Protection and Switchgear

Second Edition

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Features of

Learning Objectives

After going through this chapter, the students will be able to

- Classify overcurrent relays based on the type of characteristic
- Understand the application of overcurrent relay using different relay characteristics
- Explain the working of phase and ground relays
- Explain the concept of directional protection and directional relay characteristics
- List the features available in modern digital/numerical overcurrent and Earth-fault relays
- Explain overcurrent relay coordination in interconnected power system using LINKNET algorithm

Learning Objectives Each chapter of the book has a section 'Learning Objectives', which briefs about all the topics discussed in the chapter.

Figures and Tables Numerous well-illustrated figures and tables are given for better understanding of concepts.

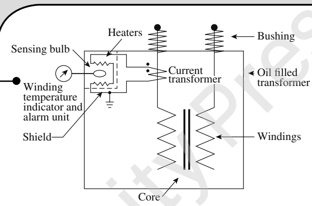

Fig. 6.10 Connection of WTI and alarm unit with transformer

Table 6.1 Transformer category (ANSI/IEEE Standard C57.109-1985 curves)

Category	Minimum nameplate (kVA)		Reference protective curve
	Single-phase	Three-phase	
I	5–500	15–500	Fig. 6.8
II	501–1667	501–5000	Fig. 6.9
III	1668–10,000	5001–30,000	Fig. 6.10
IV	Above 10,000	Above 30,000	Fig. 6.11

Example 2.15 The relays shown in Fig. 2.36 are directional and non-directional relays. Identify the directional relays. The breaking capacities of the breakers are given in Table 2.10. The PS of relays are given in Fig. 2.36; the TDS value of the relays R_2 and R_5 is set at 0.1. Determine the TDS of other relays.

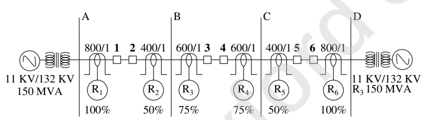

Fig. 2.36 Single line diagram of power system

Solution:

The relays R_1 and R_6 are non-directional, whereas all others relays are directional because the fault current direction can change on bus B and bus C.

We will split the network into two radial networks.

The TDS value of relays R_2 and R_5 is given as 0.1. The TDS of the other relay can be calculated on the basis of its operation in the

Table 2.10 Breaking capacities of breakers

Breaker no.	Capacities (MVA)
1, 6	1000
3, 4	800
2, 5	500

Examples Each chapter supports numerous well-illustrated numerical examples.

Summary Recapitulation at the end of each chapter enables quick revision of important concepts discussed in the chapter.

Recapitulation

- Busbar is the intersection of an electrical network where many lines are connected together and have very high fault levels (fault MVA).
- The various configurations of busbar arrangement used in substations are single busbar arrangement, single busbar arrangement with sectionalizer, main and transfer busbar arrangement, double busbar arrangement, and one-and-half breaker arrangement.
- The protection schemes used for busbar are directional relaying scheme, differential relaying scheme, and high impedance voltage differential scheme.
- Further, differential relaying schemes can be divided into circulating current differential scheme, biased differential scheme, and opposed voltage balance scheme.
- It is necessary to evaluate the problems and remedies of CT saturation during implementation of the differential relaying scheme of busbar protection.
- Currently, a study of centralized and decentralized type digital busbar protection schemes is going on.
- In practice, digital protection along with check zone feature is the commercially used busbar protection scheme for double bus arrangement.

the Book

Additional Multiple Choice Questions Besides the multiple choice questions provided at the end of each chapter, the book also supports Additional Multiple Choice Questions that has as many as 130 questions along with answers.

