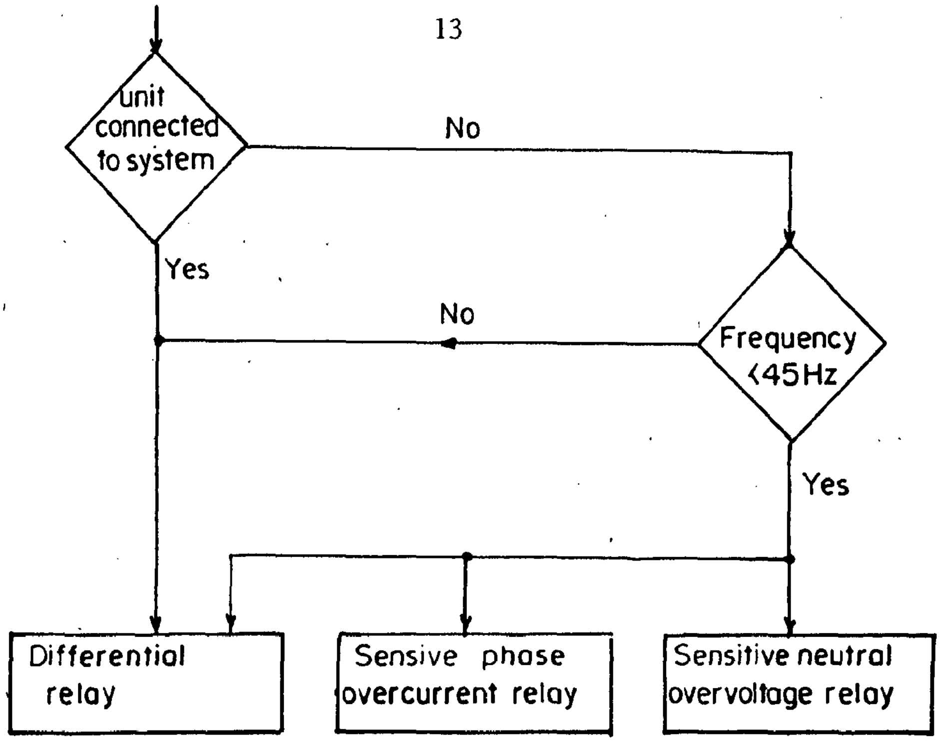

FIG.2.3 AN ARRANGEMENT FOR PLACING RELAYS IN SERVICE ONLY WHEN THE GENERATOR CKT. BREAKER &/OR ITS ASSOCIATED DISCONNECTS ARE OPEN. [17]

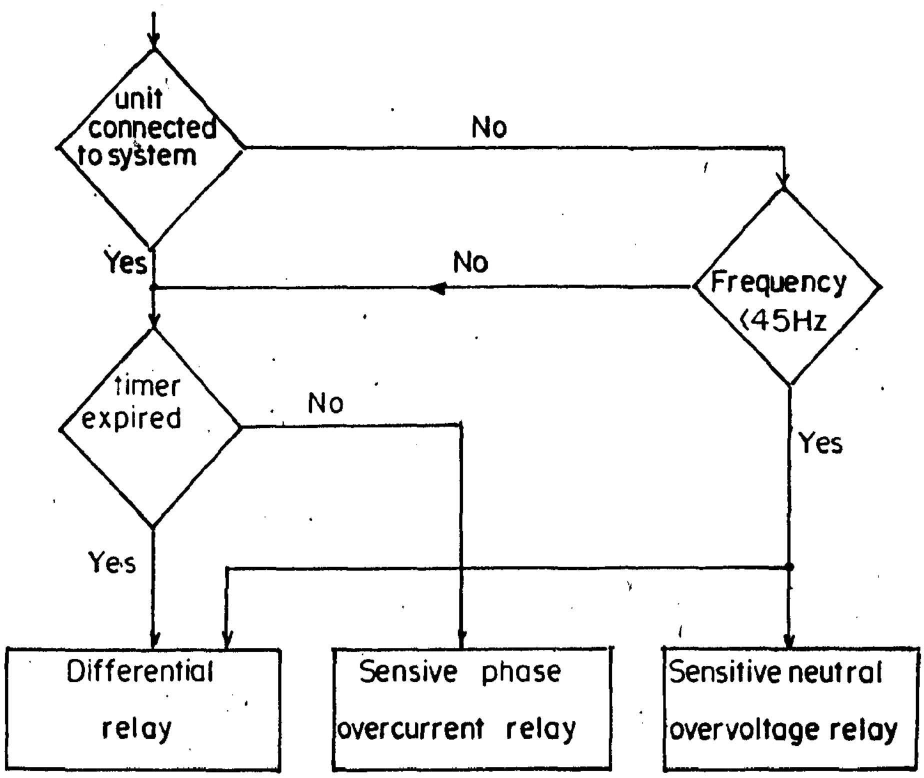

FIG.2.4 AN ARRANGEMENT WITH THE ADDITIONAL FEATURE OF DELAYING THE DISABLING OF RELAYS FOR SHORT DURATION. [17]

is low. The normal practice, for protecting generators under these conditions, is to connect sensitive phase overcurrent and neutral overvoltage relays which are disabled by a frequency relay when the frequency is sufficiently close to 50 Hz. An interlock arrangement is used to make sure that these relays are placed in service only when the generator circuit breaker is open and frequency is low, say below 45 Hz (Fig. 2.3). Inadvertent energization can also occur when circuit breakers are accidently closed. In such a situation, the interlocks in Fig. 2.3 would tend to remove the frequency sensitive protection from service and the normal generator protection would not treat the energization as a fault. One way to leave the sensitive phase overcurrent and neutral overvoltage relays in service, after inadvertently energizing a generator, is to delay disabling them for a short period. Figure 2.4 shows the modified logic diagram incorporating this delay feature.

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CHAPTER - III

100% STATOR GROUND FAULT PROTECTION

3.1 INTRODUCTION

It is a usual practice to ground the unit connected generator through a high resistance, usually a distribution transformer with a resistance loaded secondary, with the objective of reducing fault currents during phase-to-earth faults in the stator [12, 16]. The fault current is limited to 5-10A in order to minimise core burning.

A phase-to-earth fault in the generator winding is detected by the displacement of neutral voltage which occurs during the fault. The magnitude of the displacement voltage is proportional to the distance of the fault from the neutral point. Obviously, as the fault moves towards the neutral, the neutral displacement voltage becomes progressively smaller and for a fault at the neutral itself this voltage is zero. Thus depending on the minimum sensitivity of the relay, faults in 90-95% of the winding only can be detected. Similar protection is offered by standard overcurrent ground fault relays. The ground fault overcurrent relay is supplied from a current transformer connected in series with the distribution grounding transformer secondary resistor whereas the neutral displacement overvoltage relay will be connected across the secondary resistor through a voltage transformer.

Even though the overcurrent or overvoltage ground fault protection is straight-forward and dependable, it suffers from two disadvantages.

(a) It will not detect ground faults occuring in 5 to 10% of stator windings at the neutral end. An undetected fault near the winding neutral is very dangerous as it effectively short-circuits the neutral impedance. A second stator earth fault could subsequently occur in the winding due to deterioration of the insulation. The second fault will result in the flow of currents of devastating magnitudes.

(b) It is not self-monitoring. An open circuit or short circuit anywhere in the relay, primary or secondary of the current transformer, or an open or shorted grounding resistor may not be detected before a fault occurs.

Therefore, to protect large generators, the normal overcurrent or overvoltage ground fault protection should be supplemented with an additional protection to continuously monitor the generator grounding system and ensure ground fault protection to 100% of the stator winding. There are basically the following three types of schemes available/proposed for 100% ground fault protection [3,7,12,19,21,23,24,28].

(a) Type 1 - Subharmonic injection scheme

(b) Type 2 - Fundamental frequency overvoltage and third harmonic undervoltage scheme

(c) Type 3 - Third harmonic voltage comparison scheme

3.2 SUBHARMONIC INJECTION SCHEME

The neutral voltage injection scheme detects ground faults by injecting a 12.5 Hz voltage between the generator neutral and ground and measuring the resultant 12.5 Hz current [11,24]. When a ground fault occurs the 12.5 Hz current increases and causes the relay to operate. The 12.5 Hz injection signal is synchronized to the 50 Hz generator terminal voltage. Since the 12.5 Hz current measurement is done by integrating during a complete half cycle (12.5 Hz), all other system signals existing at the harmonics of 12.5 Hz (i.e. 25 Hz, 50 Hz and higher) will be integrated to zero and will not influence the measurement. A simplified representation of the scheme due to Pope [24] is given in Fig. 3.1.

Security against maloperation is achieved by coding the 12.5 Hz injection voltage. The signal consists of alternating interval where the transmission of the 12.5 Hz signal is "on" and "off". Each test period of 560 ms includes an "on" interval of 240 ms (3 cycles) followed by a 320 ms "off" interval when no transmission takes place. The "on" "off" sequence takes place continuously with measurements made during each test period. A timing diagram for one test period illustrating the measurement technique is shown in Fig. 3.2. Measurements are made during three successive "on" interval half-cycles of the 12.5 Hz signal. The measurement technique makes independent integrations of two negative and one positive half cycles (T_1 - T_3 in Fig. 3.2). These integrals for each "on" interval are compared against a reference set by the pickup potentiometer. The results of these three comparisons are stored in memory. During the "off" interval, similar integrations are made of six successive 12.5 Hz half-cycles (B_1 - B_6 in Fig. 3.2). Only 12.5 Hz noise and leakage current in the neutral circuit contribute to these integrals. For increased security, sensitivity of the pickup circuit is automatically increased to 40-60% of nominal pickup during the "off" interval. If any of the six integrals in each "off" interval falls above the threshold setting in the relay, the relay trip signal is blocked and an alarm sounds. Two conditions must be satisfied to produce a trip output. First, all three half-cycle integrations during the "on" interval must be above the pickup setting. Second, none of the "off" interval integrations during the same test period shall be above the blocking threshold setting. The memory is reset at the end of each test period. When these two conditions are satisfied during one test period a trip output is given.

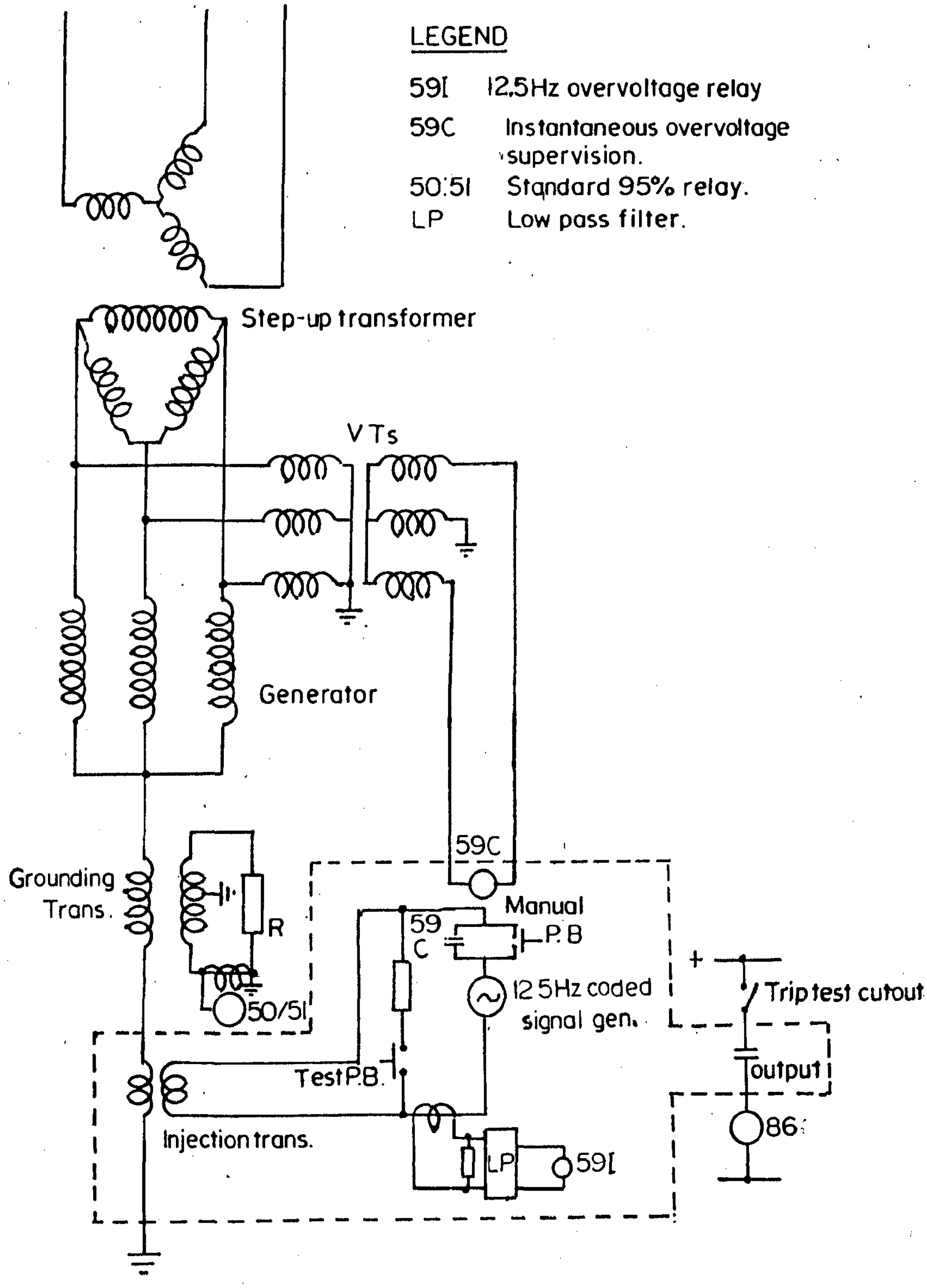

FIG.3.1 SUBHARMONIC INJECTION SCHEME.[24]

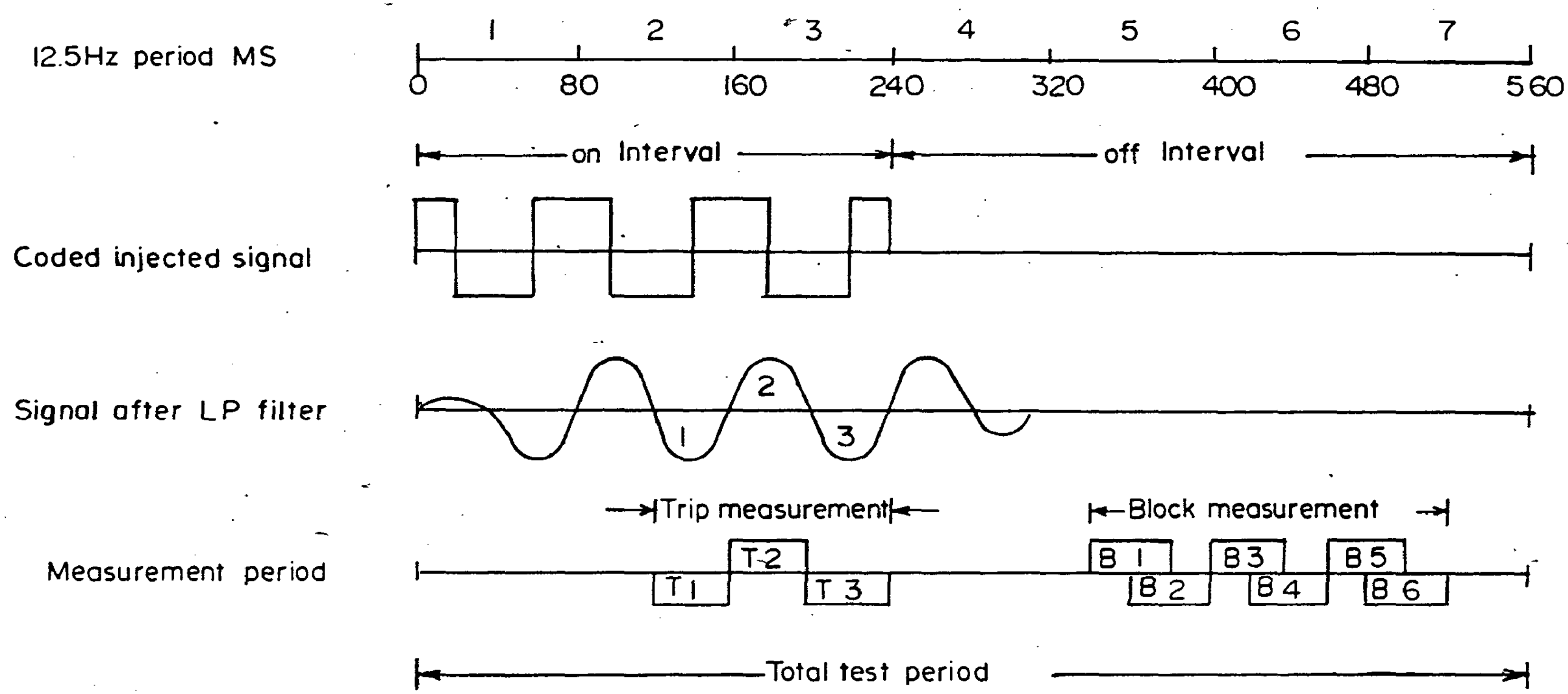

FIG. 3.2 TIMING CHART SUB - HARMONIC SYSTEM. [24]

The operation time varies between one and two test periods (560-1120 ms) depending on when during the test period the ground fault occurs. When the generator is on turning gear and not excited, the injection voltage must be turned off for personal safety reasons. A voltage supervision relay (59C in Fig. 3.1) is used to deactivate the injection scheme when the generator voltage is below 40% of rating. However, the injection scheme can be put in service with the generator on turning gear by using the manual pushbutton shown in Fig. 3.1 This allows a check for grounds after maintainence and before energizing the generator.

