ENHANCING THE PROTECTION OF BUS BAR USING ADVANCED NUMERICAL TECHNIQUE

DISSERTATION
Submitted in partial fulfillment of the
requirement for the award of the
Degree of

MASTER OF TECHNOLOGY
IN
Electrical Engineering
(Power Systems)

By

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Under the Guidance of

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Punjab
April 2014

CERTIFICATE

This is to certify that the dissertation titled "Enhancing the Protection of Bus Bar Using Advance Numerical Technique" that is being submitted by " ***Simmi Bhadauria***" is in partial fulfillment of the requirements for the award of MASTER OF TECHNOLOGY DEGREE, is a record of bonafide work done under my /our guidance. The contents of this dissertation, in full or in parts, have neither been taken from any other source nor have been submitted to any other Institute or University for award of any degree or diploma and the same is certified.

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Objective of the Dissertation is satisfactory / unsatisfactory

Examiner I **Examiner II**

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I would like to thank Lovely Professional University for giving me the opportunity to use their resources and work in such a challenging environment.

First and foremost I take this opportunity to express my deepest sense of gratitude to my guide **Mr. Kirpal Singh Doad** for his able guidance during my report work. This report would not have been possible without his help and the valuable time that he has given me in his busy schedule.

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Last but not the least I would like to thank all the staff members of Department of Electronics and Electrical Engineering who have been very cooperative with me.

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CERTIFICATE

This is to certify that Simmi Bhadauria bearing Registration no. 11210797 has completed objective formulation of the dissertation titled, **“Enhancing the Protection of Bus Bar Using Advanced Numerical Technique”** under my guidance and supervision. To the best of my knowledge, the present work is the result of her original investigation and study. No part of the dissertation has ever been submitted for any other degree at any University.

The dissertation is fit for submission and the partial fulfillment of the conditions for the award of degree of Master of Technology in Electrical Engineering.

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DECLARATION

I, Simmi Bhadauria, student of Master of Technology under Department of Electronics and Electrical Engineering of Lovely Professional University, Punjab, hereby declare that all the information furnished in this dissertation report is based on my own intensive research and is genuine.

This dissertation, to the best of my knowledge, does not contain part of any work which has been submitted for the award of degree either of this university or any other university without proper citation.

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ABSTRACT

With the advancement in power system and increasing demand of interconnected grid system, the security and protection has become a major concern. As bus bar being the coupling point of many circuits in the power system, it has led an interest towards protection of bus bar. Although fault on a bus bar are not often but if they occur they may cause a damage equivalent to many simultaneous faults and results in complete shutdown of the system

Keeping this in view a new simple technique for bus bar protection based on instantaneous value of current signal has been proposed in the dissertation. This technique is based upon percentage differential protection principle. For the analysis of this method only the fault component of the current is considered neglecting the pre-fault current component. Current samples have been taken for quarter half cycle of current wave with an assurance that CT will not saturate in this interval. MATLAB/SIMULINK is used for simulation to implement the technique.

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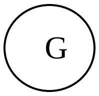
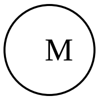
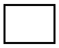
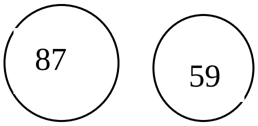
	Current transformer
	Transformer
	Generator
	Motor
	Circuit Breaker
	Bus Bar
	Feeder
	Isolator
	Differential relay
	Fault

I_{PRI}, I_{SEC}	Primary and secondary winding current respectively
R_{PRI}, R_{SEC}	Primary and secondary winding resistance respectively
X_{PRI}, X_{SEC}	Primary and secondary winding reactance respectively
Z_{line}	Line impedance
V_{EXC}	CT secondary induced emf
V_{SEC}	CT secondary winding voltage
X_M	Magnetizing reactance
I_1, I_2	Currents of current transformer 1 and 2 respectively
Δ I	Difference current flowing through operating coil
Id, id	Differential current
Ir, ir	Restraining current
I_{OP}	Operating coil current
I_{RES}	Restraining coil current
S	Stabilizing Factor

LIST OF ABBREVIATIONS

CT	Current Transformer
PU	Processing Unit
PC	Personnel Computer
CU	Central Unit
GI	Grid Interface

CHAPTER 1

INTRODUCTION

1.1. Power System Protection

A power system comprises of four major sections namely generation, transmission, distribution and utilization. The electrical energy is generated, transmitted and then distributed to various group of consumers by the electric utility. As the power system consists of number of large components and is spread over vast territories, the probabilities of occurance of fault, abnormal conditions and failure of components are therefore significant [27]. Fault causes damaging of equipments and also harms the personnel and results in huge losses to the consumer as well as electric utilities. Therefore each element of the system should be protected against damage due to abnormal or adverse operating conditions and fault. To isolate the faulted part or component of the power system protective relays are used which give signal to the trip circuit of the circuit breaker, the trip circuit is then activated and the faulty part is removed from the system.

Protective devices therefore play an important role in power system as they not only provide protection but apart from this they also ensure increased reliability and stability of the system. Their major function is to detect the fault and isolate the faulted part from the system and to achieve this goal the power system is divides itself in number of various protection zones like bus zone, transformer zone, line zone, generator zone and motor zone.

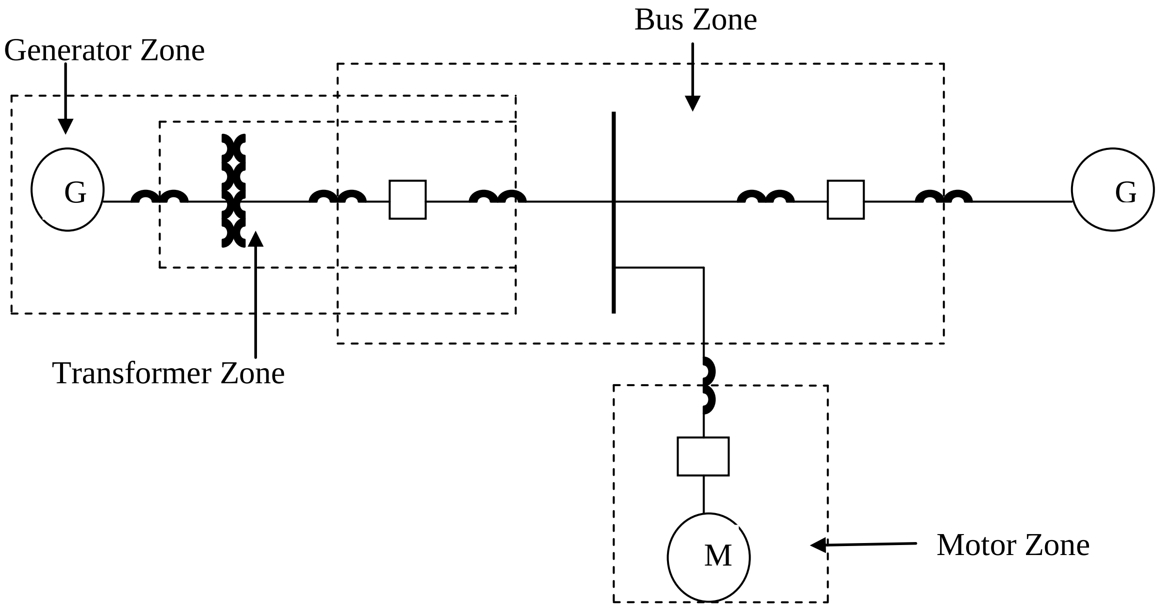


Fig.1.1. Power system protection zones

Each of these zones is protected by the protective relay. It is the responsibility of the relay to protect a zone, the main function of the relay is to sense the abnormal condition and give signal to the circuit breaker to operate and disconnect the faulted zone from the remaining power system during the occurrence of fault. In order to record the waveforms of system current and voltage the relay alert the operator to start the recording equipments.

All the protection zones overlap with each other in order to ensure that none of the power system part is left unprotected. In case if the primary relay do not operate or fail to operate then to ensure the isolation of faulted component a back-up relay is also provided. There is a particular time delay after which the back-up relay operates and along with the isolation of faulted zone it also isolates the adjoining zone or zones.

Earlier in power system fuses as a protective device were used to protect the equipments and line and still they are in use. Fuses have the advantage that they were inexpensive and effective but apart from this they have major disadvantages like they were not able to discriminate between the load side and supply side fault and also after the clearance of fault they were not able to restore back the circuit to the normal condition also they need to be replaced after every operation.

However a significant amount of improvement has been seen in the power system protection with the development of electromechanical relay. Electromechanical relays are capable to control the operating time and are also capable of restoring the circuit. Thus the selectivity and the sensitivity of the power system have been greatly improved.

In 1950s introduction of solid state relays took place. Due to the inadequate design of the electronic components and higher failure rate these relays were initially not accepted by the users [27]. However with the development in the semiconductor technology and improved designs various types of electromechanical and solid-state relays are in use today. With the recent advancement in very large scale integrated circuit gave rise to the development of numerical or digital relays.

The trip circuit of the circuit breaker is energized by the relay and this then opens the circuit breaker. The system current and voltage is sensed by the relay through current and voltage transformer respectively. If a fault occurs then it is sensed by the protective relay and this relay then energizes the trip relay finally the breaker contacts get closed. This activates the breaker coil and results in opening of the circuit breaker so that the faulted component or faulted part can be disconnected from the power system.

1.2. Bus Bars

The most vital element in power stations and substations is the bus bar. The bus bar is the junction of an electrical network where many line are connected together i.e. it is a point of coupling of many circuits, transformer, generator and load. Any fault in the bus bar results in the failure such as equipment damage, system instability and service interruption [26]. However with the advancement of modern design methods the probability of occurrence of fault on the bus bar has been reduced to negligible, but if a fault occurs on a bus bar then it results in a considerable damage and distruption of supply unless some form of quick-acting automatic protection is provided for isolation of the faulty bus bar. The bus bar zone or area that is to be protected includes not only the bus bar themselves but also the isolating switching, circuit breakers, instrument transformers and bus sectionalizing reactors etc.

Special attention for bus bar protection is required because of the following reasons: -

1. Fault level at bus bar is very high.
2. The fault on the bus bar would result in widespread supply interruption.
3. The system stability is adversely affected by fault in bus zone.

A fault on a bus bar is appreciably more severe both with respect to the safety to personnel, system stability and damage [26]. A major system shutdown may be caused in the absence of adequate bus protection. It is therefore very much important that the bus zone protection should be quick acting, stable and most reliable. Thus desirable features of bus bar protection should be: -

1. High speed operation (less than 3 cycles).
2. Discrimination between fault in its protected section and fault elsewhere.
3. Stability for external faults.
4. Freedom from unwanted operation.
5. No operation due to CT saturation or power swing.
6. Separate control of trip circuit of each circuit breaker.
7. ‘Main’ and ‘check’ protection to ensure the isolation only when desirable.
8. Non-auto-reclosure, no single pole tripping of circuit breaker for bus-fault.
9. Interlock over-current protection for tripping generator unit in the event of operation of bus-zone protection.

1.3. Bus-Bar Arrangements [26]

There are several bus bar arrangements and the choice of a particular bus bar depends upon following different factors: -

1. System voltage.
2. Substation position in the system.
3. Reliability of supply.
4. Flexibility and cost.
5. Simplicity.
6. Maintenance possibility without interruption of supply or danger to the operating personnel.
7. Extension provision with the load growth.
8. Economical installation should be there to meet the required need and continuity of supply.
9. Availability of alternative arrangements in the event of an outage of any of the apparatus.
10. Importance of load and local condition. Freedom from total shutdown and its period desired.

1.3.1. Single Bus-Bar Arrangement

It is one of the simplest arrangements and consists of a single set of bus bars for full length of the switchboard. All the generators, transformers and feeders are connected to this set of bus bar [27]. Circuit breaker controls all the generators and feeders whereas isolation of generators, feeders and circuit breakers from the bus bar for maintenance purpose is provided by the isolators.

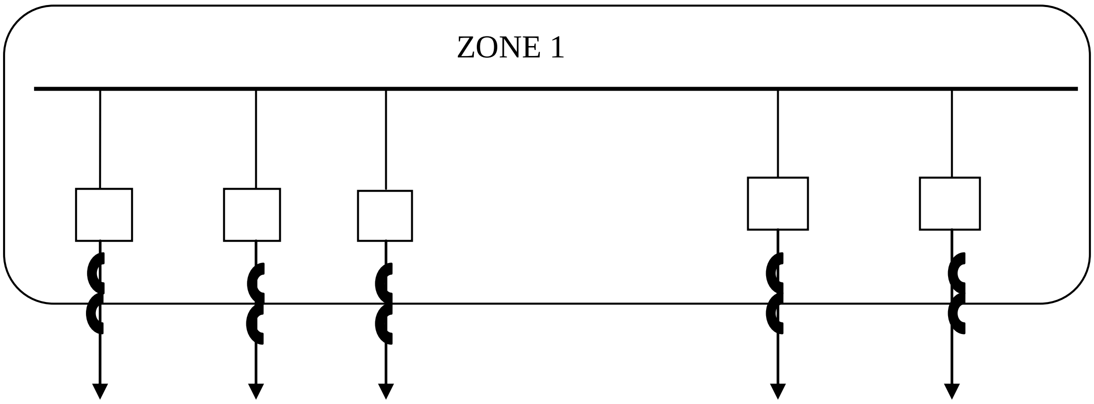


Fig.1.2. Single bus bar arrangement

Advantages: -

1. It has a low initial cost.
2. Maintenance is low.
3. It can be used for small and medium sized station where shutdown can be permitted.

Disadvantages: -

1. During a bus bar fault all the healthy feeders are also disconnected.
2. Maintenance on any of the station feeders is not possible without interruption of supply.

1.3.2. Single Bus-Bar Arrangement with Bus Sectionalization

Complete shutdown during a fault on a bus bar can be avoided by using sectionalization in a single bus bar arrangement. It is possible to sectionalize the bus bar by circuit breaker so that a fault on one part does not cause a complete shutdown. It is a common practice to sectionalize the bus in large generating stations where several units are installed [26]. Normally in a substation there are 2 to 3 sections of a bus bar but it is limited by the short circuit current to be handled. It is possible to achieve maximum advantage of this scheme by even distribution of incoming and outgoing feeders on the sections.

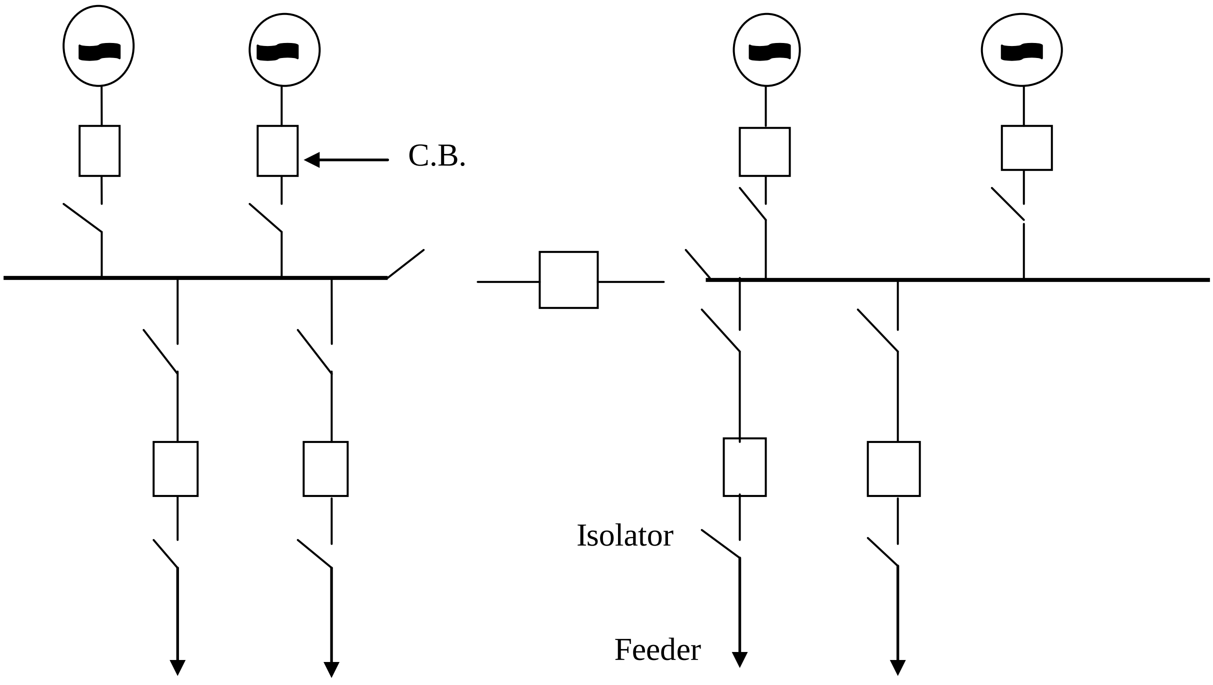


Fig.1.3. Single bus with sectionalization

Advantages: -

1. Maintenance of one section is possible without interrupting the supply of other section.
2. Circuit breaker breaking capacity can be reduced by inserting a reactor between the sections.

Disadvantages: -

1. Healthy feeders may be affected, in case if there is a fault on any one of the sections of the scheme.
2. If air break isolators are used as a sectionalizer, then isolation is not carried out automatically at the time of fault.

1.3.3. Main and Transfer Bus Arrangement

Such an arrangement is suitable for highly interconnected power network in which flexibility is very important. It consists of two bus bars known as 'main' bus bar and 'transfer' bus bar used as an auxiliary bus bar. With the help of a bus bar, each generator and feeder may be connected to either bus bar which consists of a circuit breaker and isolating switches [28]. The bus coupler enables the change-over from one bus bar to the other under load conditions. This arrangement is adopted where the loads and continuity of supply justify additional costs.