ADDITIONAL MULTIPLE CHOICE QUESTIONS

1. Selectivity, which is one of the requirements of protection system, is also known as
   (a) dependability (c) security
   (b) relay coordination (d) none of the above
2. Economics criteria of the protective scheme indicates to combine features of
   (a) maximum protection with minimum cost
   (b) maximum protection with maximum cost
   (c) minimum protection with maximum cost
   (d) none of the above

(c) cables
(d) all of the above

8. Electromechanical relays are still used by the utilities due to their
   (a) ruggedness and withstanding capacity of voltage spikes
   (b) lower cost
   (c) simple construction
   (d) all of the above
9. Operating torque is provided in single input relay with the

Review Questions

1. Explain the different ratings and functions of CBs.
2. Explain the isolating and load-break switches.
3. Enumerate the different types of fuses for low voltage applications and write a detailed note on HRC fuse.
4. Explain the construction and operating principle of MCB.
5. Why is the ELCB used in domestic supply?
6. Write a note on ACBs.
7. Discuss the advantages of oil as an insulating medium in a CB.
8. Draw a well-labelled diagram of an MOCB and explain each part and how it works.
10. State the merits of SF_6 gas compared to other arc-quenching mediums.
11. Explain the working of the following SF_6 CB:
    (a) Non-puffer type SF_6 breaker
    (b) Puffer type SF_6 breaker
12. Explain the maintenance procedures for medium voltage CBs.
13. Give the classification of tests to be carried out on CB.
14. Explain the short circuit test plant and procedures of testing for high voltage CBs.

Review Questions Each chapter supports a wealth of short and long answer questions to help students during exam preparation.

Numerical Problems Numerical problems are also given in the book in relevant chapters.

Numerical Exercises

1. A 100 MVA, 11 kV, generator with $x_d'' = 25$ % is connected to a transformer rated 125 MVA, 13.8/220 kV with leakage reactance of 10%. If the base of 150 MVA and 230 kV is used on HV side of transformer, determine the per unit value to be used for the generator and transformer.
2. The single line diagram of an unloaded power system is shown in Fig. 19.40. The rating of each component is given as below.

Generator1 (G1): 30 MVA, 18 kV, $x_d'' = 0.2$pu, Generator2 (G2): 30 MVA, 15 kV, $x_d'' = 0.15$pu, Transformer (T1) is composed of three single phase unit, each rated 10 MVA, 127/18 kV, X = 10%, Transformer (T2): 35 MVA, 230/15 kV, X = 10%, Transmission line-1 has total reactance of 50Ω and line-2 has total reactance of 70Ω. Compute the per unit reactance of all components and draw reactance diagram marking all reactances in per unit.

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Bibliography For those who wish to gather some additional information on certain topics, Bibliography at the end of the book provides a list of books and journals references.

Foreword

In spite of all the care and precautions taken in the design, installation, and operation of power systems and power equipment, abnormal conditions and faults do occur in the system. Some faults such as short circuits can prove highly damaging, not only to the component that develops the fault but also to adjacent components and, sometimes, to the entire power system. Fault occurrence and component damage can be minimized through careful design of the protection system, which primarily includes protective relays, current and voltage transformers feeding these relays, and the switchgear responsible for disconnecting the faulted element(s). As the size of generating stations and complexity of power systems (in terms of interconnections) go up, the demand on the protection system in terms of sensitivity, selectivity, speed, and reliability increases.

This book, *Protection and Switchgear*, authored by Bhavesh Bhalja, R.P. Maheshwari, and Nilesh G. Chothani, deals with this complex subject holistically. It is a fine combination of theory and practice. In my assessment, it will serve as a good reference book to undergraduate and postgraduate students, as also to subject teachers. With a pro-student style and a number of exercises, multiple choice questions, and solved and unsolved questions in every chapter, the book can also become a textbook for colleges, institutes, and universities. I believe that because of an emphasis on practical aspects and the coverage of modern protective equipment, practising engineers will also find it a good handbook/guide.

I congratulate the authors for writing this complete reference book on power system protection, including switchgear, and sincerely hope that it will benefit numerous students, teachers, and practising engineers.

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Preface to the Second Edition

Developments in advanced signal processing, information and communication, and Intelligent Electronic Devices (IEDs) have a tremendous potential to refine or even redefine the formation and implementation of switchgear and protection technology. Increased computing power at low cost has provided opportunities to implement more computation-intensive methods/algorithms in real time. At the same time, Phasor Measurement Units (PMUs) providing faster and diverse synchronized measurements over a wide area, and new communication options have also emerged. It is necessary to design a reliable protection system which can detect and locate events, analyse system integrity, and take corrective action. Subsequently, processing and communication delays, erroneous data, and cyber-attacks pose challenges to security as well as dependability of protection.