This scheme can be readily tested while in service by using the test pushbutton shown in Fig. 3.1. A stator ground fault is simulated by pressing the test pushbutton, which places a short circuit across the 12.5 Hz signal generator output. The trip test cutout switch must be opened during this test to prevent tripping the generator.

The main drawback of the scheme is its inability to detect open circuits in the grounding transformer primary or secondary. An open grounding transformer will result in a decrease in the 12.5 Hz current level whereas the scheme operates on an increase in current level caused by shorted capacitance. An undercurrent relay with time delay may be applied to detect a loss of the injected 12.5 Hz signal and give alarm thereby indicating a grounding problem or relay failure.

This is in addition to the normal stator ground fault overcurrent or overvoltage relay that covers about 90% of the winding.

3.3 FUNDAMENTAL FREQUENCY OVER VOLTAGE AND THIRD HARMONIC UNDER VOLTAGE SCHEME

A voltage relaying system of this type for 100% stator ground fault protection of a unit-connected generator uses two relays with overlapping zones [12, 24]. These relays are connected as shown in Fig. 3.3.

The overvoltage protection circuit consists of a voltage transformer across the neutral resistor, a 150 Hz blocking filter, an overvoltage level detector and a timer. The 150 Hz blocking filter and overvoltage level detector are calibrated as a unit. The setting of the level detector is decided by the voltage appearing on the relay for a phase-to-ground fault on the machine terminals. For example in order that it detects ground faults in the first 95% of the stator winding, measured from the generator terminals, it must be set for 5% of the voltage expected across the relay for a phase-to-ground fault at the terminals.

The overlapping 150 Hz undervoltage relay is tuned to operate on the 150 Hz component of the voltage appearing at the generator neutral. The undervoltage protection path consists of the voltage transformer across the neutral resistor, a 50 Hz blocking filter, an undervoltage level detector on-line logic and a timer. It provides earth fault protection to more than 5% of the stator winding close to the neutral.

Since the undervoltage unit responds to an absence of third harmonic voltage, a supervision scheme is required to prevent false trips when the generator is out of service. In case of generators, that do not produce significant third harmonic voltage until loaded, an alternate protective scheme would be required since the third harmonic undervoltage relay would be out of service under light load conditions.

The determination of the pickup level of undervoltage unit requires calculation of third harmonic voltage distribution, field checking of the value, and an analysis of the variation of the third harmonic voltage at the neutral for ground faults at various points of the stator winding.

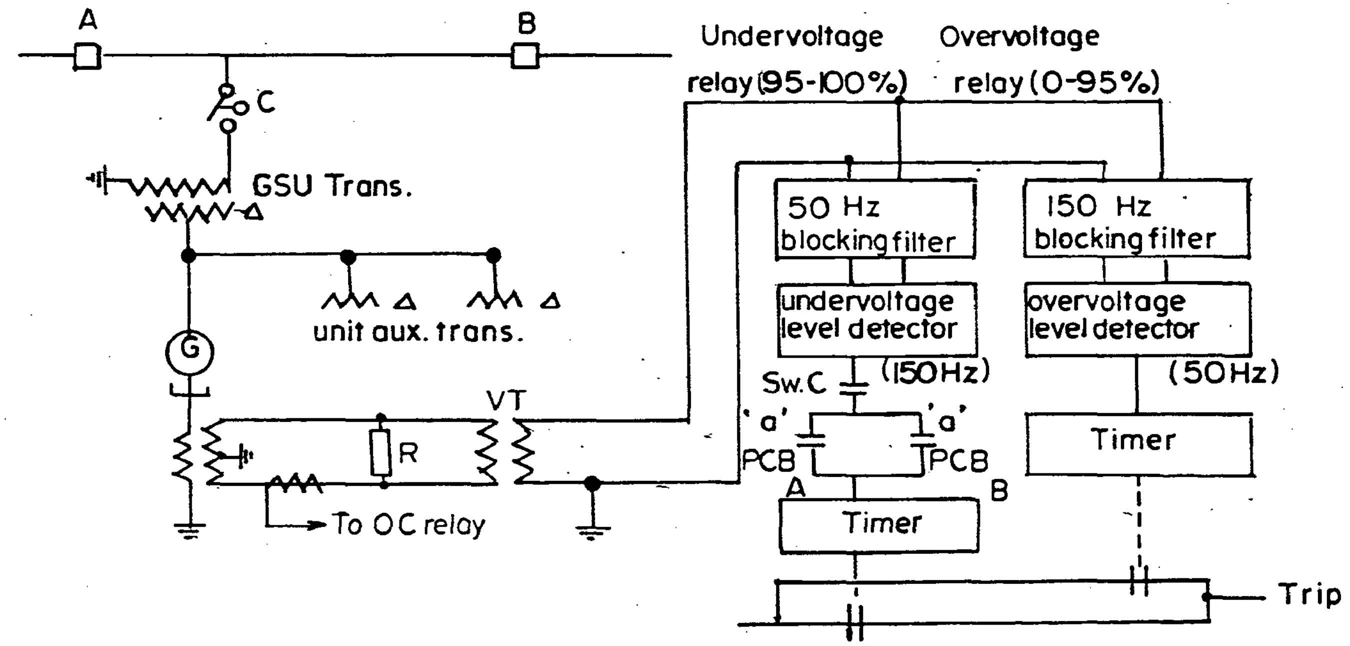

FIG.3.3 FUNDAMENTAL FREQUENCY OVERVOLTAGE & 3rd HARMONIC UNDERVOLTAGE SCHEME .[12]

3.4 THIRD HARMONIC VOLTAGE COMPARISON SCHEME

In this method the relay compares the magnitude of the third harmonic voltage at the generator neutral to that at the generator terminals. Stator ground faults near the neutral or terminal end of the generator will upset the normal third harmonic distribution resulting in relay operation [23,24]. This relay also supplements the normal 95% overvoltage or overcurrent relay to provide total stator winding ground fault coverage. A simplified scheme of this type is shown in Fig. 3.4. The relay measuring circuit consists of a d'Arsonval type dc contact making milli-ammeter (0.75-0-0.75 mAdc), two bridge rectifiers, two 150 Hz pass filters one isolating/matching transformer and a set of star/delta voltage transformers.

The matching transformer is used to balance the third harmonic voltage from the generator neutral end with the third harmonic voltage from the generator terminal end under normal conditions. This approach assumes that the ratio between the terminal and neutral end voltages will remain constant for varying unit load levels. If the ratio of terminal to neutral voltage changes considerably, the difference voltage will cause the relay to operate.

Marttila suggests a variation of this method wherein the total generator third harmonic source voltage is obtained from measurements of the third harmonic content in the neutral and residual terminal voltages [21]. The derived third harmonic source voltage is then continuously compared to the third harmonic components of the neutral and terminal voltages to detect a fault in the first 15% of the windings near the neutral.

This scheme is claimed to have the advantage that it does not require any complicated calculations or setting procedures. Practical implementation

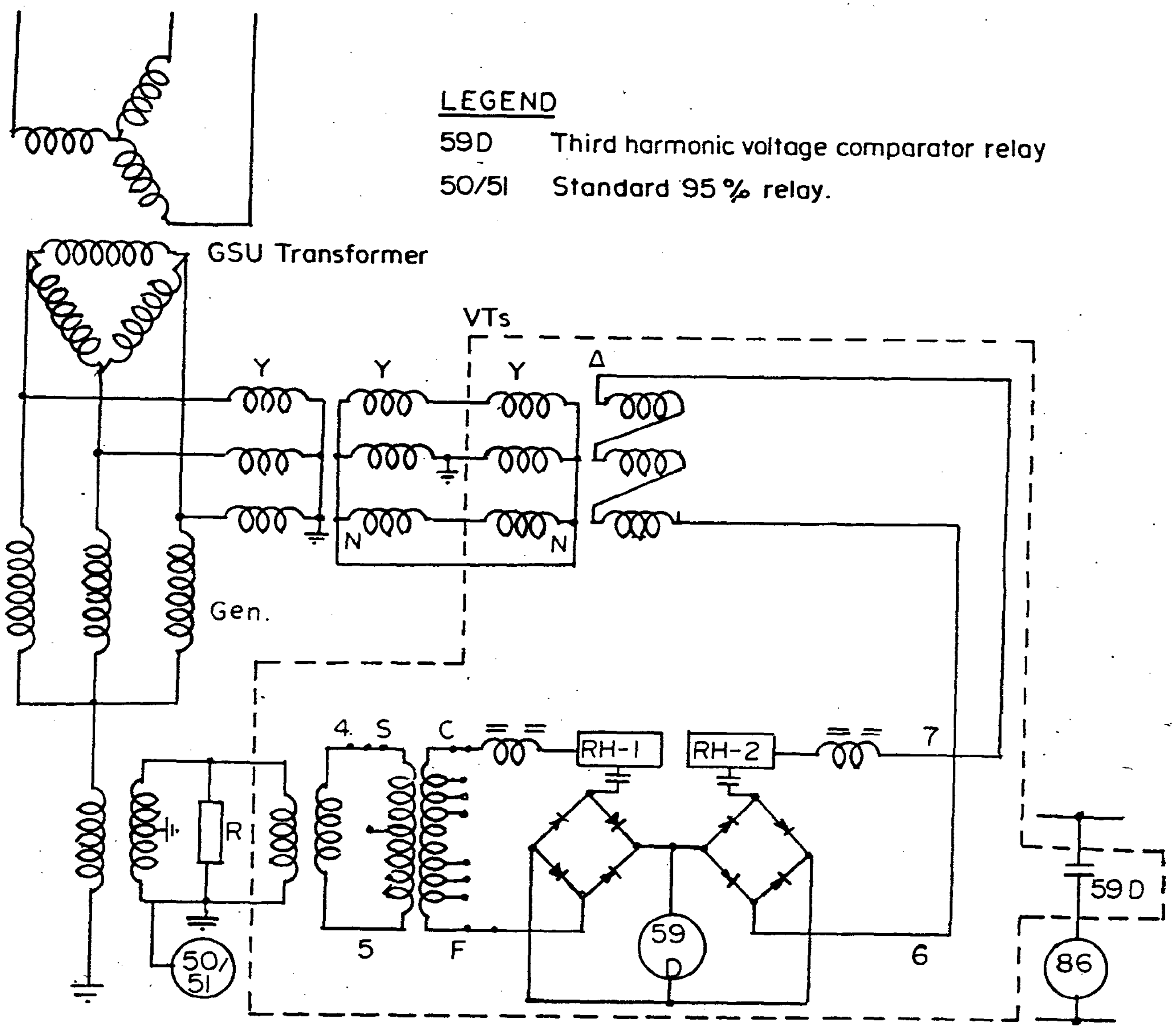

FIG.3.4 THIRD HARMONIC COMPARISION SCHEME .[24]

of this method requires that the third harmonic source voltage be of sufficient magnitude for reliable measurement and that the trip criteria is not satisfied during normal operation of the generator.

The three methods of 100% stator ground fault protection discussed here will be compared in Chapter-V, which also describes a new microprocessor based digital relay for this protection developed by the author.

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CHAPTER - IV

INCIPIENT FAULT DETECTION

4.1 GENERAL

A newer concept in protection aims at the use of monitoring techniques capable of detecting faults at the incipient stage itself. Some monitoring devices are already in use while work on many others is still at the developmental stage. Important devices are discussed in this chapter.

4.2 CORE MONITOR

Failure of insulation due to local overheating has been a significant contributor to the forced outage time of electric generators. Employing a device to give an early warning of overheating, before extensive damage takes place, led to the development of the Core Monitor [4,5,6]. This device employs an ion chamber which senses local overheating by detecting the presence of particulate products of thermal decomposition of organic materials. This monitor, to some extent, can detect interturn faults in the windings also.

4.2.1 Principle

In the initial stages of the work it was found that generator materials such as core lamination enamel, epoxy paint and various polymeric coatings produce copious quantities of particulates on overheating (of the order of $10^7/cm^2$ of coating and 0.001 to 0.01 microns in size), which could be detected sensitively with a condensation nuclei detector (CND). It was noticed that these particles could not be detected until a given polymer reached a characteristic temperature, at which point thermal decomposition would take place with abrupt vigorous emission of condensation nuclei.

If a less thermally stable polymer, such as polyalphamethylstyrene, was coated over the stable generator materials, overheating could be detected at lower temperatures. In one test using polyalphamethylstyrene (Fig. 4.1), it was seen that the concentration of condensation nuclei rose sharply during first 5 minutes, remained at a high level during the next 5 minutes and then dropped, rather sharply to zero in the next 6 minutes or so.

4.2.2 Ion Chamber Detector

Since a CND, operating like a Wilson Cloud Chamber, is a complex device, search for a simpler and less expensive device led to the development of the Core Monitor. Fig. 4.2 is a schematic diagram of the ion chamber or Core Monitor. As the sample hydrogen enters the mixing chamber it is bombarded by alpha particles from the thorium-232 contained in a mantle lining the mixing chamber. The bombardment produces ion pairs of hydrogen, some of which recombine and some enter the electrode chamber where the negative ions are attracted to the outer electrode. The current produced (of the order of 10 picoamperes) by the ions attracted to the outer, or collector, electrode is measured and charted on a recorder. With the flow rate (depending on the machine speed) and pressure of the hydrogen constant, the ion current remains constant. When condensation nuclei are produced by thermal decomposition, they pick up ions on collison and bear them past the collector electrode thereby causing a drop in the ion current, the magnitude of which is related to the concentration of condensation nuclei present.

4.2.3 Sample Results

Fig. 4.3 shows a signal obtained with a Core Monitor upon overheating a coated strip inside the generator. The ion current is seen to drop quite

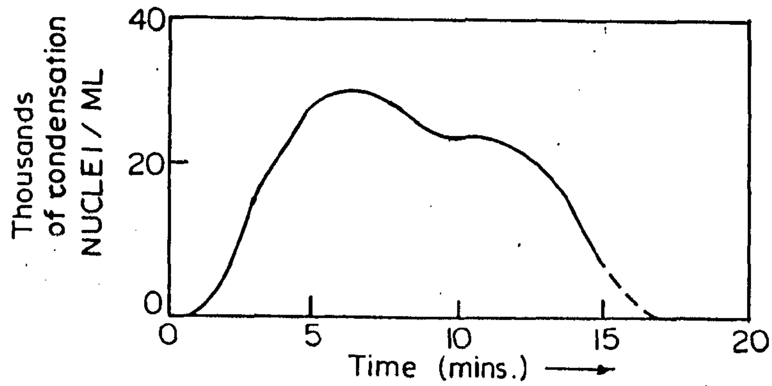


FIG.4.1 RESULT OF EXPERIMENT IN A LARGE GENERATOR TO DETECT OVERHEATING OF POLYALPHAMETHYLSTYRENE ON ENAMELED CORE LAMINATION WITH A CND [4]

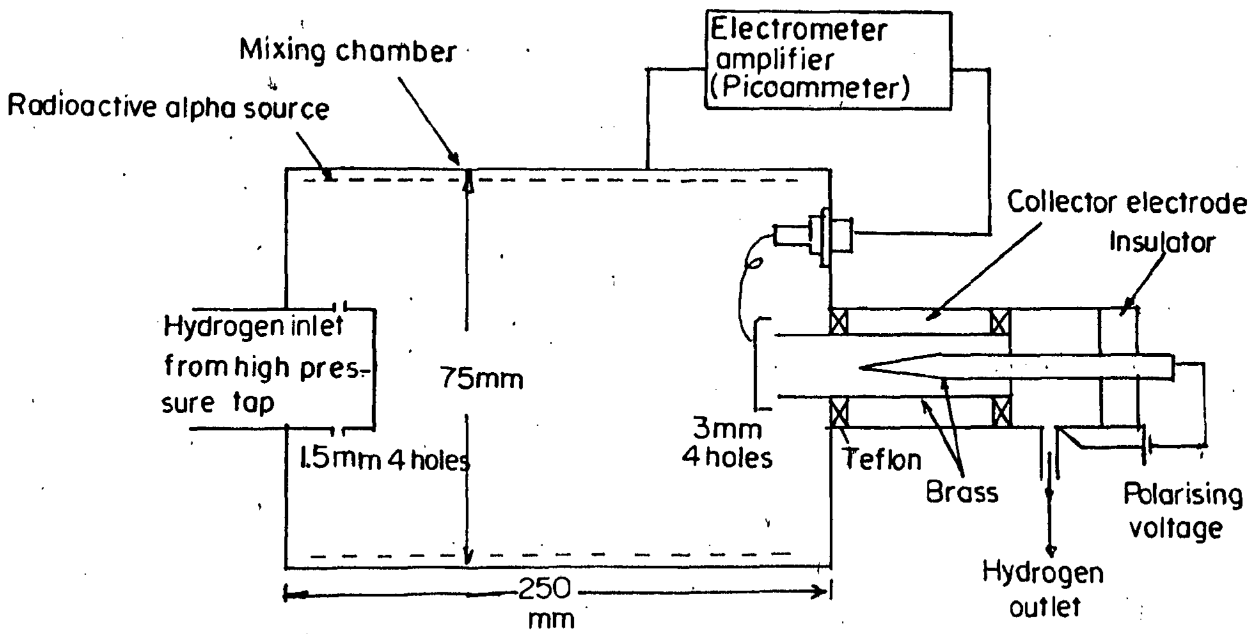


FIG.4.2 ION CHAMBER FOR DETECTION OF PYROLYSATES [4]

