DESIGN OF A HARMONIC RESTRAINED STATIC RELAY FOR A SINGLE PHASE TRANSFORMER

by

Mir Mothaher Hossain

A project report submitted to the Department of Electrical and Electronic Engineering, BUET in partial fulfillment of the requirements for the degree of Master of Engineering in ELECTRICAL AND ELECTRONIC ENGINEERING

নং 102883
তাং 17.12.06

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
DHAKA-1000, BANGLADESH
June, 2006

#102883#

The project report titled " Design a of Harmonic Restrained Static Relay for a Single Phase Transformer" submitted by Mir Mothaher Hossain, Roll no: 040206201, Session: April, 2002 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Engineering in Electrical and Electronic Engineering on June 17, 2006.

Board of Examiners

1 ______________________

Dr. Mohammad Ali Choudhury **Chairman**
Professor (Supervisor)
Department of Electrical & Electronic Engineering,
BUET, Dhaka-1000

2 ______________________

Dr. Md. Quamrul Ahsan **Member**
Professor
Department of Electrical & Electronic Engineering,
BUET, Dhaka-1000

3 ______________________

Dr. S. Shahnawaz Ahmed **Member**
Professor
Department of Electrical & Electronic Engineering,
BUET, Dhaka-1000

Declaration

It is hereby declared that this project or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Mir Mothaher Hossain

Dedication

To my parents

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ACKNOWLEDGEMENT

It is a matter of great pleasure on the part of the author to acknowledge his profound gratitude to his supervisor Dr. Mohammad Ali Choudhury for his support, continuous guide, suggestions, advice, assistance and wholehearted supervision throughout the progress of this project work.

Author is grateful to Almighty Allah for giving him the strength and courage to complete this project.

ABSTRACT

Large Transformers are provided with differential relays to isolate them during severe internal faults. In the case of transformers, the differential relays need to prevent tripping for inrush currents. As a result all differential relays for transformers are equipped with mechanism to discriminate fault current from magnetizing inrush current to prevent false tripping of breakers during transformer switch on.

In this project a static circuit is designed to discriminate transformer fault current and magnetizing inrush current based on identifying the second harmonic content of the transformer line current. A fault current of a transformer is high in magnitude but almost free from second harmonic and DC offset. Whereas, the magnetizing inrush current has substantial second harmonic and also it has DC offset. The circuit in this study consists of a current sensing unit (a CT and voltage divider), two notch filters to detect 50Hz and 100Hz components of the line current and the calculation circuit based on IC circuits (OPAMPS, multipliers and logic gates) to find the ratio of second harmonic to fundamental value of the line current continuously. The circuit provides the decision based on the ratio whether the relay should trip or not the circuit breaker.

The circuit is designed for a single phase transformer and tested by simulation and found to serve the purpose for which it has been designed. Such three identical circuits may also provide the same degree of performance for a three-phase transformer differential protection with harmonic restraints.

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CHAPTER 1

Introduction

1.1 Introduction

Large power transformers belong to a class of vital and very expensive components in electric power systems. If a power transformer experiences a fault, it is necessary to take the transformer out of service as soon as possible so that the damage is minimized. The costs associated with repairing a damaged transformer may be very high. The unplanned outage of a power transformer can also cost electric utilities millions in revenue and assets. Consequently, it is of a great importance to minimize the frequency and duration of unwanted outages. Accordingly, high demands are imposed on power transformer protective relays. The requirements include dependability (no missing operations), security (no false tripping), and speed of operation (short fault clearing time). The operating conditions of power transformers, however, do not make the relaying task easy. Protection of large power transformers is perhaps the most challenging problem in the area of power system relaying.

1.2 Magnetizing Inrush

The phenomenon of magnetizing inrush is a transient condition, which occurs primarily when a transformer is energized. It is not a fault condition, and therefore does not necessitate the operation of protection, which, on the contrary, must remain stable during the inrush transient, a requirement, which is a major factor in the design of protective systems for transformers.

When an inductor is energized by a steady alternating voltage, the flux linking the inductive circuit varies from a peak negative value to an equivalent peak positive value during one half cycle of the voltage wave. The flux change of twice the maximum flux value is proportional to the time integral of the voltage wave between successive zero points. On switching on the zero point of the wave, the full flux change is required during the first half cycle, but with the flux initially zero, the maximum flux developed will be nearly twice the normal peak value.

If the inductor is linear, as, for example, is an air-cored inductor, the current taken will also rise to nearly twice the steady state value. A transformer primary winding, however can be treated as an iron cored inductor in which the normal peak flux is close to saturation value. An increased of flux to double this value corresponds to extreme saturation. The magnetizing current therefore rises to a very high value, which may exceed the rated full load value- hence, the term inrush.

Residual flux can increase still further. If the initial remanent flux, instead of being zero, has an initial positive value, that is, an initial value in the same direction as the flux change, the increment of flux must remain the same, since it is proportional to the half cycle voltage loop, and the peak value attained will be of the order of 2.8 times the normal value with 80% remanence.

The very high flux densities quoted above are so far beyond the normal working range that the incremental relative permeability of the core approximates to unity and the inductance of the winding falls to a value near that of the air cored inductance. The current wave, starting from zero, increases slowly at first, the flux having a value just the above the residual value and the permeability of the core being moderately high. As the flux passes the normal working value and enters the highly saturated portion of the magnetizing characteristic, the inductance falls and the current rises rapidly to a peak which may be 5- 14 times the steady state magnetizing current. When the peak is passed at the next voltage zero, the following negative half cycle of the voltage wave reduces the flux to the starting value, the current falling symmetrically to zero. The current wave is therefore fully offset and, as with the offset wave in a linear inductor, is only restored to the steady state condition by the circuit losses. The time constant of the transient is relatively long, being from 0.1 seconds for 100 kVA transformer and up to 1.0 seconds for a large unit. As the magnetizing characteristic is non-linear, the envelop of the transient current is not strictly of exponential form; the magnetizing current can be observed to be still changing up to 30 minutes after switching on.

Switching at other instants of the voltage wave produces lower values of transient current. If the point on the wave is chosen so that the residual flux is the correct value for that instant under steady conditions, no transient will occur and the steady no load current will be reached immediately.

In the case of three phase transformers, the point on wave at switch on differs for each phase resulting different inrush currents. Some inter-phase mutual interference also takes place, because of the combination of the phase fluxes in the yokes. In this way it is possible for a phase with a point on wave of energization which in itself would produce no inrush transient to receive nevertheless an inrush current of substantial magnitude. In this case current wave will not be offset from the zero axis but will be distorted [1].

1.3 Harmonic Content of Inrush Waveform

The waveform of transformer magnetizing current contains a proportion of harmonics, which increases as the peak flux density is raised to the saturating condition. As long as the waveform is symmetrical about the horizontal axis, only odd harmonics will be present. The condition is typical for normal alternating currents flowing through impedances, which have no directional polarizing property. The magnetizing current of a transformer is of this class and will contain a third harmonic and smaller amounts of fifth and higher harmonics progressively. If the degree of saturation is increased, not only will the harmonic content increase as a whole but the relative proportion of fifth harmonic will increase and eventually overtake and exceed the third harmonic. At a still higher level the seventh would overtake the fifth harmonic but this involves a degree of saturation that will not be experienced with power transformers.

The energizing conditions which result in an offset inrush current produce a waveform which is not symmetrical about the horizontal axis but which is symmetrical, neglecting decrement, about certain ordinates. Such a wave typically contains both even and odd harmonics. Typically inrush currents contain substantial amounts of second and third harmonics and diminishing amounts of higher orders. As with the steady state wave, the proportion of harmonics varies with the degree of saturation, so that as a severe inrush transient decays, the harmonic makeup of the current passes through a range of conditions. Even the inrush current, which has no offset, is not symmetrical about the horizontal axis but possesses mirror image symmetry about chosen ordinates. This waveform, therefore, possesses even, as well as odd, harmonics [1].

1.4 Stabilizing Differential Protection During Magnetizing Inrush Conditions

The magnetizing inrush phenomenon described in section 1.2 produces current input to the energized winding which has no equivalent on the other sides of the transformer. The whole of the inrush current appears, therefore, as unbalance and is not distinguishable from internal fault current. The normal bias is not, therefore, effective and protection setting to a value, which would avoid operation, would make the protection of little value.

Time Delay

Since the phenomenon is transient, stability can be maintained by producing a small time delay. This has been achieved by various means. An instantaneous relay can be shunted by a fuse link, a so-called kick fuse therefore diverting most of the current. The fuse is chosen so as to carry the inrush transient without blowing; only in the event of an internal fault does the fuse blow and permit the relay to operate. Induction pattern relays of the I.D.M.T. type can also be used to give a suitable time delay.

The above time delay might be thought insufficient to give stability with a severe inrush current. In practice it is generally sufficient arising from the relatively poor response of the induction element to uni-direction current.

Harmonic restrained

If damage to important transformers is to be minimized it is essential to clear faults without delay, and another solution to non-operation of the relay during the inrush phenomenon must be found.

The inrush current, although generally resemble an in zone fault current, it differs greatly when the waveform are compared. The distinctive difference in the waveforms can be used to distinguish between the conditions.

As stated before, the inrush current contains harmonic of all orders, but these are not equally suitable for providing bias. The study of this subject is complex, as the waveform depends on the degree of saturation and on the grade of iron in the core. The principal conclusions can be summarized as follows.

a) D.C. or offset component (zero harmonic)

A uni-direcional component will usually be present in the inrush current of a single phase transformer and in the principal inrush currents of a three phase transformer unit. However, if at the instant of switching the residual flux for any phase is equal to the flux which would exist in the steady state at that point on the voltage wave, then no transient disturbance should take place on that phase.

Large inrush currents will flow in the other two phase corresponding to high peak flux values established in these phase cores. The flux circulates through the yokes, the saturation of which affects the first phase, which would have had no inrush effect, causing a substantial transient current to flow in this phase as well. This latter current, however, will not be offset from the zero axis, although the current waveform will be distorted.

If the uni-directional current component were used to stabilize a differential current component system, some sort of cross-phase biasing would be required because of this effect.

Since many fault current waveforms will have initial offset, delay in tripping would result from the use of this component.

b) Second Harmonic

This component is present in all inrush waveforms. It is typical of waveforms in which successive half period portions do not repeat with reversal of polarity but in which mirror image symmetry can be found about certain ordinates.

The proportion of second harmonic varies somewhat with the degree of saturation of the core, but is always present as long as the uni-directional component of flux exists. Normal fault current do not contain second or other even harmonics, nor do distorted currents flowing in saturated iron cored coils under steady state conditions.

The output of a current transformer, which is energized into steady state saturation, will also contain odd harmonics. However, should the current transformer be saturated by the transient component of the fault current, the result in saturation is not symmetrical and even harmonics are introduced into the output current. This can have the advantage of improving the through fault stability performance of differential relay, but it also has the adverse effect of increasing the operation time for internal faults.

The second harmonic is therefore an attractive basis for a stabilizing against inrush effects, but care must be taken to ensure that the current transformers are sufficiently large so that the effect produced by transient saturation do not delay normal operation of the relay.

c) Other harmonics

The third harmonic is also present in the inrush current in roughly comparable proportion to the second harmonic. The separate phase inrush currents are still related in phase to the primary applied electromotive forces and the harmonics have a similar time spacing, which brings the third harmonic waves in the three windings into phase. If the windings are connected in delta, the line current are each the difference of two-phase currents. As the inrush components vary during the progress of the transient condition it is possible for this difference to pass through zero, so that the third harmonic component in the line current vanishes; this component cannot, therefore, be regarded as a reliable source of bias.

To this must be added the further consideration that a sustained third harmonic component is quite likely to be produced by CT saturation under heavy in zone fault conditions.