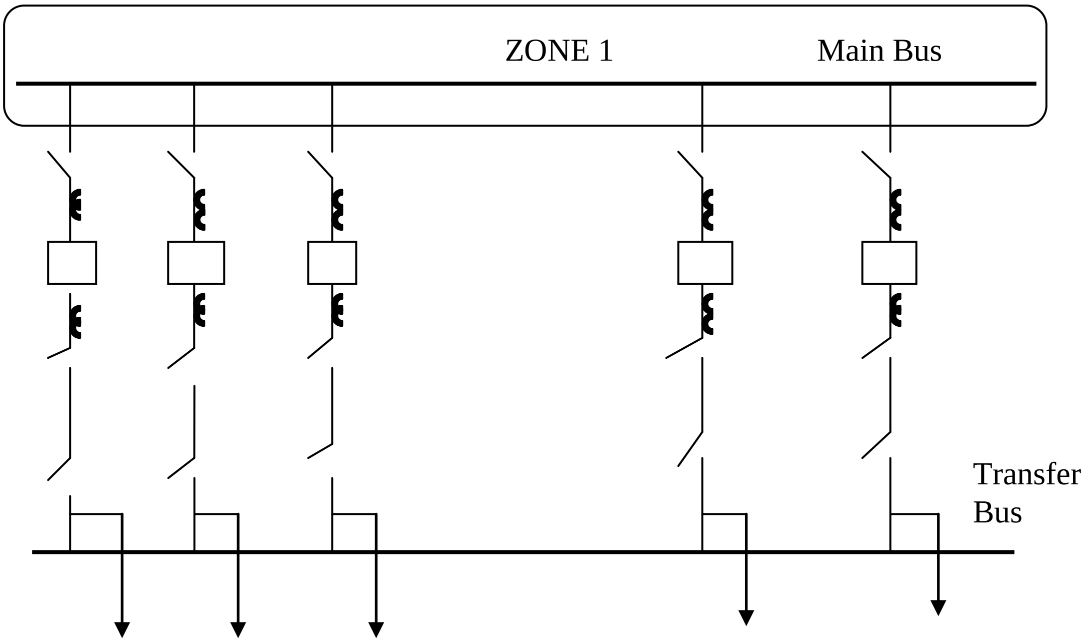


Fig.1.4. Main and transfer bus arrangement

Advantages: -

1. Continuity of supply is ensured in case of bus fault and if the fault occurs on one of the bus then the entire load is transferred to the auxiliary bus.
2. As the entire load can be transferred to the auxiliary bus, the repair and maintenance can be carried out on the main bus without interrupting the supply.
3. Each load can be supplied from either bus.
4. The maintenance cost of substation is lowered.

Disadvantages: -

1. Cost is higher as compared to that of single bus bar arrangement.
2. After transfer of all loads on to the transfer bus, a fault on any of the circuits connected to the transfer bus would shutdown the entire station.

1.3.4. Double Bus Double Breaker Arrangement

Such a bus bar arrangement does not require any bus coupler and permits switch over from one bus to the other whenever desired without interruption [26]. This bus bar arrangement is very costly and its maintenance cost is also high. This arrangement provides maximum reliability and flexibility.

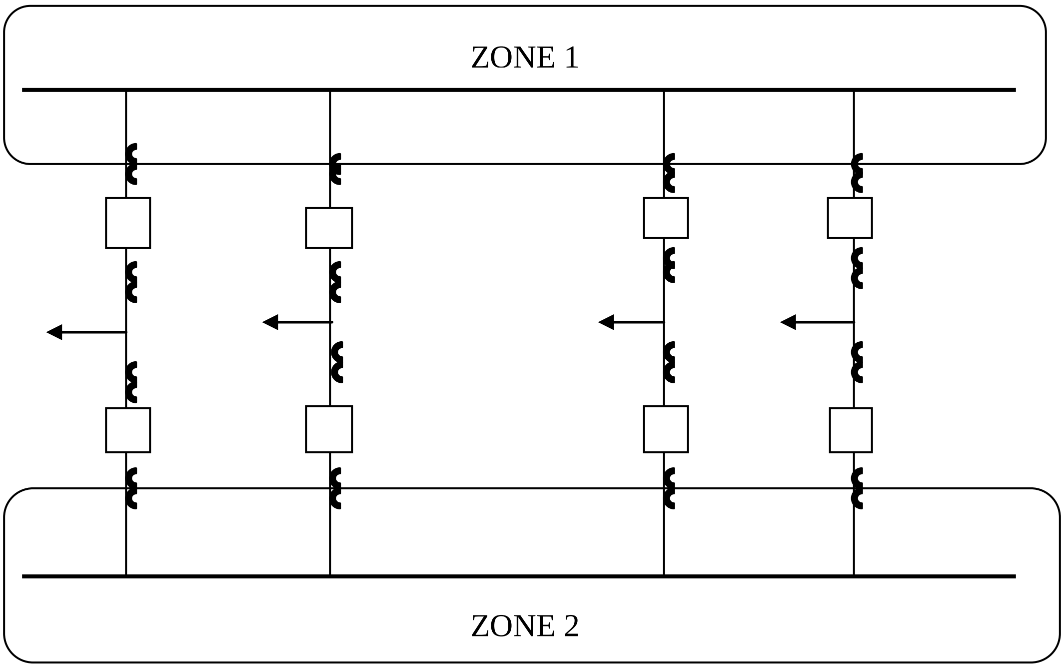


Fig.1.5. Double bus double breaker arrangement

1.3.5. One-and a Half Breaker Arrangement

This arrangement provides saving in the number of circuit breakers and is an improvement over double bus bar arrangement. This arrangement requires three circuit breakers for two circuits. It provides security against loss of supply as a fault in a bus or in a breaker will not interrupt the supply. Possibility of addition of circuits to the system is another advantage [28]. The main drawback of this arrangement is complications in relaying system because at the time of fault two breakers are to be opened.

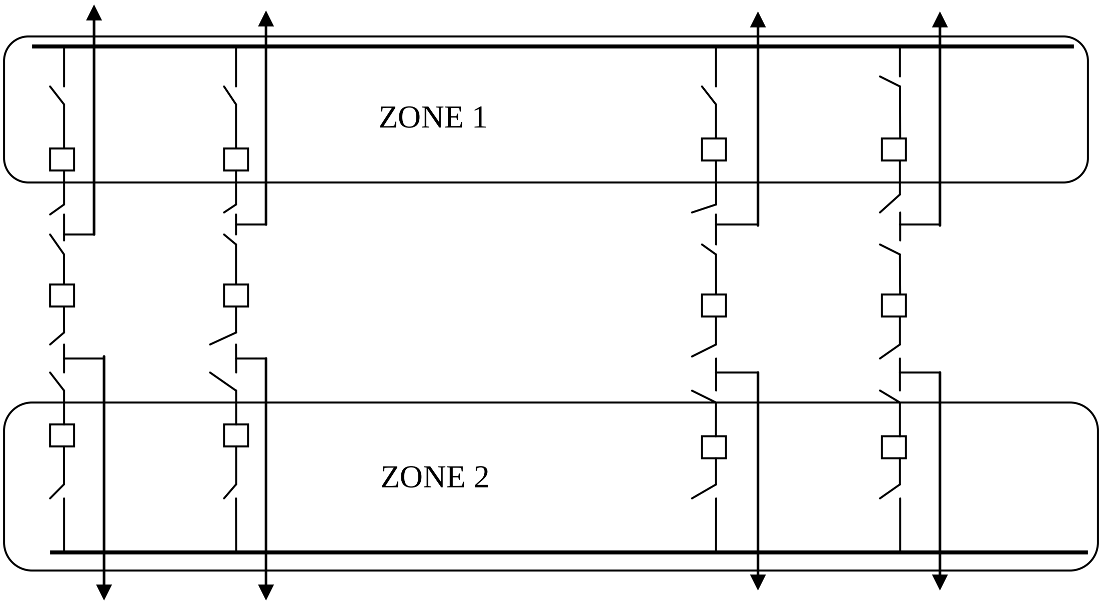


Fig.1.6. One and a half breaker arrangement

1.3.6. Ring Main Arrangement

This arrangement is an extension of the sectionalized bus bar arrangement where the ends of the bus bar are returned upon themselves to form a ring. This arrangement provides greater flexibility as each feeder is supplied by two paths so that the failure of a section does not cause any interruption of the supply [27]. The drawbacks of the system are – difficulties in addition of any new circuit in the ring, possibility of overloading of the circuit on opening of any section of the breaker and necessity of supplying potential to relays separately to each of the circuit.

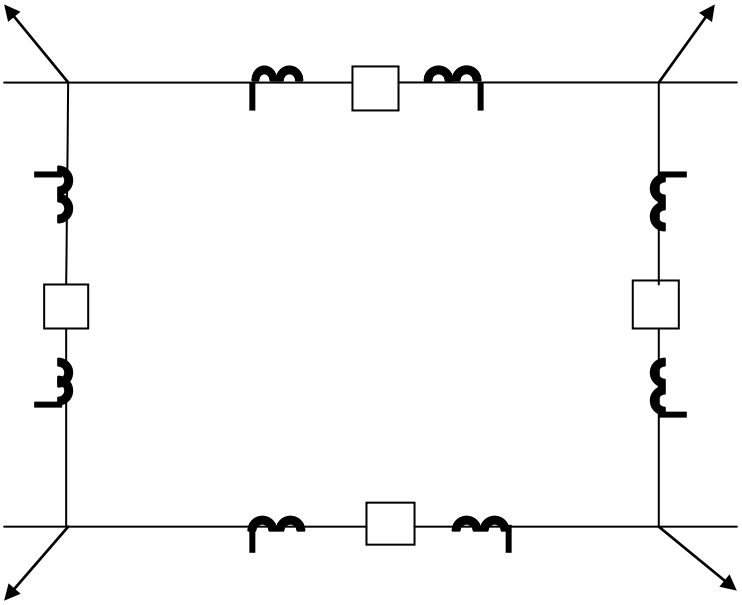


Fig.1.7. Ring main arrangement

1.4. Bus bar Faults

The prime and foremost requirement of the bus bar protection scheme is the identification of fault in a particular region and the disconnecting of breakers associated with that particular region so that the healthy section of the power system network remains unaffected. This feature of the bus bar protection scheme minimizes interruption to the plant. This justifies that discrimination on the basis of time graded relays is not a good choice and hence there is a need for unit protection scheme for the bus bar.

Bus bar protection scheme should not operate for any external or through fault otherwise it will cause unnecessarily tripping of other healthy lines connected to the bus bar. This is a very important feature of bus bar protection scheme with respect to the stability of the power system.

The following are the main causes of bus fault [27]: -

1. Insulation failure due to the deterioration of the material.
2. Flashover caused by prolonged and excessive over-voltages.
3. Failure of circuit breakers or other switchgears.
4. Human error in operating and maintaining switchgear.
5. Foreign objects falling across bus bar.
6. Contact by animals.

1.5. Bus bar Protection Scheme

1.5.1. Directional Comparison Protection Scheme

In case if it is not economical to change or add new CTs, bus fault protection is achieved by a directional comparison scheme using the existing line CTs. The principle of this scheme is that if power flow in one or more circuit is away from the bus, an external fault exists whereas an internal bus fault exists if power flow in all the circuits into the bus.

Series Trip Directional Scheme: - In this scheme all the directional relay trip contacts are connected in series [28]. In case of an internal fault the contacts close simultaneously and energize the auxiliary relay to trip both the line circuit breakers.

Directional Blocking Scheme: - In this scheme all the tripping contacts are connected in parallel and then to the tripping relay, whereas all the blocking contacts are connected in parallel and then to the blocking relay. When external fault occurs, the blocking relay operates and blocks the operation of bus protection as per requirement by opening one of its contacts, which is in series with the tripping relay.

Directional Comparison Scheme [27]**: -** The use directional blocking scheme can be avoided by the directional comparison scheme which uses a voltage restraint relay. However the main problem with this scheme is that the relay settings must be reviewed and changed whenever system changes are made near the protected bus.

Advantage: - The advantage of the directional protection scheme is that it is not affected by CT saturation as it compares the direction of the current and not the magnitude.

Disadvantage: -

1. The reliability is affected by too many series contacts also its circuitry is too complex hence it requires careful and periodic review. This scheme requires more time to provide coordination which initiates all series connected contacts of directional relays to clear a bus fault.
2. This scheme is not applicable for large cable networks where the capacitance charging current is appreciable in comparison with minimum ground fault current.
3. Sometimes, along with the directional relay, instantaneous over-current relay is used as a fault detector to identify the existence of fault which increases.

1.5.2. Differential Protection Scheme

1.5.2.1. Circulating Current Differential Protection

This scheme operates on Kirchhoff's current law that is the current entering the substation bus equals the vector sum of current leaving the substation bus. For an internal fault at bus, the differential relay operates whereas in case of external fault the differential relay does not operate and no current is fed to the relay coil [29]. The main requirement of this scheme is that the CTs should be of the same ratio. If this condition is not satisfied, then the differential relay may mal-operate particularly during heavy external through-fault.

Advantages: - The main advantage of the circulating current differential scheme is that it is a very simple type of protection scheme.

Disadvantage: -

1. This scheme requires identical CTs for all the lines connected to the bus.
2. This scheme may mal-operate in presence of a transient DC component in the fault.

1.5.2.2. Biased Percentage Differential Protection

This protection scheme is used in order to avoid mal-operation of relay due to CT saturation and transient DC current. The differential relay has two coils, namely, restraining coil and operating coil. Maximum security against external fault is obtained when all the CTs have identical CT ratio [26]. The restraining current is the average of the incoming and outgoing line currents at the bus. The differential relay operates when the differential current in the operating coil exceeds a fixed percentage of the restrain current in the restraining coil.

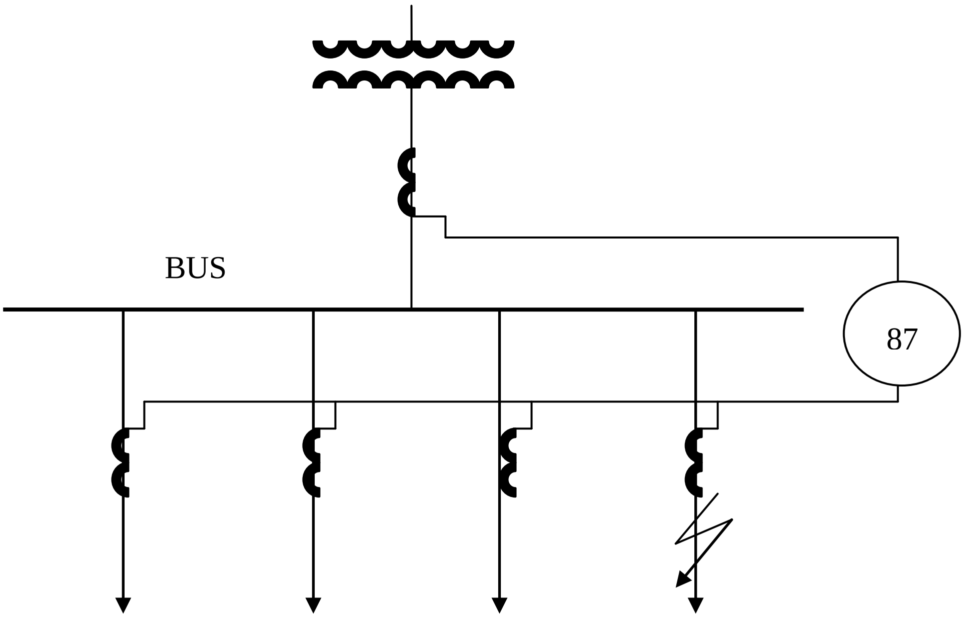


Fig.1.8. Biased percentage differential scheme

Advantages: - The main advantages of this scheme are high tolerance against substantial CT saturation, reduced requirement of dedicated CTs and its applicability where comparatively high-speed tripping is required.

Disadvantage: - The fundamental limitation of this scheme is that the relay may mal-operate in case of close-in external fault due to complete saturation of the CT.

1.5.2.3. High Impedance Voltage Differential Protection

High impedance voltage relaying scheme is used to overcome spill current due to CT saturation in case of external fault. The effect of saturation is controlled by keeping the CTs secondary and lead resistance is low and by adding resistance to the relay circuit. In this scheme full wave bridge rectifier adds substantial resistance to the circuit [28]. The series L-C circuit is tuned to 50 Hz fundamental frequency to respond only to the fundamental component of current and make the overvoltage relay immune to DC offset and harmonics. This scheme discriminates between internal and external faults through the relative magnitudes of the voltage across the differential junction points.

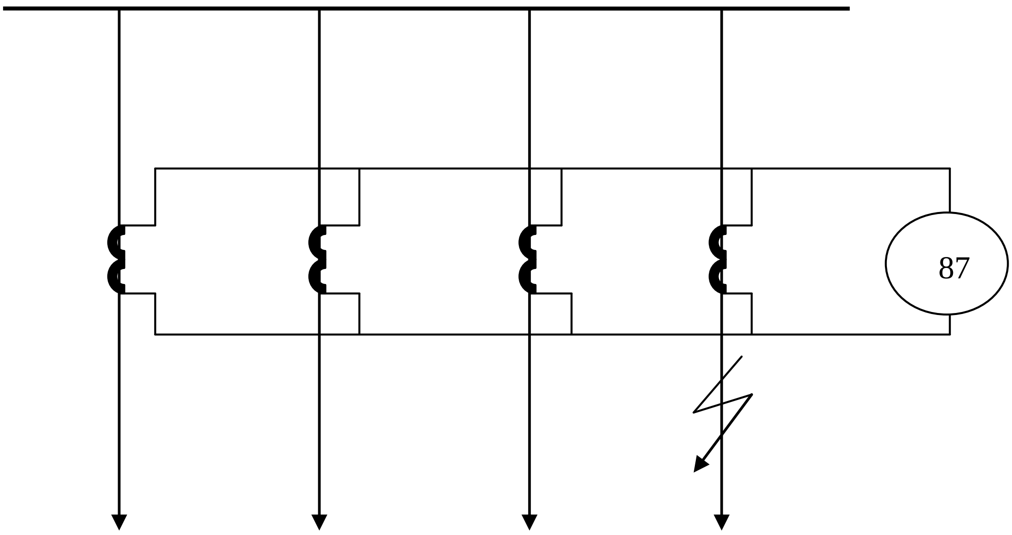


Fig.1.9. High impedance differential scheme

Advantages: - The main advantages of this scheme are- its stability against transient DC component due to the tuned circuit, improved CT saturation characteristics because of stabilizing resistors and faster operating time.