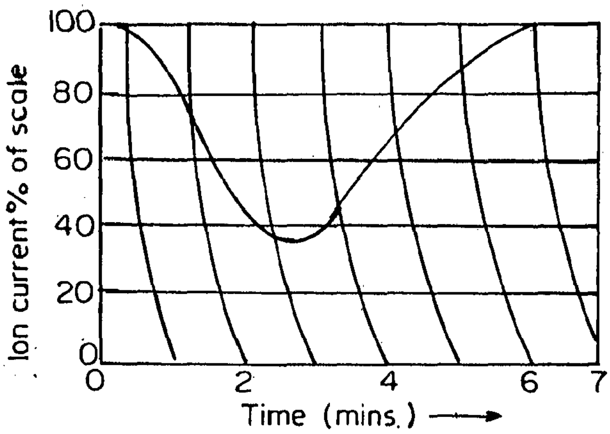


FIG.4.3 SIGNAL OBTAINED ON A CORE MONITOR FROM THE THERMAL DECOMPOSITION OF ABOUT 750mm^2 OF EPOXY PAINT ON CORE LAMINATION ENAMEL IN A GENERATOR [4]

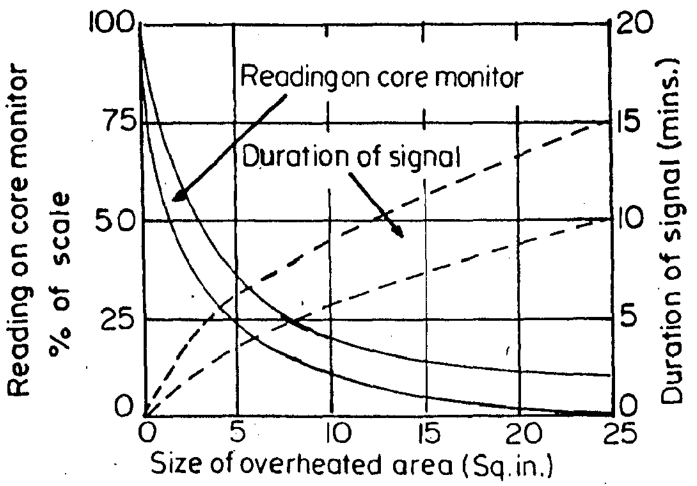


FIG.4.4 ESTIMATED READING ON CORE MONITOR AND DURATION OF SIGNAL Vs AREA OF OVERHEATED COATING [4]

sharply and then return to its original value at a slower rate. This pattern is typical of a hot spot. The strength of a signal (i.e. drop in ion current) and its duration are related to the size of a hot spot. From tests conducted on various coated metal strips that were heated rapidly by resistance heating inside a generator, graphs were constructed (Fig. 4.4) which would enable the operator to approximate the area of the hot spot from the strength and duration of a signal on the Core Monitor.

4.2.4 Current Developmental Work

When an alarm is obtained on a Core Monitor it is difficult to locate the overheated area as the alarm is given before any charring or damage. The present developmental work aims at pinpointing the faulted area so that corrective action can be taken swiftly.

4.3 BROKEN STRAND DETECTION [9,10,14]

Generators possess high reliability due to the good insulation of stator windings. To maintain dielectric strength, it is necessary that the insulation systems of the stator windings be held firmly in place and all joints be of high mechanical, thermal and electrical integrity. Generator stator components can develop problems due to conductor fatigue and subsequent failure, caused by steady state and transient magnetic forces, resulting in their loosening and vibration.

4.3.1 Principle of Detection

The failure can lead to arcing in the gap between broken copper strands. These arcs cause radio frequency (RF) currents to flow through the stator winding. Measurement of these currents in the stator's neutral connection is used for early detection of broken copper strands due to fatigue failure.

4.3.2 Detection on Basis of RF Spectrum

In this method the RF measurement setup shown in Fig. 4.5 is used. The current transformer having a frequency response from 30 Hz to 30 MHZ is used to measure the radio frequency current flow in the generator's neutral lead. The neutral lead is chosen for measurement because it is at a low potential with respect to ground and because any arcing in the generator will cause RF currents to flow in the neutral lead. The current transformer is coupled to a radio noise meter, which is a sensitive narrow band tunable instrument that can measure signal levels in micro-volts quasi-peak over a wide frequency spectrum. The quasi-peak reading is a weighted average approaching the true value of the frequency component being measured.

RF spectrum measurements on several generators in normal condition provide the unfaulted spectrum signature. Arcing can be detected if the RF spectrum of the generator under test is outside the average RF range. The change in the RF spectrum of a faulted generator before and after repairs is shown in Fig. 4.6.

4.3.3 Fixed Frequency Monitor

For generators with ratings between 600 MVA to 850 MVA, fixed frequency monitors at 1 MHz provide maximum sensitivity of arc detection. A fixed frequency monitor setup is shown in Fig. 4.7. The normal level of RF (at a monitoring frequency of 1 MHz) is well below 300 micro volts

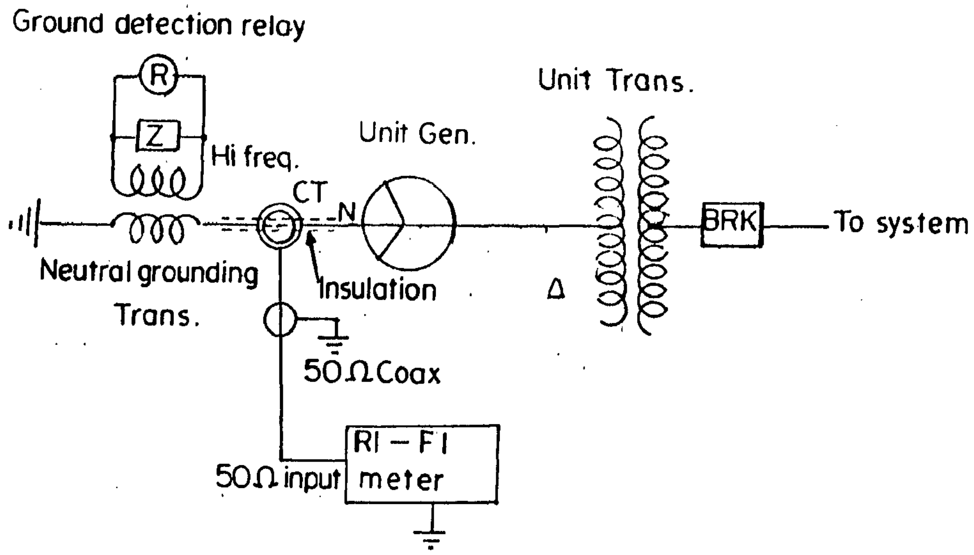


FIG.4.5 PLACEMENT OF RADIO FREQUENCY MEASURING EQUIPMENT FOR MAKING ON LINE MEASUREMENT OF RADIO FREQUENCY ACTIVITY ON LARGE TURBINE GENERATORS .[9]

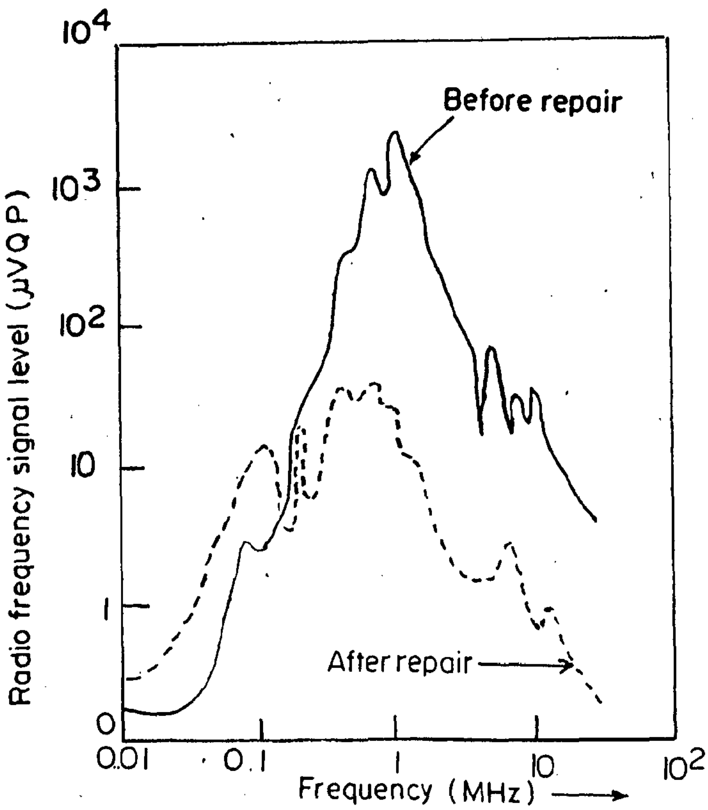


FIG.4.6 RF SPECTRA BEFORE & AFTER REPAIR.[9]

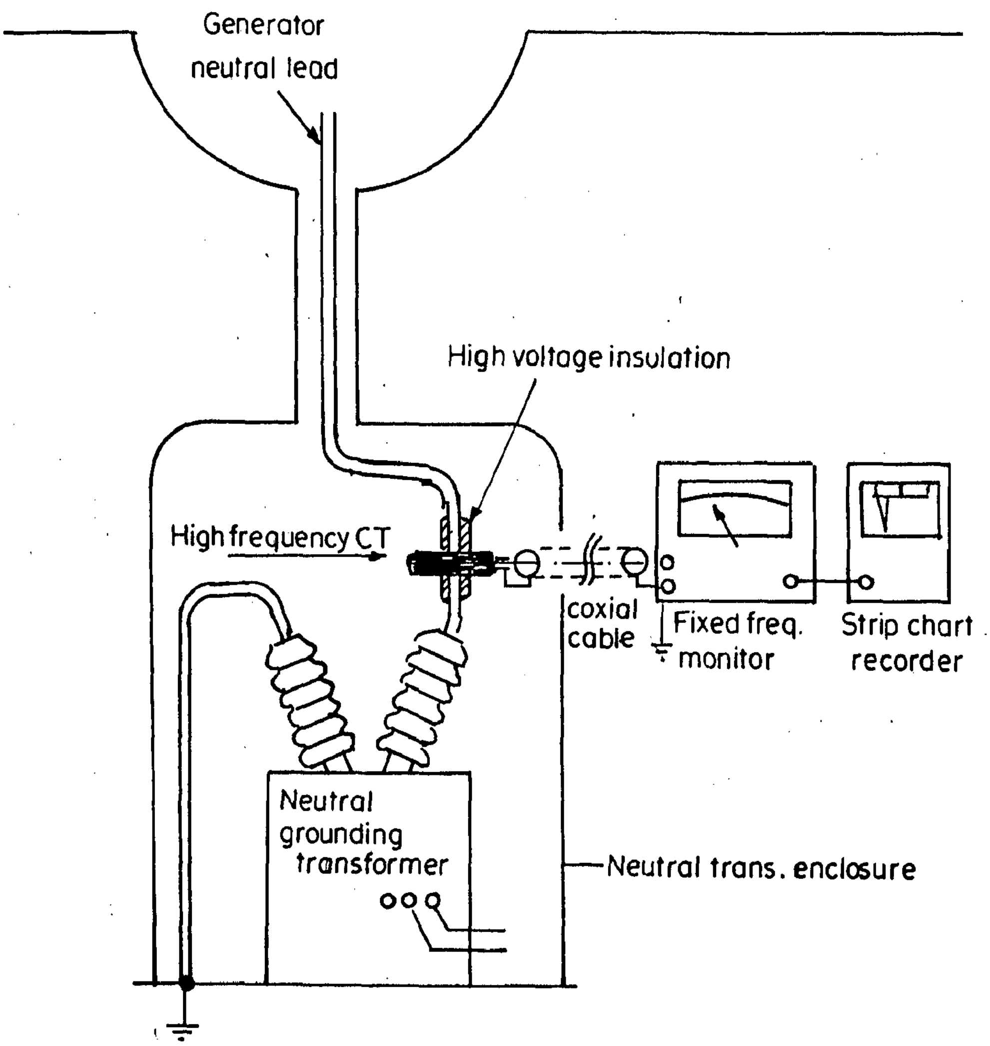


FIG.4.7 FIXED FREQUENCY RF MONITOR SCHEMATIC.[9]

for healthy large generators. An increase in the RF to a level of 500 micro volts to 1000 micro volts indicates a low level arcing possibly due to one or two broken strands. An increase above 1000 micro volts indicates that more than two strands are arcing. The RF monitor strip chart showing normal operating conditions and the faulted case where six strands were found to be arcing are shown in Fig. 4.8(a) and (b).

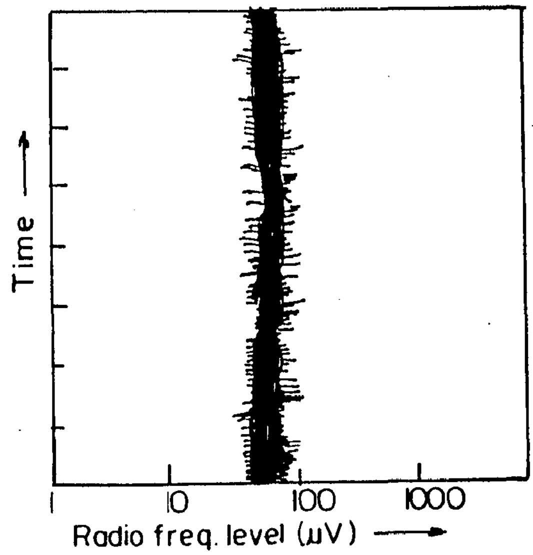
RF monitors can be installed easily on any generator using a neutral grounding transformer. They result in a significant improvement of unit availability by early detection of developing malfunctions in the stator windings.

4.4 PARTIAL DISCHARGE MONITOR

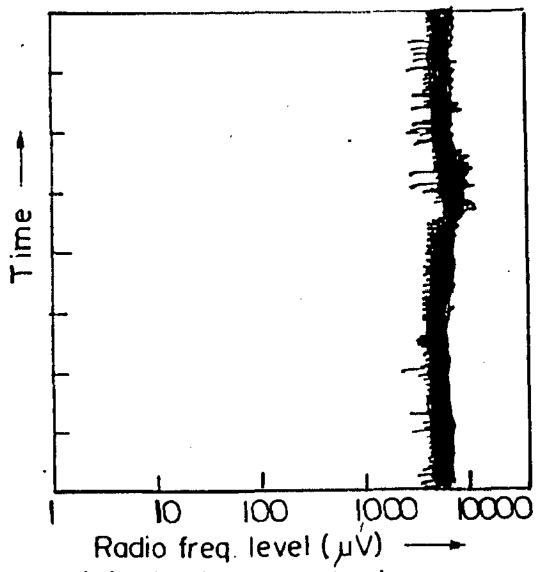
Partial discharges are produced in the generator either by broken conductors or due to slot discharges. The partial discharges pass through stator windings and can be measured at the generator terminals. The partial discharges are picked up, processed and recorded in the recorder. The wave shape and amount of discharge is indicative of winding failure at the incipient stage. This device is similar to a radio-frequency monitor and can be applied to generators whose neutral is not brought out for grounding purposes.

4.4.1 Monitoring Method [20]

The partial discharge test requires the installation of high voltage capacitors on the stator winding. Individual partial discharge pulses originating in a generator insulation system are picked up via these permanently installed capacitive couplers (about 80 pF). These couplers are connected in pairs/phase to the circuit ring bus at the connections



(a) Normal level of RF



(b) With 6 strands broken

FIG.4.8 RF MONITOR STRIP CHART RECORDS [9] to parallels, or to pole jumpers or connection points near the line end. Co-axial cables connect the low voltage side of the couplers to a convenient terminal box outside the machine. A differential amplifier is used to amplify discharge pulses and apply to a Partial Discharge Analyser (PDA) The PDA is a portable, microprocessor controlled instrument which determines the number and magnitude of the partial discharges in the winding.

4.4.2 Interpretation of Results

Generator windings in good condition display relatively low partial discharge activity while those in a bad condition display higher discharge [20,30]. Identification of the probable insulation failure is possible by the measurement of positive and negative discharge pulses independently. Slot discharges are indicated by predomination of positive discharge activity and variation of the discharges with load (Fig. 4.9). Coating deterioration is identified by a much more positive discharge activity than negative discharges (Fig. 4.10). Delamination condition shows an equal positive and negative discharge activity which is more sensitive to temperature changes than load variation (Fig. 4.11).