Due to major reforms in protection technology since the publication of the first edition in 2012, a sizable portion of the existing content had to be expanded and rewritten in the second edition. In the second edition, we have tried to include more topics which have emerged as important due to the developments that took place during the last five years. We hope students, practising engineers, and faculty members will welcome this second edition.

Salient Features of Second Edition

- Three new chapters — Chapter 18 Smart Grid Technologies and Applications, Chapter 19 — Symmetrical and Unsymmetrical Faults in Power Systems, and Chapter 20 Basic Concept and Application of Controlled Switching.
- Static differential and distance relay with various types of amplitude and phase comparator for static relays.
- Different types of digital filters along with their comparison.
- Large number of multiple choice questions especially for students/faculty and utility engineers.
- Large number of solved and unsolved examples in each chapter for practice and self-evaluation.
- Case study on overcurrent relay coordination along with its source code.
- Comparison among various distance relay characteristics, different types of circuit breakers and their selection is also incorporated.
- Description of earthing transformer and frequency protection is included which provides better understanding.
- In-depth explanation of phasor measurement unit which works as the heart of the wide area protection, monitoring, and control.
- Reclosing scheme used in practice for transmission lines is included which improves reliability of the power system network.
- Various technical challenges due to integration of renewable energy sources with the existing grid are discussed. In addition, the issue of islanding, its hazards and risk of islanding are also added.
- PSCAD examples on inverters and converters which are extensively being used in the field are included in this edition.

New to this Edition

As gradually protection system is moving from electromechanical relays to static and numeric relays, the following are included in chapter 1:

1. Types of amplitude and phase comparator for static relays
2. Static differential relay for unit protection
3. Static distance relay

In this chapter, a new section on digital filters is also introduced along with the description of tools for distorted relaying signals.

In chapter 2, a case study for overcurrent relay coordination along with its source code is included to help the reader to develop his own code.

For better understanding from selection point of view, comparison among various distance relay characteristics is included in chapter 3.

In chapter 4, we have included permissive inter-tripping scheme and carrier-aided distance scheme for acceleration and pre-acceleration of zone II.

New rate of change of frequency protection as well as additional solved and unsolved examples have been included in chapter 5.

As we considered description of earthing transformer an important issue, it is included in chapter 6.

In order to minimize outage time and also to improve reliability of power and distribution network, the current practice is to use auto-reclosing feature with the existing circuit breaker. In chapter 11, auto-reclosing scheme used in practice for transmission lines is included.

Today, more emphasis is being given to tap renewable energy sources. However, integration of renewable energy sources with the existing grid imposes many technical challenges. The same are presented in chapter 12. In addition, the issue of islanding, its hazards, and risk of islanding are also incorporated in this chapter.

A comparison of different types of circuit breakers and its selection is included in chapter 14.

In chapter 15, stability, overshoot, and voltage withstand test are included to make the presentation complete as per present requirements.

The industry is moving towards more robust protection systems and for that PMUs are deployed. The description of PMUs is included in chapter 16.

As power system cannot be experimented, simulations of the system with various types of equipment are the only option for its behavioural study. For the simulation study of power system, PSCAD has emerged as an important tool. This was included in the first edition itself. But over the period, as inverters and converters are extensively being used, their case study is also included in chapter 17 of the revised edition.

To keep pace with development in power system protection, three new chapters have been added in the revised edition.

Chapter 18 Smart Grid Technologies and Applications discusses the various components and benefits of smart grid—an improved electricity supply chain that runs from a major power plant all the way inside to your home, and also highlights the challenges that may arise while designing a smart grid.

Chapter 19 Symmetrical and Asymmetrical Fault Analysis deals with per unit system, symmetrical components, transformation of unbalanced phasors into balanced symmetrical components and vice versa, transient phenomenon that occurs in transmission line and formation of sequence networks.

Chapter 20 Basic Concept and Application of Controlled Switching discusses controlled switching which is a recent practice followed by most of the utilities for reduction in inrush current and voltage across circuit breaker assembly.