Disadvantages: - The disadvantages of this scheme are- need for dedicated CTs this increases the cost, mal-operation of relay when the secondary leakage resistance is present and inapplicability of the scheme to the reconfigurable bus bar.

1.5.2.4. Linear Coupler Protection Scheme

In case of iron core CT, the saturation is rectified using linear couplers as they use air core. The secondary of all linear couplers are connected in series. Because of the linear characteristics of the linear coupler, the output voltage of the coupler is proportional to the derivative of the input current [28]. If the voltage sum across the relay is zero, then the input current is equal to the output current at the bus. For an internal fault, all the line currents flow towards the bus and thus the induced voltage appears across the relay.

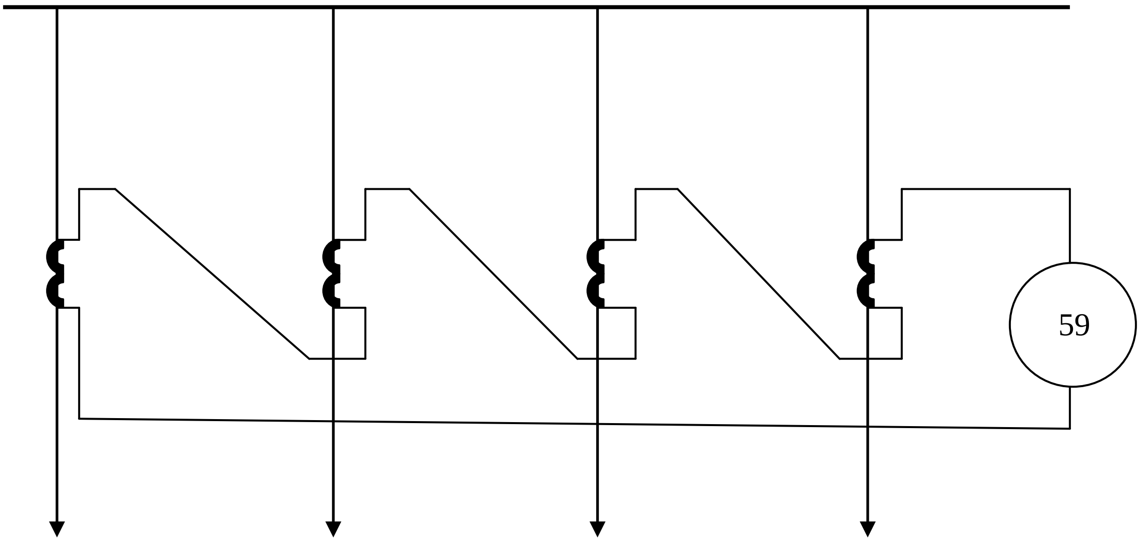


Fig.1.10. Linear coupler scheme

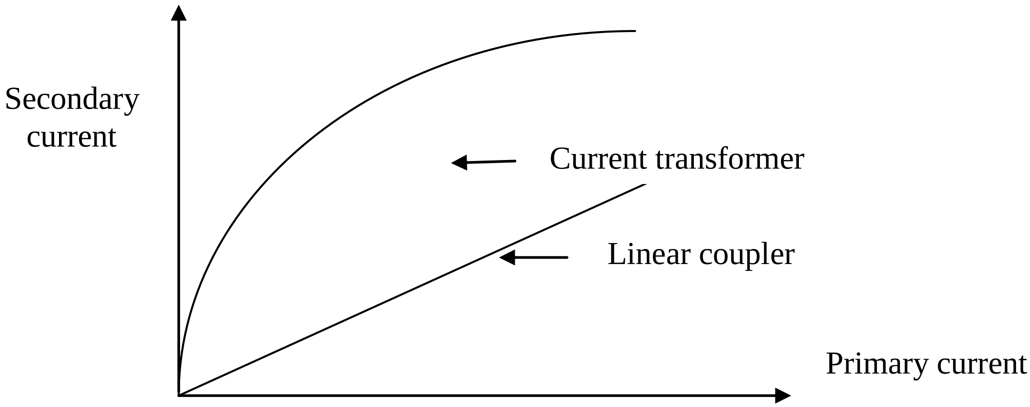


Fig.1.11. Characteristic of current transformer and linear coupler

Advantage: - A linear coupler can operate at low energy relays compared to conventional CTs.

Disadvantage: - This protection scheme needs extra equipment to realize the benefits of microprocessor-based relays which increase the overall cost of the scheme.

1.6. CT Error

There is a certain linear range of the magnetizing curve up-to which CT can be operated without any error but if the CT is operated beyond this range then error occurs and it badly effects the differential protection [28]. This is true particularly for the stabilized differential protection where the pick-up sensitivity automatically increases as the measured current increases. The situation becomes worst when CT gets saturated means the magnetizing induction increases beyond the knee point of the magnetizing curve and results in flow of large magnetizing current. This thus threatens the protection stability.

1.6.1. Equivalent circuit of CT

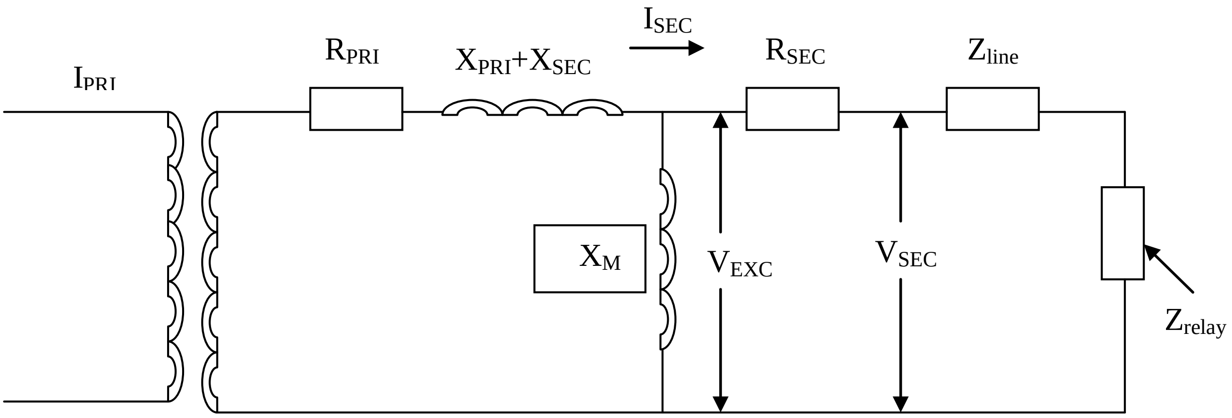


Fig1.12. Equivalent circuit diagram of CT

A simplified equivalent circuit for current transformer is shown in the Fig.1.5. Here Z_{line} and Z_{relay} represent the impedance of the line and relay respectively. I_{PRI} and I_{SEC} are respectively the primary winding current and secondary winding current with R_{PRI} and R_{SEC} as the primary and secondary winding resistances respectively. Xm is the magnetizing reactance that remains negligible during complete saturation and normally have a value of 100-10kΩ. V_{EXC} and V_{SEC} are the induced emf of the CT secondary winding and secondary voltage of the CT terminal respectively.

As the CT primary winding is always connected in series with the line so it carries the full line current. If there is a short circuit then the line current becomes too large and it also flows in the CT primary. Thus there is also an increase in secondary current.

Ideally during normal condition the primary current and secondary current are proportional to each other. To allow the current to flow in the secondary circuit, the CT must develop sufficient voltage due to this some part of the primary becomes magnetizing current and thus produces flux in the core of the current transformer. This magnetizing current normally is very small and therefore the secondary current still remains proportional to the primary current [27]. But to overcome the CT secondary voltage drop if the CT develops large voltage then core flux level becomes very high. In case if this flux exceeds the saturation level then exciting becomes large and this results in decrease in secondary current. As soon as the primary current exceeds the saturation level the core gets saturated and secondary current is distorted. It is therefore important to detect the CT saturation and block the operation of the relay whenever necessary.

1.6.2. Current Transformer Vector Diagram

Errors in current transformer mainly arise when the burden is shunted by the exciting impedance [29]. This thus takes some portion of the input current to excite the core which then results in reduction of the amount of current that may otherwise be passed to the burden.

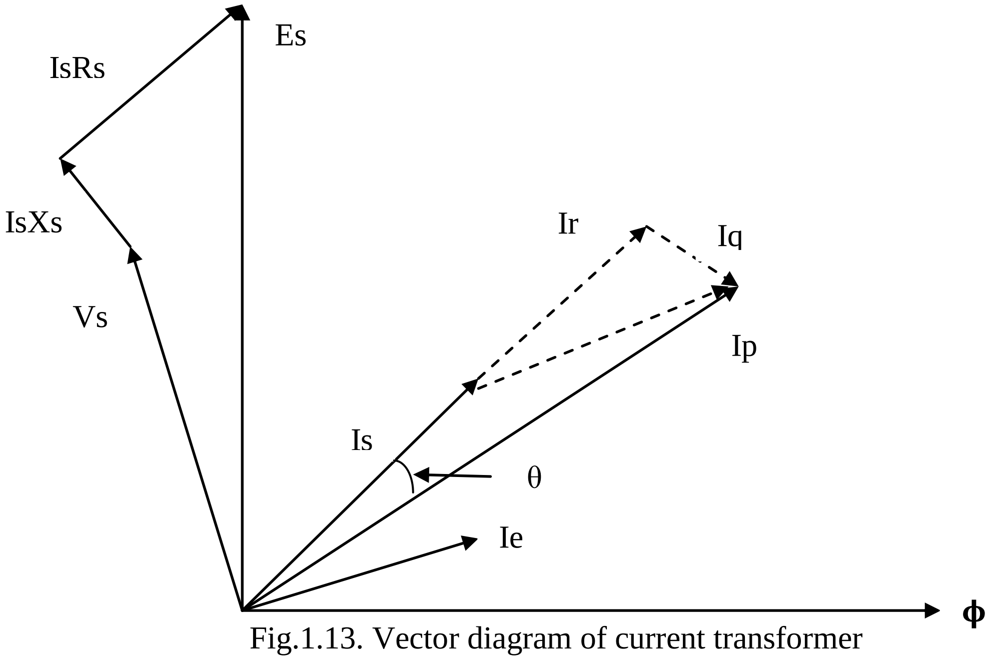


Fig.1.13. Vector diagram of current transformer

Where Es = Secondary induced emf

Vs = Secondary voltage output

Ip = Primary current

Is = Secondary current

θ = Phase angle error

ϕ = Flux

IsRs = Secondary resistance voltage drop

IsXs = Secondary reactance voltage drop

Ie = Exciting current

Ir = Component of Ie in phase with Is

Is = Component of Ie in quadrature with Is

From figure it is clear that Is= Ie – Ip and Ie depends upon Ze and Es i.e. it depends upon exciting impedance and secondary e.m.f. so it can be represented as: -

$$Es = Is\ (Zs + Zb) \tag{1.1}$$

Here Zb is the represents burden impedance and Zs secondary winding self-impedance.

1.6.3. CT Secondary Current Rating

Secondary current rating of the current transformer is decieded on the basis of burden on the secondary winding and also by the standard practices followed by the user. 5A and 1A are the standard secondary current rating for the current transformer. The burden that is imposed at rated current by the numerical or digital relay is normally independent of rated value of the current [29]. It is because at rated current the winding of the device develops a given number of ampere-turns in order to make the actual number of turns and current to be inversely proportional to each other and thus the winding impedance becomes inversely proportional to the square of the current rating. But static or electromechanical earth fault relays may have a secondary burden that varies according to the current tapping used.

With a 5A CT the burden of the CT lead would be 75VA to which a relay burden of about 1VA for numerical relay and 10VA for electromechanical relay must be added to make a total burden of 85VA. Such a burden would demand for large and expensive CT.

With a CT secondary rating of 1A the CT lead burden get reduced to about 3VA so that with the addition of same burden of numerical as well as electromechanical relay the total burden add up to maximum of 13VA. This burden thus do not require large CT as it can be easily provided by the normal CT dimensions and results in saving in weight, size and cost [26]. Thus modern CTs normally have 1A as secondary winding rating. However if the primary rating is high then a CT with higher secondary current can be used so as to limit the number of secondary turns. For such cases a secondary rating of about 2A, 5A or even 20A for extreme cases may be used.

1.6.4. Rated Short-Time Current of CT

When the short circuit current flows in the system the CT becomes overloaded and will be short-time rated. Usually for a standard time of 0.25, 0.5, 1.0, 2.0 or 3.0 seconds the CT is capable to carry the rated short time current. For a particular time rating CT will carry a lower current which is inversely proportional to the square of the ratio of the current values for a longer time [29]. However it is not convenient to assume its converse the current values that are greater than the short time current value (S.T.C) are not permissible.

1.6.5 Causes of CT Saturation

CT saturation depends upon following factors: -

1. Core cross-sectional area
2. Level of DC offset in the current
3. CT ratio
4. Connected burden
5. Core material
6. Level of remanent flux

Saturation occurs due to dc component of the fault current. The effect of CT saturation is shown by following waveform [28]: -

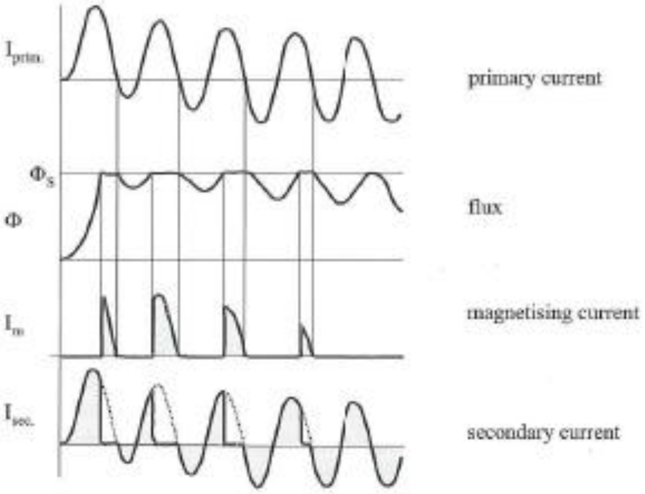


Fig.1.14. Transient CT saturation

When the flux is required in negative sense then the primary current is transformed again. A sequence of unsaturated and saturated interval occurs. With the decay of the dc component there is an increase in the unsaturated interval until there is no further CT saturation. A small saturation can be accommodated by stabilizing that causes a very small error current. But special measures like saturation detector with transient blocking are required for severe saturation so as to avoid unwanted tripping.

1.6.6. Reduction of DC Component of the Current

The secondary time constant with closed iron CT amounts to several seconds. Thus it becomes easy to correctly transform the dc component of the fault current. The secondary time constant linearized core CT is very small about 60ms. Therefore the dc component of the fault current quickly gets damped and even swings to a negative value [28].

The decay time constant of the dc component is determined by L/R ratio which plays an important role in the selection of protective relaying. This time constant is different for different circuits. For lines the value of L/R ratio is 0.01 sec whereas for generating plants its value is 0.3 sec. Thus to reduce the dc component proper selection of L/R ratio (i.e. proper time constant) is necessary.

The following criteria must be satisfied by the minimum time to saturation: -

1. The protection stability is ensured during the external fault if CT transforms the through fault current till the fault switches off. Thus the relevant time in this case

is a combination of operating time of the circuit breaker and the protection. This time for EHV level is approximately 100 ms.

2. During internal faults to comply with the measurement process within the protection it is required to have a minimum saturation free time.

1.6.7. Practical Conditions for CT

Following are some of the reasons due to which the practical conditions for CT differ from that of the theory [29]: -

1. No consideration for iron losses. This thus reduces the secondary time constant the equivalent resistance remains variable and depends upon both the exponential and sine terms. It is not possible to include it in any linear theory and is also very complicated to evolve satisfactory treatment.
2. Burden inductance or secondary leakage has not been taken into account. Effect of burden reactance on maximum transient flux is very small because the value of this burden reactance is smaller than the Le (exciting inductance).
3. As the theory is totally derived from the linear excitation characteristic hence it is true approximately only up-to the excitation curve knee-point [28]. To allow non-linearity a precise solution is not applicable. Large number of solutions has been obtained due to the replacement of excitation curve with the number of chords. Hence for each chord a linear analysis can be made.

The mean flux is build up by the d.c. or asymmetric component of the current over a period that corresponds to several cycles of the sinusoidal component while a high flux swing is produced by the latter component about the mean level that is set by the former component. When the total asymmetric current and exciting current becomes equal there is no increase in the asymmetric flux because after this point the voltage drop and the output current of the burden resistance becomes negative. Due to saturation the point at which the asymmetric current and exciting current becomes equal occurs when the flux level becomes lower than the expected value obtained by the theory.

When the CT is saturated by the exponential component of the current then there is a decrease in the magnetizing inductance and the alternating component thus increases to a large value.