4.5 FIBRE OPTIC VIBRATION MONITOR [31]

Hydrogen cooled stator-end windings have been a major contributor to unavailability of generators over 500 MW. High vibration caused by resonance has been the main cause of the problem. High vibration along with loose blocking can result in insulation wear and fatigue cracking of conductor strands leading to high maintenance costs and forced outages. Until recently, symptoms of end-winding distress were only observable by off-line inspections. In the late 1970's, an optical vibration sensor capable of measuring on line end-winding vibration was developed. This

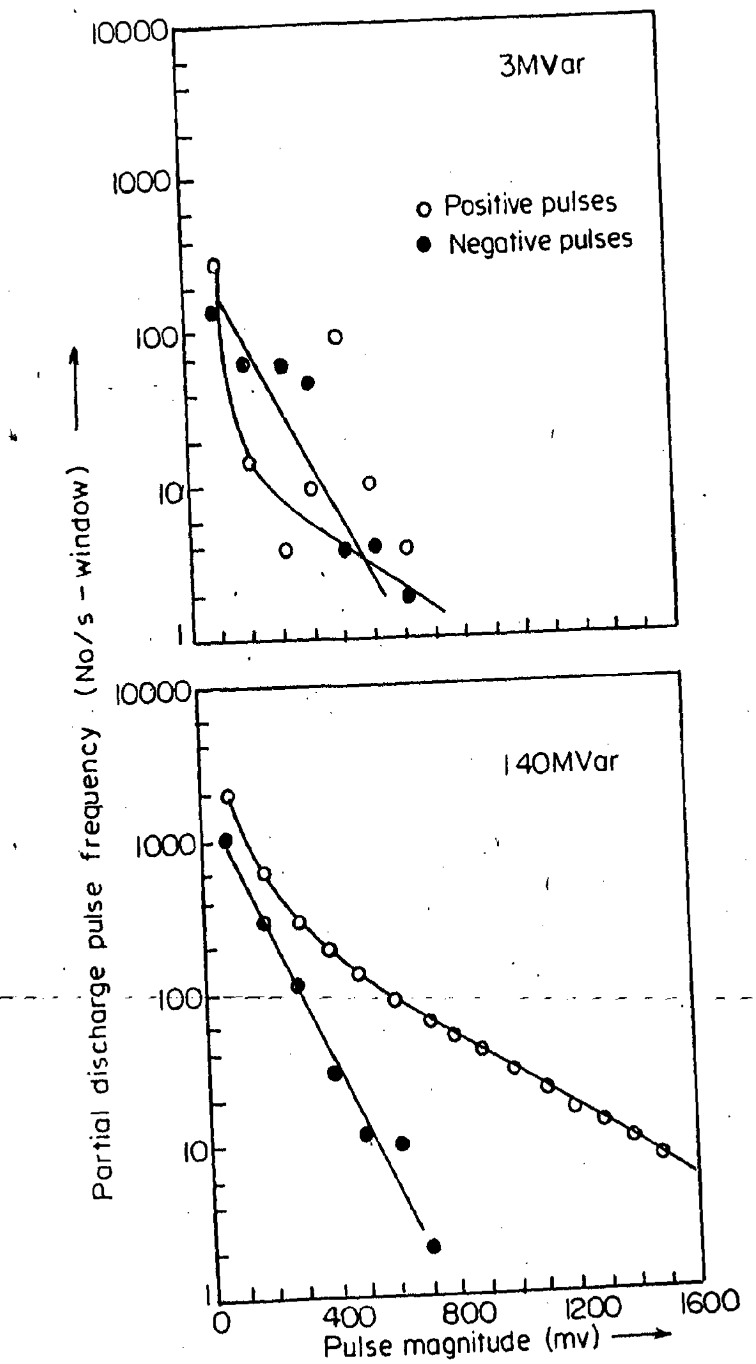


FIG.4.9 DISCHARGE ACTIVITY FOR SLOT DISCHARGES [20]

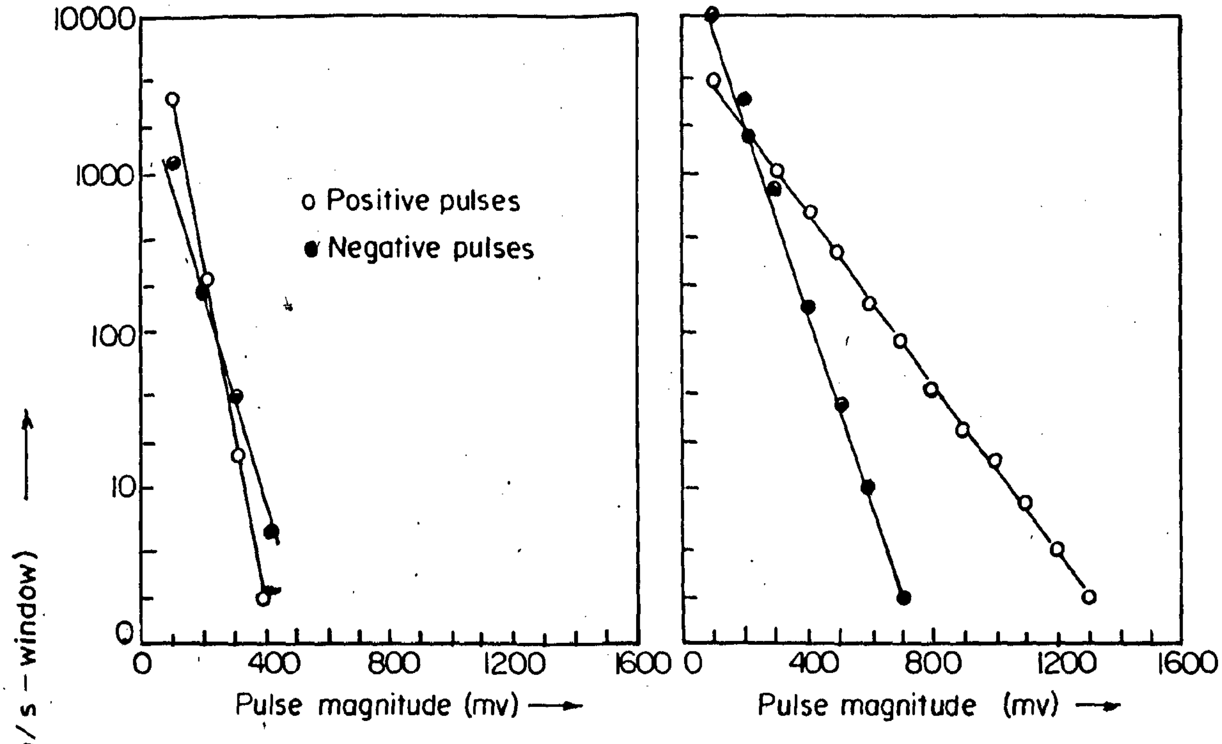


FIG.4.10 DISCHARGE ACTIVITY SHOWING COATING DETERIORATION. [20]

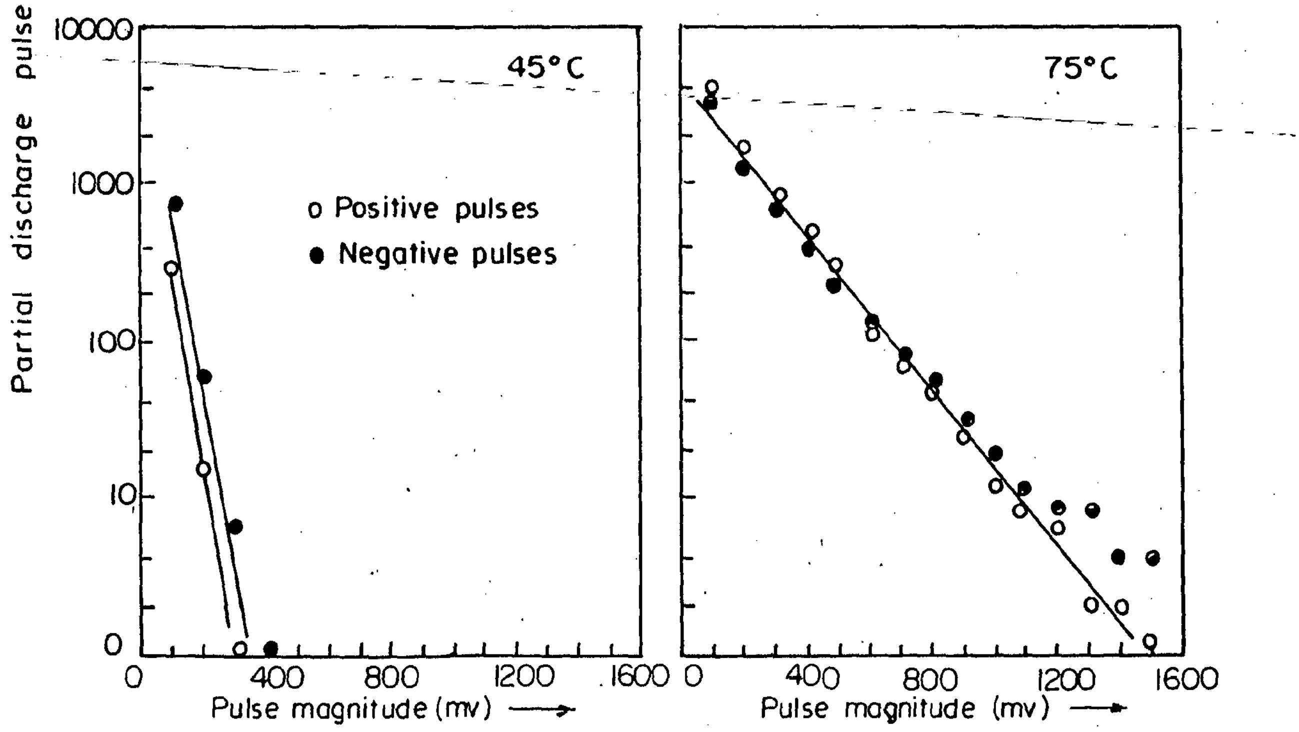


FIG.4.11 PDA TEST DATA FOR DELAMINATION CONDITION. [20]

has developed into the fibre optic vibration monitor which allows continuous vibration data to be displayed in the control room.

4.5.1 Winding End Turn Vibration

The generator end windings experience forced vibration during operation. The forced mechanical vibration frequency is two times the electrical synchronous frequency of the generator. Therefore, stator end-winding vibration occurs at 120 Hz for 60 Hz systems (100 Hz for 50 Hz systems). Any excitable natural frequency near 120 Hz (100 Hz) will amplify the nominal vibration level resulting in rapid deterioration of the stator end-windings. Figure 4.12 compares the vibration amplitude of two generators of identical design and similar operation. Generator B has a winding natural frequency near 120 Hz while Generator A does not. This shows the large difference that can exist between generators of the same design due to structural changes within the generator.

4.5.2 Monitor Setup and Operation

The heart of the fibre optic vibration monitor system is the vibration sensor. The device is sensitive to vibratory motion in one direction calibrated at one frequency (120 Hz or 100 Hz). The small size (25 mm x 25 mm x 75 mm) and the electrical isolation of the optical circuit allow the sensors to be mounted directly to the stator coil ends. Its operating principle can be understood from Fig. 4.13. A grid of evenly spaced slots is mounted at the end of a flexible reed. The reed is tuned to be resonant at a natural frequency slightly above 120 Hz (100 Hz). During operation, the small amplitude forced vibrations of the stator end windings are amplified at the grid end of the resonant reed. A continuous beam of light is directed through the grid at a right angle to the vibratory motion.

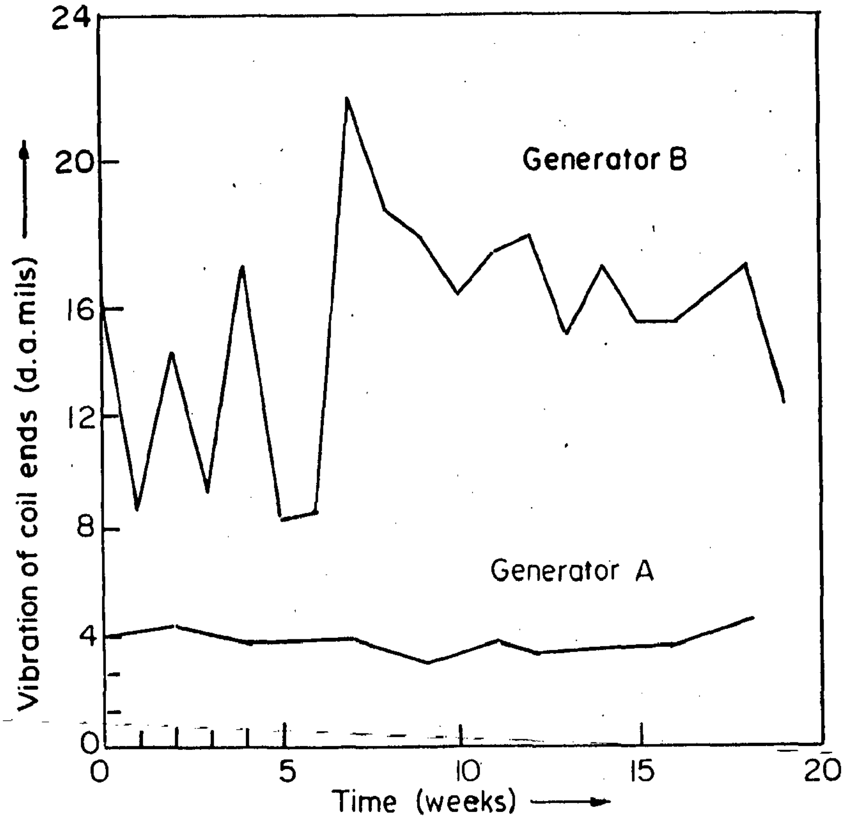


FIG.4.12 VIBRATION COMPARISION OF IDENTICAL GENERATORS SHOWING DIFFERENT DISCHARGE ACTIVITY .[31]

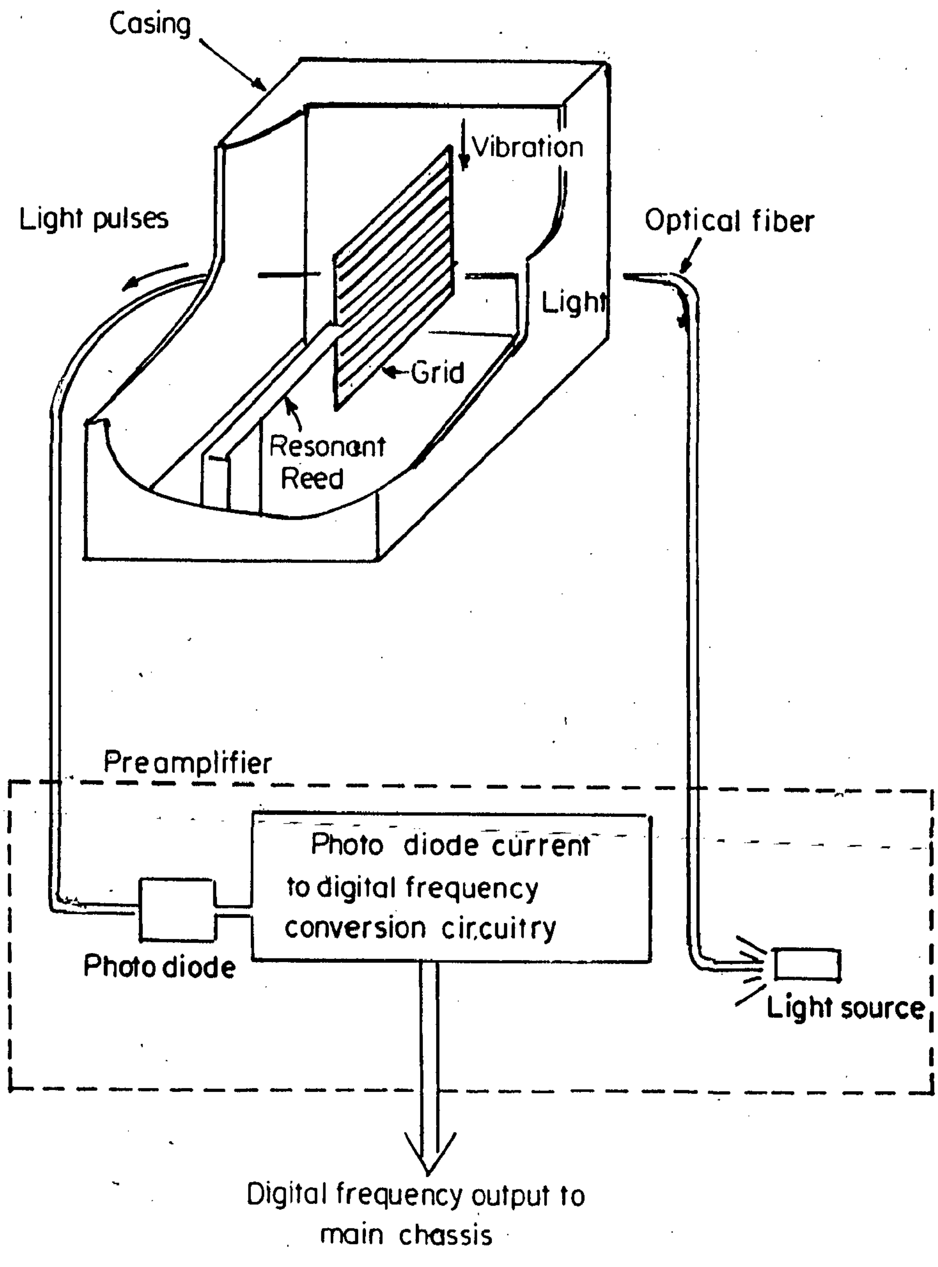


FIG.4.13 FIBER OPTIC VIBRATION SENSOR.[31]

As each slot in the grid moves through the beam of light, a pulse of light enters the optical cable on the other side of the grid. The number of light pulses in a given period of time is proportional to the amplitude of vibration. A tuned sensor is desired since the end-winding vibration is mostly at two times the electrical synchronous frequency only. If high vibration is detected, dynamic testing is used to find the natural frequency that is the root cause of the vibration.