Online Resources

To aid the faculty and students using this book, additional resources are available at www.india.oup.com/orcs/9780199470679

For Faculty

Solutions Manual and Lecture PPTs, Chapter-wise MCQs

For Students

MCQ test generators, PSCAD simulations

Acknowledgements

During revision of this book, we received valuable suggestions and positive feedbacks from many students, faculty members, and practising engineers working in the utility/industry. Influence of all these readers has had a major impact on the revision of this book. We hope that their support will continue in future as well.

The publishers and authors would like to extend their special thanks to the following reviewers who spared their valuable time to review this book.

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Feedback

We are happy to welcome any encouraging criticism of the book and will be thankful for an evaluation by the readers. The suggestions can be sent to bhaveshbhalja@gmail.com

Bhavesh Bhalja
R. P. Maheshwari
Nilesh G. Chothani

Preface to the First Edition

A modern power system is a complex arrangement of machinery, with countless interfacing control loops and distribution and transmission channels, along with automated protection and safety support systems. Although engineers may take due care, faults in the protection scheme are inevitable.

Statistical data reveals that a large number of relay trippings occur due to improper or inadequate relay settings rather than due to actual faults. Hence, it is the duty of a protection engineer to design a protection scheme, either for the apparatus or for the lines, which provides maximum protection features at minimum cost. Therefore, it is extremely important for power system engineers and students of electrical engineering to study the various protection schemes in detail. These include power and control circuits of the equipment to be protected, various relay characteristics, relay design, and construction of the relays. Moreover, protective devices cannot perform their task without the support of instrument transformers such as current and potential transformers and switchgears such as circuit breakers, isolators, fuses, earthing switches, etc. Thus students of electrical engineering and engineers working in the industry should have adequate theoretical and practical knowledge of protective devices and switchgears. This knowledge is also helpful during design, erraction, procurement, and maintenance of various power system components. Study of relays and switchgears is also important to understand the procedure of actual relay setting in the practical scenario.

Today, in order to economize, each component of a power system is operated with relatively small margins from stipulations. This can cause rapid damage, with safety implications and huge penalties resulting in the loss of revenue due to system downtime and repair costs. Component failure either at the micro or macro levels is a vital factor that affects the reliability of power supply to the end users. Keeping this in mind, this book discusses in detail the implementation of sophisticated protection systems at each hierarchy of the power system and also the utility of switchgear.

About the Book

This book aims to give a comprehensive, up-to-date presentation of the role of protection safety systems, switchgears, and their advances in modern power systems. It begins with a survey of the theories and methods of protection and switchgear. Additionally, it provides a theoretical summary along with examples of real life engineering applications to a variety of technical problems. It bridges the gap among the theoretical advances, experimental validations, and engineering in real life.

This book is designed as a textbook for undergraduate students of engineering for a course on protection and switchgear. It will also be immensely useful for power system engineers seeking information about the principles and working of protection and switchgear systems.

Salient Features

- Provides in-depth coverage of apparatus protection, circuit breaking fundamentals, and selection and testing of circuit breakers using actual field data.
  This book covers analytical techniques, selection, and testing of switchgears in an easily comprehensible manner. It also covers transformer, generator, induction motor, and busbar protection in detail. For each apparatus, digital protection is also discussed. It also discusses various digital relaying schemes for line and equipment protection.

- Contains a chapter on recent developments in protection relays.
  This chapter discusses topics such as wide-area protection, synchronized sampling, wide-area phasor measurement technology, application of artificial intelligence in protective relays, and application of wavelet transform in protective relaying.
- Contains a chapter on power systems computer aided design (PSCAD)
  PSCAD is a powerful and flexible graphical user interface of the world renowned EMTDC solution engine. It enables the user to schematically construct a circuit, run a simulation, analyse the results, and manage the data in a completely integrated, graphical environment. This chapter provides a detailed discussion on this interface with screen shots to help students understand this software.
- Includes solved examples, numerical exercises, review exercises, and multiple choice questions at the end of each chapter
  The problems have been included with the intention of helping students realize that many problems that will be faced in practice will require careful analysis, consideration, and some approximations.
- Appendices at the end of the book
  A number of appendices have been provided at the end of the book such as the international code list for protective relaying schemes with a description of each device, data sheets of different types of relays, system line parameters for overcurrent relay coordination, and simulation of transmission line systems.