All this means that the third harmonic is not desirable means of stabilizing a protective system against inrush effects. All other harmonics are theoretically present in an inrush current but the relative magnitude diminishes rapidly as the order of harmonic increases; there may be 5% of fourth order of harmonic in a given inrush current. This component would be similar in response to the second harmonic but the small magnitude hardly justifies the provision of an extra filter circuit.

A still smaller proportion of fifth harmonic will be present. This component is not subject to cancellation as is the third harmonic, and can be present in the output of a CT in an advanced state of saturation, therefore offering no benefit. Still higher harmonics are of magnitude too small to be worth consideration.

The percentage of fifth harmonic in the transformer magnetizing current increases significantly when the transformer is subjected to a temporary over voltage condition. Some manufacturers apply a measure of fifth harmonic bias to the relays to restrain if the magnetizing current contains 30% fifth harmonic [1].

1.5 Literature Review of 2^{nd} harmonic restrained differential relaying

Three characteristics generally provide means for detecting transformer internal faults [2]. These characteristics include an increase in phase currents, an increase in the differential current, and gas formation caused by the fault arc [3], [4]. When transformer internal faults occur, immediate disconnection of the faulted transformer is necessary to avoid extensive damage and/or preserve power system stability and power quality. Three types of protection are normally used to detect these faults: over current protection for phase currents, differential protection for differential currents, and gas accumulator or rate-of-pressure-rise protection for arcing faults. Over current protection with fuses or relays provided the first type of transformer fault protection [5]; it continues to be applied in small capacity transformers. Connecting an inverse-time over current relay in the paralleled secondaries of the current transformers introduced the differential principle to transformer protection [5]. The percentage differential principle [6], which was immediately applied to transformer protection [5], [7], [8], provided excellent results in improving the security of differential protection for external faults with CT saturation. Differential relays are prone to misoperation in the presence of transformer inrush currents, which result from transients in transformer magnetic flux. The first solution to this problem was to introduce an intentional time delay in the differential relay [5], [7]. Another proposal was to desensitize the relay for a given time, to override the inrush condition [7], [8]. Others suggested adding a voltage signal to restrain [5] or to supervise the differential relay [9]. Researchers quickly recognized that the harmonic content of the differential current provided information that helped differentiate faults from inrush conditions. Early relays used all the harmonics to restrain. With a relay that used only the second harmonic to block, idea of harmonic blocking instead of restraining was used. Many modern transformer differential relays use either harmonic restraint or blocking methods. These methods ensure relay security for a very high percentage of inrush and overexcitation cases. However, these methods do not work in cases with very low harmonic content in the operating current. Common harmonic restraint or blocking, introduced, increases relay security for inrush, but could delay operation for internal faults combined with inrush in the nonfaulted phases. Transformer overexcitation is another possible cause of differential relay misoperation. Additional fifth-harmonic restraint to prevent such misoperations was proposed. Others have proposed several methods based on wave shape recognition to distinguish faults from inrush and have applied these methods in transformer relays. However, these techniques do not identify transformer overexcitation conditions.

Inrush or overexcitation conditions of a power transformer produce false differential currents that could cause relay misoperation. Both conditions produce distorted currents because they are related to transformer core saturation. The distorted waveforms provide information that helps to discriminate inrush and overexcitation conditions from internal faults.

The study of transformer excitation inrush phenomena has spanned more than 50 years [10]–[12]. Magnetizing inrush occurs in a transformer whenever the polarity and magnitude of the residual flux do not agree with the polarity and magnitude of the ideal instantaneous value of steady-state flux. Transformer energization is a typical cause of inrush currents, but any transient in the transformer circuit may generate these currents. Other causes include voltage recovery after the clearance of an external fault or the energization of a transformer in parallel with a transformer that is already in service. The magnitudes and waveforms of inrush currents depend on a multitude of factors, and are almost impossible to predict.

The original harmonic-restrained differential relays used all harmonics to provide the restraint function [10]. The resulting high level of harmonic restraint provided security for inrush conditions at the expense of operating speed for internal faults with CT saturation. Other methods for discriminating internal faults from inrush conditions are based on direct recognition of the wave shape distortion of the differential current. Identification of the separation of differential current peaks represents a major group of wave shape recognition methods [11].

1.6 Objectives with specific aims and possible outcome

Objective of this project is to design a harmonic restrained static relay for a single-phase transformer. This relay features prevention of a trip signal in the presence of magnetizing inrush current but no fault in the system. But the relay trips in case of a fault being there in the transformer during turn ON of the transformer and also during its operation in the steady state. Harmonic restrained electromechanical, analog and digital static and numerical relays are available for transformer differential protection [1]. In this project work the same relay is designed and studied using ORCAD software with available commercial IC modules.

1.7 Outline of the Thesis

The design of the static relay for a transformer protection having harmonic restrain is made by simulation. Current transformers on the both sides of transformer senses line current of the transformer. This current is converted to a voltage and passed to an active filter composed of operational amplifier to sense the presence of second harmonic current. Another filter circuit is also designed to sense the 50Hz fundamental component of the line current. Absolute magnitude calculation circuits determines the magnitude of both currents and the ratio of two currents is determined by using a multiplier IC used as a divider. The minimum value is achieved by the different switching instant within the cycle of a cycle of a supply voltage, which is taken as preset value. Then the ratio is compared with a preset value (0.56) to decide that the current is a magnetizing current or a fault current [12, 13]. The decision is conveyed to the static differential that is also designed in this project by using operational amplifier circuits.

Chapter 2 of the thesis describes the inrush current phenomenon in a single-phase transformer. Chapter 3 illustrates the inrush restrain algorithm used for transformer differential protection. This chapter also gives the results of the simulation and discusses the results. Chapter 4 concludes the thesis with notes on achievements and recommendation on future work.

CHAPTER 2

Inrush current of a transformer

2.0 Magnetizing Inrush

A Brief Analysis Magnetizing inrush current in transformers results from any abrupt change of the magnetizing voltage. Although usually considered a result of energizing a transformer, the magnetizing inrush may also be caused by [13,14]:

(a) occurrence of an external fault,
(b) voltage recovery after clearing an external fault,
(c) change of the character of a fault (for example when a phase-to-ground fault evolves into a phase-to-phase-to-ground fault), and
(d) Out-of-phase synchronizing of a connected generator.

Since the magnetizing branch representing the core appears as a shunt element in the transformer equivalent circuit, the magnetizing current upsets the balance between the currents at the transformer terminals, and is therefore experienced by the differential relay as a “false” differential current. The relay, however, must remain stable during inrush conditions. In addition, from the standpoint of the transformer lifetime, tripping-out during inrush conditions is a very undesirable situation (breaking a current of a pure inductive nature generates high over voltage that may jeopardize the insulation of a transformer and be an indirect cause of an internal fault).

2.1 Cause of Inrush Current In a Transformer

In a series RL circuit excited by a sinusoidal excitation $E_m \text{Sin}(\omega t + \lambda)$, the current can be as high as twice the maximum current steady state value. This is a text book problem as below,

$$L\,di/dt + R_i = E_m \text{ Sin}(\omega t + \lambda) \tag{2.1}$$

$$di/dt + R/L = E_m / L \text{ Sin}(\omega t + \lambda) \tag{2.2}$$

the solution of which is

$$i = E_m / \sqrt{(R^2 + \omega^2 L^2)}\,\text{Sin}(\omega t+\lambda - \theta) - E_m e^{-RL/t} / \sqrt{(R^2 + \omega^2 L^2)}\,\text{Sin}(\lambda - \theta) \tag{2.3}$$

Where $\theta = \tan^{-1}(\omega L / R)$, phase angle between v, i and λ is the switching angle. For $\lambda - \theta = 0, \pi, 2\pi \ldots$ etc

$$i = E_m / \sqrt{(R^2 + \omega^2 L^2)}\ \text{Sin}\ \omega t \tag{2.4}$$

For $\lambda - \theta = \pi/2, 3\pi/2 \ldots$ etc

$$i = \pm E_m e^{-RL/t} / \sqrt{(R^2 + \omega^2 L^2)} + E_m / \sqrt{(R^2 + \omega^2 L^2)}\ \text{Cos}\ \omega t \tag{2.5}$$

in which transient current may be as high as twice steady state value. Transformers are not single R-L circuit, rather they are usually iron core R-L circuit exhibiting nonlinear characteristics. As a result when the current goes above normal steady state value, the core gets saturated reducing the slope of B-H curve. This results in excess current drawn by a transformer even when the transformer is not loaded. This excess current drawn by a transformer during turn ON process depending on the instant at which the switch is turned ON is known as magnetizing inrush current of a transformer.

2.2 Inrush due to switching

Initial magnetizing due to switching a transformer in is considered the most severe case of an inrush. When a transformer is de-energized (switched-off), the magnetizing voltage is taken away, the magnetizing current goes to zero while the flux follows the hysteresis loop of the core. This results in certain remanent flux left in the core. When, afterwards, the transformer is re-energized by an alternating sinusoidal voltage, the flux becomes also sinusoidal but biased by the remanence. The residual flux may be as high as 80-90% of the rated flux, and therefore, it may shift the flux-current trajectories far above the knee-point of the characteristic resulting in both large peak values and heavy distortions of the magnetizing current.

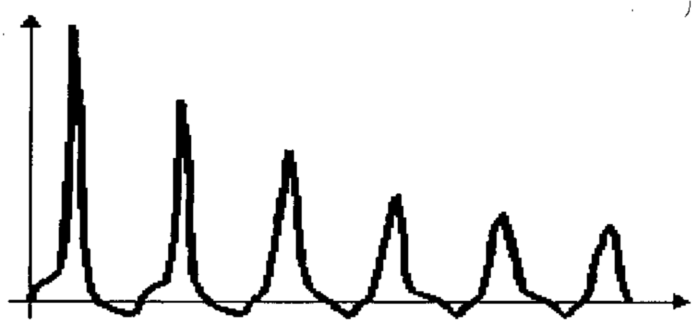


Figure 2.1 Inrush current for a transformer energized at zero instantaneous voltage

Figure 2.1 shows a typical inrush current. The waveform displays a large and long lasting dc component, is rich in harmonics, assumes large peak values at the beginning (up to 30 times the rated value), decays substantially after a few tenths of a second, but its full decay occurs only after several seconds (to the normal excitation level of 1-2% of the rated current). In certain circumstances, some small changes of the excitation current are observable even minutes after switching a transformer in [15,16]. The shape, magnitude and duration of the inrush current depend on several factors. These are,

A. Size of a transformer
B. Impedance of the system from which a transformer is energized
C. Magnetic properties of the core material
D. Remanence in the core
E. Moment when a transformer is switched in
F. Way a transformer is switched in

2.3 Harmonic content of the inrush current

The second harmonic always dominates because of a large dc component. However, the amount of the second harmonic may drop below 20%. The minimum content of the second harmonic depends mainly on the knee-point of the magnetizing characteristic of the core. The lower the saturation flux density, the higher the amount of the second harmonic. Modern transformers built with improved magnetic materials have high knee-points, and therefore, their inrush currents display a comparatively low amount of the second harmonic. Since the second harmonic is the basic restraining criterion for stabilizing differential relays during inrush conditions, certain difficulties arise when protecting such modern transformers [14,18,19]. It is also known that when the inrush current assumes large values, the amount of the second harmonic decreases [15,16].

2.4 Inrush in three phase transformers

Inrush currents measured in separate phases of a three-phase transformer may differ considerably because of the following:

- The angle of the energizing voltages are different in different phases.

- When the delta-connected winding is switched-in, the line voltages are applied as the magnetizing voltages.
- In the later case, the line current in a given phase is a vector sum of two winding cur-rents.
- Depending on the core type and other conditions, only some of the core legs may get saturated.

As a result of the aforementioned, the current in a particular phase and in a grounded neutral may be either similar to the single-phase inrush pattern or become a distorted but oscillatory waveform. In the later case, the amount of the second harmonic may drop dramatically, creating problems for differential relaying. Figure 5 presents an example of energizing a three-phase transformer. The currents in the phases A and B assume the typical inrush shape, while the phase C current is an oscillatory waveform.