During transient period the exciting current is as shown below [29]: -

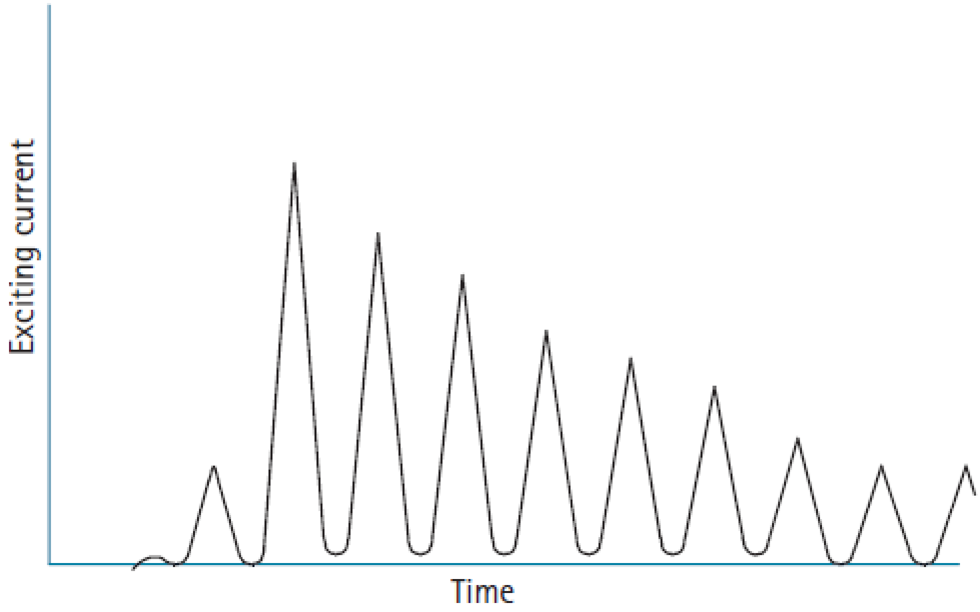


Fig.1.15. Exciting current of CT during transient asymmetric input current

Due to saturation the secondary current is distorted. This distorted CT current is shown below [29]: -

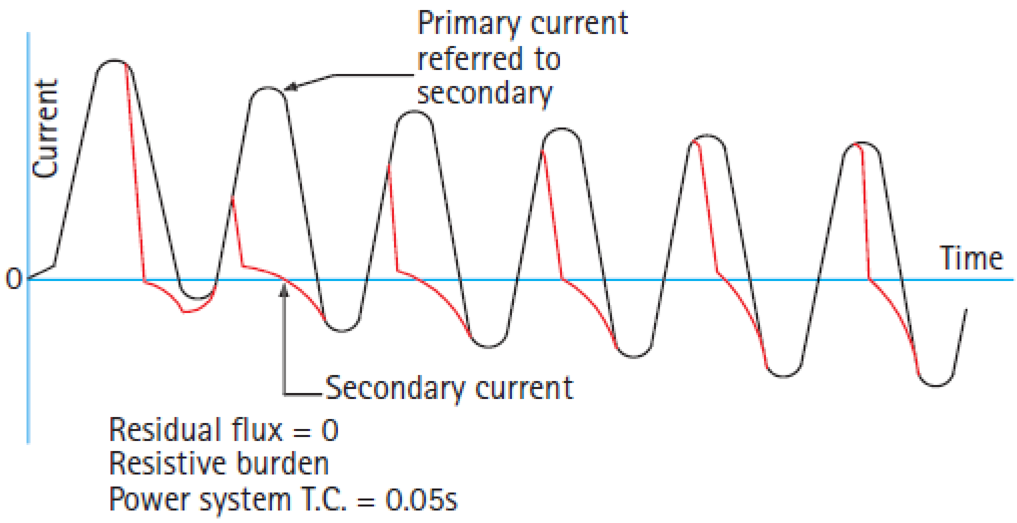


Fig.1.16. CT secondary current distortion due to saturation

The starting point of the transient flux excursion varies on the excitation characteristic due to the presence of residual flux. Remanence that is of same polarity as that of the transient will reduce the symmetric current value of a given time constant that can be transformed by the CT without any saturation. Whereas the remanence with reverse polarity will largely increase the CT ability to transform the transient current.

If in the analysis a linear non-saturable CT is considered then it is possible to transform the sine current without any loss in accuracy. The transformation of centre of the flux swing to any other point on the excitation curve causes the exciting inductance to vary this then cause an error that can be too large [27]. The effect of this is very small in case of measurements but the effect is very large for the protection equipments that are required to operate properly during condition of fault. During transient saturation the output current gets reduced that prevents the relay to operate if the conditions are close to the relay settings. But this should not be misunderstood by the increase in the primary current r.m.s. value due to the presence of asymmetric current that offsets an increase in the ratio current. When there is a through fault then the CT error from several CTs will differ and causes an unwanted operation.

1.7. Summary

This chapter has described briefly about the idea of power system protection. The bus bar protection concepts and need for protection of bus bar is also covered. Various types of bus bar arrangement and protection schemes have also been discussed. A brief idea about current transformer, condition for CT saturation and error arising due to saturation are also covered in this chapter.

CHAPTER 2

LITERATURE REVIEW

YC Kang.et.al. (2005) in their paper [1] “A Bus bar Differential Protection Relay Immune to CT Saturation” implemented a bus bar protection technique based on differential protection relay scheme operating in conjunction with a CT saturation detection algorithm. The detection algorithm detects the start and end of each saturation period based on the third difference function of the current. Test result indicates that the relay can discriminate between internal and external faults even when CT is severely saturated.

Mohindar S.Sachdev.et.at (2000) in their paper [2] “A Bus bar Protection Technique and Its Performance during CT Saturation and CT Ratio Mismatch” implemented a digital technique for bus bar protection. The protection schemes make use of positive and negative sequence models of the power system in a fault detection algorithm. Data for testing the proposed technique was generated by modeling the system using transient simulation software EMTDC. Technique is stable during CT saturation and is not affected by CT ratio mismatch.

Bhavesh Bhalja.et.al. (2011) in their paper [3] “A New Differential Protection Scheme for Bus bar Considering CT Saturation” proposed a bus bar protection technique based on differential relaying scheme. The proposed scheme has been tested extensively using PSCAD/EMTDC software package. This scheme provides stability against external faults and is more sensitive towards high resistive faults. This scheme also find effective to avoid the effects of early and severe CT saturation.

M.M.Eissa (2005) in his paper [4] “High Speed Differential Bus bar Protection Using Wavelet-Packet Transform” proposed a bus bar protection based on Wavelet- packet Transform method .ATP simulations are used to test and validate the proposed technique for model power system faults. It is found that the technique is stable during CT saturation and is not affected by CT error and ratio mismatch and technique is also sensitive in event of high fault resistance.

Guibin Zou and Houlei (2012) in their paper [5] “A Travelling-Wave-Based Amplitude Integral Bus bar Protection Technique” proposed a protection technique for bus bar according to the propagation theory of travelling wave. When fault occurs on the bus bar detected initial travelling waves on the connected lines will come from their back which is defined as positive direction travelling wave. When a fault occurs on any one of these lines, the detected internal travelling waves on healthy lines are positive direction travelling waves however travelling wave direction on the faulted line is negative. Thus a criterion discriminating fault direction can be established according to the amplitude integral relationship between positive direction travelling wave and negative direction travelling wave. Simulation results show that the proposed method can discriminate between internal and external faults and the protection performance are immune to fault resistances, fault inception angles, fault types and CT saturation.

Z.Chen.et.al (2004) in their paper [6] “Integrated Line and Bus bar Protection Scheme Based on Wavelet Analysis of Fault Generated Transient Current Signals” proposed a technique that is directional relaying which integrates the power line protection with the bus bar protection together. In this technique the relay installed at the bus bar is responsible for the detection of fault direction with respect to the bus bar. The transient signals captured from the CTs related to the power line connected to the bus bar are processed with a wavelet technique to determine the fault direction. The technique relies on the detection of fault generated high frequency current transient signals and wavelet technique signal processing method. Simulation results show that the scheme is insensitive to fault location and its type, fault path resistance and fault inception angle.

Gang Wang.et.al (2004) in their paper [7] “A New Numerical Distributed Bus bar Protection” proposed a new numerical protection for bus bar. The proposed protection employs a protection technique based upon the polarities of transient current waves for identifying internal and external bus fault. In this technique polarities of the transient current can be extracted using wavelet transform modulus maximum. The communication scheme of protection signal buses combined with Ethernet LAN is presented and implemented for the protection of distributed bus bar system.

S.H.Haggag.et.al. (2012) in their paper [8] “A Novel Measurement Technique for Extra High Voltage Bus bar Fault Detection” introduces a new for fault detection tool of Extra High Voltage (EHV) bus bar. This new tool is to be used by the extra high voltage digital relays to detect bus bar faults besides differentiating between close up line faults and bus bar faults. This tool uses a new technique that squares both of the instantaneous voltage signal and its complement to produce the unity relation in normal operating conditions and this unity relation remains undistorted as long as the power system is operationg normally however if there is a sudden change in voltage signals due to any abnormal conditions then this unity relation is distorted. This tool is proved to be fast, accurate and easily implementable within a digital relaying scheme.

S.M.Elbana.et.al. (2011) in their paper [9] “An Artificial Intelligence Based Approach for Bus bar Differential Protection Faults Analysis in Distributed Systems.” presented a new Fuzzy Interface System (FIS) technique along with Artificial Neural Network (ANN) is proposed. The objective of this paper is to detect the occurrence of fault on the bus bar and locating the fault accordingly. The proposed approach demonstrates successful performance for performing the two main tasks i.e. fault detection task and fault location task using Adaptive Neuro Fuzzy Interface System (ANFIS) technique. The reliability of this proposed technique is tested in varying system conditions with respect to fault type , inception instant, resistance and pre-fault conditions. The phasor concept is used to overcome the CT saturation and ratio mismatch.

P.Jena and A.K.Pradhan (2008) in their paper [10] “Bus bar Protection- A Solution to CT Saturation” proposed a bus bar protection technique based on phase change in positive sequence current of incoming and outgoing line current transformers is proposed. The angle difference of during fault and pre-fault current signals of incoming and outgoing CTs are the indicators of external or internal faults for bus bar protection. The advantage of this method is that it does not use magnitude information of the current and thus overcomes the CT saturation issues. The performance of the technique was investigated for varying operating conditions for CT saturation, ratio mismatch and different fault inception angles, for different types of faults and for several bus bar configurations.

N.Perera.et.al (2011) in their paper [11] “Wavelet Based Transient Directional Method for Bus bar Protection” analyzed a transient based fault direction identification method for bus bar protection. In this method wavelet transform is used to extract the traveling wave front originating from a fault. By comparing the polarity of the wave fronts bus bar zone faults are identified. Electromagnetic Transient Type (EMT) simulation program is used to simulate or implement the proposed protection scheme. This wavelet based technique is then further compared with conventional differential protection scheme. Effect of CT saturation, CT ratio-mismatch and fault impedance were also investigated. Result shows that this technique is capable of providing fast bus bar protection.

M.R.Aghaebrahimi and H.Khorshadi Zadeh (2008) in their paper [12] “Fuzzy Neuro Approach to Bus bar Protection; Design and Implementation” has presented a new approach for bus bar protection using Fuzzy neuro and symmetrical component theory which provides stable operation even in case of severe CT saturation. Digital signal processor board is used to implement this fuzzy based technique and data generated in EMTDC simulation is used to investigate the proposed technique under varying system considerations. This technique also provides capability to relay to discriminate between internal and external fault. Results obtained from the performance of this technique proved that this technique provides fast and accurate protection.

He Jiali.et.al. (1997) in their paper [13] “Implementation Of a Distributed Digital Bus Protection System” has presented a distributed feature of bus protection and also focuses on the design features , hardware structure , data communication network protection and protection algorithm of protection system. Experimental result shows that this principle is feasible and possesses distinguishing advantages over traditional centralized principle. It is also possible to prevent series blackout of the whole bus system due to mis-operation of protection and hence improves the reliability of the system.

K.Brewis.et.al. (2001) in their paper [14] “Theory and practical performance of interlocked over-current bus bar zone protection in the distribution substation” discussed about the protection theory and application issues that are to be considered for the design of bus bar protection schemes utilizing the instantaneous current elements contained in numeric over-current relays and in-service performance is also reported. Implementation of blocking scheme in this paper helps to eliminate the disconnection of whole system due to extensive damage that results from inherent, relatively slow, over current clearance time for a bus bar fault. Blocking scheme also provides improvement in back-up protection in case of failure of an outgoing feeder relay or trip circuit failure or a stuck circuit breaker. Analysis shows that this scheme is cost-effective means of installing discriminative phase and earth fault protection of primary substation bus bars.

Cheng Li-jun (2004) in his paper [15] “The Research of the Sampling Method for CT Saturation for Numerical Bus bar Protection” focuses on the problems caused by CT saturation in bus bar protection. To overcome the problem of CT saturation the author in this paper proposed two methods that are, the synchronizing identification method and the phase current comparison method. These two methods employed for CT saturation checking have been successfully used in the numerical bus bar protections serving in China EHV/HV power systems.

J D Duan.et.al. (2004) in their paper [16] “A Novel Distributed Bus Protection Based On Travelling-Wave Power Directions and Wavelet Transformation” proposes a wavelet-transform based algorithm using the traveling wave-directions of transmission lines connected to the bus for providing bus protection. EMTP simulation is used to verify the proposed technique. Simulation results show that it is not affected by adverse effect of CT saturation due to use of faulty information of travelling waves. This scheme also distinguishes well between internal and external bus faults. Its performance is also checked under the influence of various conditions such as fault type, fault resistance etc and proves to be reliable. Also the distributed architecture used in this technique is more economical and convenient then the existing bus architecture.

Shiyong Wang.et.al. (2009) in their paper [17] “A Novel Bus bar Protection Scheme Based on Wavelet Multi-Resolution Signal Decomposition” proposed a bus bar protection scheme based on wavelet transform. This bus bar protection scheme utilizes the characteristics of multi-resolution signal decomposition of wavelet transform to decompose the fault current signals into different frequency bands. This protection scheme utilizes high frequency currents along with power frequency currents as high frequency currents enables the bus bar protection to operate fast and power frequency currents can improve the reliability of protection system. Alternative Transients Program

(ATP) simulations are used to test and validate the proposed scheme. The test results indicate that the technique is stable during CT saturation and insensitive to fault path resistance, fault inception angle and fault type. The scheme is simple, fast, reliable and stable under various system conditions.

P Fitzgerald.et.al. (2001) in their paper [18] " A New Directional Relay For Distribution Network Protection Using Transient Comparison Technique" presented a new protection technique for the protection of distribution system networks in which the proposed relays are installed at each substation bus bar of a distribution network and are responsible for the detection of fault direction relative to the bus bar. The relay contains transient detection and comparison unit and is interfaced to the CTs of each incoming and outgoing lines from that bus bar. Real Time Digital Simulator (RTDS) is used to carry out simulation studies with respect to real distribution system network. Simulation studies shows that the scheme is insensitive to type, position and inception angle of fault.

R.Hughes and E.Legrand (2001) in their paper [19] "Numerical Bus bar Protection Benefits of Numerical Technology in Electrical Substation" discussed about several numerical techniques that can be employed for bus bar protection along with their advantages over non-numeric conventional system. Simulation studies were carried out for providing compensation both average modulus and average phase angle compensation considering the number of iterations to achieve the precision requirement according to the number of feeders and the initial error. Real time analysis of simulation ensures that the network operates has greater freedom to operate the system as needed rather than be confined by the design and operational requirement of the protection system.

Z Chen.et.al. (2000) in their paper [20] "Wavelet Transform Based Accurate Fault Location and Protection Techniques for Cable Circuits" presented a new fault location technique applicable to power cable circuits. The proposed fault locator consists of transient detection device installed at the bus bar to detect high frequency voltage transient signals. The wavelet transform is used as a filter bank to decompose the fault signals. Simulation studies were carried out using EMTP software. The simulation studies show that the wavelet transform is very effective to extract the transient components from the complicated fault signals. The proposed scheme is also insensitive to fault type and inception angle of fault and system source configuration.

H.Dashti.et.al (2007) in their paper [21] “Current Transformer Saturation Detectors for Bus bar Differential Protection” presented two different techniques to detect CT saturation. The first technique is based on the fact that the wave shape of CT secondary current is changed significantly at the instant of saturation. Based on this technique an algorithm which uses second derivative of CT output current is developed. The second technique utilizes the principle of zero. It also compares the predicted and measured of the current signal at the time of zero crossing. Simulation studies were carried out PSCAD/EMTDC software package. Simulation results shows that the first algorithm is faster as compared to second one but the zero crossing technique is more stable when extreme saturation occurs in first of third of the cycle. Therefore the combination of both techniques is the best choice.

Lei Liu.et.al. (2009) in their paper [22] “ Simulation Of Electromagnetic Transients Of The Bus bar In Substation By the Time-Domain Finite-Element Method” analyzed the electromagnetic interference (EMI) generated from the aerial bus bars in substation by calculating the transient electromagnetic wave process on the bus bars using the time-domain finite-element (TDFE) method. The feasibility and efficiency of the proposed TDFE method have been demonstrated by comparing the numerical results with experimental measurements. Results show that the proposed TDFE method can effectively suppress the instability caused by the finite-difference time-domain (FDTD) method. This TDFE method can be used to calculate the whole wave processes of the voltage and current along the multiconductor transmission lines (MTL) which is not possible by using EMTP software.

H.Watanabe.et.al. (2001) in their paper [23] “An Enhanced Decentralized Numerical Bus bar Protection Relay Utilizing Instantaneous Current Values from High Speed Sampling” focuses on decentralized bus bar protection by adopting instantaneous current values technique for varying system conditions. The authors have also shared their experience in the field of numerical bus bar protection followed by the details of the configuration of the new system. The proposed decentralized bus bar protection relay has a CT saturation countermeasure element (CTSCE) to prevent CT saturation which may be sufficient infringe upon the operating zone of the percentage characteristics and cause mal-operation of the relay. This technique results in enhanced performance, high reliability and total cost saving capability.

Onita Calota (2012) in his paper [24] “Behaviour of Bus bar Differential Protection under Transient Conditions” presented main aspects related to the bus bar protection in connection to the behaviour of current transformer under transient conditions. The transient performance of the transformer was studied using the modeling technique and based on the results of this study it is possible to make right choice of transformer to have acceptable errors. Analysis has been done regarding the behaviour of the CT saturation and the bus bar protection during transient conditions.

Bogdan Kasztenny.et.al. (2001) in their paper [25] “Digital Low-Impedance Bus Differential protection With Reduced Requirements for CTs” presents a new algorithm for the protection of bus bars using microprocessor based low impedance bus bar relay. The proposed technique combines percentage differential and current differential protection principles for increased security. For fast operation the proposed approach uses an adaptive trip logic that shifts between the 2-of-of-2 operating mode and the differential principle alone depending on a detection of CT saturation. Initial verification of the algorithm has been performed using Real Time Digital Simulator (RTDS) generated waveforms and MATLAB simulations. Simulation results shows that the proposed technique is immune to CT saturation and is extremely secure and fast.