Content and Coverage

The book is divided into 17 chapters. A brief description of these chapters is given here.

Chapter 1 starts with the fundamentals of protective relaying, which include the history and incremental developments, followed by the classification of protective relays. It also includes construction of various protective relays. The concept of digital/numerical relay is also discussed along with a block diagram and the function of each block. At the end, various algorithms used in digital relays are discussed.

Chapter 2 focusses on overcurrent protection of the transmission line. It covers various characteristics of bidirectional and directional overcurrent relays. Guidelines for phase and ground relay settings along with the relay coordination procedure are explained with suitable examples.

Chapter 3 gives special emphasis to problems and remedies of distance protection. Various distance relay characteristics are discussed along with the derivation of quantities fed to the phase and ground distance unit.

Chapter 4 discusses the importance of the pilot relaying scheme used for transmission lines. It covers various pilot relaying, carrier blocking, and transfer tripping schemes along with the control circuits and R–X diagrams.

Chapters 5, 6, and *7* deal with apparatus protection, which includes the generator, transformer, and induction motor. Various types of protection such as overcurrent, earth fault, and differential are discussed in detail along with relevant circuit diagrams and examples. For each apparatus, digital protection is also discussed.

Chapter 8 discusses different arrangements of the busbar and the concept of busbar protection. Further, recent trends in double bus arrangement are explained. Special schemes such as centralized and decentralized busbar protection are also elaborated.

Chapter 9 explains the principle, construction, and performance of the current transformer (CT) and the potential transformer (PT). Further, specifications of CT and PT are given, which will be helpful during their procurement.

Chapter 10 presents various neutral grounding schemes and their effect on the power system. This chapter focusses on the sources of transient surges and the protective measures against them. It also covers various devices used in the field for protection against overvoltage owing to switching and lightning.

Chapter 11 presents various types of reclosing relays and the procedure for automatic reclosing and synchronizing.

Chapter 12 covers the behaviour of the power system during severe upsets such as islanding and under frequencies. Different load shedding techniques and islanding schemes are also discussed.

Chapters 13 and *14* discuss the fundamentals of circuit breaking, arc phenomenon, and the factors affecting the arc interruption process. Moreover, construction and working of various types of switches, fuses, and circuit breakers are explained in detail with their relative merits and demerits. The chapter concludes with different testing methods of circuit breakers.

Chapter 15 discusses testing, commissioning, and maintenance of relays used in the field. Different relay testing methods and relay test setups are also covered.

Chapter 16 presents applications of soft computing techniques in protective relays. Recent trends in the development of relay algorithms are also discussed in detail.

Chapter 17 provides an introduction to a new computational tool in power system engineering, PSCAD. It covers different library components and procedures for constructing a sample case. Various case studies related to the power system are discussed as tutorials at the end of this chapter.

Codes of protective devices used in control circuits as per IEC standards, fundamentals of symmetrical component theory, data sheets of various relays, and line and system parameters of simulated systems are given in the appendices.

Bhavesh Bhalja
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Nilesh G. Chothani

Brief Contents

Detailed Contents

1 Protective Relaying Fundamentals

Learning Objectives

After going through this chapter, the students will be able to:

- List the key requirements of protective devices against overload
- Differentiate between unit protection and non-unit protection
- Explain primary and backup protection of power systems
- Explain the use of thermal relay in the protection of equipment against overload
- Discuss the advantages and disadvantages of static relays and compare with electromechanical relays
- Explain the concept of adaptive relaying
- Discuss half-cycle and full-cycle discrete Fourier transform algorithm

1.1 General Background

Socio-economic growth and rapid industrialization have resulted in the fast increase in per capita consumption of electricity the world over. Modern electric power systems catering to huge energy demands are spread over wide areas and contain several major components such as generators, transformers, and transmission and distribution lines. They are designed to provide uninterrupted electrical power supply. The increase in demand has necessitated the use of large-capacity power equipment and complex interconnections among them. This has increased the pressure on the protection systems multifold.

The advent of large generating stations and highly interconnected power systems has made early fault identification and rapid equipment isolation imperative to maintain system integrity and stability. It is evident that in spite of all the precautions taken in the design and installation of such systems, there are possibilities that abnormal conditions or faults may arise. Some faults such as short circuits may prove extremely damaging not only to the faulty components, but also to the neighbouring components and to the power system as a whole. So it is of vital importance to limit the damage to a minimum by speedy isolation of the faulty section, without disturbing the working of the rest of the system.