2.5 Saturation of current transformers during inrush

Due to the large and slowly decaying dc component, the inrush current is likely to saturate the CTs even if the magnitude of the current is comparatively low. When saturated, a CT introduces certain distortions to its secondary current. Due to CT saturation during inrush conditions, the amount of the second harmonic may drop considerably [20].

2.6 Inrush during removal of a fault.

When an appropriate relay and an associated Circuit Breaker (CB) clear a near external fault, the voltage at the terminals of a transformer recovers to its normal level. This creates conditions similar to energizing of a transformer, and inrush current may occur. However, two factors make the situation different:

The step change of the voltage is usually much lower than during switching the transformer in. Only when a three phase solid fault at the interconnected bus bar occurs and gets removed, the situation corresponds to switching in. Usually, there is no significant offset in the flux generated during an external fault, and therefore, the probability of severe saturation of the transformer core becomes low.

Consequently, the magnitude of the recovery inrush current is significantly lower than in the case of the initial inrush. The shape and harmonic profile of the recovery inrush current are similar to those measured during initial energizing.

2.7 Sympathetic inrush

This phenomenon occurs when a transformer parallel to another, already energized transformer is being energized. Assume one transformer (T2) has a large positive remanent flux and is switched-in at the unfavorable voltage phase, and obviously, this transformer (T2) will draw a large inrush current. The slowly decaying dc component of the inrush current produces a significant voltage drop across the resistance of the equivalent power system (the reactance does not contribute to the voltage drop because the time derivative of the decaying dc component is low). The resulting dc voltage drop shifts abruptly the voltage at the bus bar connected with the transformer (T2). The change of the bus bar voltage decreases saturation of the transformer (T2), and consequently, reduces the inrush current of the transformer. The another transformer (T1), in turn, is exposed to this abrupt change of the voltage and may generate its own inrush current but in opposite direction. The dynamics of the phenomenon is as follows:

Initially only T2 draws an inrush current; then T1 increases its own inrush current while T2 decreases its current; finally both the currents decay as both the units get completely energized. Because the dc offset of the current in the supplying line is reduced, the damping of this current is also reduced. Consequently, the sympathetic inrush may last much longer as compared to their individual switching-in (even for minutes [15,16]). Two problems may potentially occur during sympathetic inrush:

The inrush current in the already energized unit (T1) may be significant enough to cause problems for the protection of this transformer. Conditions leading to the sympathetic inrush. The current in the supplying line is a vector sum of both the inrush currents, and as such may be similar to an offset fault current. This, in turn, would create problems when the parallel transformers share a common protection system.

CHAPTER 3

Inrush Restraint Algorithms

3.1 Inrush Restraint Algorithms

Historically, a delay achieved by different means was used to prevent false tripping during inrush conditions. Either the relay was disabled for a given time when switching a protected transformer in, or a special was used [17]. The delay, however, is no longer considered an acceptable means of restraining the differential relay during magnetizing in-rush, especially for large power transformers. Modern means of restraining differential relays during magnetizing inrush are by recognizing inrush from the wave shape of a differential current either indirectly (harmonic analysis) or directly (waveform analysis)[19- 24].

3.2 Harmonic restraint

This is a classical way to restrain the relay from tripping during magnetizing inrush conditions. The magnetizing inrush current appearing to a relay as the differential signal displays certain amounts of higher harmonics. Generally, low levels of harmonics enable tripping, while high levels indicate inrush and restrain the relay.

In the simplest approach, the amplitude of the second harmonic in the differential current in a given phase is the combined harmonic signal, while the amplitude of the fundamental frequency component in the differential current in the same phase is used as the combined differential current. Another approach is to use the RMS value for the combined differential current Extra logic is needed to decide whether or not the entire three-phase relay should get restrained if either one, two or three phases detect inrush conditions. Using cross-polarization or a cumulative (three-phase) second may flexibly shape the relay behavior under such circumstance harmonic. It is experienced that the three phase harmonic restraint is more secure [14].

The harmonic restraint in general, regardless of the method of composing the combined harmonic and differential signals, displays certain limitations.

First, the estimator of the harmonic component (usually the second harmonic only) needs a certain amount of time for amplitude. Even if the harmonic is not present in the differential signal at all, the ratio is initially significantly overestimated (until the fault data fills out the estimator data window). This means that the harmonic restraint usually will not permit tripping for the time approximately equal to the data window length of the estimators (typically one cycle).

Second, in modern transformers the amount of higher harmonics in the magnetizing current may drop well below 10% (the second harmonic as low as 7%, while the total harmonic content at a level of 7.5% [15,16]). This may lead, however, to delayed or even missing operations of the relay due to the harmonics in the differential currents during internal faults accompanied by saturation of the CTs. Cross-restraint or time-controlled threshold provide only a partial solution to this problem.

Third, the second harmonic ratio may temporarily (for several cycles) drop below the safe 20% due to transients.

3.3 Waveform-based restraints

There are basically two inrush-restraining methods of this kind [9]: the first, and more common approach, pays attention to the periods of low and flat values in the inrush current ("dwell-time" — criterion 1), the second algorithm pays attention to the sign of the peak values and the decaying rate of the inrush current (criterion 2).

A. Criterion 1

The hypothesis of magnetizing inrush may be ruled out if the differential current does not show in its every cycle a period lasting no less than 1/4 of a cycle in which the shape of the waveform is both flat and close to zero. This relaying principle was known in the era of static relays and there are certain analog schemes developed for implementing it.

This form of direct waveform restraining regardless of its implementation shows weaknesses:

(a) The recognition of an internal fault versus magnetizing inrush takes one full cycle,

(b) The CTs, when saturated during inrush conditions (very likely due to the dc component in the current), change the shape of the waveform within the dwell periods and may cause a false tripping,

(c) During severe internal faults, when the CTs saturate, their secondary currents may also show periods of low and flat values exposing the relay to missing operations.

B. Criterion 2

The hypothesis of magnetizing inrush may be ruled out if the differential current [21-24]:
has its peaks displaced by half a cycle,
and any two consecutive peaks are not of the same polarity.

This method needs robust detection of the peak values. Timing between two consecutive peaks must be checked with some tolerance margin accounting for the frequency deviations.

Theoretically, this method needs three quarters of a cycle to distinguish between internal faults and inrush conditions. The first peak of the fault current appears after a quarter of a cycle, the next one - half a cycle later. With the second peak arriving, the criterion rejects the inrush hypothesis and sets the tripping permit.

As its advantage, this method tolerates deep saturation of the CTs during both inrush conditions and internal faults. The main disadvantage of this algorithm is the need of cross polarization between the phases. Not always all three phases show the typical inrush unipolar waveform. Also, during very smooth energization of a protected transformer (what may accidentally hap-pen owing to the adequate relation between the switching angle and the remanent flux), this criterion will fail.

3.4 Harmonic Restrained Static Relay For A Single Phase Transformer

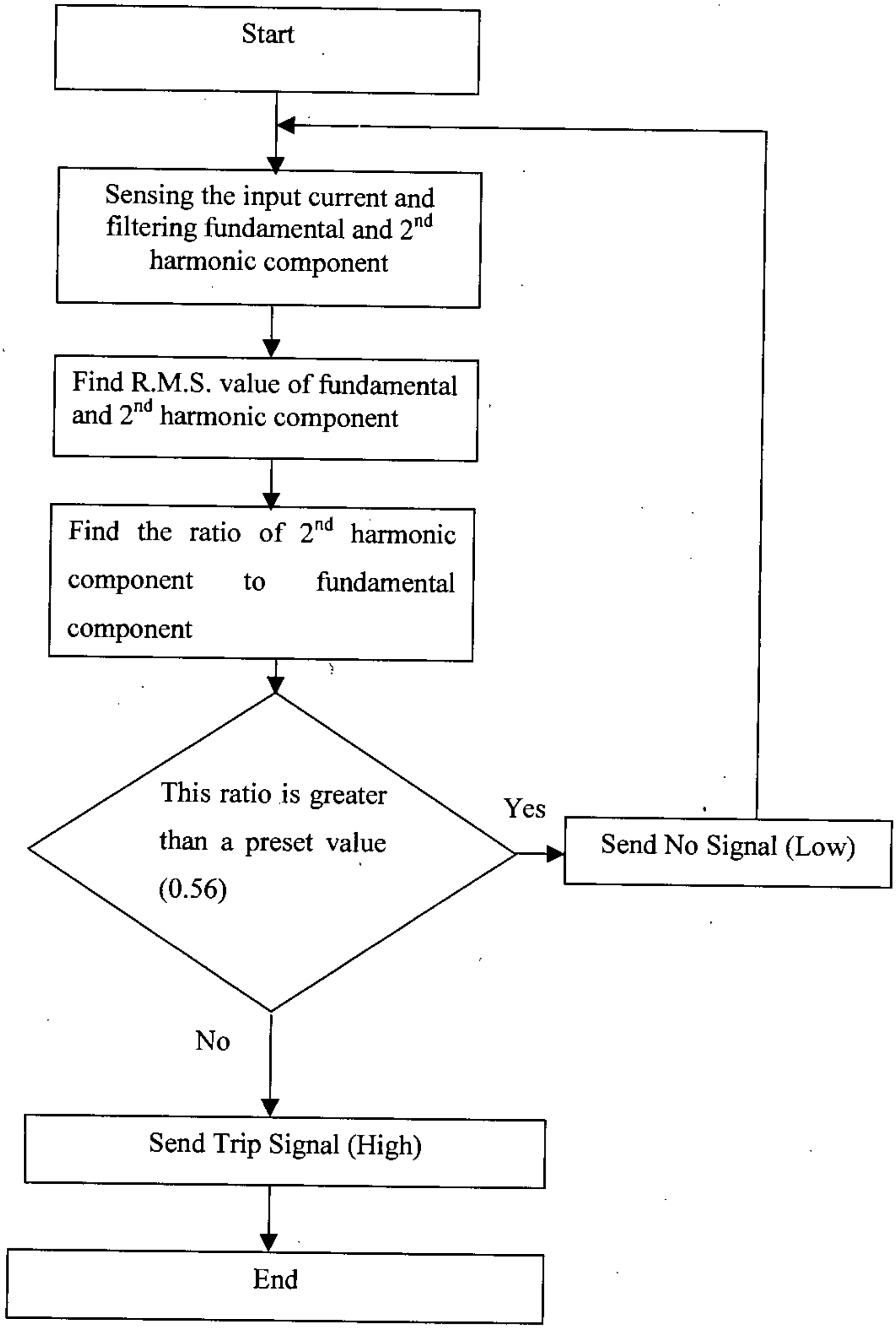
Power transformer protection is accomplished by high-voltage side fuses, over-current relays, differential relays, and pressure relays. Differential relays are commonly used on large power transformers in all applications. The percentage differential relay, which has an operating coil and several restraint coils, is the standard. The current to operate increases as the fault current increases, giving good sensitivity but avoiding false trips caused by CT ratio errors. The two main problems that arise in applying differential relays to power transformers are the phase shift in delta-wye banks and the transient inrush of magnetizing current.

The transient inrush appears as a differential current, like an internal fault. If the relay is desensitized, then its performance on faults is degraded. The inrush current can last for a long time on large banks, so time delays are not a very good answer. The solution became apparent when the harmonic content of the inrush current, rich in second harmonics, was compared to that of fault current, almost no second harmonics. The modern differential relay for power transformer protection usually employs a second-harmonic restraint to prevent tripping on inrush currents.