CHAPTER 3

PRESENT WORK

3.1. Numerical Bus Bar Protection

For bus bar protection usually static technology is used so far but with the application of numerical relay the numerical technology is now readily available [7]. The recent developments in the numerical technology are:-

1. Capability to tolerate fault by providing multiple communication paths against loss of a particular link.
2. This technology provides a mean to link the various units involved in the system by the extensive use of a data bus.

As the requirement for the bus bar protection in respect of immunity to mal-operation is very high so it has made the development process very rigorous. The principle adopted is the distributed processing of measured value which is explained as below through a block diagram.

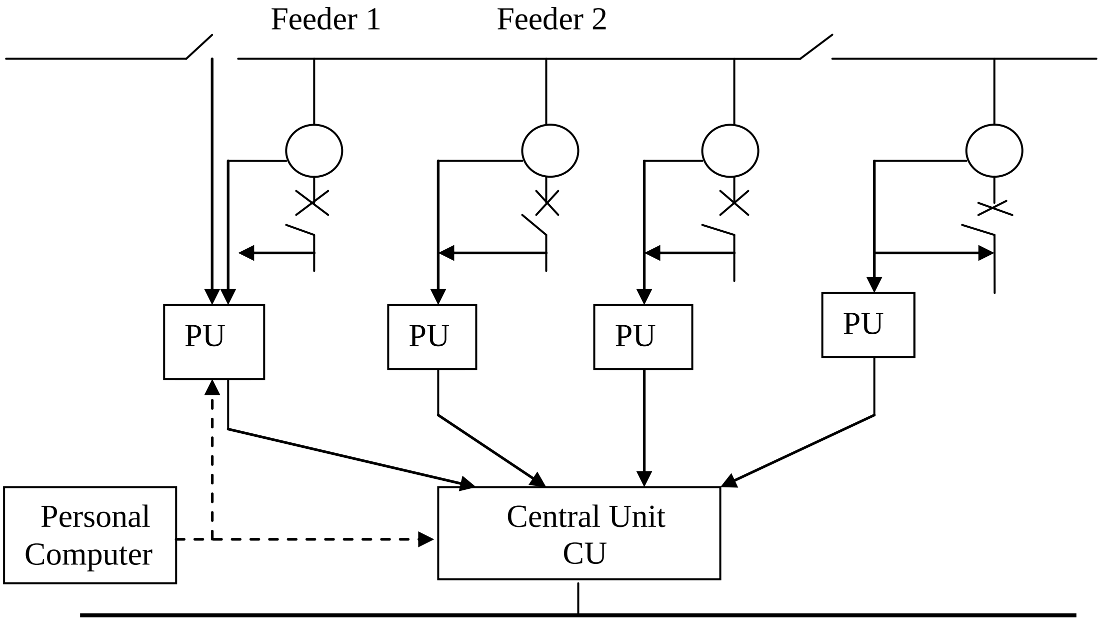


Fig.3.1. Block Diagram of Numerical Protection Scheme

As shown in the figure each feeder have their own processing unit through which they collect information on the state of feeder (voltages, current, isolator status and circuit breaker etc.) and then communicates this collected information to the central unit by means of high-speed fiber-optic data links. More than one central unit can be used for large substation abut for small substation all the units can be co-located which provides a traditional centralized architecture. Interface units at a bay may be used for simple feeders along with the data transmitted to a single centrally located peripheral unit. The function of the central unit is to perform the necessary calculations required for the protection. The available important functions are:-

1. Breaker failure protection.
2. Backup over-current protection.
3. Dead zone protection.
4. Protection.

In addition to above protection functions some monitoring functions have also to be performed which includes:-

1. Transformer supervision.
2. Circuit breaker monitoring.
3. Monitoring of isolators.
4. Disturbance recording.

In distributed topology it becomes very important to synchronize the measurements taken by the peripheral units [13]. Keeping this in view a numerically controlled oscillator which has high reliability is fitted to each peripheral as well as central unit and is time synchronized with each other. Eventually if there is a sudden loss of synchronizing signal then it is possible to continue the processing of incoming data with the help of highly stable oscillator connected to the affected feeder unit or units without any significant error until the synchronization is restored again.

It is the responsibility of the peripheral units to collect the required data like currents and voltages and then process it in the digital form to further transmit it to the central unit. To eliminate the errors that are caused by CT saturation, modeling of CT response is also included. With the improvement in processing power the differential protection algorithm has become more sophisticated. Difference between successive current samples can easily be evaluated with this scheme along with the calculation of the sum of the measured values and if this difference exceeds the threshold then it indicates a faulty condition. Hence it is important to choose a threshold such that if the normal load condition changes apart from the inrush condition than it should not exceed the threshold value in any case. It is easy to reconfigure the protection with the help of numerical technology to cater for the changes in the substation configuration which is one of the great advantages of numerical technology. For example if an extra feeder is added then it is important to also add an extra peripheral unit and fiber-optic connection to the central unit to this feeder.

3.2. Numerical Protection Reliability

The major concern associated with the introduction of numerical protection technique is the reliability which includes both security and availability. The most popular protection scheme for bus bar protection is the conventional high impedance schemes. Very few components are there in the basic measuring element which is very simple in concept. The performance of the protection scheme and the calculation of the stability limits and other parameters can easily be predicted without the need of costly testing.

The comparative study related to the reliability of the numerical scheme and conventional high speed schemes shows that it is not simple to assess the relative reliability as it might appear. The main advantages of numerical technique are [29]: -

1. Numerical techniques provides monitoring feature such as alarm feature in case the scheme is faulty. In some cases it is possible to perform the online simulation of scheme function from the CT inputs to the tripping outputs. This makes easy to check the scheme function regularly to ensure the availability of full operational mode at all the time.
2. The use of numerical scheme has greatly reduced the number of external circuits such as switching and other auxiliary relay components because the function of these components can be internally performed within the software algorithm automatically.

To examine the issues related to the security (ex. the ability not to cause unnecessary or indiscriminate operation) and dependability (i.e. the ability to operate when desired) various reliability analyses have been performed using fault tree analysis method. The conclusion obtained by these analyses is as follows:-

1. Security of conventional high impedance schemes and numerical schemes are comparable.
2. It is also observed that dependability of numerical scheme is far better than conventional high impedance scheme.

In-built monitoring system is an additional advantage of numerical technique because of which the potential availability of numerical technology as compared has improved considerably as compared to the conventional high impedance scheme as it is possible to detect the fault within the equipment itself and generate the alarm through this numerical scheme which is not possible with the conventional scheme.

3.3. General Advantages of Numerical Technology

1. Devices can be operated from remote and locally with a PC through serial interface.
2. Apart from the protection functions it is possible to execute the additional task such as disturbance recording and operational measurement with the help of numerical relay. Also modern numerical relays are multi-functional.
3. Since all the measured values that are important are directly indicated with the integrated measuring function so normally the external measuring instruments are not required during commissioning and testing.
4. Due to event driven maintenance, integrated self-monitoring, instead of costly preventive routine maintenance may be applied.

Particular advantages for differential protection: -

1. Continuous self-monitoring covers all the communication links.
2. In case of conventional devices to adapt the different CT ratios and transformer vector group there is a need of additional matching transformers. However this adaption is implemented internally by computation through numerical relay.
3. Significant reduction in complexity is achieved by the decentralised construction of the bus bar protection with communication through fibre optic cables and PC based configuration.
4. With modern efforts it is possible to implement phase segregated measurements because of which same pick-up sensitivity can be achieved for all types of faults and in the event of multiple faults reliable pick-up can also be achieved easily.
5. The in-rush stabilisation and intelligent measuring algorithm of filters have greatly been improved by the digital measuring techniques that provide additional stabilization during CT saturation.

3.4. Restrained Differential Protection

The differential protection scheme compares the measured values with respect to magnitude and phase. This is done by direct comparison of instantaneous values or by vector i.e. phases comparison. Kirchhoff's law is used in each case which states that the vector or geometric sum of currents entering or leaving the node must add up to zero at any time and point. The convention most commonly followed is that the current flowing into the protected zone are positive while the currents leaving the protected zone are taken as negative.

3.5. Current Differential Principle

This can be explained by the following figures –

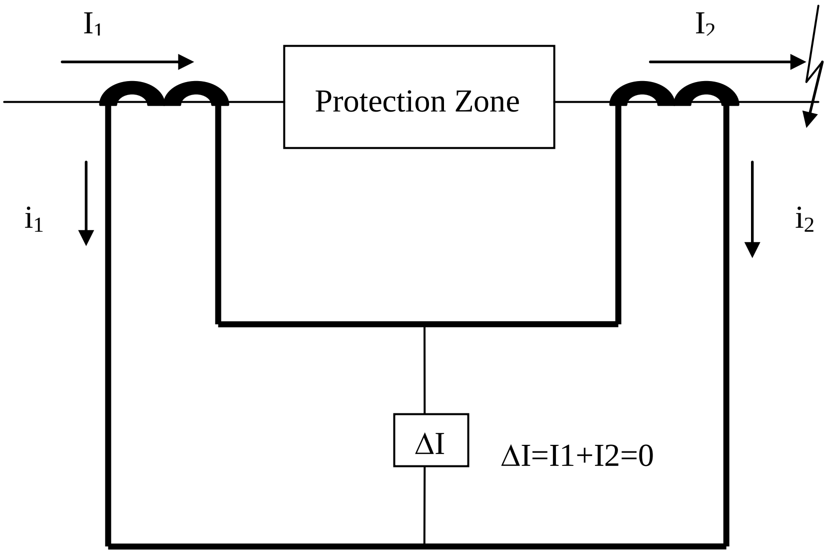


Fig.3.2. (a) External fault

The current transformer in the differential protection zone are connected in series on secondary side so that the current circulate through the current transformers during an external fault as shown in figure 3.2 (a) and no current flows through the differential measuring branch where the differential relay is situated [3].

In the event of the internal fault the fault current flows towards the fault location so that the secondary current add up and flow through the differential branch. The differential relay picks up and initiates tripping.

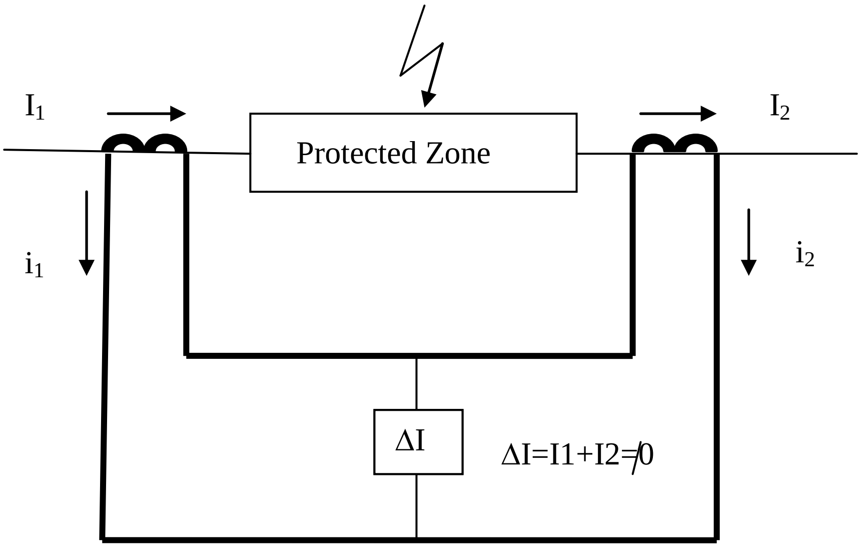


Fig.3.2. (b) Internal fault

For bus bar protection the current from the number of feeders must be summated as shown below in the figure: -

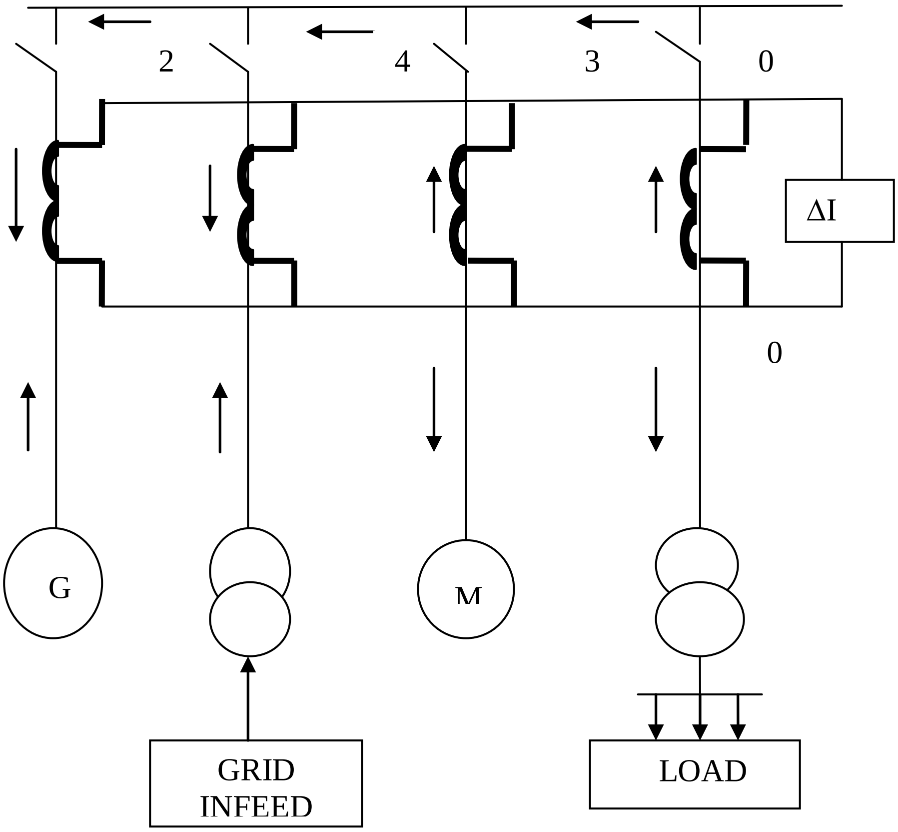


Fig.3.3. Bus bar protection load or through fault condition

The vector sum of feeder current for load and external fault is equal to zero and hence no differential current flows in the relay. However during internal fault the vector sum of feeder current does not becomes zero and this then add up to a large differential current that flows through the relay.

3.6. Biased Differential Protection

In differential protection also called as unbiased differential protection only operating coil is used through which differential current flows and trip decision is made accordingly. But in restrained differential protection also known as biased differential protection restraining coil is used through which restraint current flows also along with operating coil. The trip signal is initiated if the differential current exceeds the restraint current.

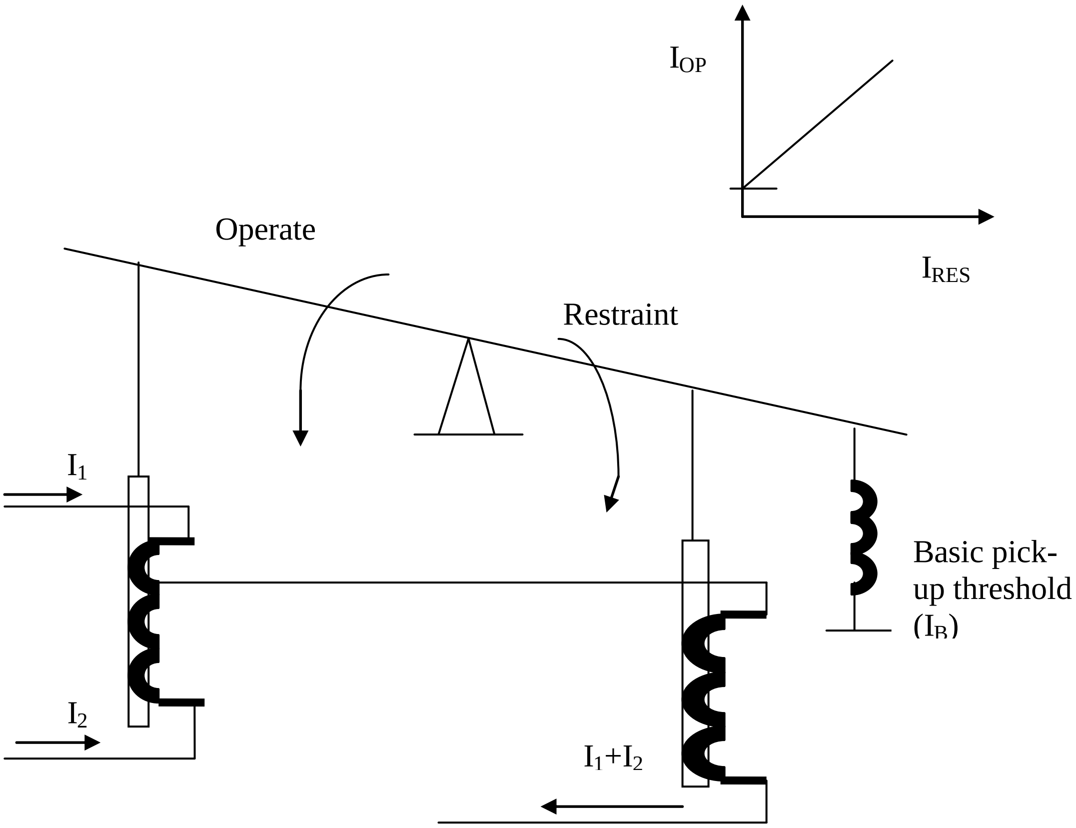


Fig.3.4. Biased differential relay

So the differential current Id that flows through the operating coil is given by the following formula:-

$$Id = \left| \sum_{j=1}^{N} (I_j) \right| \qquad (3.1)$$

This differential current is the algebraic sum of all CT secondary phase current.

The restraint current Ir that flows through the restraining coil is given as:-

$$Ir = \sum_{j=1}^{N}(|Ij|) \tag{3.2}$$

Where N is the number of lines connected to the bus bar.

The pick-up criterion is as follows: - Id > Ir.

To deciede the relay logic a factor known as stabilizing factor is used which at an instant k is given as :-

$$S = Id / Ir \tag{3.3}$$

i.e. the stabilizing factor is the ratio of differential current to restraint current. Based upon the value of this stabilizing factor the relay logic is decieded.