A *fault* is a condition that causes abnormal stoppage of current in the desired path or makes the current to flow towards an undesired path. Faults include, but are not limited to, short or low-impedance circuits, open circuits, power swings, overvoltages, elevated temperature, and off-nominal frequency operation. They are generally caused by the failure of insulation, breaking of conductors, or shorting of two supply wires by birds, kite string, tree limbs, etc. Occurrence of a fault can cause the following problems:

1. Interruption in the power supply to the consumers
2. Substantial loss of revenue due to interruption of service

3. Loss of synchronism
4. Extensive damage to equipment
5. Serious hazard to personnel

All power system equipment must, therefore, be protected to avoid system collapse and the associated consequences. The protective relays stand watch and in the event of a failure such as short circuit or abnormal operating conditions, de-energize the unhealthy section of the power system and restrain interference with the remainder of it. They are also used to indicate the type and location of failure so as to access the effectiveness of the protective schemes.

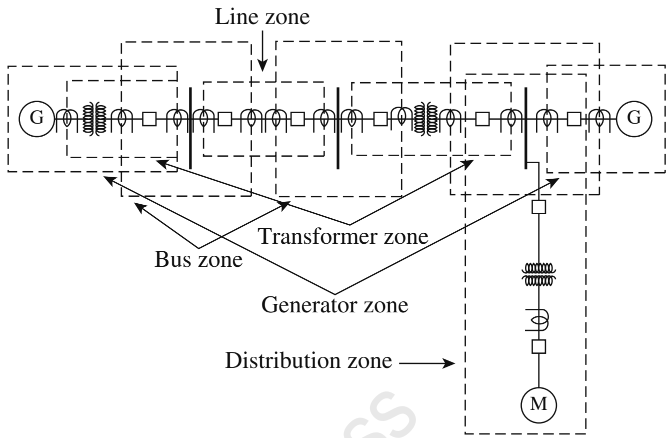


Fig. 1.1 Typical primary relay protection zones in a power system

1.2 Zones of Protection

A power system is normally segmented into a number of protective zones as shown in Fig. 1.1. A zone is protected by a system of relays, circuit breakers, and associated equipment. The circuit breakers are arranged in a manner that makes it possible to isolate the protected zone while the remaining system continues to supply energy to the customers. Each zone covers one or more components of the system. To provide complete protection for the entire system, that is, to avoid having an unprotected region, neighbouring zones are arranged to overlap each other. When a system is experiencing an abnormal condition, the relays first identify this condition and then send trip signals to appropriate circuit breakers that open to isolate the affected zone.

1.3 Requirements of Protection Schemes

Protection schemes are required to possess the following properties to perform their functions.

Selectivity This is the ability of protection devices to isolate only the faulty network of the power system from the healthy part to minimize the outage area and also to maintain normal power supply for the rest of the power system. The possibility of failure to operate and failure of protective relays and circuit breakers should be considered in determining the selectivity of protective relays. Hence, selectivity is also known as *relay coordination*. The coordination of primary relays and backup relays can be achieved by different operation zones and operation time delays.

Reliability Reliability is the ability of protection devices to operate properly during the period they are in service. It is also defined as the ability of protective devices to operate properly during their operational life. It can be categorized as follows:

Dependability It is the certainty of correct operation in response to system trouble.

Security It is the ability of the protection schemes to avoid maloperation between faults.

Speed It is apparent that quick disconnection of the faulted area or the elements can significantly improve the stability of the power system, reduce outage duration, and minimize the damage of faulted elements. Therefore, when a fault occurs, the protective relays should identify the fault and operate as fast as possible. The total time to remove the fault is determined as the sum of operation time of relays and circuit breakers. Typically, a high-speed relay can operate in the range of 10 to 30 ms. However, high operation time is not always required, especially in low-voltage systems for economic reasons.

Discrimination A protection system should be able to discriminate between fault and loading conditions even when the minimum fault current is less than the maximum full load current.