3.4.1 Proposed Design

The design of the static relay for a single-phase transformer protection having harmonic restrain is made by simulation. Current transformer on the both sides of transformer senses line current of the transformer. This current is converted to a voltage and to an active filter composed of operational amplifier to sense the presence of second harmonic current. Another filter circuit is also designed to sense 50 Hz fundamental component of the line current. Absolute magnitude calculation circuits determines the magnitude of both currents and the ratio of two currents is determined by using a multiplier IC used as a divider. The minimum value is achieved by the different switching instant within the cycle of a supply, which is taken as preset value. Then the ratio is compared with the preset value (0.56) to decide that the current is a magnetizing current or a fault current [12, 13]. However this preset value varies from transformer to transformer, and is to be determined for the specific transformer by extensive simulation both under switching and fault conditions. The decision is conveyed to the static differential relay. Initially a delay (15 ms) is used to avoid initial transient condition. The design flow chart is provided in section 3.4.2 and the description of the design of each section is provided in section 3.4.3.

3.4.2 Flow Chart of the Harmonic Restrained Static Relay



3.4.3 Design of various stages of the Harmonic Restrained Static Relay

3.4.3.1 Sensing the input current

The outputs from current transformer proportional to the appropriate primary line currents are filtered to produce a bias restraint voltage.

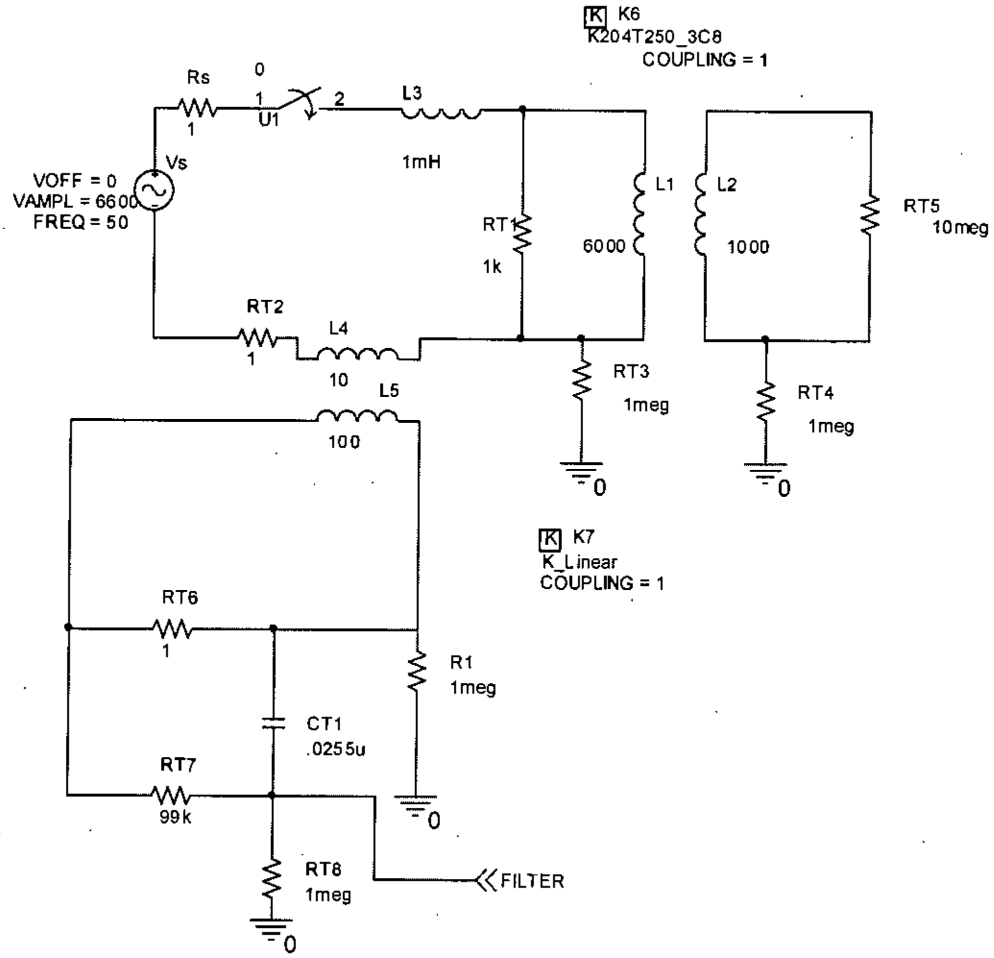


Fig 3.1 Current Sensing Circuit

3.4.3.2 Notch Filter Design

In a band-reject filter frequencies are attenuated in the stop-band while they are passed outside this band. The band reject filters can be classified as wide band-reject and narrow band-reject filter. The narrow band reject filter is commonly called the notch filter, is commonly used for the rejection of a single frequency. In this design two notch filter are used for the detection of 50 Hz and 100 Hz component. The notch-out frequency is the frequency at which maximum attenuation occurs; it is given by

$$f_N = 1/(2*\pi*R*C) \qquad (4.1)$$

To design an active notch filter for a specific notch-out frequency f_N, $C \leq 1\mu F$ has been chosen and then the required value of R has been calculated.

a) Notch Filter 50 Hz Detection

Let C = 0.068 μ F. Then from equation (1) the value of R is 24 k Ω.

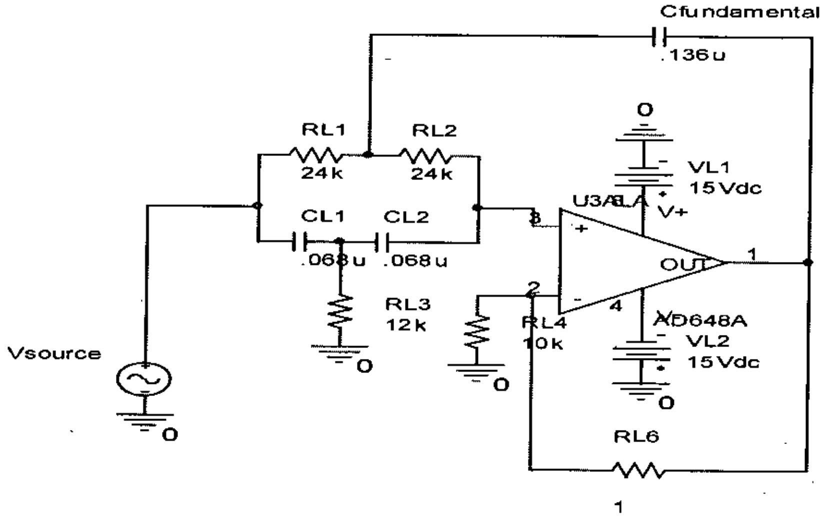


Fig 3.2 (a) Notch Filter for 50 Hz Detection

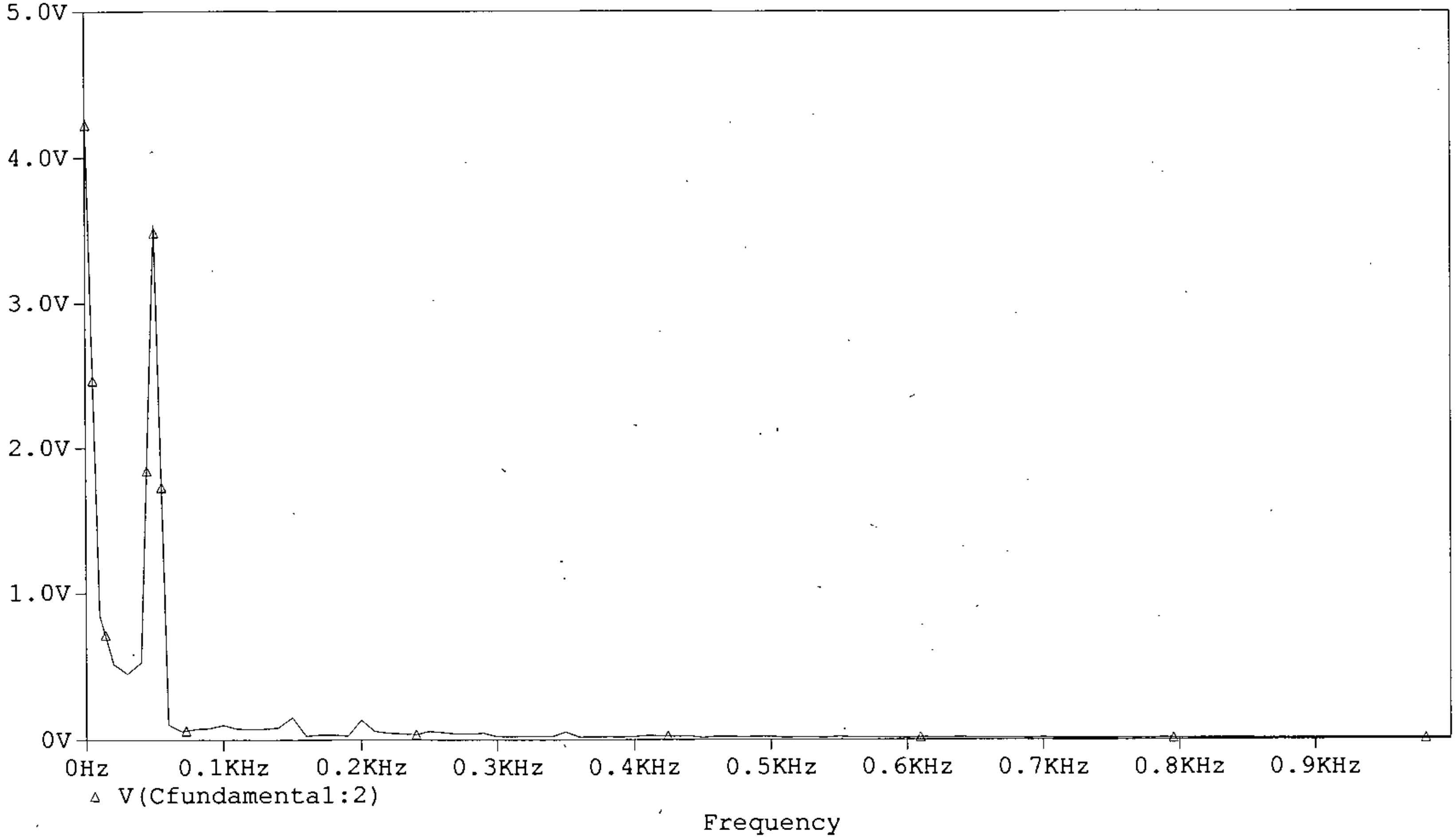


Fig 3.2 (b) Frequency Response of the notch filter of fig 3.2 (a)

b) Notch Filter 100 Hz Detection

Let C = 0.068 μ F. Then from equation (1) the value of R is 48 k Ω.