For the internal fault without CT saturation all the CT current will have the same phase and hence the differential current will be equal to the restraint i.e. Id = Ir and due to this the value of stabilizing factor will nearly be equal to 1 i.e. $S \approx 1$[23]. But this phase angle difference between the current phasors of the CT currents will get disturbed if during the internal fault some of the CTs which will make the stabilizing factor to be less than 1.However for the external fault without CT saturation the differential current Id becomes zero i.e. Id = 0 and also the value of stabilizing factor will nearly be equal to zero. If some of the CTs saturate or the CTs are of different characteristics instead of same characteristic then the differential current will be observed. So to take into account these factors, usually the value of S is taken between 0.6 and 0.85. For example is the value of S is taken 0.7 then the relay will operate if the value of S lie between 0.7 and 1.

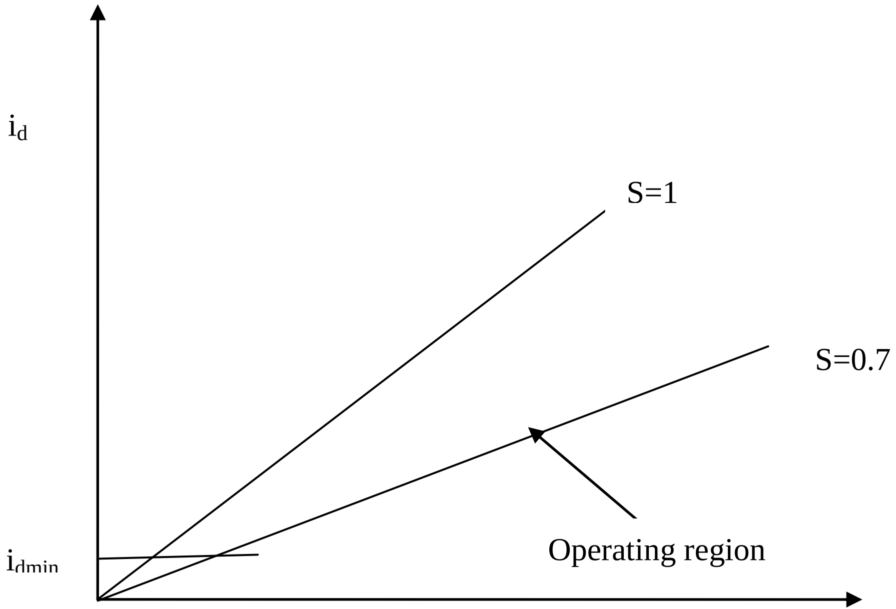


Fig.3.5. Operating Characteristic of biased differential relay

3.7. Circulating Current Principle

This principle can be explained by the help of following figure: -

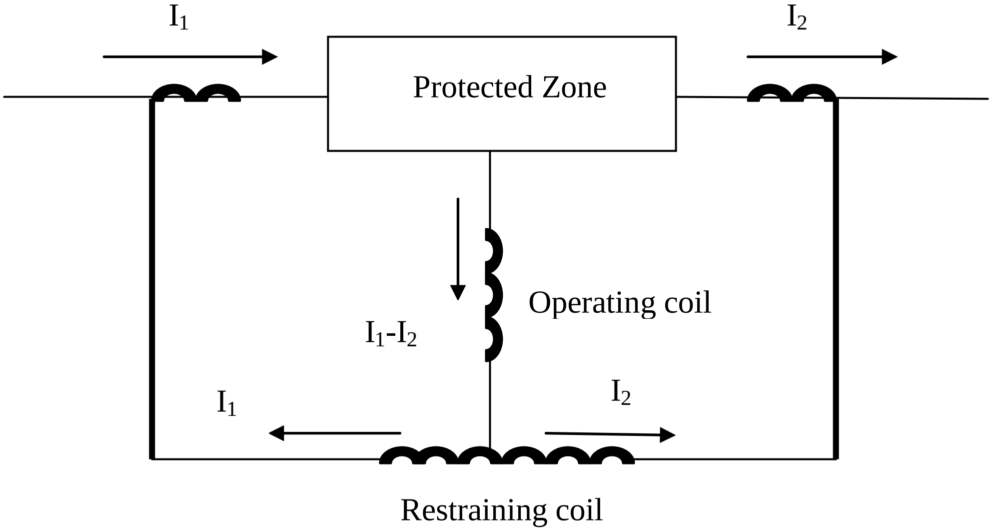


Fig.3.6. Differential protection with restraining and operating coil

The restraining current Ir = I_1-I_2 in the pilot wire is supplied by the auxiliary transformer whereas the differential current Id= I_1+I_2 is supplied by the auxiliary transformer connected in shunt with the pilot wire. The CTs are usually connected to the pilot wire cores with the phase opposition. As shown in the figure 3.5 the cross-over of the CT connection are not applied consequently. Hence the CTs secondary voltages are in phase when the current flows through the feeder. Thus a circulating current is driven through a pilot wire loop. This principle is therefore called as release principle. The two voltages are therefore in phase opposition with each other during internal fault this thus reduces the pilot wire current. Theoretically the pilot wire current becomes zero in case if the in-feed at both sides is same.

3.8. Measuring Principle Comparison

During normal operation no current flows through the pilot wire with opposed voltage principle. The current through pilot wire core must be zero in case of internal fault. No trip is possible if the pilot wires are interrupted. During external fault if the pilot wire short circuits then the tripping would occur. So to prevent the incorrect tripping when the pilot wire short circuits in case of external fault or load condition it is necessary to apply a separate over-current condition.

The circulating current principle causes the flow of stabilizing current through the pilot wire which in turn prevents pick-up during external fault. This principle is therefore termed as the blocking scheme. Now if the pilot wires are interrupted then it causes flow of high through fault current. Here also an additional over-current principle is applied. If the pilot wires short circuits then it causes over restraint and results in blocking of the tripping.

3.9. Operating characteristics

The differential protection response can be represented easily by the current diagram as shown below: -

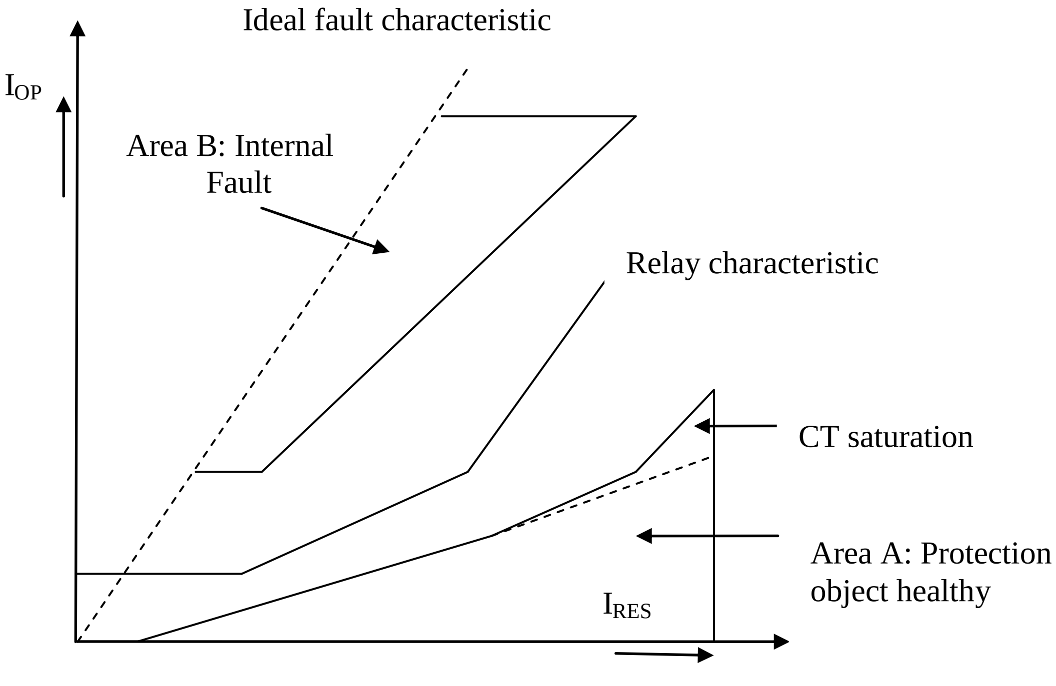


Fig.3.7. Operating characteristics of differential protection

On vertical axis differential current is shown while on horizontal axis restraint current is shown.

Two states can therefore be distinguished initially as follows:-

A. A state representing a protected (healthy) object: -

Ideally when there is no differential current then in that case only the summated or restraint current is present during through (external) fault and load condition. Thus in the diagram horizontal axis represents the protected or healthy state. Inaccuracies and mismatches that are caused to the current transformer by the tap changers causes fault differential current to flow which is proportional to the current that flows through the protected object.

Depending upon the CT dimensions, CT saturation may take place above a threshold that results in rapid increase in the fault differential current. Area A is represents the range of protected object.

B. Short circuit state in protected object

An ideal fault condition exists in this case. A line with 45^0 inclinations represents this state in the diagram and is referred as ideal fault characteristic. During internal fault the discussion made regarding the phase angle difference of the load current and in-feed current flowing through the protected object results in the ratio of differential current to the restraining current to be smaller than 1. However in practice the internal faults appear below the 45^0 line range.

3.10. Numerical Relay Characteristics

In the relay characteristic the range of the protected object for faulty and healthy state have been defined. The following diagram shows the characteristic: -

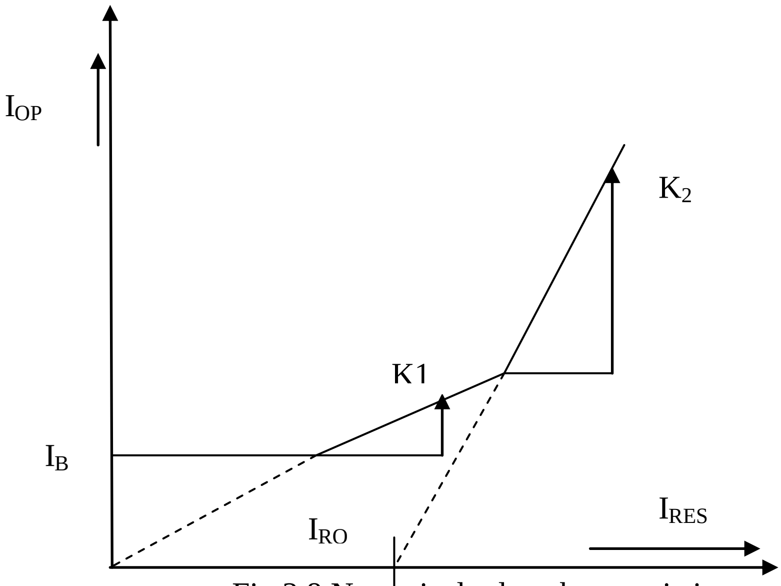


Fig.3.8 Numerical relay characteristic

To discriminate between restraint and operating state a boundary can be formed by the placing the relay characteristic in that particular zone. Usually the conventional devices have fixed characteristic which is flat at starting and have steeper slope thereafter from a designated threshold. Whereas it is possible to apply numerical relay characteristic in piecewise linear shape.

Zone a: - $Iop > I_B$

Zone b: - $Iop > K_1 . I_{RES}$

Zone c: - $Iop > K2. (I_{RES} – I_{RO})$

Where I_B, K_1, K_2 and I_{RO} are the setting parameters.

Instantaneous values (i.e. each sample in the numerical relay) are used to analyze the dynamic response or even filtered values (i.e. values obtained from the appropriate numerical protection data window) can be used to analyze dynamic response.

The points represented by the Iop and I_{RES} for the internal fault must lie above the relay characteristic whereas these points for external fault must lie below the relay characteristic.

3.11. Proposed Technique

In this thesis the technique used for numerical bus bar protection is based upon the instantaneous values of the current transformer.

Let the instantaneous values of the CT currents be i_1 (k), i2 (k)…..i_N (k) at the sampling instant k in the lines 1, 2…….N respectively. In this technique in order to eliminate the effect of pre-fault current only the fault component of the currents are considered. Thus at an instant k the instantaneous differential current due to fault component is given by the following formula:-

$$\text{Id (k)} = \left| \sum_{j=1}^{N} \left(I_j \text{ (k)} - I_j \text{ (K} - \text{Ns} \right) \right| \tag{3.4}$$

and the instantaneous restraint current due to the fault component is given as:-

$$\text{Ir (k)} = \sum_{j=1}^{N} \left| \left(I_j \text{ (k)} - I_j \text{ (K} - \text{Ns} \right) \right| \tag{3.5}$$

where Ns represent the number of samples in one complete cycle of the current waveform and the current I_j (K − Ns) indicates the current of the j^{th} line one cycle before with respect to the sampling point k. Now at an instant k the stabilizing factor can be calculated as: -

$$\text{S (k)} = \text{Id (k)} / \text{Ir (k)} \tag{3.6}$$

So the relay logic is decieded based upon the value of this stabilizing factor S (k).

The sampling rate here is taken as 40 samples per cycle in order to obtain sufficient number of distinct current sample before CT gets saturated. The sampling frequency is taken as 2 KHz for a 50 Hz system which is not very high. It has been observed that after the initiation of the fault the CT do not saturate during first quarter period even for the severest fault. If the stabilizing factor S exceeds its value more than 0.6 then it indicates that the fault is bus bar fault or internal fault otherwise it is considered as an external or through fault. In this thesis 0.7 threshold value is taken to take into account the errors in the data acquisition and processing system and also the non-uniform nature of CT characteristics.

3.12. Summary

This chapter contains a brief description about numerical technology and its advantages for using it as a bus bar protection scheme. The biased restraining differential protection scheme which is the main concept of this thesis is covered completely discussed in this chapter.

CHAPTER 4

SIMULATION AND RESULTS

4.1. Description of the Simulink Model

To verify the proposed scheme a sample power system is modeled in MATLAB/SIMULINK for various types of faults and a sampling rate of 40 samples per cycle is taken to collect the current samples.

Three bus bar system model is used with two distributed line sections. These three bus bars are named as B22, B500 and B2 respectively. A three phase source is connected at one end while at the other end a synchronous machine is used as an input source. Further a current transformer (CT) is connected between the bus bars B22 and B500 and the CT current positive direction is shown in the figure with an arrow. A three phase series RL load is also used.

4.2. Simulink Model

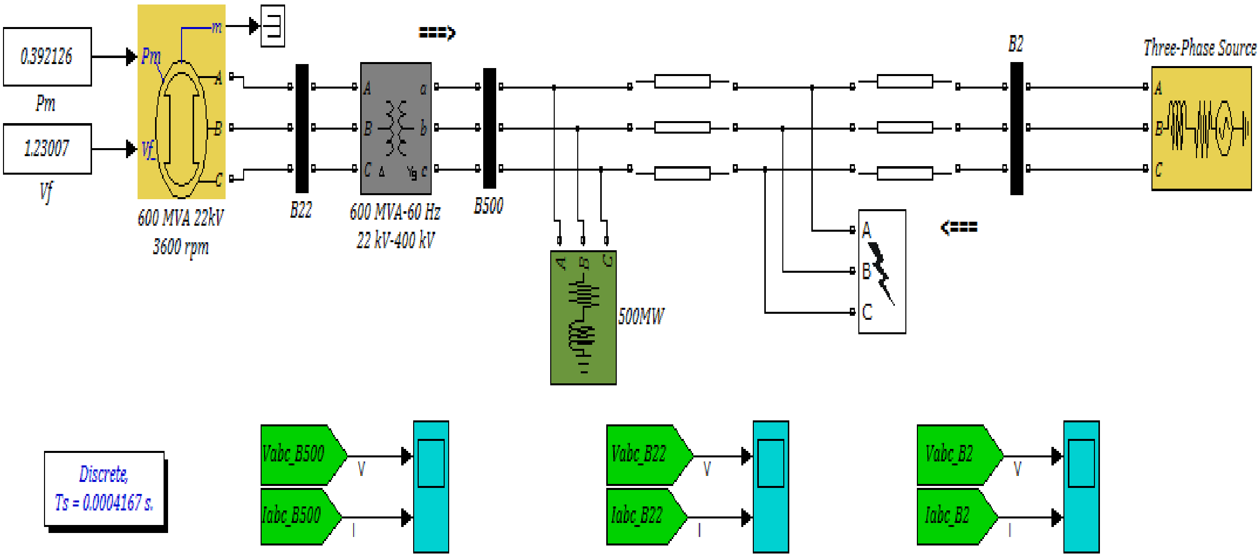


Fig.4.1. Simulation model of a sample power system model

4.3. Fault Detection Algorithm

The fault is detected on the basis of difference between the value of the current sample and the sample one cycle before. If this difference is found to be zero then it is confirmed that there is no fault and the system is stable i.e. the system is operating in steady state. But if this difference is not zero and found to exceed a value more than 0.05 then it confirm that there is a fault. For example if suppose for phase A of the line if the difference is: -

$$Ia(k) - Ia(k - Ns) > 0.05 \qquad (4.1)$$

then it is stated that there is a fault in phase A of the line and k is an instant at which the fault has occurred in phase A. Similarly the fault in other phases can also be detected. To confirm the fault in a particular phase the next sample of the same faulted phase is again checked and if both these consecutive current samples of the faulted phase exceeds the threshold value of 0.05 then it is confirmed that there is a fault and the fault instant is taken as k and Ns here represents the number of samples in one complete cycle of the current.

4.4. Flow Chart for the Proposed Scheme

A flow chart is designed for fault detection algorithm. The flow chart consists of following important information: -

1. Indices Ma, Mb and Mc are used in order to check the number of times the stabilizing factor of each phase (phases A, B and C) i.e. Sa (k), Sb (k) and Sc (k) respectively becomes more than the threshold value (set value).
2. Computation of the stabilizing factor.
3. Fault is detected on the basis of fault detection algorithm explained in 4.3.
4. The differential current of phases A, B and C are denoted as Ida (k), Idb (k) and Idc (k) respectively.
5. The restraint current of phases A, B and C are dented as Ira (k), Irb (k) and Irc (k) respectively.