The fibre optic vibration monitor provides measurement at six locations on each end of the generator . Fig. 4.14 shows the sensor mounting location and optical cable routing. A schematic diagram of the monitor is given in Fig. 4.15. The system is composed of vibration sensors, internally routed optical fibres, fibre optic cable bundles, preamplifiers and a readout box which permit the stator end-winding vibration amplitude signals to be displayed within the control room.

The monitor will provide an alarm if the vibration level exceeds an adjustable present level which is typically between 10 to 15 double amplitude mils. Winding improvement is then carried out to prevent further damage (Fig. 4.16).

4.6 STATOR BAR WATER TEMPERATURE MONITORING [5]

For water cooled generators, it has been possible to monitor only average water temperature by using conventional measuring devices. However, flow restrictions in an individual bar shall produce excessive heating of the respective stator bar. Water temperature of both top and bottom bars can be measured using insulated temperature sensors. The bar temperature monitoring device measures outlet temperatures of each bar and continually compares it with the baseline value measured on healthy machines. The

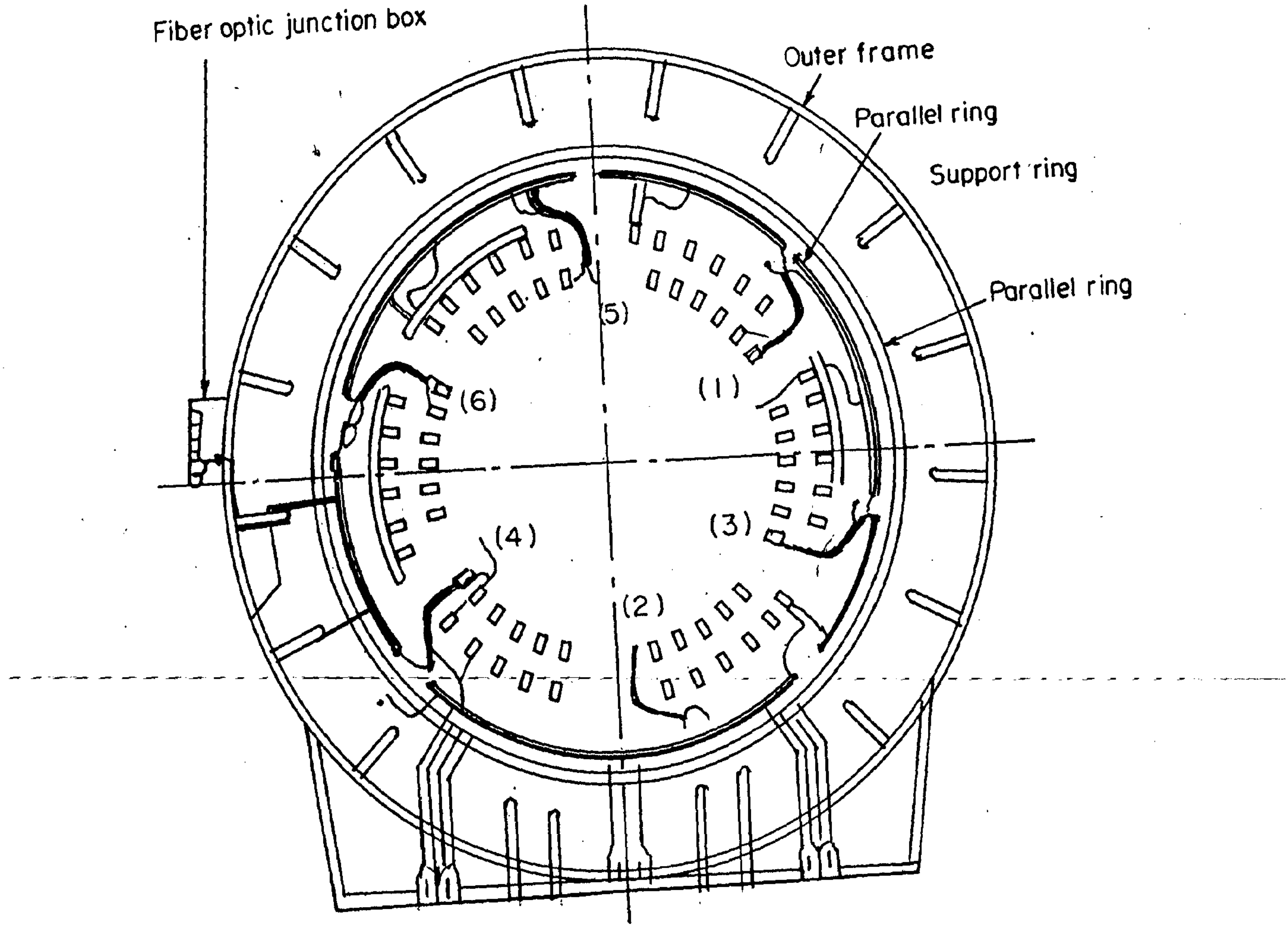


FIG.4.14 STANDARD SENSOR LOCATIONS (6) FOR THE EXCITER END.[31]

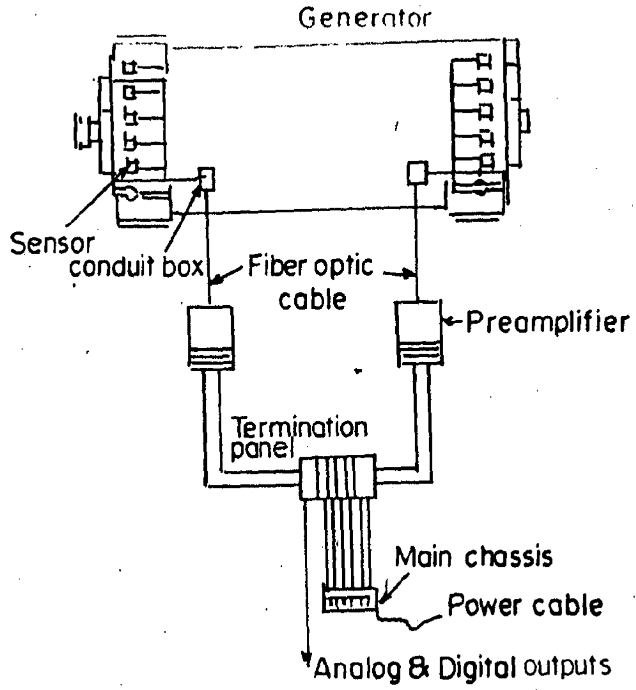


FIG.4.15 FIBER OPTIC VIBRATION MONITORING SYSTEM.[31]

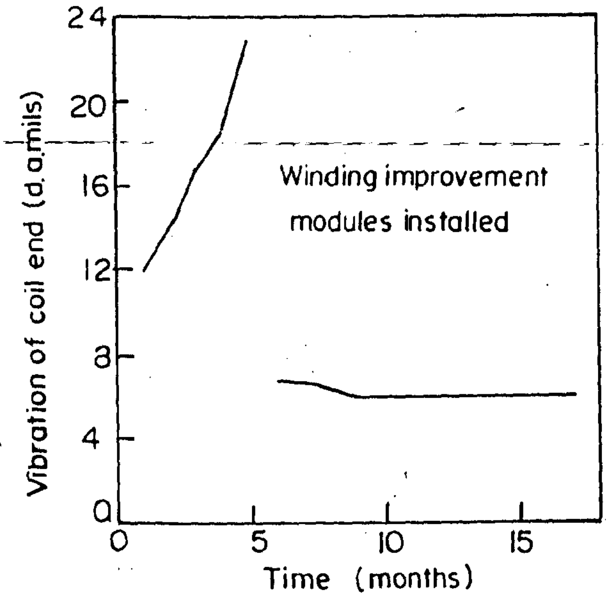


FIG.4.16 THE EFFECT OF MODULE INSTALLATION ON A FAULTY GENERATOR.[31]

data of all bar temperatures is fed to a computerised temperature detector. High water temperature in a bar indicates a choked slot either due to conductor corrosion or other reasons.

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CHAPTER - V

MICROPROCESSOR BASED 100% STATOR GROUND FAULT RELAY

5.1 GENERAL

The requirement of protecting the complete stator windings of large generators against earth faults needs no further emphasis. The hazardous condition that prevails due to the shorting of the grounding resistance by an earth fault near the neutral has been discussed in Chapter-III. The present chapter highlights the drawbacks of the existing schemes and presents the development of a microprocessor based 100% stator ground fault relay.

5.2 COMPARISON OF AVAILABLE SCHEMES

As seen in Chapter-III, there are basically two approaches, one based on injection of an external subharmonic frequency voltage at the neutral and the other based on the measurement of third harmonic voltages seen at the neutral and terminal ends of generators. Third harmonic schemes are of two types :

(a) Neutral undervoltage schemes which detect an earth fault near the neutral end by sensing a reduction in the neutral third harmonic voltage from its pre-fault steady state value.

(b) Voltage comparison schemes based on a comparison of the neutral and terminal end third harmonic voltages.

A comparison of various features provided by each type of protection scheme is given in Table 1 [24].

TABLE 1 – COMPARISON OF 100% STATOR GROUND FAULT PROTECTION SCHEMES [24]

	Subharmonic Injection Scheme	Fundamental Frequency Overvoltage and Third Harmonic Undervoltage Scheme	Third Harmonic Comparison Scheme
1. Percentage Coverage Portion of generator bus, connected transformer windings, stator winding, neutral connections protected.	Covers 100% of stator winding and connected equipment. Additional protection required for 100% coverage.	The combination of overvoltage and third harmonic undervoltage covers 100% of the stator winding and connected equipment.	Covers the terminal and neutral ends of the stator winding and connected equipment. Conventional stator protection is required to cover center portion of stator winding.
2. Self-monitoring			
(a) Detects short circuits in stator grounding system.	(a) Operates for shorts across the primary or secondary of the grounding transformer.	(a) Operates for shorts across the primary or secondary of the grounding transformer.	(a) Operates for shorts across primary or secondary of the grounding transformer.
(b) Detects open circuits in stator grounding system.	(b) Will not detect or alarm for open grounding transformer primary or secondary.	(b) Operates for open grounding transformer primary or secondary. Will not detect or alarm for open grounding resistor.	(b) Operates for open grounding transformer primary or secondary.
3. Field measurements required for setting.	Yes	Yes	Yes
4. Setting calculation	Moderately difficult	Moderately difficult	Easy
5. Ground detection on turning gear or at standstill.	Yes	No	No
6. Sensitivity affected by machine loading.	No	Yes	Yes
7. Connection to neutral of generator V.T.'s	No	No	Yes
8. Tripping time	560-1120 ms at 12.5 Hz	Overvoltage unit = 1500 ms Undervoltage unit = Adjustable	528 ms at two times operating voltage.
9. Test features	Yes	No	No
10. Power supply required	Built-in	No	No
11. Approximate price	3X	X	X
12. Applicable to multiple units on same bus.	Yes	Maybe	No

5.3 LIMITATIONS OF AVAILABLE METHODS

Subharmonic injection methods have the following drawbacks :

(a) An expensive sub-harmonic signal generator is required which makes these schemes about three times costlier than third harmonic schemes.

(b) Existing generator grounding system requires alteration.

Third harmonic schemes also have the following drawbacks :

(a) Commissioning requires elaborate calculations to suit the particular generator being protected.

(b) As the level of third harmonic voltage varies with power output supervision may be required to prevent maloperation during low power operating conditions.

(c) Inherent protection stability against external system disturbances is poor and stability can be ensured by delaying the trip resulting in slow operation.

5.4 DIGITAL METHODS

Khan and Cory have suggested two digital methods for 100% stator ground fault protection coupled with a parallel digital 90% scheme based on an over voltage of fundamental frequency at the neutral [19]. In one approach, using the neutral voltage as the main relaying measurand, the operating signal at n^{th} sample ($SO_3(n)$) is obtained as

$$SO_3(n) = |E_{N3}(n) - r_{(n)}|$$

where,

$r_{(n)}$ is a reference based on the pre-fault value of third harmonic voltage, and

E_{N3} is the current value of measured third harmonic voltage.

In the second scheme, which is a voltage comparison scheme with E_N, E_A, E_B and E_C as the measurands, the operating signal is obtained as

$$SO_3(n) = |E_{N3}(n) - A\ E_{a3}(n)|$$

$$E_{a3}(n) = 1/3[\bar{E}_{A3}(n) + \bar{E}_{B3}(n) + \bar{E}_{C3}(n)]$$

and A is a gain factor.

The restraint signal in both the cases is given by $SR_3 = r(n)/k$, where k is a sensitivity factor. The fundamental and third harmonic components are extracted using a digital Fourier filter.

These schemes are liable to give a false trip whenever the load on the generator changes suddenly. The change in load causes a considerable change in the third harmonic content of the generated voltage. If the relay is set not to operate on such a change its sensitivity to faults close to neutral will be adversely affected.

5.5 PROPOSED METHOD

The proposed method also relies on the third harmonic components seen at the neutral and terminal ends of the generator. The scheme is implemented on a 16-bit microprocessor.

5.5.1 Third Harmonic Voltages

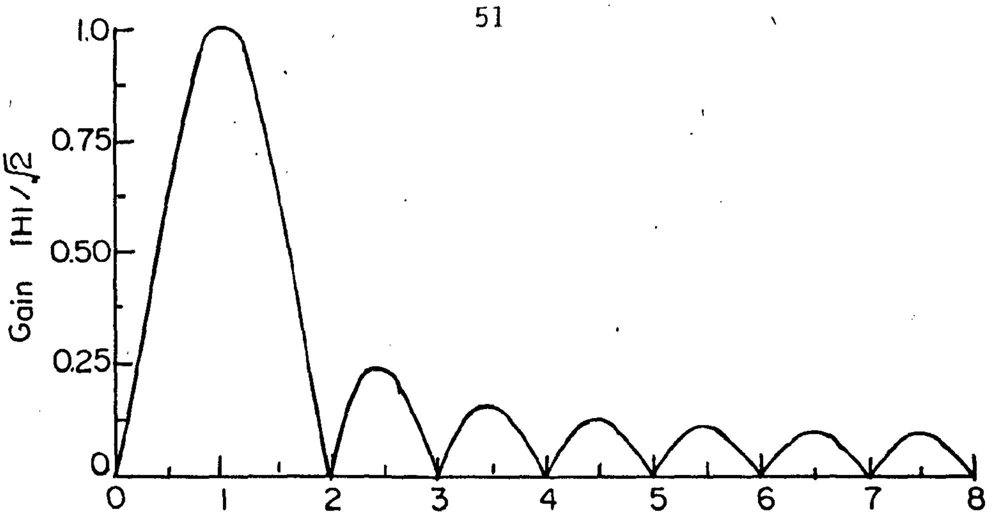
Marttila has evaluated the third harmonic voltage contents of various generators ranging from 160 MW to 540 MW for different load conditions [21]. The minimum third harmonic voltage was found to range between 0.2% to 2% of the fundamental rated phase to neutral voltage of the generator. The maximum value was generally between 4% to 6% of the rated voltage. The maximum level of third harmonic voltage occurred near the rated real power output and the minimum value at zero real power output.

5.5.2 Filter Selection

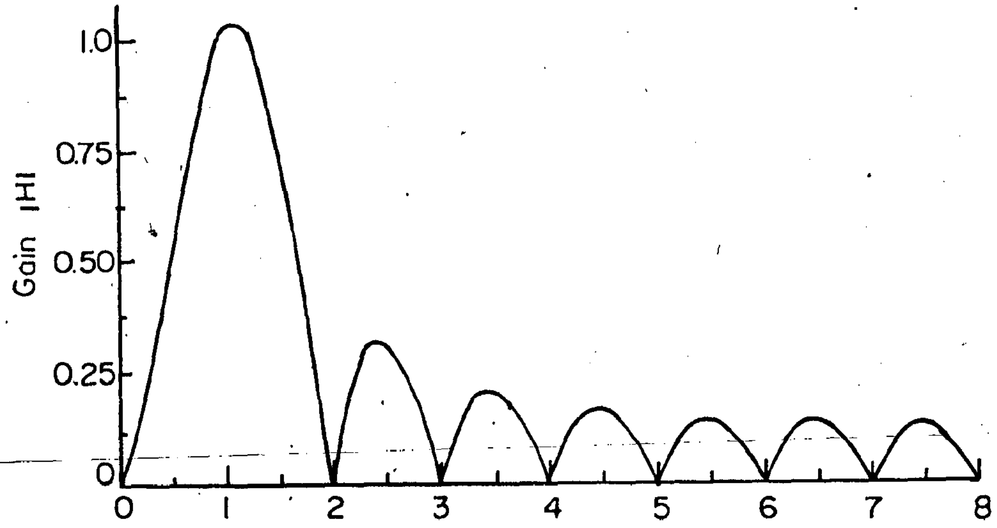
Verma and Kakoti have evaluated various filter algorithms for extraction of fundamental and harmonic contents [34]. Existing algorithms require the sine and cosine components both to be calculated to obtain the filtered value. This would take a considerable amount of microprocessor time thereby restricting the number of relaying functions within each sampling period. It was seen that only the cosine component of the Fourier algorithm can be used seperately without adversely affecting the filter response as can be seen from Figs. 5.1(a) and (b) respectively.