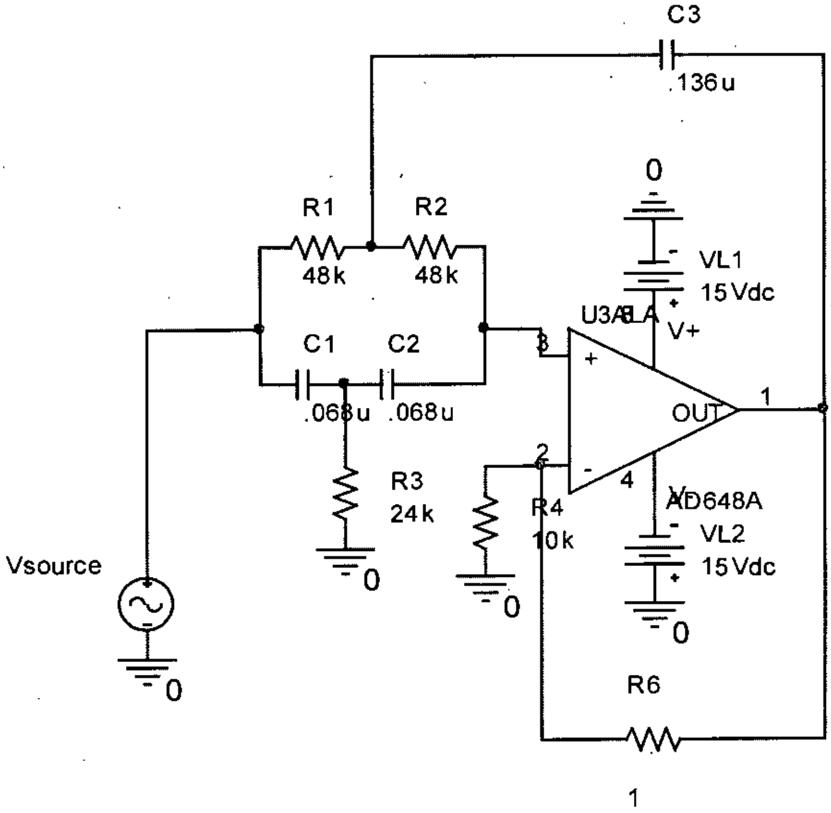


Fig 3.3 (a) Notch Filter for 100 Hz Detection

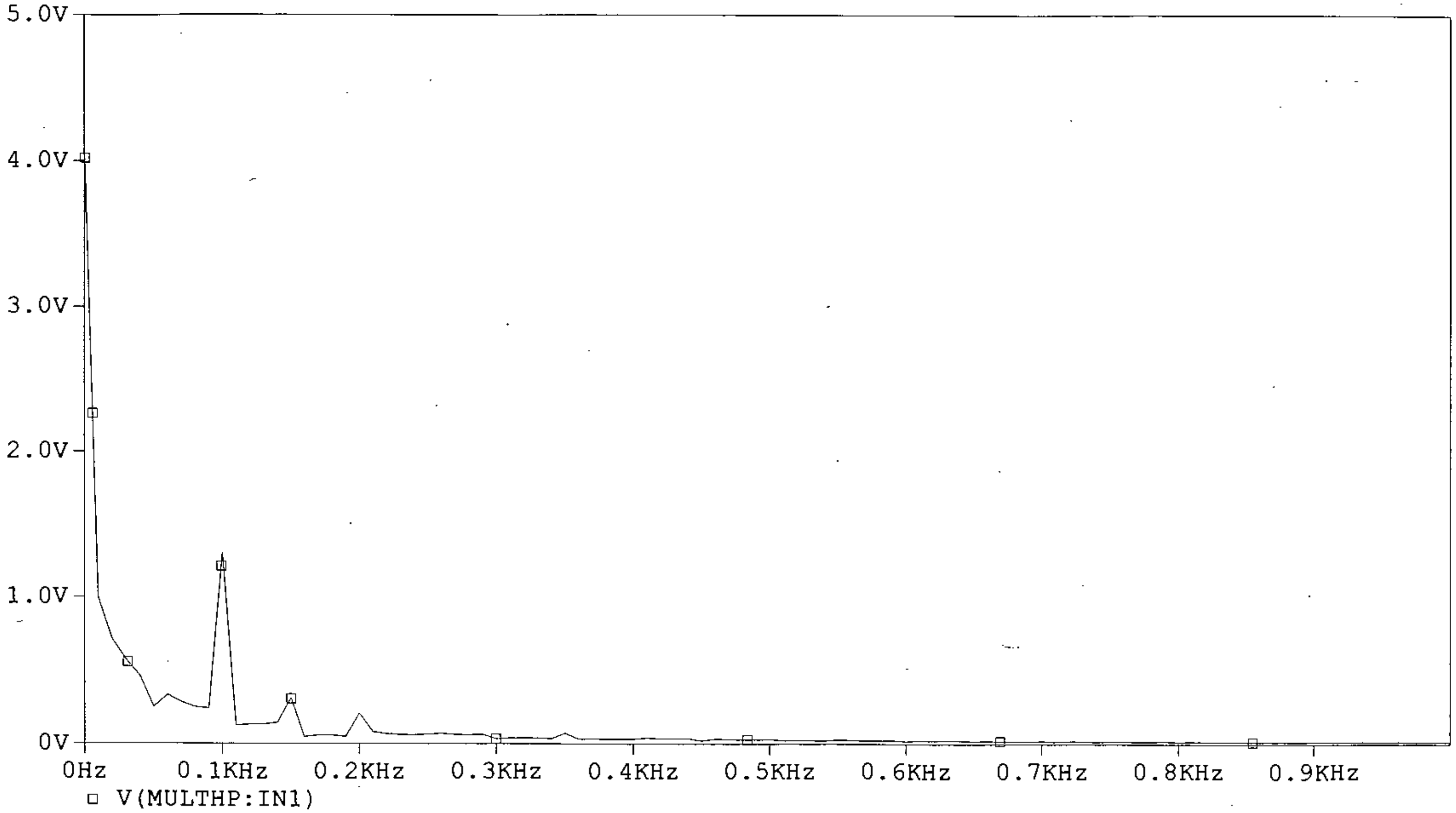


Fig 3.3 (b) Frequency Response of the notch filter of fig 3.3 (a)

3.4.3.3 RMS Value Circuit

The RMS value of an as signal is defined as

$$V_{rms} = \sqrt{(1/T \int_0^T V^2(t)\, dt)}$$

To achieve this, three separate operations are required (1) SQUARING (2) INTEGRATING and (3) SQUARE ROOTING

Fig 4.4 shows the basic circuit for RMS detection. The first multiplier in the circuit performs squaring operation. The Op-Amp A1 is connected in integrator configuration. The squared output is integrated by OP-Amp A1. The final Op-Amp along with multiplier in feedback loop performs square root operation from A1. Hence the final output is V_{rms}.

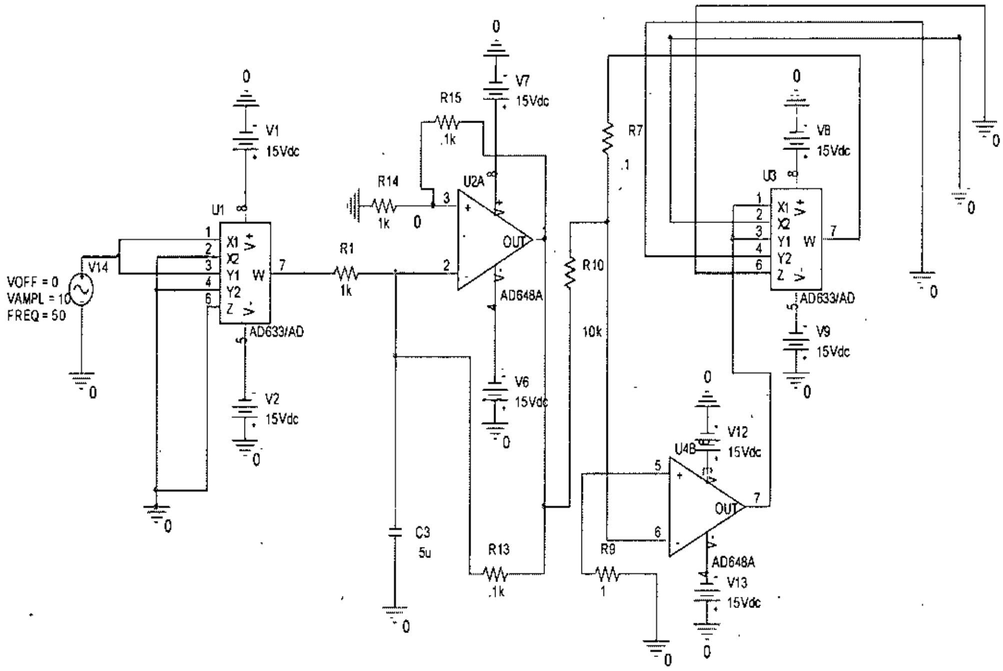


Fig 3.4 RMS Value Circuit

3.4.3.4 Divider Circuit

In Fig 4.5 shows the divider circuit. Here, the multiplier is connected in the feedback loop of an Op-Amp. The operation of the circuit is as follows.

The denominator is applied to the X1 input of the multiplier and the numerator is applied to one summing input of the Op-Amp, with the other input coming from the output of the multiplier. In close loop operation the output of the Op-Amp is forced to some voltage, such that the output of the Op-Amp must then be equal to

$$V_o = 10\ V_{numerator} / V_{denumerator}$$

It is to be noted that, the sign of the denominator must be negative or the polarity of the feedback will reverse itself and cause the circuit to latch up. This latch up is not destructive and is common to all division circuits.

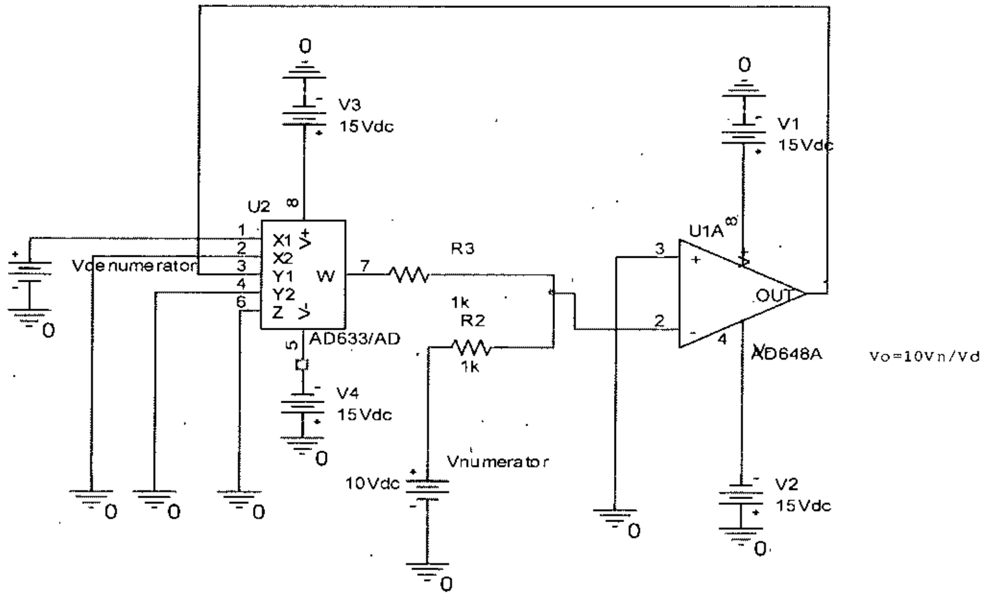


Fig 3.5 Divider Circuit

3.4.3.5 Decision Circuit

In Fig 4.6 shows the decision circuit. Here, a positive-voltage as a preset value (0.56Vdc) is applied in the positive terminal of the Op-Amp. The output of the RMS value is connected to the negative terminal of the Op-Amp. If RMS value is higher than preset value then output of the decision circuit is **LOW.** A 15 ms second delay switch is used in the output of the Op-Amp to avoid initial transient condition.