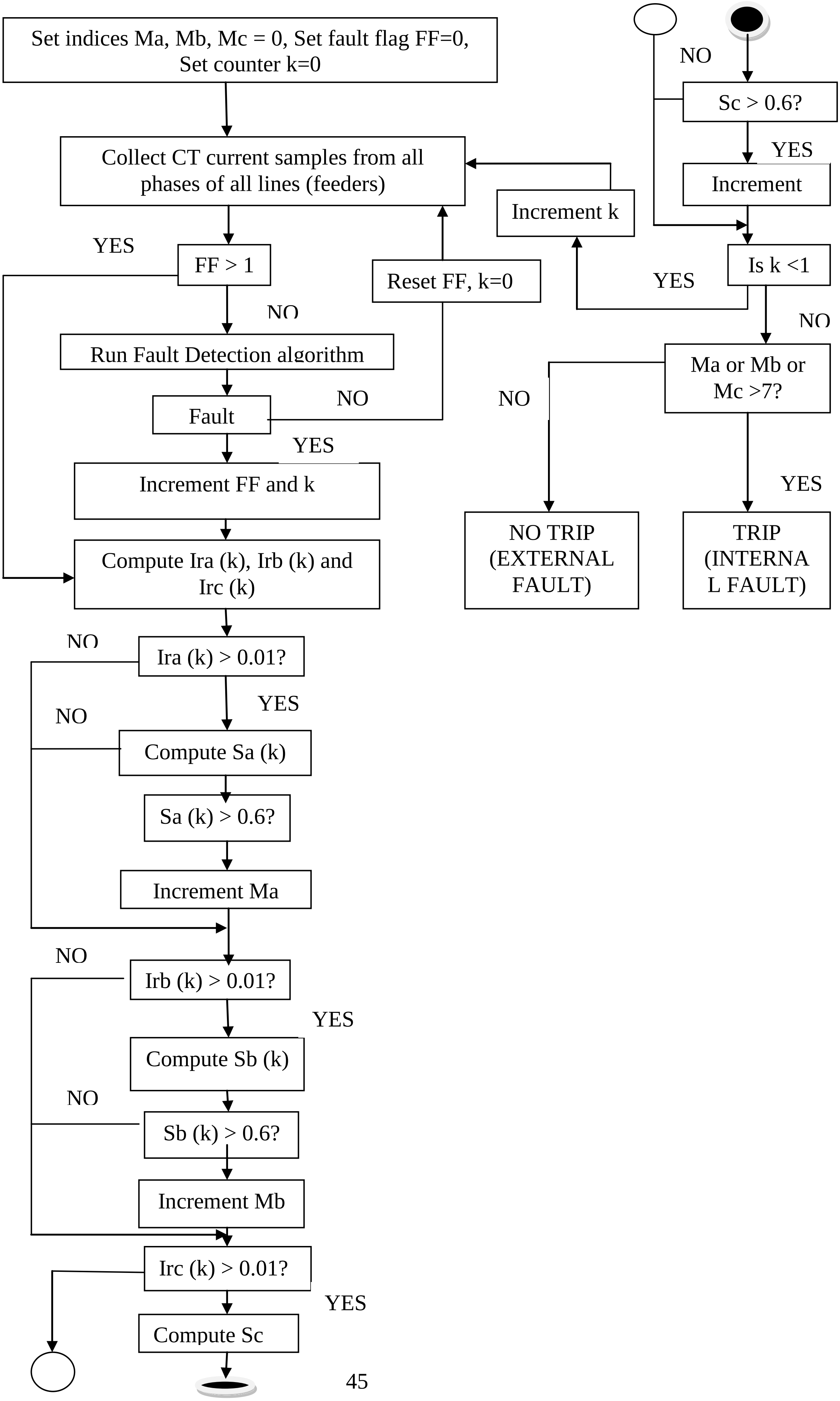


Fig.4.2. Flow chart

4.5. Results

Simulation is performed following the flow chart for fault detection algorithm and in order to verify the proposed technique L-L, L- G, L-L-G and L-L-L are created and are examined and it has been observed that CT do not saturate even for the severe fault because the trip signal is initiated successfully by this scheme to avoid CT saturation.

4.5.1. Line-Line-Ground Fault (Phase A- Phase C- Ground)

Waveforms for L-L-G fault for bus bars B22, B500 and B2.