The Fourier Transform algorithm for extraction of fundamental frequency component with sixteen samples per cycle is given by

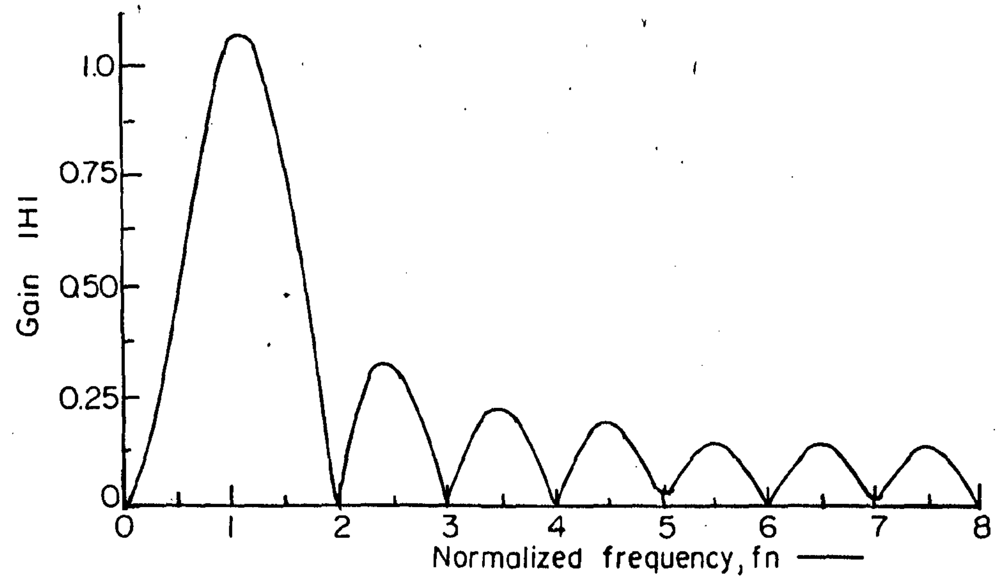
$$F_c' = 0.125[0.5(Sk_{16} + Sk_0) - Sk_8 + 0.924\,(Sk_1 - Sk_7 - Sk_9 + Sk_{15}) + 0.707\,(Sk_2 - Sk_6 - Sk_{10} + Sk_{14}) + 0.383\,(Sk_3 - Sk_5 - Sk_{11} + Sk_{13})] \quad \ldots(1)$$



(a) COMBINED FOURIER TRANSFORM ALGORITHM.



(b) COSINE TRANSFORM ALGORITHM



(c) MODIFIED COSINE TRANSFORM ALGORITHM.

FIG.5.1 FREQUENCY RESPONSES.

$$F_s' = 0.125[Sk_4 - Sk_{12} + 0.383\ (Sk_1 + Sk_7 - Sk_9 - Sk_{15})$$
$$+ 0.707\ (Sk_2 + Sk_6 - Sk_{10} - Sk_{14}) + 0.924(Sk_3 + Sk_5 - Sk_{11} - Sk_{13})] \qquad (2)$$

$$F' = \sqrt{F_c'^2 + F_s'^2} \qquad (3)$$

where,

F_c' and F_s' are the real & imaginary components of the combined filtered value (F') and S_{kn} is the sample at the $(K-N+n)^{th}$ sampling instant. N is the number of cycles (= 16).

The Cosine Transform algorithm uses only expression (1) for extraction of the component. To further simplify the computation of the filtered value on a microprocessor, the coefficients can be modified to reduce the number of multiplications required as in expression (4). The response of the modified filter can be seen in Fig. 5.1(c).

$$F_c' \text{ modified} = 0.125[0.5(Sk_{16} + Sk_0) - Sk_8 + (Sk_1 - Sk_7 - Sk_9 + Sk_{15})$$
$$+ 0.75(Sk_2 - Sk_6 - Sk_{10} + Sk_{14}) + 0.375(Sk_3 - Sk_5 - Sk_{11} + Sk_{13})] \qquad ...(4)$$

In the present work the Cosine Transform algorithm has been used in its unmodified form. In case the microprocessor is used for a number of relaying functions, the time taken for data processing for each relaying function can be reduced by using the modified filter algorithm.

5.5.3 Relay Principle

The proposed relay initially checks for an open/short circuit in the grounding connections by comparing the third harmonic components in the voltages at the neutral and terminal ends of the generator. In case the difference between the two exceeds a specified value an alarm is given by the relay.

If the grounding circuit is okay, the relay checks for a fault between 40% and 100% of the stator winding by comparing the fundamental frequency component of the voltage across the grounding resistor (V_{N1}) with the threshold value (V_{NTH40}). In case a fault is detected an instantaneous trip signal is issued. In case of no fault, the neutral voltage V_{N1} is compared with a lower threshold value (V_{NTH5}) to check for a fault between 5% and 40% of the stator winding. The fault criteria in both cases is duplicated by comparing the fundamental frequency component of the open delta terminal voltage (V_{P1}) with its corresponding threshold values (V_{PTH40} and V_{PTH5}).

If a fault is not detected by the overvoltage criteria, its presence between 0% and 5% of the winding is checked by comparing the third harmonic content of the neutral voltage (V_{N3}) with the minimum threshold value (V_{N3TH}). The minimum third harmonic threshold value (V_{N3TH}) is kept at half the value of third harmonic voltage seen at the neutral end at no load. In case V_{N3} falls below V_{N3TH}, the relay gives a trip.

A fault on the high voltage side of the generator step-up transformer may cause a voltage shift of about 30-40% of the voltage at the neutral. A typical calculation available from discussions on [12] is given at Appendix 'A'. In order to differentiate between faults internal to the stator windings and external (high voltage side) faults, the reach of the third harmonic undervoltage relay is increased to cover 40% of the winding from the neutral end. The threshold setting of the undervoltage relay set to cover 40% of the winding is calculated after accounting for filter errors. Since the third harmonic voltage varies with load, load current is monitored to obtain the threshold value. A linear variation of third harmonic voltage with load is assumed. A trip signal is issued if the third harmonic voltage at the neutral falls below the calculated threshold value. In case the third harmonic voltage is above the threshold value, the relay trips after a time delay of 10 to 50 cycles (adjustable) to serve as back-up for external faults. To prevent maloperation of the relay at low load levels, the 40% undervoltage criteria is not considered if the load current falls below 40% of full load value. In this case tripping is delayed by 10-50 cycles.

The trip and alarm criteria are summarized below :

(a) Issue alarm signal if $|V_{P3} - V_{N3}| >$ threshold value indicating an open/short circuit in the grounding connections.

(b) Issue instantaneous trip signal if

(i) $V_{N1} \geq V_{NTH\ 40}$ or $V_{P1} \geq V_{PTH\ 40}$ indicating a fault between 40% and terminal end of the generator upto the low voltage winding of the generator step-up transformer.

(ii) $V_{NTH\ 40} > V_{N1} \geq V_{NTH\ 5}$ or $V_{PTH\ 40} > V_{P1} \geq V_{PTH\ 5}$ and $I > 40\%\ I$ full load and $V_{N3} < V_{N3\ 40}$ indicating a fault between 5% and 40% of the winding.

(iii) $V_{N3} \leq V_{N3\ TH}$ indicating a fault between neutral and 5% of the winding.

(c) Issue delayed tripping if

(i) $V_{NTH\ 40} > V_{N1} \geq V_{NTH\ 5}$ or $V_{PTH\ 40} > V_{P1} \geq V_{PTH\ 5}$ and $I < 40\%\ I$ full load and/or $V_{N3} > V_{N3\ 40}$ indicating a fault on the high voltage side of the generator step-up transformer.

5.5.4 Relay Schematic and Hardware

The block scheme of the relay is shown in Fig. 5.2. Voltage signals V_N and V_P are obtained from a voltage transformer across the neutral grounding resistor and open-delta voltage transformers connected to terminals respectively. The load current is obtained from a current transformer which is converted to a voltage signal before being fed to the relay. Frequencies beyond 400 Hz, in all three inputs, are cut off using an analogue (active) second order low pass filter to prevent aliasing. The sinusoidal output from the filter is level shifted to get a unipolar signal for the ADC 0809. The two voltage signals V_N and V_P are sampled simultaneously using sample and hold circuits. The digital values of the input parameters are fed to the microprocessor through I/O ports.

The programmable timer of MC-68230 chip is made to generate a periodic interrupt at every 1.25 ms. The clock for the ADC is obtained from the microprocessor clock.

5.5.5 Relay Software

The flowcharts for the main program and the interupt service routine are given in Fig. 5.3. The main program initializes both the stack pointers, I/O ports and timer. Thereafter the microprocessor waits for the interrupt after loading the count in the timer registers and enabling the interrupt.

The interrupt service routine reloads the timer, enables the next interrupt and sends a common sample and hold pulse for both V_N and V_P. The latest values of V_N and V_P are read through the ADC and their sample tables are updated. Thereafter the fundamental frequency components (V_{N1} and V_P) and the third harmonic components (V_{N3} and V_{P3}) are calculated

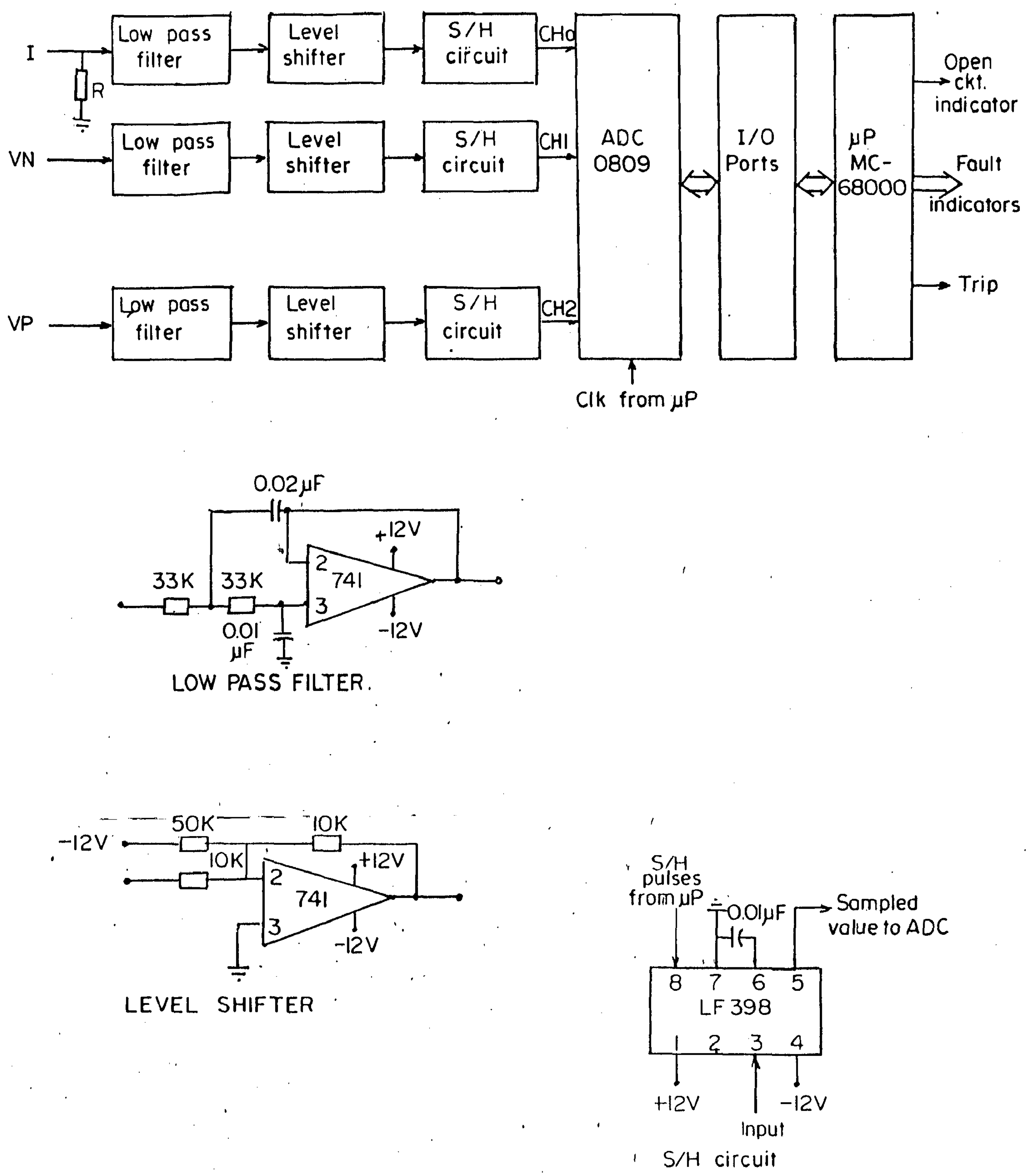


FIG.5.2 BLOCK SCHEMATIC OF 100% STATOR GROUND FAULT RELAY.

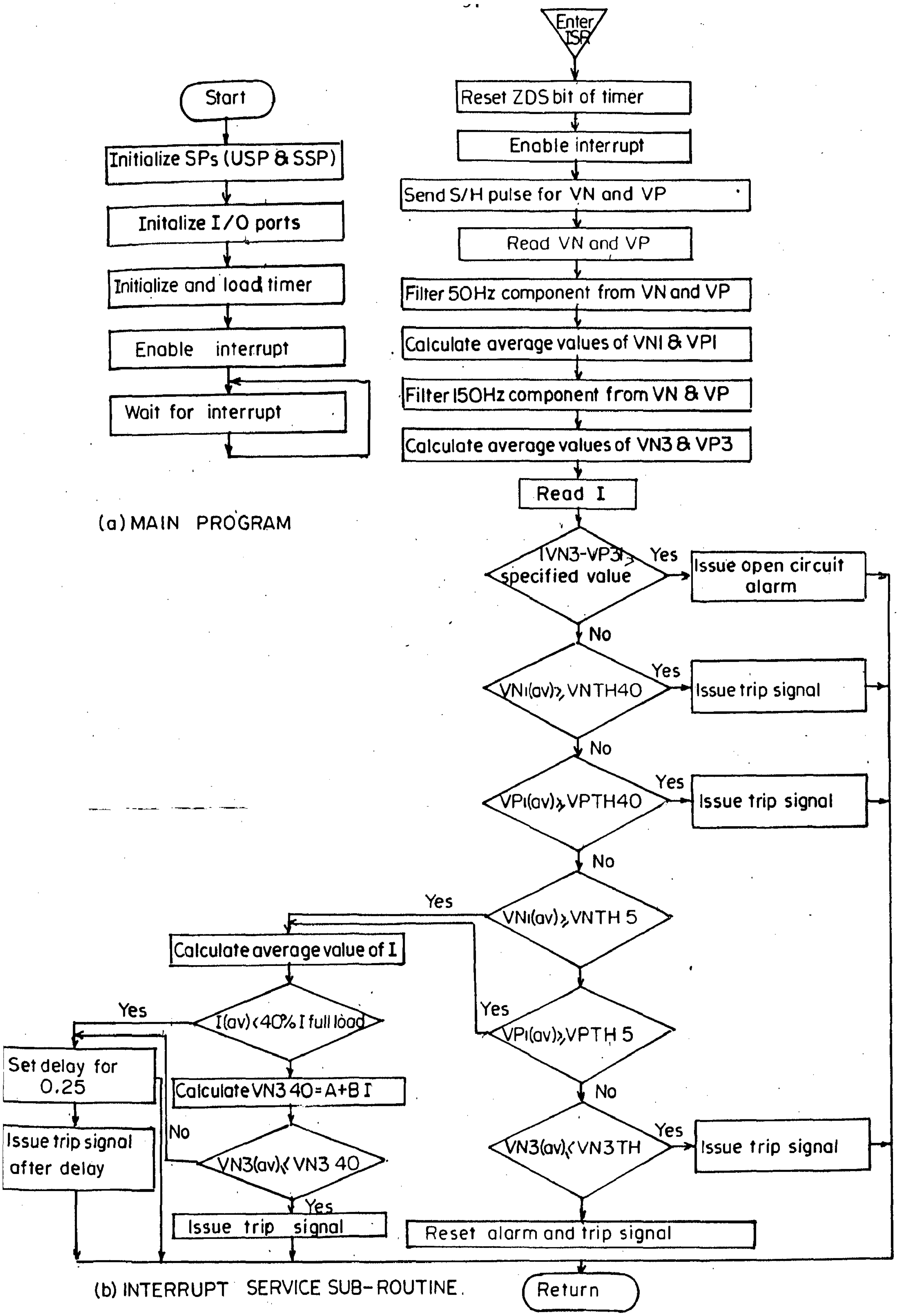


FIG.5.3 PROGRAM FLOW CHART FOR THE RELAY.

using the Cosine Transform Algorithm. The average values of V_{N1}, V_{P1}, V_{N3} and V_{P3} are calculated. The load current value is also read.

The difference between the third harmonic components $|V_{P3} - V_{N3}|$ is compared with the maximum difference value seen under normal conditions. In case the difference is greater than the normal value the relay issues an open circuit alarm and returns to the main program.

If the grounding circuit is okay, the relay uses the fundamental frequency overvoltage criteria to detect a fault between 5% and 100% of the winding. In case $V_{N1}(av)$ is more than $V_{NTH\ 40}$ an instantaneous trip is obtained. If $V_{N1}(av)$ is above $V_{NTH\ 5}$, the average value of load current I is calculated. If the load current is below 40% rated value, the relay trips after a time delay of 0.2 s. If the load current is above 40% rated value $V_{N3\ 40}$ is calculated and compared with $V_{N3}(av)$. If $V_{N3}(av)$ is less than $V_{N3\ 40}$ a trip is generated. If not the trip signal is delayed by 0.2 s indicating an external fault.