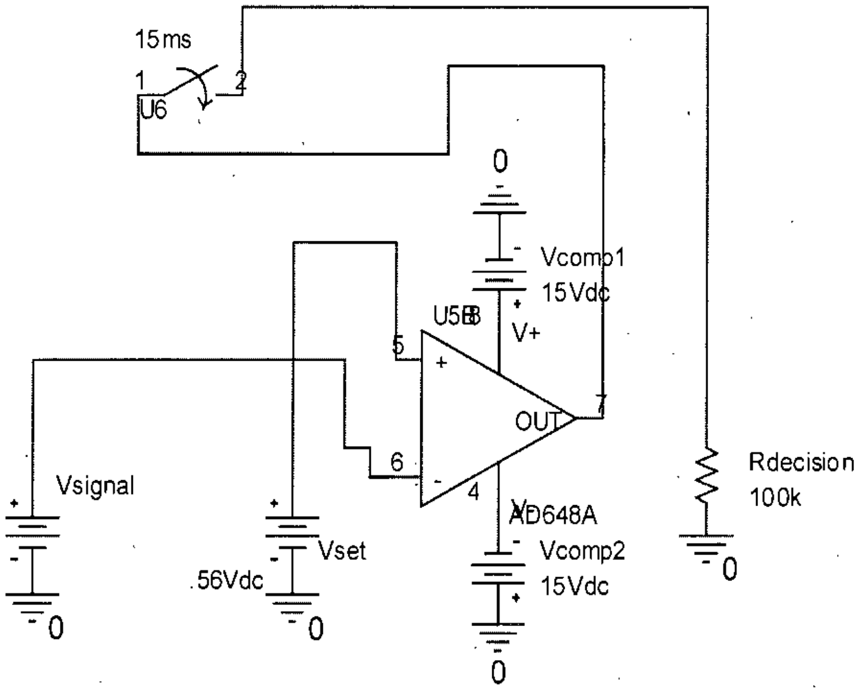


Fig 3.6 Decision Circuit

3.4.3.6 Total Circuit

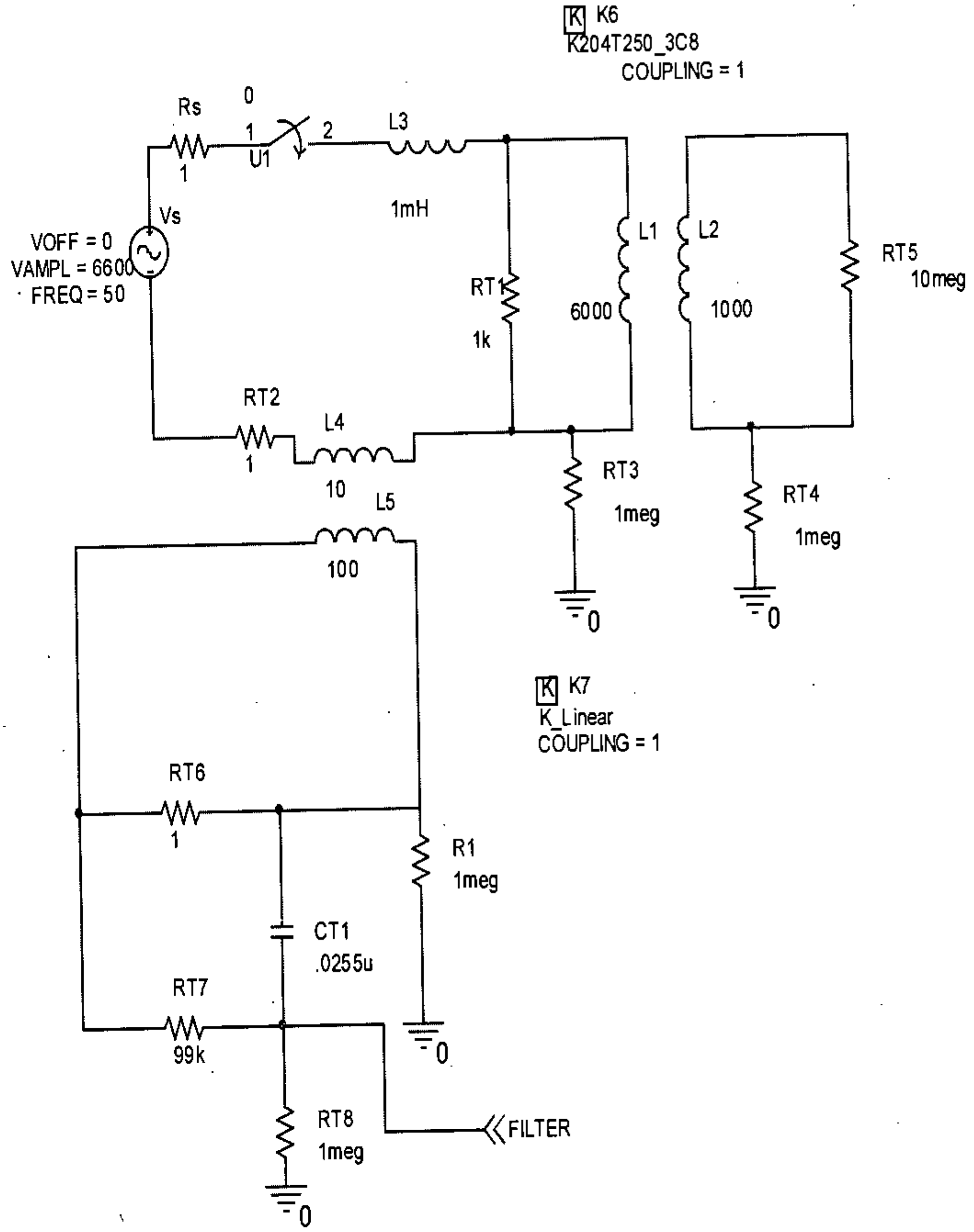


Fig 3.7 Current Sensing Section

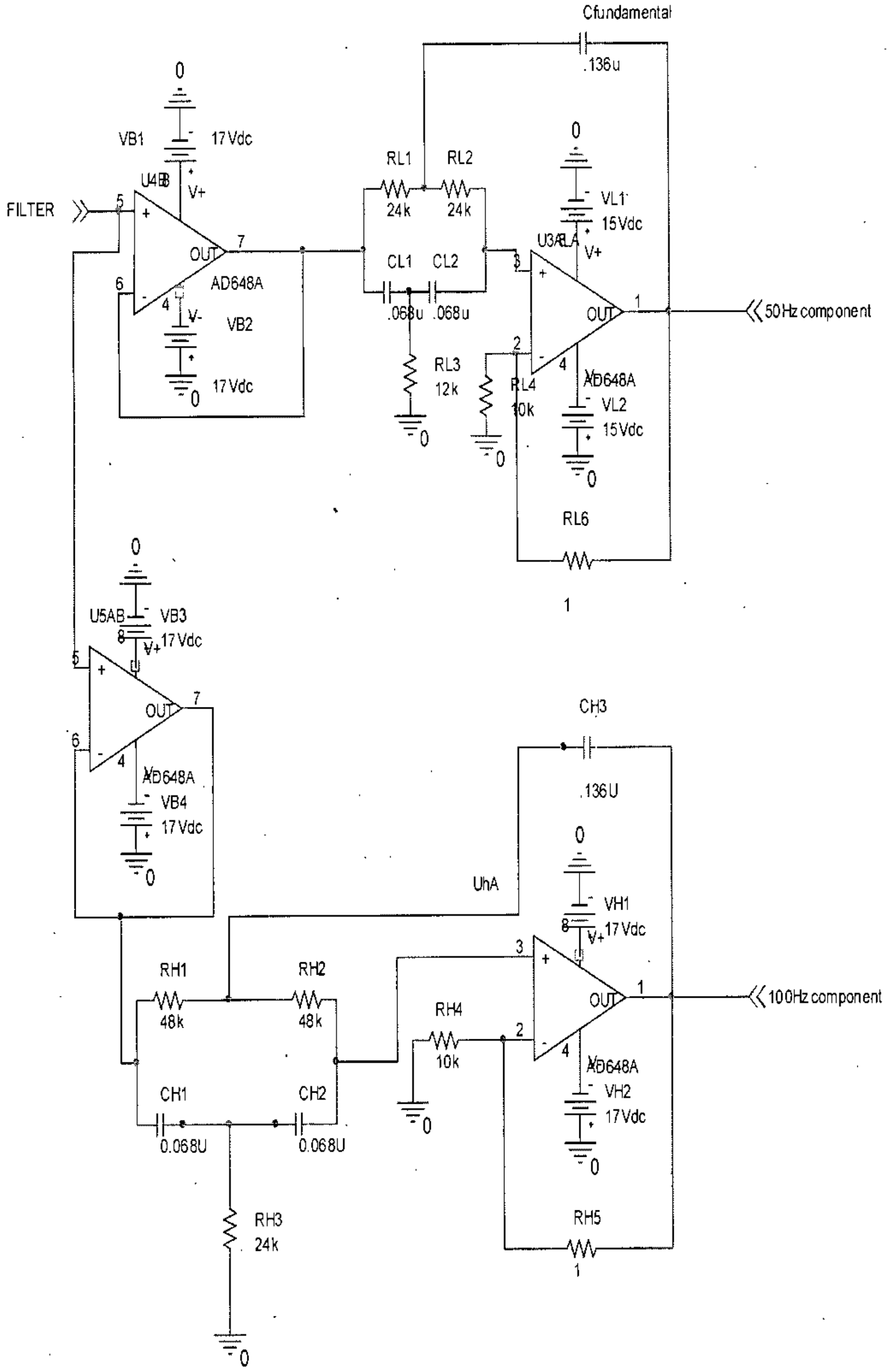


Fig 3.8 Filtering Section

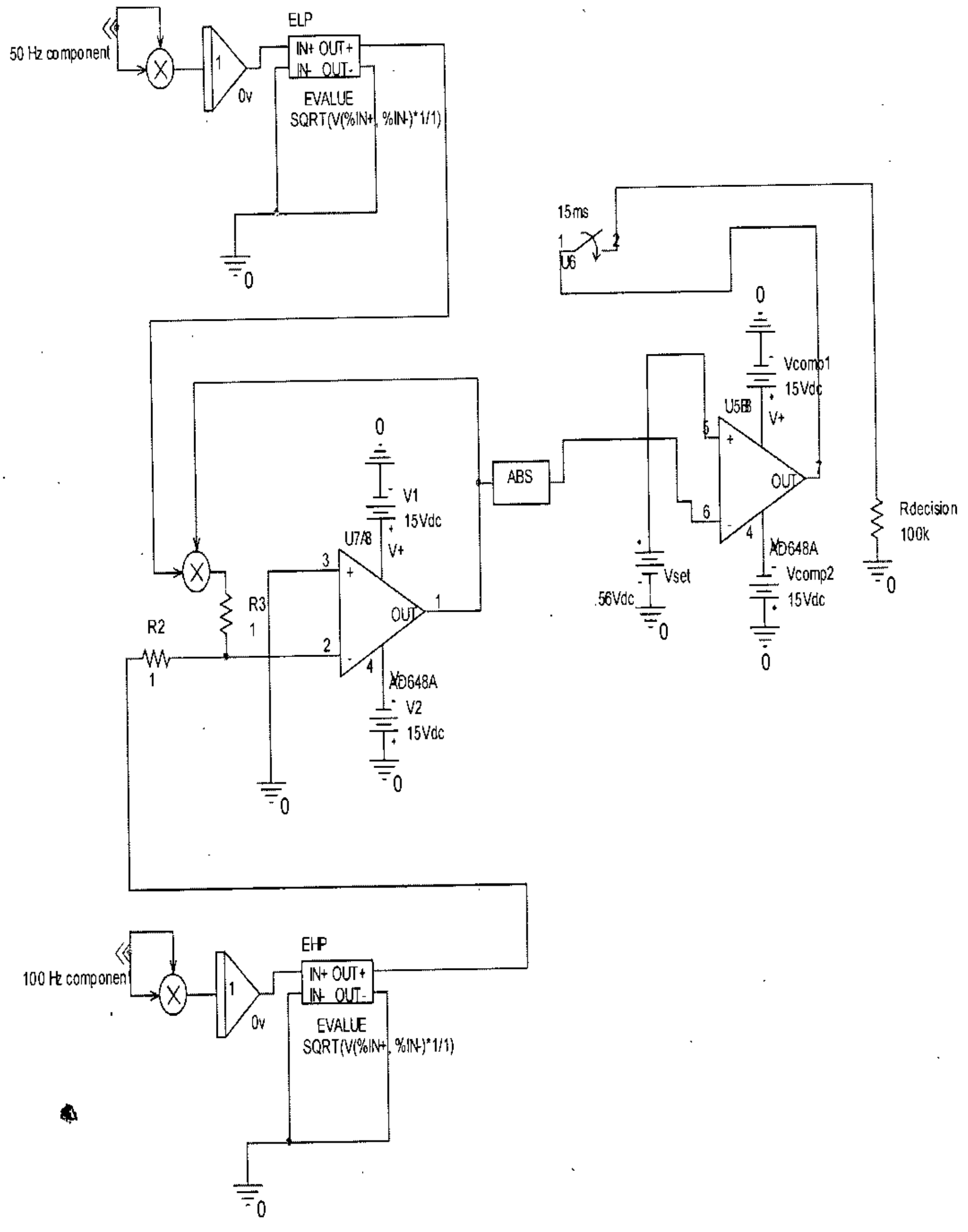


Fig 3.9 Section of RMS determination, Division and Decision-making.