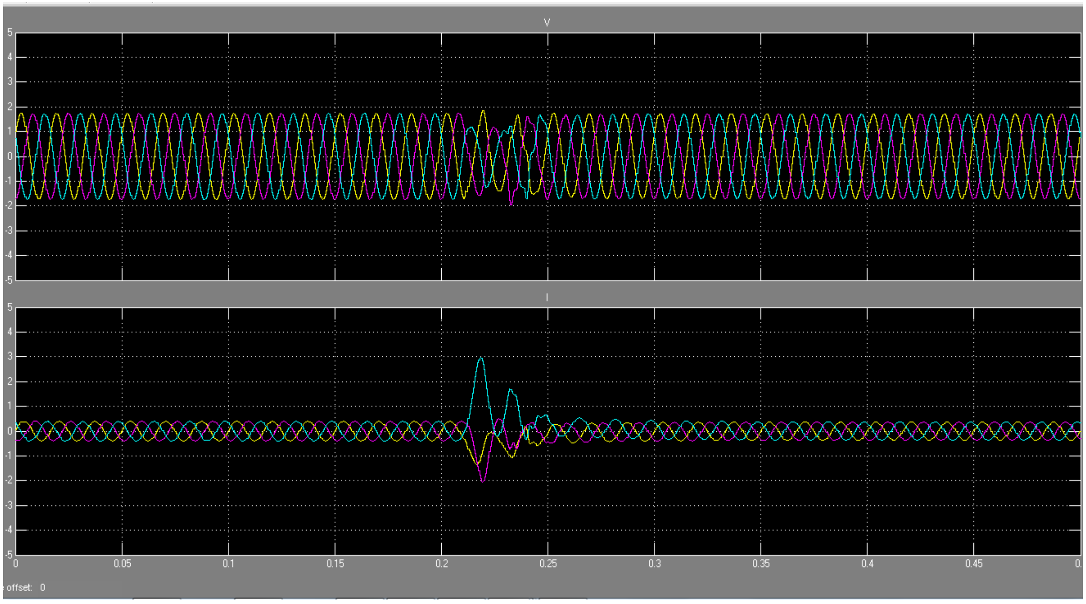


Fig.4.3. (a) Voltage and current waveforms for bus bar B22

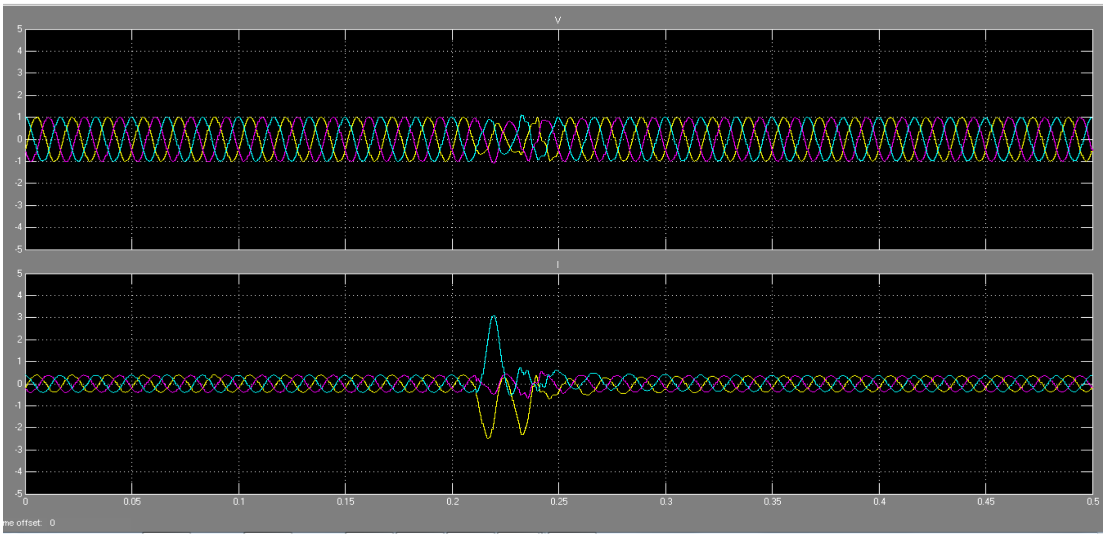


Fig.4.3. (b) Voltage and current waveforms for bus bar B500

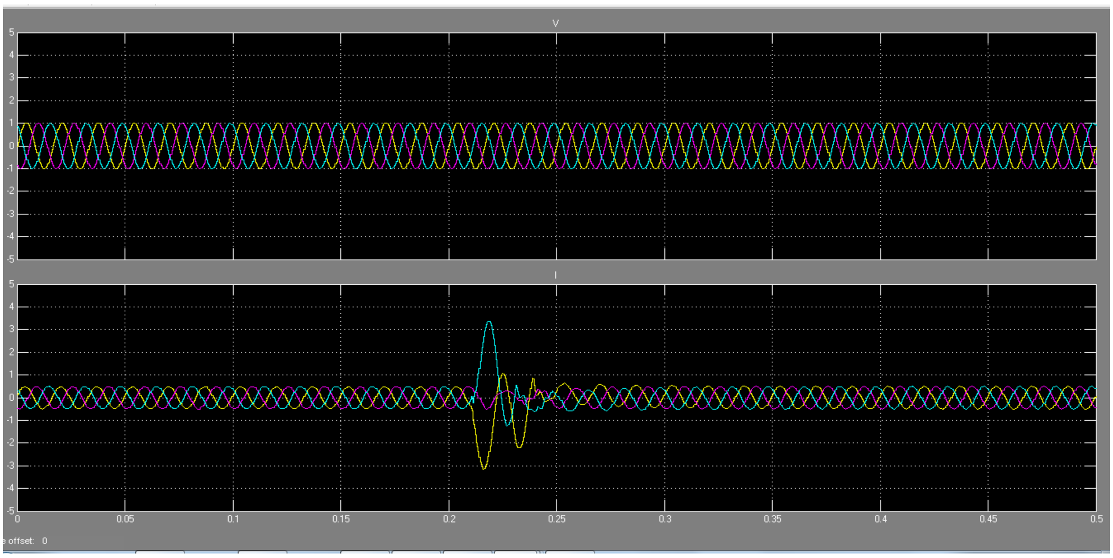


Fig.4.3. (c) Voltage and current waveforms for bus bar B2

4.5.2. Line-Line fault (Phase A- Phase C)

Waveforms of L-L fault for bus bars B22, B500 AND B2

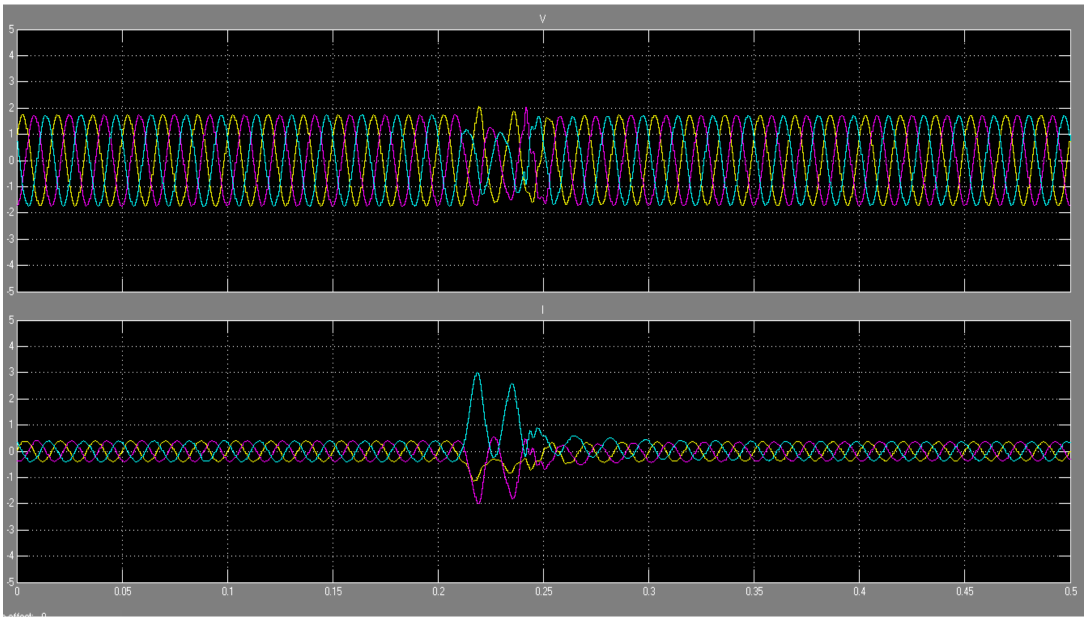


Fig.4.4. (a) Voltage and current waveforms for bus bar B22

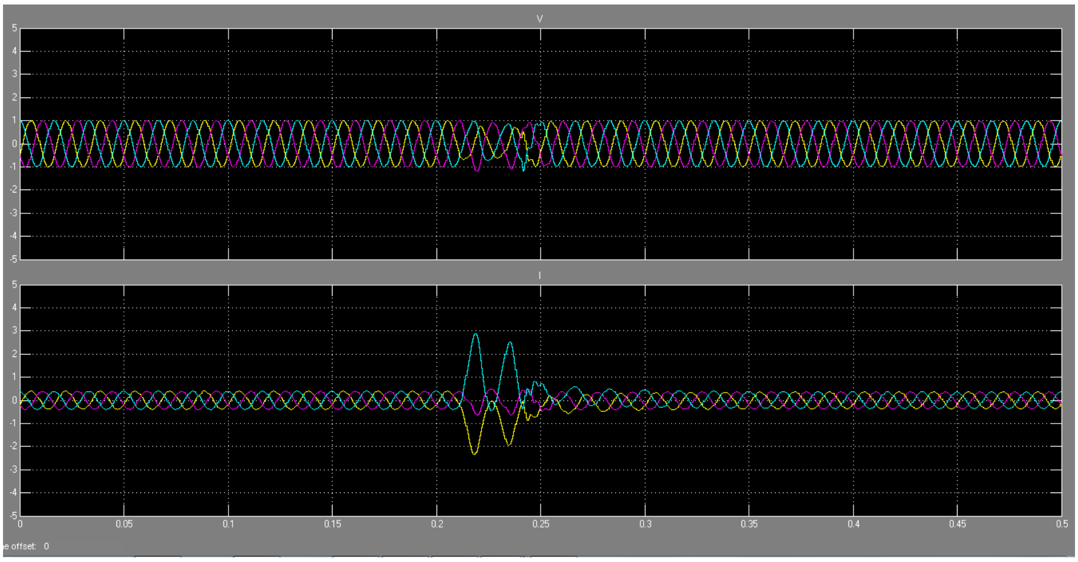


Fig.4.4. (b) Voltage and current waveforms for bus bar B500

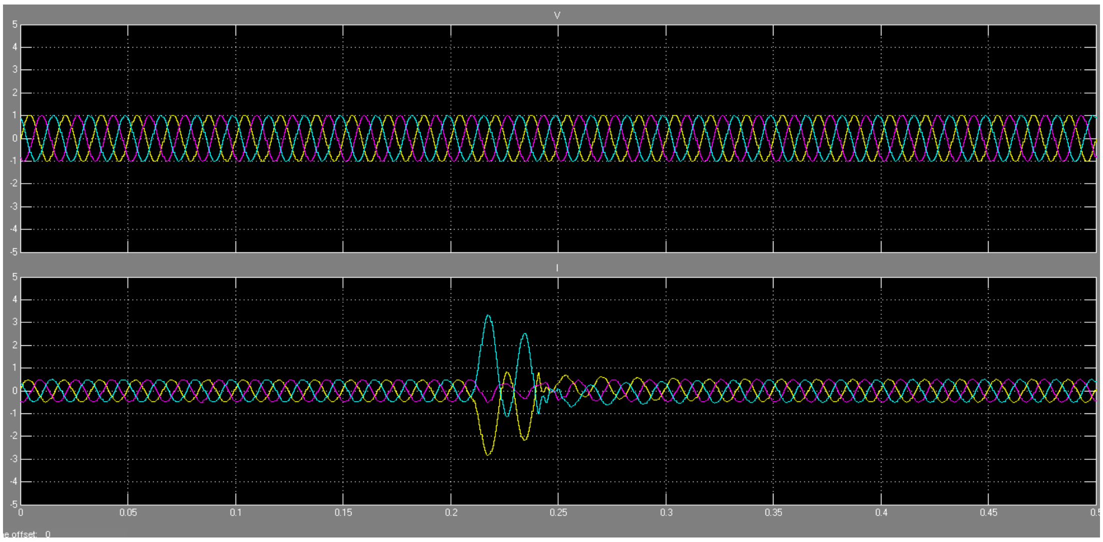


Fig.4.4. (c) Voltage and current waveforms for bus bar B2

4.5.3. Line-Ground fault (Phase A- Ground)

Waveforms of L-G fault for bus bars B22, B500 and B2

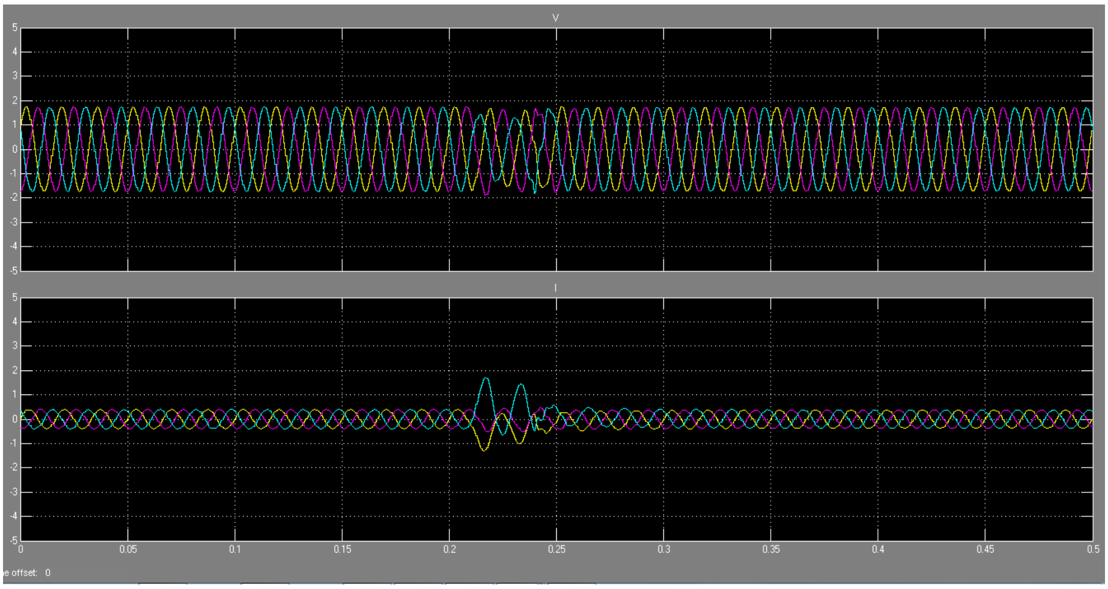


Fig.4.5. (a) Voltage and current waveforms for bus bar B22

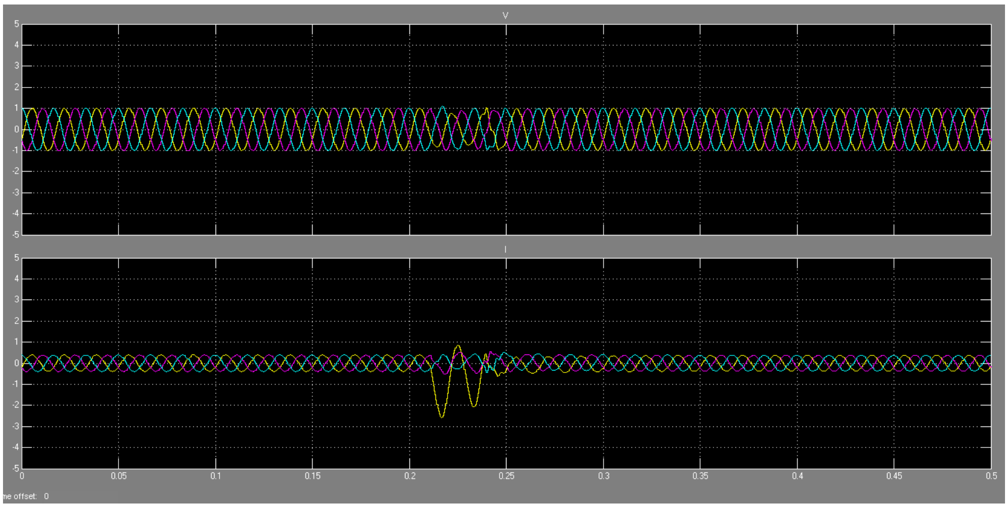


Fig.4.5. (b) Voltage and current waveforms for bus bar B500

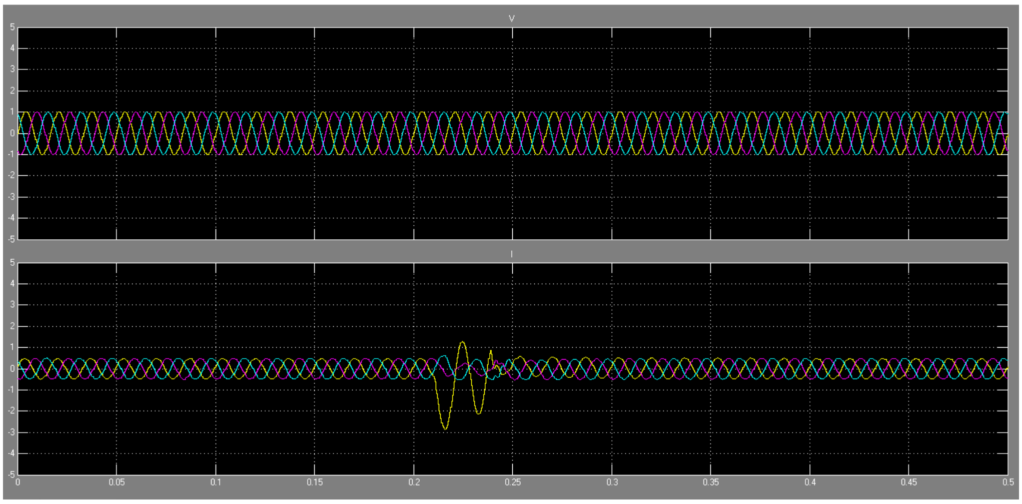


Fig.4.5. (c) Voltage and current waveforms for bus bar B2

4.5.4. Line-Line-Line fault (Phase A – Phase B – Phase C)

Waveforms of L-L-L fault for bus bars B22, B500 and B2

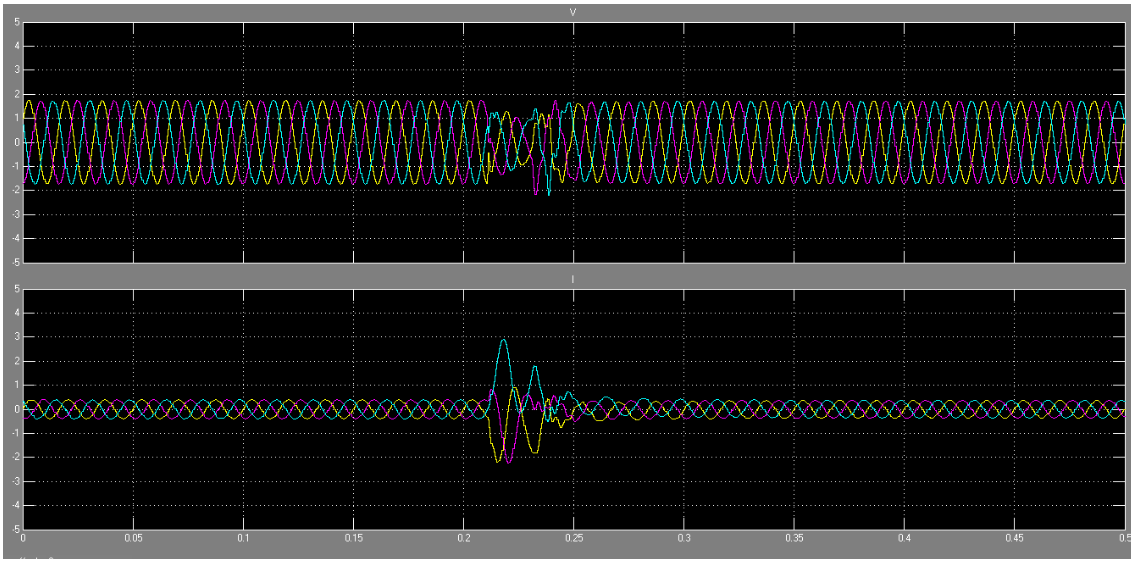


Fig.4.6. (a) Voltage and current waveforms for bus bar B22

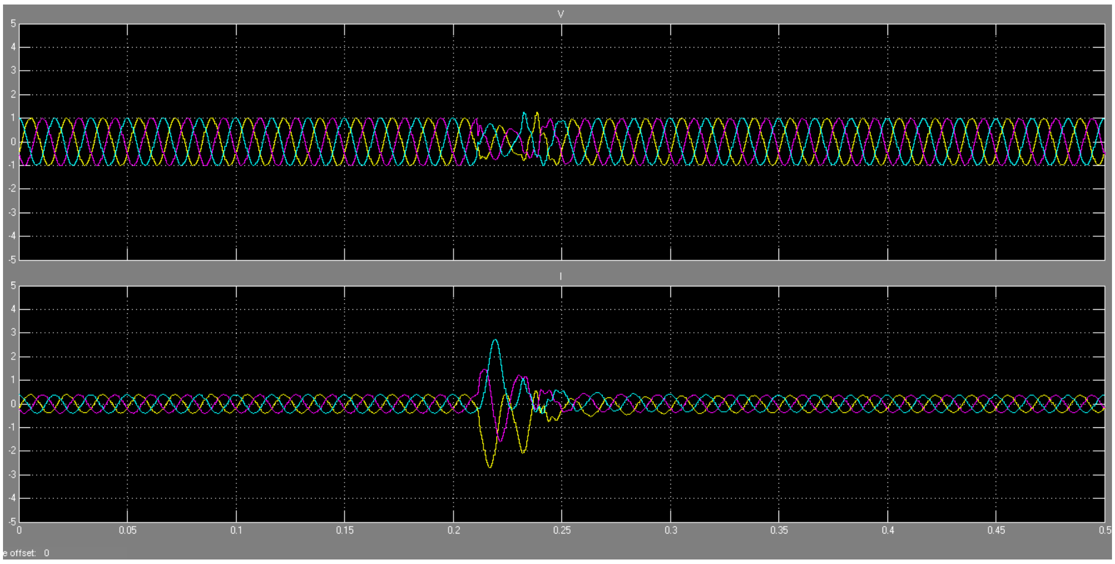


Fig.4.6. (b) Voltage and current waveforms for bus bar B500

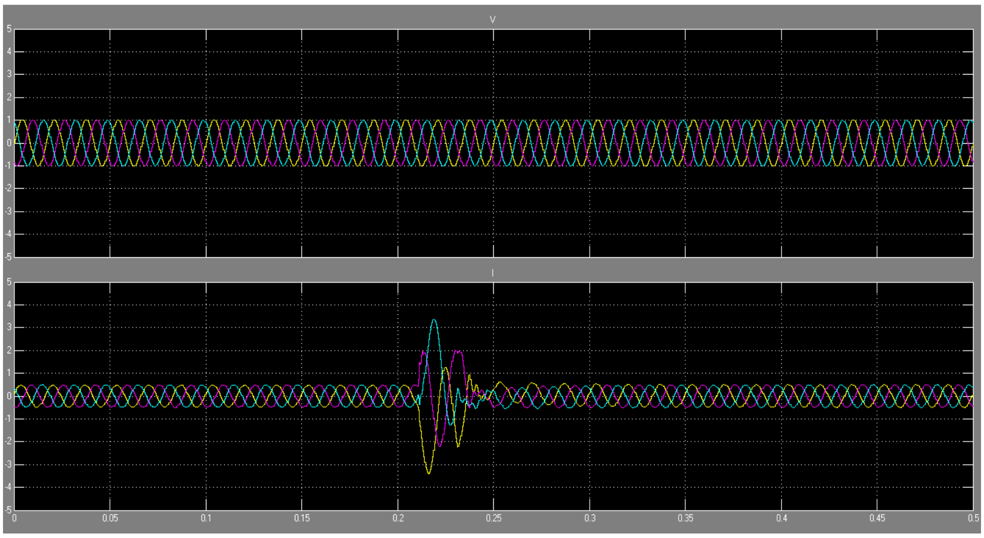


Fig.4.6. (c) Voltage and current waveforms for bus bar B2

Similarly the waveforms of other phases for L-L-G, L-L, L-G and L-L-L faults can be obtained.

4.6. Conclusion

In this thesis a very simple and new scheme based on instantaneous values of CT secondary currents for numerical bus bar protection is proposed. The reliability of the scheme is tested by simulating a sample power system model consisting of three bus bar system and two distributed section of lines. The protection algorithm is very simple and it does not require calculation of phasor values. Various fault conditions have been examined and it was found that the technique is highly reliable and stable as CT do not saturate for the first quarter cycle of the current waveform. The algorithm used also discriminates between internal fault and external fault.

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APPENDICES

Appendix: - A. Simulation Data

1. Synchronous machine parameters: -

Machine type - Salient pole rotor type (3600 rpm).
Nominal power – 600 MVA
Line-to Line voltage – 22KV
Reactances (pu) [Xd, Xd’, Xd”, Xq, Xq’, Xq”] = [1.81, 0.3 0.23, 1.76, 0.25, 0.05]

2. Bus bars parameters: -

Bus bar B22: - Nominal voltage used for per unit measurement – 22KV
Bus bar B500 and B2: - Nominal voltage used for per unit measurement – 400KV

3. Transformer parameters: -

Nominal power: - 600MVA
Winding 1 parameters: - Vrms = 22KV
Resistance R1 (pu): - 0.000885
Inductance L1 (pu): - 0
Winding two parameters: - Vrms = 400KV
Resistance R2 (pu): - 0.000885
Inductance L1 (pu): - 4.3237e^{-4}
Magnetizing resistance Rm (pu) and magnetizing inductance Lm (pu): - 500

4. Line parameters: -

All lines used are distributed type and have same parameters.
Line length: - 140 km
Resistance per unit length (ohms/km): - [0.12, 0.309]
Inductance per unit length (H/km): - [2.3342e^{-3}, 3.440e^{-3}]
Capacitance per unit length (F/km): - [10.876e^{-9}, 7.751e^{-9}]
5. Three phase source parameters: -
Nominal voltage: - 400KV
Three phase short circuit level at base voltage: - 35000KV
X/R ratio: - 21.

Appendix B: - Coding

```
clc;clear;close all;warning off;
freq = 60;
Ns_Cycle = 40;

%% Algorithm
%% Initialization
Trip = 0;
Ma = 0;
Mb = 0;
Mc = 0;
FF = 0;
k = 0;
%% Collect data
open_system('busbar_prot');
sim('busbar_prot');
Ia = [dataB500.signals(1,2).values(:,1),...
    dataB2.signals(1,2).values(:,1),...
    dataB22.signals(1,2).values(:,1)];
Ib = [dataB500.signals(1,2).values(:,2),...
    dataB2.signals(1,2).values(:,2),...
    dataB22.signals(1,2).values(:,2)];
Ic = [dataB500.signals(1,2).values(:,3),...
    dataB2.signals(1,2).values(:,3),...
    dataB22.signals(1,2).values(:,3)];
Iad = zeros(1200,1);
Ibd = zeros(1200,1);
Icd = zeros(1200,1);
Iar = zeros(1200,1);
Ibr = zeros(1200,1);
Icr = zeros(1200,1);
Sa = zeros(1200,1);
Sb = zeros(1200,1);
Sc = zeros(1200,1);
T = zeros(1200,1);
for i = 1:1200
    if i <= Ns_Cycle
        Iad(i) = abs(sum(Ia(i,:)));
        Ibd(i) = abs(sum(Ib(i,:)));
        Icd(i) = abs(sum(Ic(i,:)));
        Iar(i) = sum(abs(Ia(i,:)));
        Ibr(i) = sum(abs(Ib(i,:)));
        Icr(i) = sum(abs(Ic(i,:)));
    else
        Iad(i) = abs(sum(Ia(i,:) - Ia(i-Ns_Cycle,:)));
        Ibd(i) = abs(sum(Ib(i,:) - Ib(i-Ns_Cycle,:)));
        Icd(i) = abs(sum(Ic(i,:) - Ic(i-Ns_Cycle,:)));
        Iar(i) = sum(abs(Ia(i,:) - Ia(i-Ns_Cycle,:)));
```

```
        Ibr(i) = sum(abs(Ib(i,:) - Ib(i-Ns_Cycle,:)));
        Icr(i) = sum(abs(Ic(i,:) - Ic(i-Ns_Cycle,:)));
    end
    Sa(i) = Iad(i)/Iar(i);
    Sb(i) = Ibd(i)/Ibr(i);
    Sc(i) = Icd(i)/Icr(i);
end

for i = Ns_Cycle+1:(Ns_Cycle*freq)/2
    if FF > 1
        Ira = Iar(i);
        Irb = Ibr(i);
        Irc = Icr(i);
        if Ira > 0.01
            Saa = Sa(i);
            if Saa > 0.6
                Ma = Ma+1;
            end
        end
        if Irb > 0.01
            Sbb = Sb(i);
            if Sbb > 0.6
                Mb = Mb+1;
            end
        end
        if Irc > 0.01
            Scc = Sc(i);
            if Sc > 0.6
                Mc = Mc+1;
            end
        end
        if k < 10
            k = k+1;
        else
            if (Ma > 7)||(Mb > 7)||(Mc > 7)
                Trip = 1;
            else
                Trip = 0;
            end
        end
    else
        %% fault Detection
        if ((Ia(i)-Ia(i-Ns_Cycle))>0.05)||((Ib(i)-Ib(i-Ns_Cycle))>0.05)||((Ic(i)-Ic(i-
Ns_Cycle))>0.05)
            FF = FF+1;
            k = k+1;
        else
            FF = 0;
            k = 0;
        end
```

```
    end
    if Trip == 1
        T(i) = 1;
    else
        T(i) = 0;
    end
end

%% Result
figure()
plot(dataB500.time,dataB500.signals(1,2).values);
legend('a','b','c');
title('3 Phase Current @ B500');
xlabel('Time [Sec]');
ylabel('Current [pu]');
grid on
figure()
plot(dataB500.time,dataB2.signals(1,2).values);
legend('a','b','c');
title('3 Phase Current @ B2');
xlabel('Time [Sec]');
ylabel('Current [pu]');
grid on
figure()
plot(dataB500.time,dataB22.signals(1,2).values);
legend('a','b','c');
title('3 Phase Current @ B22');
xlabel('Time [Sec]');
ylabel('Current [pu]');
grid on
figure()
plot(dataB500.time(2:end),T);
ylim([-1 2]);
title('Trip Signal');
xlabel('Time [Sec]');
ylabel('T');
grid on
```

BIODATA

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- Presented paper on "**NUMERICAL TECHNIQUES FOR BUS BAR PROTECTION**" in the **INTERNATIONAL CONFERENCE** ON EMERGING TRENDS IN MECHANICAL AND ELECTRICAL ENGINEERING **(ICETMEE-2014)** organized **by Rustamji Institute of Technology, BSF, Tekanpur.**

- **Navpreet Singh Tung, Ashutosh Bhadoria, Kiranpreet Kaur, Simmi Bhadauria** "Dynamic Programming Model based on Cost Minimization algorithms for Thermal Generating Units" International Journal of Enhanced Research in Science, Technology and Engineering(IJERSTE) Vol. 1,Issue 1,Oct-2012.

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