If the overvoltage criteria does not detect a fault, $V_{N3}(av)$ is compared with the minimum threshold value $V_{N3\ TH}$. In case $V_{N3}(av)$ is less than $V_{N3\ TH}$ a trip is obtained. If not the relay resets all alarm and trip signals and returns to the main program.

5.5.6 Test Results

Calculations were performed to obtain fault values for a typical generator. The calculations are given at Appendix 'B'. Input signals corresponding to the calculated values were simulated in the laboratory and fed to the relay. The relay response is shown in Fig. 5.4. A fault in the first 13% of the windings was detected by the third harmonic undervoltage relay for

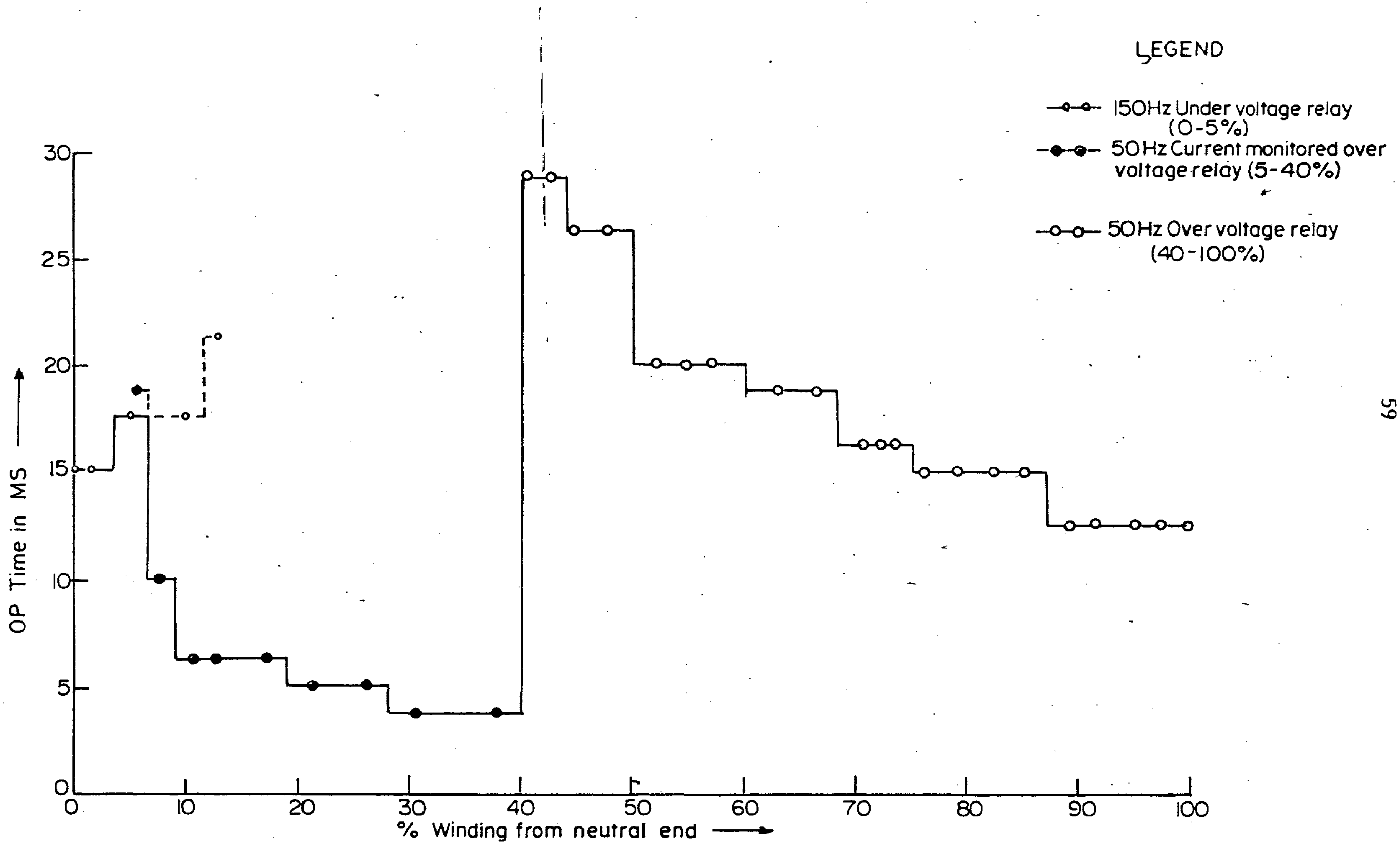


FIG. 5.4 OPERATING TIME CHARACTERISTIC OF 100% EARTH FAULT RELAY.

calculated conditions. A fault between 5-40% of the winding was detected by the current monitored fundamental frequency over voltage relay while the remaining portion between 40-100% was covered by the fundamental frequency over voltage relay.

In the overall combined characteristic of the relay, tripping in the first 6% of the winding was obtained by the undervoltage relay and beyond that by the current monitored overvoltage relay.

The minimum operating time seen was 3.75 ms and the maximum time 28.75 ms.

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CHAPTER - VI

MICROPROCESSOR BASED DIFFERENTIAL RELAY

6.1 GENERAL

Differential relaying forms the backbone of generator stator winding protection. An improved version of the variable bias differential relay [33] covered in Chapter-II has been implemented on a 16-bit microprocessor.

6.2 RELAY PRINCIPLE

On a balanced three-phase system, the fifth and seventh order harmonics appear in the phase to phase voltage only, while the third, ninth and fifteenth harmonics appear as zero sequence components in the neutral voltage [12]. To provide an error free operation the harmonics should be eliminated from the measured signals. The relay works on simultaneous sampling of the currents at both ends of a phase winding. The fundamental frequency component is extracted from the currents using the discrete Cosine Transform filter. The difference between the average value of the fundamental components of the current gives the differential current Id. If this is found to be above the minimum setting of differential current, the through current is calculated by summing the average values of the two currents. Corresponding to this value of It, the through current, the operating differential current value is obtained from the look-up table stored in memory. A trip signal is generated if the differential current Id, exceeds the operating differential current value.

6.3 RELAY SCHEMATIC AND HARDWARE

The block schematic of the variable bias differential relay is shown in Fig. 6.1. The current signals, for each phase, from both the line

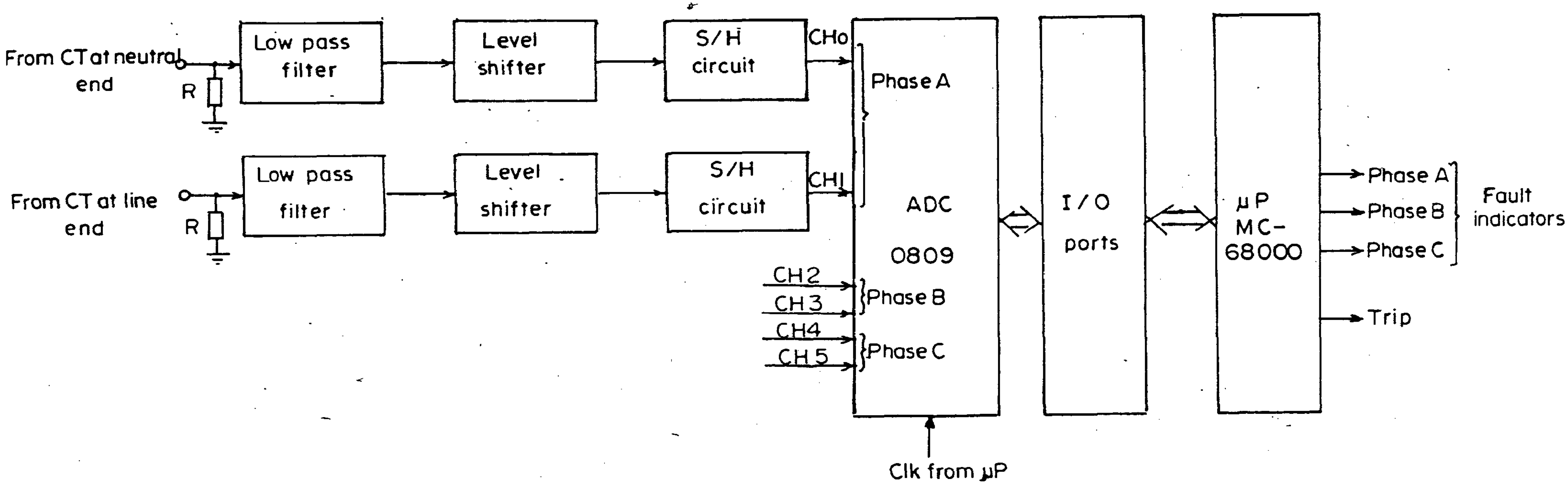


FIG.6.1 BLOCK SCHEMATIC OF THE DIFFERENTIAL RELAY.

end and neutral end of the generator stator winding are obtained by using current transformers. These current signals are converted to voltage signals by using resistances and fed as relay inputs.

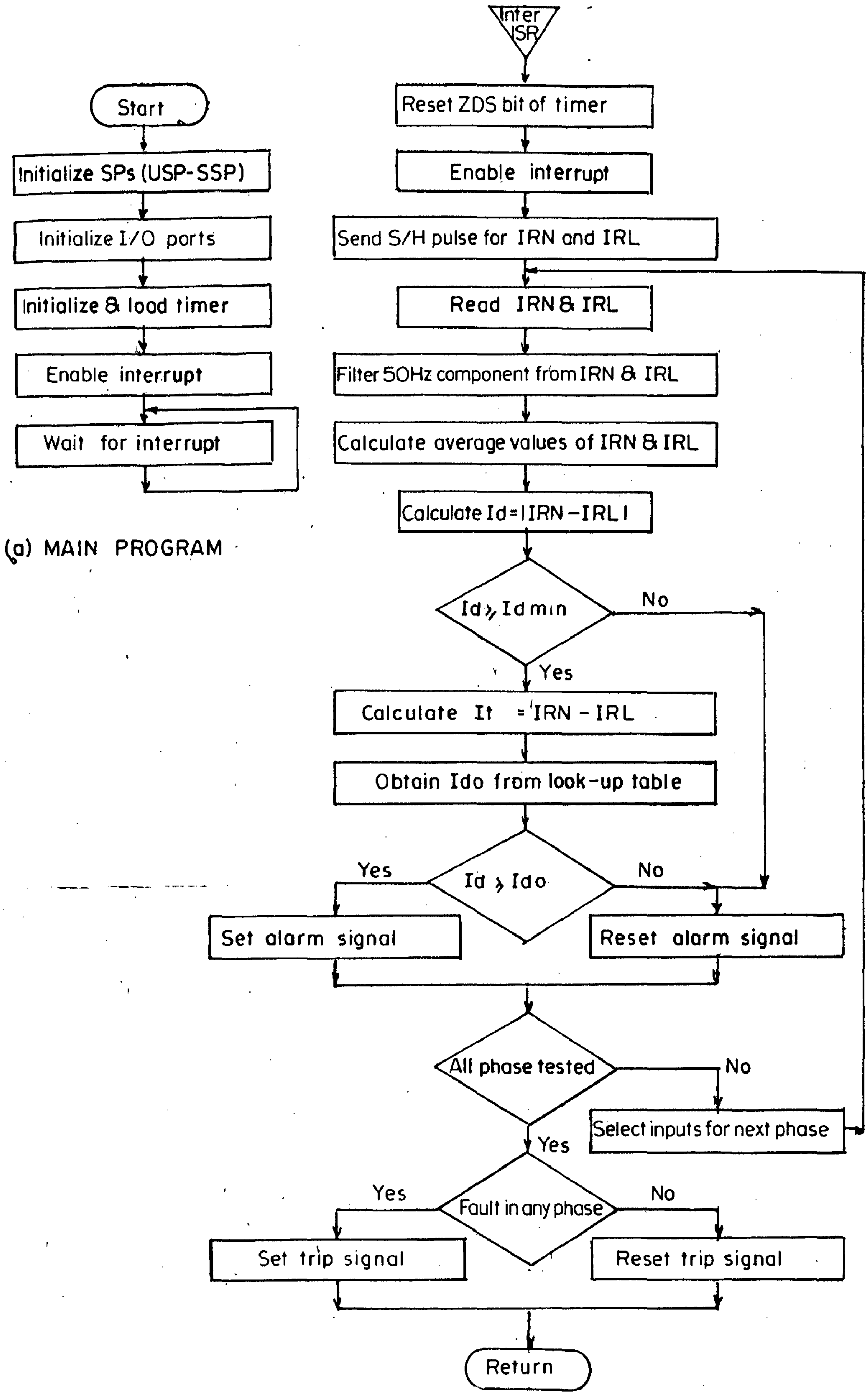
The input signals containing harmonics are band limited to half the sampling frequency using analogue (active) low-pass filters to prevent aliasing. The frequency limited signals are level shifted to obtain unipolar signals and fed to separate channels of the 8 bit ADC (0809) through sample and hold circuits (LF 398).

The digital output of the ADC is connected to MC-68000 microprocessor through a port. The timer of the MC-68230 chip is programmed to generate an interrupt signal every 1.25 ms corresponding to the sampling interval of 16 samples per cycle of the fundamental frequency (50 Hz). The indication and trip signals are issued through an output port.

6.4 RELAY SOFTWARE

The flow charts for the relay software are shown in Fig. 6.2(a) and (b). The main program initializes the I/O ports and the two stack pointers (user stack pointer and supervisor stack pointer). The timer of MC-68230 is initialized and count is loaded to generate an interrupt after every 1.25 ms. The microprocessor then waits for the interrupt which makes it enter the interrupt service routine.

In the interrupt service routine the interrupt is enabled by resetting the ZDS (Zero Detect Status) bit of the timer. The count is automatically reloaded in the timer registers from the count pre-load register for the next interrupt. A common sample and hold pulse is given to sample the currents at the neutral and line ends of the first phase (I_{PN} and I_{PL}).



(b) INTERUPT SERVICE SUB-ROUTINE.

FIG.6.2 PROGRAM FLOW CHART FOR VARIABLE BIAS DIFFERENTIAL RELAY.

The latest sample values for both the inputs are read and the sample table updated. Thereafter, the fundamental frequency components of the two currents are calculated and their running average values obtained. The difference between the average values of the fundamental frequency components of I_{PN} and I_{PL} gives the average of the difference current Id(av).This value is compared with the minimum differential current setting Id min. If Id(av) is more than Id min, the sum of the fundamental frequency components of I_{PN} and I_{PL} is calculated to yield the value of It(av). Corresponding to this value of It(av), the value of I_{do}, is obtained from the look-up table storing the variable bias characteristic seen in Fig. 2.1. If Id(av) is more than I_{do} a trip signal is issued. This process is repeated for the other two phases also.

6.5 RELAY TESTING

The variable bias differential relay incorporating the 16-bit microprocessor MC-68000 was tested under simulated conditions in the laboratory. The characteristic for 10% initial bias setting was implemented. The response of the relay can be seen in Fig. 6.3.

The operating value of the differential current Id corresponded to the variable bias characteristic stored as a look up table (Fig. 2.1). A slight increase in the operating value of the differential current Id was noticed at certain discrete levels of through current It because of quantization error. This error can be reduced by increasing the ADC word size and increasing the number of points in the look-up table correspondingly. Alternatively, interpolation can be used with the available entries in the look-up table.

From Fig. 6.4 it is observed that tripping for severe faults occurs in 1.25 milli seconds, while the maximum time taken for very small values of Id is one and a half cycle (30 ms).

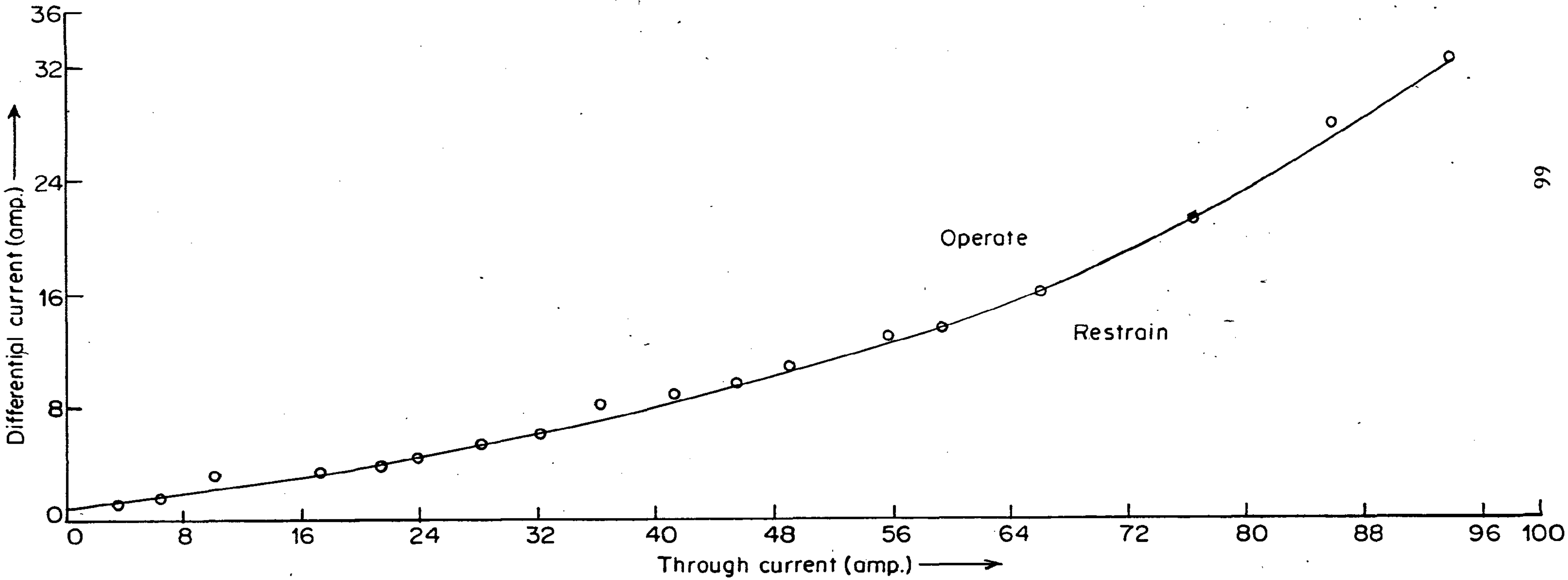


FIG.6.3. EXPERIMENTAL CHARACTERISTIC CURVES.