3.4.4 Result

For the verification of the algorithm many simulation studies have been carried out using ORCAD to obtain various transient phenomena in a typical 6.6 kV single-phase transformer shown in circuit diagram.

3.4.4.1 Transformer Inrush Currents for Different Switching Instances

The simulation is carried out by different switching instances such as 0^0, 45^0, 90^0, 135^0 and 180^0. In Table-1 shows the value of fundamental and 2nd harmonic components of Inrush current

TABLE-3.1

Instances	Fundamental Component (mV)	2nd Harmonic Component (mV)	Ratio
0^0	0.86	0.56	0.65
45^0	0.91	0.82	0.90
90^0	0.92	0.78	0.84
135^0	1.03	0.85	0.82
180^0	1.025	0.82	0.80

In Table-3.2 shows the result of relay operation

TABLE-3.2

Condition	Instances	Fundamental Component (mV)	2^{nd} Harmonic Component (mV)	Ratio	Decision
Inrush Current	0^0	0.86	0.56	0.65	No Trip
	45^0	0.91	0.82	0.90	No Trip
	90^0	0.92	0.78	0.84	No Trip
	135^0	1.03	0.85	0.82	No Trip
	180^0	1.025	0.82	0.80	No Trip
Fault Condition	0^0	1.69	0.88	0.52	Trip
	45^0	1.42	0.80	0.56	Trip
	90^0	1.73	0.90	0.52	Trip
	135^0	1.88	0.85	0.45	Trip
	180^0	1.95	0.82	0.42	Trip

3.4.4.2 Typical Results in the form of waveforms

Typical result of a transformer switching inrush and that of a fault situation is presented in waveforms at various sections of the design circuit in following subsection.

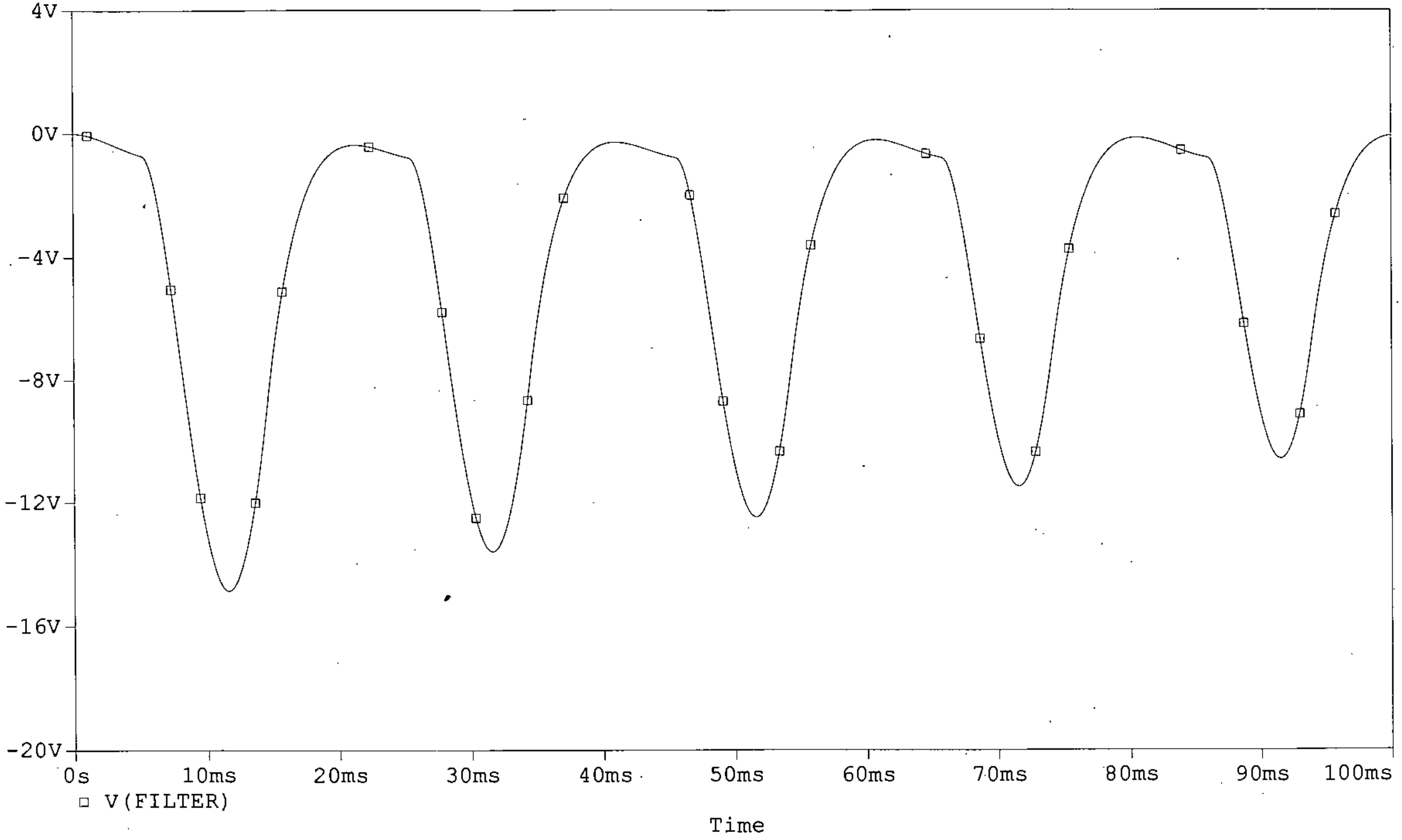


Fig 3.10 Output of CT when transformer secondary side open

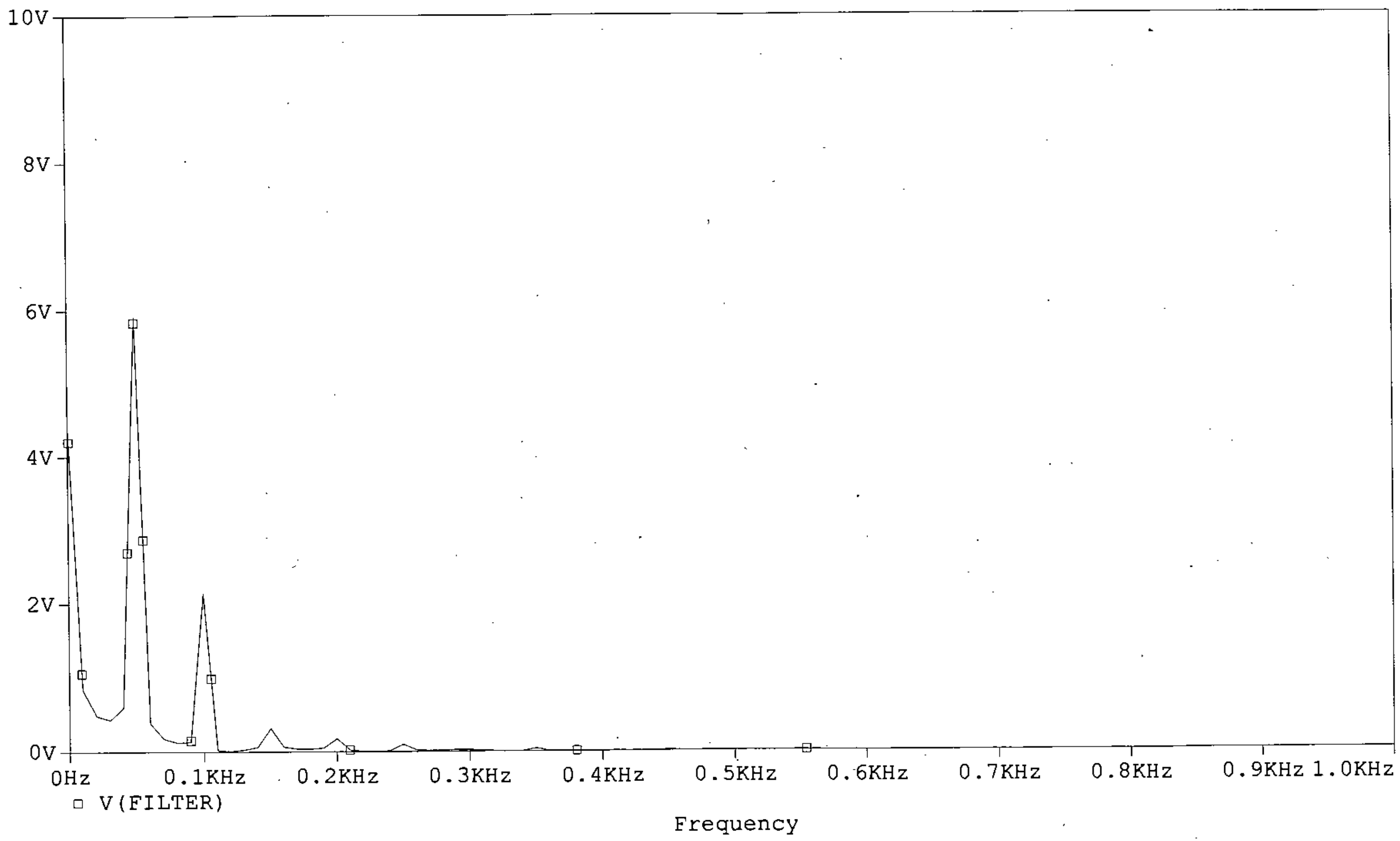
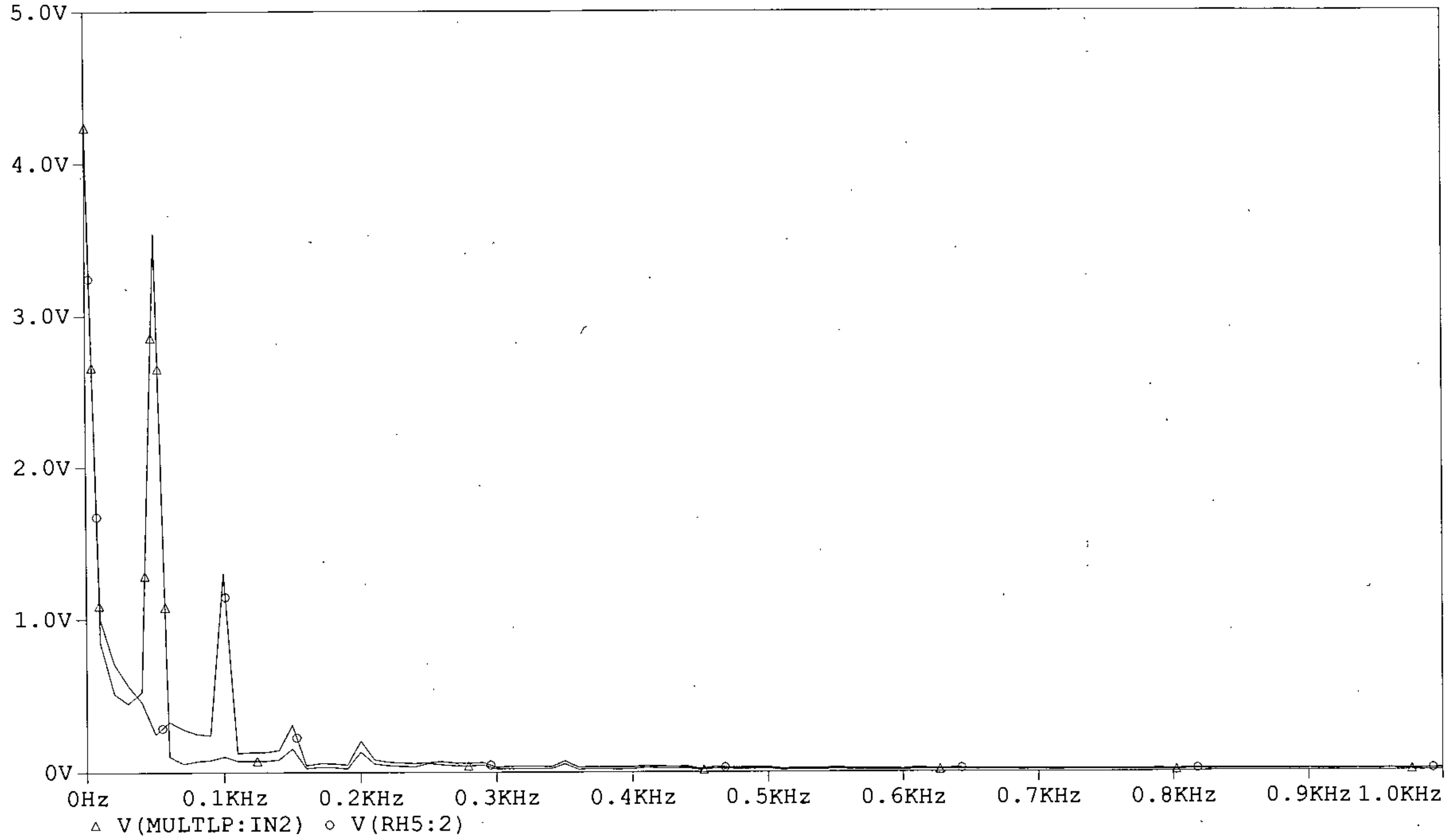