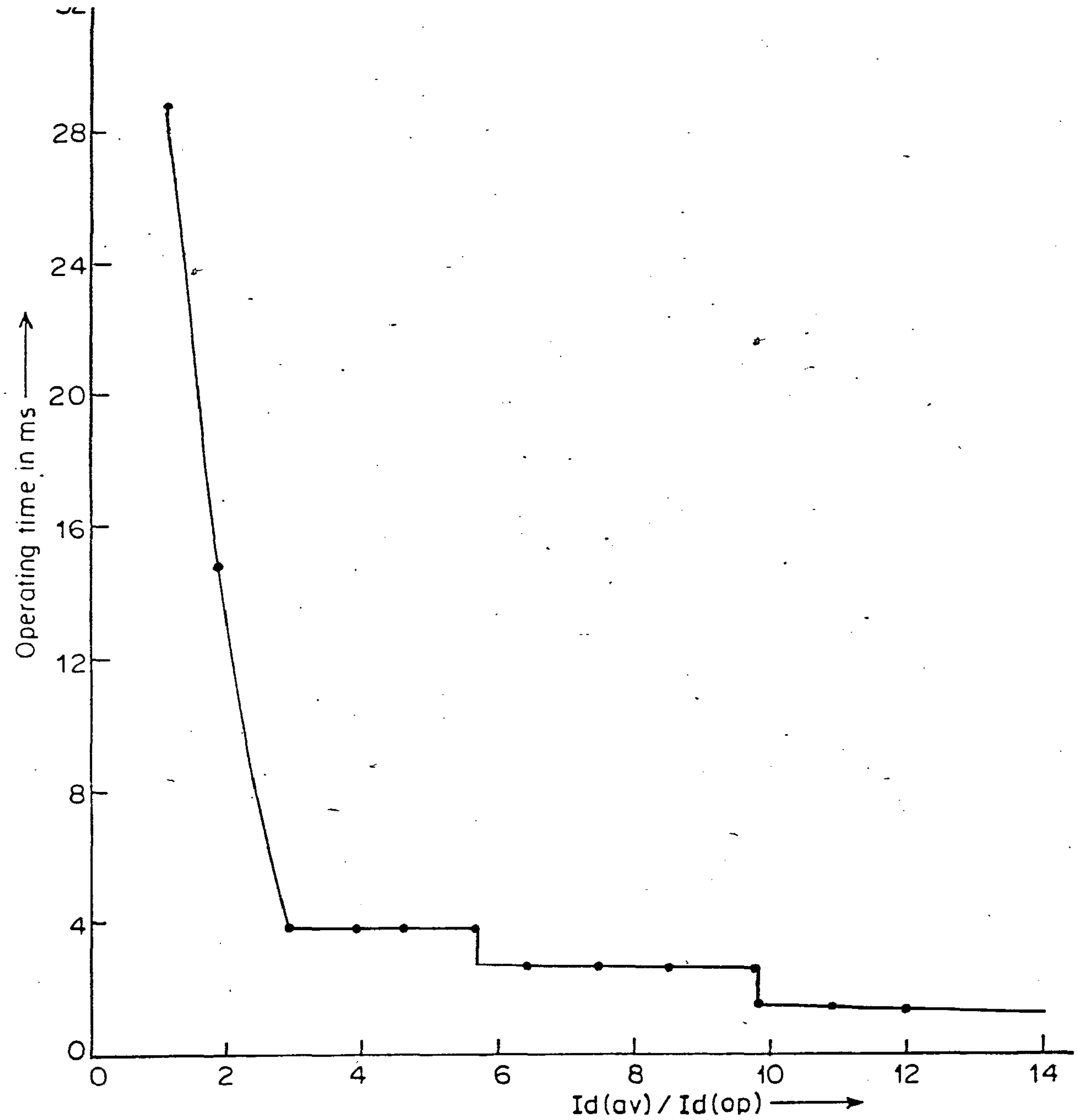


FIG.6.4. EXPERIMENTAL OPERATING-TIME CHARACTERISTIC.

Any variable characteristic can be implemented by the relay by varying the look-up table accordingly.

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CHAPTER - VII

CONCLUSIONS AND SCOPE FOR FURTHER WORK

7.1 GENERAL

Developments in stator winding protection of large units have been reviewed and two practical schemes tried out. The conclusions based on the review and practical implementation are summarized in succeeding sections.

7.2 REVIEW WORK

Digital relays are being used for differential protection of generators thereby enabling the implementation of variable bias characteristics. The variable bias feature ensures high sensitivity on light internal faults and high stability on heavy external faults.

Stator earth fault protection has also been improved. Previously, only 90-95% of the windings from the terminal ends were covered by the protection against faults. The protection was provided by fundamental frequency overvoltage or overcurrent relays located in the neutral circuit. Now, this protection is supplemented by an additional scheme, either based on a subharmonic voltage injection or third harmonic voltages of the generator, to cover remaining 5-10% of the winding near the neutral.

Interturn faults were usually left unprotected initially and the fault was allowed to build up till it would involve the earth and be detected by earth fault relays. Severe damage to the stator could occur before detection. It is estimated that the current in a shorted turn can be as high as 106,000 A for a 500 MW generator [8]. Lately, interturn protection is being considered necessary for large generators and digital methods for detecting such faults have also been developed.

With static excitation systems normal back-up overcurrent protection for external faults is inadequate as the fault current will drop below the relay setting before its operation is completed. This is overcome by using voltage restrained overcurrent relays.

Inadvertent energization is inhibifed by placing phase overcurrent and neutral overvoltage relays when the frequency is low and the circuit breakers are open.

Another recent trend is the concept of fault detection at the incipient stages by continuous monitoring. Overheating is detected by the presence of particulates in the hydrogen coolant by the ion chamber monitor. Conductor fatigue failure is detected in the initial stages by Radio Frequency monitoring or by a Partial Discharge Analyser. Abnormal stator end turn vibrations are sensed by the Fibre Optic Vibration monitor. Effective utilization of monitoring devices can help in minimizing serious faults. It may be idealistic to state that, hopefully, the normal complement of protective relaying would be relegated to a back-up function as far as the generator is concerned, and hopefully would never be called on to operate with effective utilization of the incipient fault detectors.

7.3 100% STATOR EARTH FAULT RELAY IMPLEMENTATION

The notable features of the digital 100% stator earth fault relay implemented on microprocessor by the author are as follows :

(a) Any open or short circuit in the neutral grounding circuit and the terminal end voltage transformers is detected and an alarm given.

(b) For the first time current monitoring has been incorporated to differentiate between internal and external (high voltage side) faults. Because of this feature high speed (instantaneous) tripping is possible for faults in the complete winding. In previous methods a time delay was required to prevent over-tripping on external faults.

(c) External faults are cleared by the relay after a pre-set delay as a back-up on external faults.

(d) Duplication of all relay operating conditions is done by using the open delta terminal voltage as an additional input.

(e) A cosine-transform-based algorithm has been used for extraction of fundamental frequency and third harmonic components from the input values.

(f) The relay was tested by using simulated signals calculated for different fault locations on the winding. The minimum operating time obtained was 3.75 ms and the maximum time as 28.75 ms.

(g) The microprocessor time taken by the relay during each sampling period of 1.25 ms is 0.437 ms. The balance period of 0.813 ms can be used for other relaying functions.

7.4 VARIABLE BIAS DIFFERENTIAL RELAY IMPLEMENTATION

This is the other digital relay for stator protection developed by the author. Its important features are as under :

(a) Fundamental frequency components are extracted by using the cosine transform based algorithm.

(b) Since only the fundamental frequency components are compared the difference currents will be low. The operating margins can therefore be reduced thereby increasing the sensitivity of the relay.

(c) The variable bias characteristic helps in increasing the sensitivity of the relay on low internal faults and providing high stability on heavy external faults.

(d) Any variable bias can be implemented by changing the look-up table.

(e) The microprocessor time taken during each sampling period of 1.25ms is 0.956 ms.

7.5 SCOPE FOR FURTHER WORK

A number of relaying functions may be implemented within each sampling interval to obtain a comprehensive protection scheme. In order to accomodate the relaying functions by one microprocessor the following modifications may be carried out :

(a) The number of samples per cycle may be reduced from 16 to 12 without affecting the filter response but increasing the time available for processing to 1.67 ms.

(b) An ADC with faster conversion time may be used to further reduce the processing time.

(c) The modified cosine transform algorithm may be used for filtering the input values with a considerable reduction in computing time.

A 10/12 bit ADC may be used to provide better resolution to reduce the quantization error and improve sensitivity. This was not incorporated in the present work due to non availability of the ADC.

*****

APPENDIX - A

(Refers to Article 2.3 and 5.5.3)

Calculation of Voltage Shift Due to Faults on High Voltage Side

The capacitance values of a sample 789 MW generator [12] are :

Stator winding	-	0.224	μF	(C_G)
Isophase bus	-	0.002	μF	(C_B)
Step-up transformer	-	0.020	μF	(C_u)
Auxiliary transformers	-	0.008	μF	($2\ C_A$)
Total (per phase)	-	0.254	μF	
Total (3 phases)	-	0.702	μF	
Generator rated voltage	-	25 kV		
Overall transformer turns ratio	-	120		(14.4 kV/120 V)
Line voltage	-	500 kV		

From Fig. A-1 (a), (b) and (c), the voltage appearing across the primary of the generator grounding transformer is given by :

$$V_R = \frac{V_{HO}\ Z_O}{Z_O - j\ X_{H-L}}$$

where,

V_{HO} = high side zero sequence voltage for a 500 kV phase-to-ground fault = 147 kV

C_{H-L} = generator step-up transformer high-to-low winding capacitance = 0.012 μF

C_O = generator system zero sequence capacitance per phase = 0.254 μF

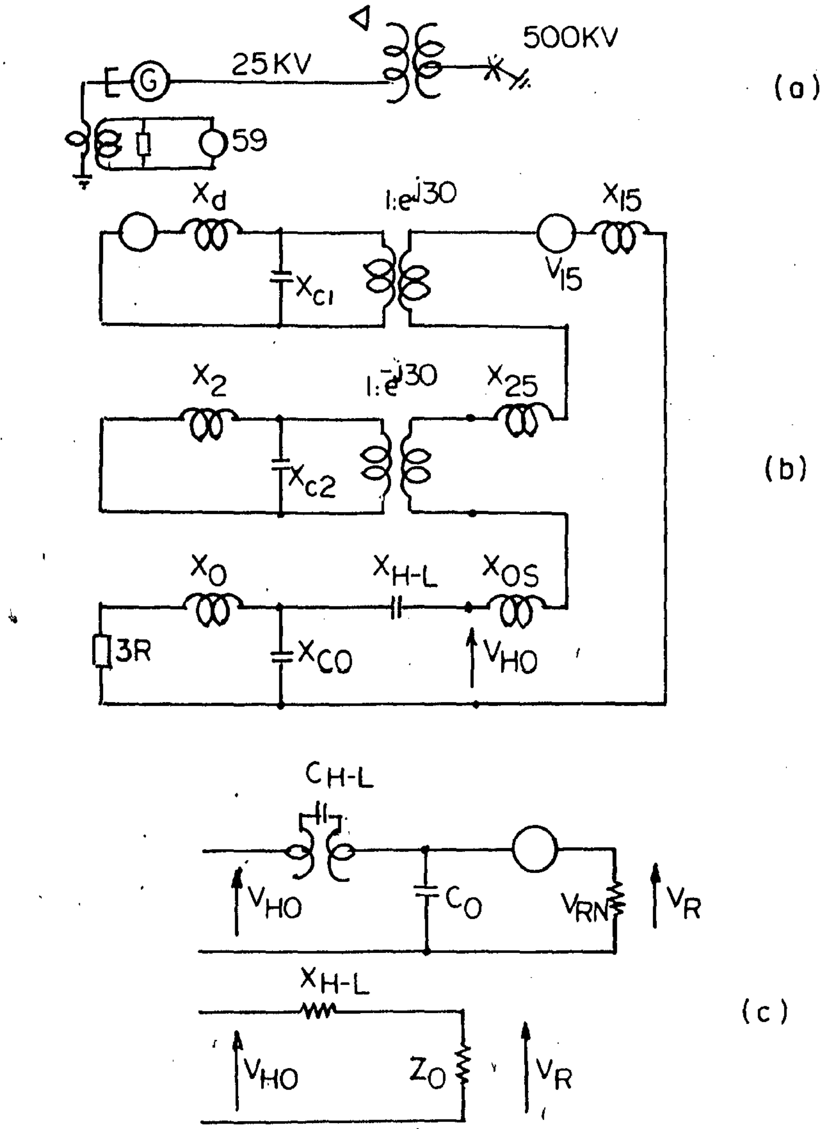

FIG.A-1 CIRCUIT FOR CALCULATING VOLTAGE SHIFT AT NEUTRAL FOR HIGH SIDE FAULT [12]

R_N = equivalent resistance in the generator neutral

= 2809 ohms

X_{CO} = zero sequence capacitive reactance per phase

$$= \frac{1}{(2\pi 50)(0.254\ \mu F)} = 12532 \text{ ohms}$$

Z_O = parallel combination of 3 R_N and X_{CO}

$$= \frac{(3\ R_N)(-j\ X_{CO})}{3\ R_N - j\ X_{CO}} = \frac{3(2809)(-j\ 12532)}{3(2809)\ -j\ 12532}$$

$$= 8024 - j\ 1798 \text{ ohms}$$

$$X_{H-L} = \frac{1}{(2\pi\ 50)(0.012\ \mu F)} = 265258 \text{ ohms}$$

$$V_R = \frac{147000\ (8024 - j\ 1798)}{8024 - j\ 1798 - j\ 265228}$$

$$= 4524 \text{ volts}$$

$$\text{Voltage shift caused} = \frac{4524}{25000/1.73}$$

$$= 31.3\%$$

Therefore, it can be seen that a voltage shift of 31.3% results at the low side due to a phase to ground fault on the high voltage bus.

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APPENDIX - B

(Refers to Article 5.5.6)

Calculation of Relay Settings and Faults Values

For the sample generator seen in Appendix A, the maximum voltage applied to the relay is for a ground fault at the terminals. The fundamental voltage applied to the relay V_R is given by the phase voltage divided by the overall transformation ratio.

$$V_R = \frac{25000/1.73}{120} = 120 \text{ V}$$

As the fault moves towards the neutral end, the voltage seen by the relay will decrease linearly and equals zero for a fault at the neutral end.

The threshold values for the overvoltage relay ($V_{NTH\ 40}$) and the current monitored over voltage relay ($V_{NTH\ 5}$) are obtained as

$$V_{NTH\ 40} = 0.40 \times 120 = 48 \text{ V}$$

$$V_{NTH\ 5} = 0.05 \times 120 = 6 \text{ V}$$

Minimum third harmonic voltage (at no load) seen at the neutral end is 103 V and the maximum (at full load) is 468 V.

Corresponding values seen by the relay are 0.86 V (min.) and 3.9 V (max.).

The threshold setting of the undervoltage relay is kept at half the minimum third harmonic voltage appearing at the neutral end.

Minimum threshold setting of third harmonic under voltage relay, V_{N3TH} = 0.43 V

The extreme values of third harmonic voltages seen by the relay for a fault at 40% of the winding are obtained as :

Min Value (at no load) = 0.66 V

Min Value (at full load) = 3.0 V

Assuming a linear variation of third harmonic voltage with load the threshold setting, $V_{N3\ 40}$, is given as :

$$V_{N3\ 40} = 0.66 + (3.0 - 0.66) \times I$$

The calculations are based on the generator data given in [12].

Variation of fault values for different fault locations are listed below-

Fault location (%)	Fundamental Frequency Voltage at Neutral (V)	Minimum Third Harmonic Voltage at Neutral (V)
0	0	0.00
5	6	0.08
10	12	0.17
15	18	0.25
20	24	0.33
25	30	0.42
30	36	0.50
35	42	0.58
40	48	0.66
45	54	0.75
50	60	0.83
55	66	0.92
60	72	1.00
65	78	1.08
70	84	1.17
75	90	1.25
80	96	1.33
85	102	1.42
90	108	1.50
95	114	1.58
100	120	1.67

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