Fig 3.11 Frequency Response of CT



Frequency

Fig 3.11 Frequency Response of Filter

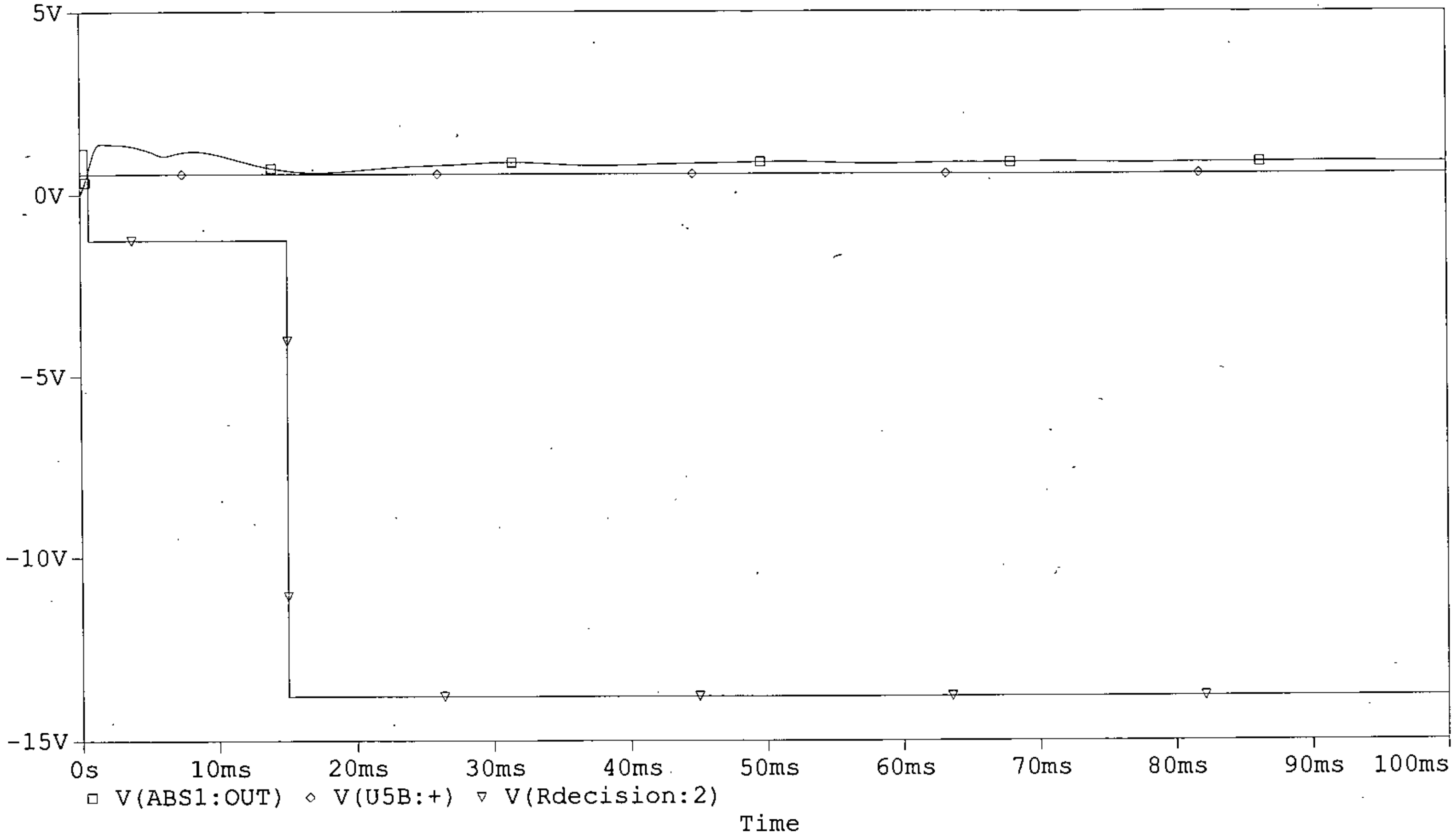


Fig 3.13 Ratio of 2nd and 1st harmonic ,preset value and Decision signa44

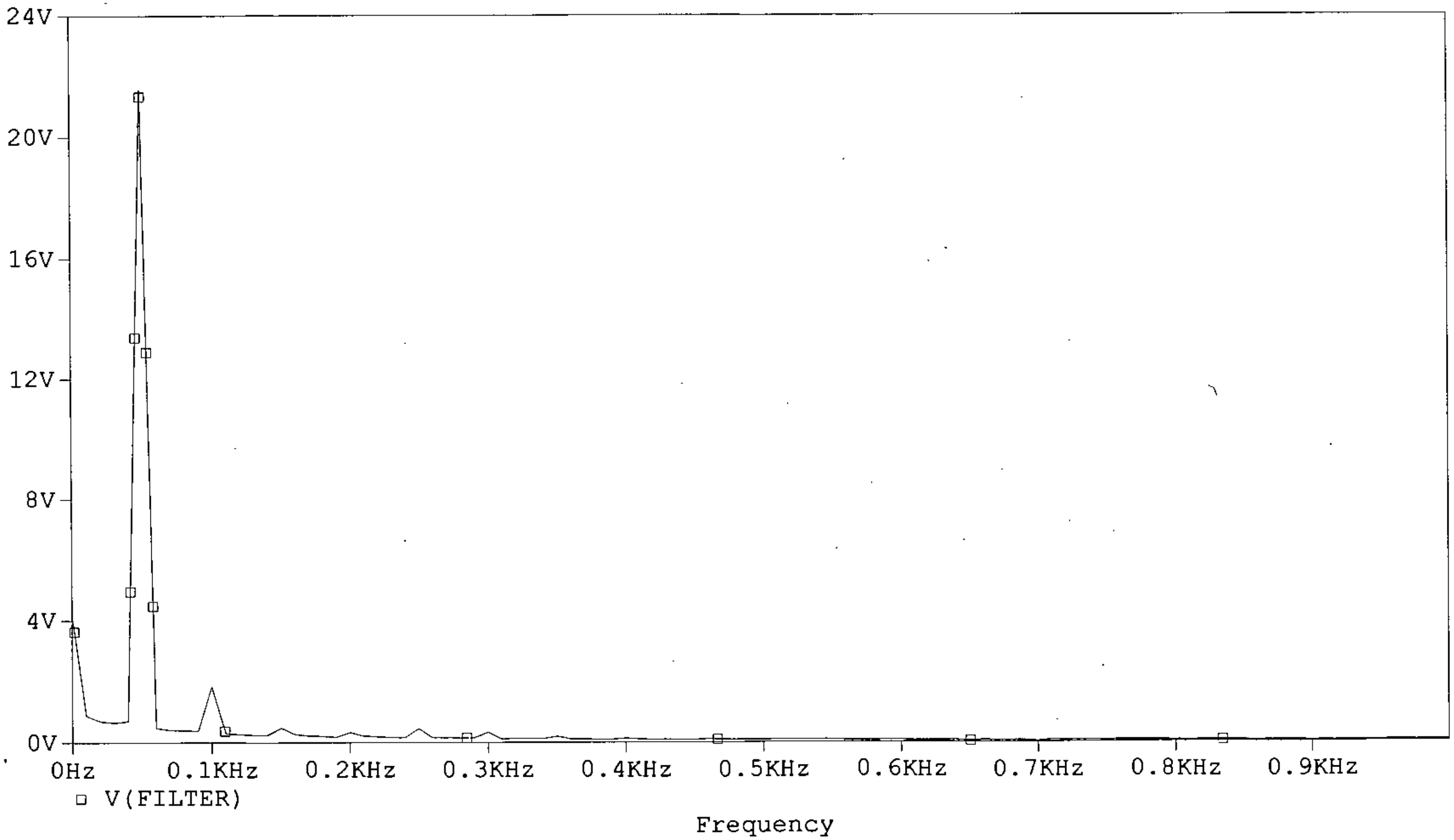


Fig 3.14 Frequency Response of CT when internal fault occurred

CHAPTER 4

Conclusions

4.0 Conclusion

This paper presents a static relay for inrush current discrimination in the protection of power transformer. Differential protection schemes are used in power transformers to isolate them during severe internal faults. These differential relay protection schemes may present transformer switch on as the initial current known as magnetizing inrush current having magnitude of 14-16 times normal load current may appear depending on the instant of switching of a applied voltage cycle and magnitude of saturation of transformer core. As a result discriminating fault current and magnetizing current is an additional requirement in transformer differential protection.

Usual practice of identifying fault current and magnetizing inrush current is to detect the harmonic behavior of the two currents. Fault current is usually a decaying sinusoid and magnetizing inrush current has DC offset, high initial magnitude and highly non-sinusoidal containing all harmonics at various magnitudes. One of the main harmonics is the second harmonics or the 100 Hz component. Various techniques i.e. electromechanical, analog and digital are employed in transformer differential relays to find the ratio of second harmonic to fundamental component of transformer. It is well known that this ratio in case of internal fault condition should be theoretically zero and in the case of magnetizing inrush current has a high value. This well-known fact is used to restrain the differential relay from operation during switch on magnetizing inrush current.

In the present work an analog static circuit is designed, simulated and studied to discriminate the fault current and magnetizing inrush current to prevent a differential relay from operation magnetizing inrush but operate during a fault condition.

The analog static circuit designed and simulated for the above purpose has been tested by simulation for various conditions of transformer internal fault and magnetizing inrush current at different switching conditions. It has been found that the designed scheme worked successfully to provide a no trip signal during turn on of the transformer but a trip signal for internal fault conditions.

4.1 Future work and Recommendations

The designed relay may be physically fabricated and tested for its practical feasibility in a future work. Also, though the design has been presented for a single-phase transformer, the procedure being same may be studied for three-phase transformer with different configuration. In the three phase transformer identical static relay should be provided for each phase of the transformer and relay prevent operation signal should be initiated if either of the three relays has high second harmonic to fundamental current ratio. The simulation study for three-phase transformer case may also be implemented and tested for practicability of the designed relay.

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