Simplicity The term *simplicity* is often used to refer to the design quality of a protective relay system. It is obvious that the simplest relay design is not always the most economical. Hence, the protective system should be as simple and straightforward as possible without disturbing its basic tasks. This improves system reliability as there are fewer elements that can malfunction and require less maintenance.

Sensitivity It is the ability of the protective device to operate correctly to the faults or abnormal conditions inside the zone of protection. It refers to the minimum level of fault current at which the protective device operates. Protective devices with good sensitivity can sense any faults within the zone of protection with respect to different fault locations, different fault types, and even different fault resistance. The sensitivity factor usually determines the sensitivity of protective relays, which depends on the parameters of protected elements and operating condition of the power system.

Economics Besides the six factors mentioned, economics of protective relays is another important factor that should be considered. A good protective relay system should combine features of both maximum protection and minimum cost. Moreover, some of these properties are contradictory to one another, and it is the duty of the protection engineer to maintain a balance among them, when choosing a protection scheme for a particular application.

1.4 Unit and Non-unit Protection

Unit protection scheme is a scheme that operates for a fault within its zone. Here, zone of protection is decided on the basis of current transformers (CTs), and includes every fault point inside the CTs where measurement of currents is carried out. This type of protection scheme is widely used in generators, transformers, and large induction motors. Differential protection scheme is the best example of this type of protection scheme.

It is universally accepted that the current-based relaying scheme is not a good choice for transmission line protection as it does not give instantaneous operation throughout the entire line. Distance relaying scheme is a good replacement for current-based relaying scheme for transmission line protection. This scheme is not affected by the ratio of source impedance to the impedance from the relaying point to the fault point. Moreover, it is less sensitive to system conditions and does not require a communication channel. A scheme that achieves protection using grading of successive relays is known as *non-unit protection scheme*. Overcurrent and distance relays are the best examples of non-unit protection schemes. However, the reach of distance relays is highly affected by fault resistance, mutual zero sequence coupling, shunt capacitances, and remote in feed. Moreover, the first zone reach of distance relays is restricted up to 80%–90% of the line because of transient overreach. More details regarding transient overreach can be found in Chapter 3. Therefore, it is not possible to achieve instantaneous operation throughout the entire line using non-unit protection schemes. This can be achieved by unit protection scheme. This concept is known as *differential protection of transmission line*.

1.5 Primary and Backup Protection

Two sets of relays, primary and backup, are usually provided for each zone of protection. Main or primary protection schemes are always there as the first line of defence. Equally important and essential is a second line of defence provided by backup schemes, which will clear the fault if the primary protection schemes fail to operate for some reason. In order to give ample time to the primary relays to make a decision, backup relays are time delayed. The measures taken to provide backup protection vary widely, depending on the value and importance of the power system equipment and the consequence of its failure. Normally, primary relays have a small operation zone but operate instantaneously, whereas backup relays have a large operation zone, namely, overreached area, and operate with a particular time delay. There are two kinds of backup relaying.

Local backup In this relaying scheme, a separate duplicate set of primary relays is used. Recently, it has been observed that local backup is required at the local station to open all the breakers around the bus, rather than at the remote terminals.

Remote backup Remote backup is provided by a relay on the next station towards the source. This remote relay will trip in a delayed time if the breaker in the faulty section has not tripped because of some reason. This is the most widely used form of backup protection.

1.6 Classification of Protective Relays

Various types of protective relays are used in practice depending on the function, actuating quantities, or component that is used. The following is the classification of protective relays.

According to the quantities by which the relay operates These are thermal relays, overcurrent relays, overvoltage/under voltage relays, under/over frequency relays, over fluxing relay, and power relays.

According to their construction These are attracted armature type relay, induction disc or induction cup type relays, and balanced beam type relays.

According to the number of sensing quantities Protective relays can be classified as single input and multiple input relays, based on this parameter. A single input relay measures (senses) only one quantity, and it responds when input quantities exceed the predetermined threshold. A multiple input relay measures two or more than two quantities and responds when the output of mixing device exceeds the predetermined threshold.

According to its function in protective scheme Relay may be divided into main relays, auxiliary relays, and signal relays.

According to components and devices used These are electromagnetic relays (mechanical devices), static relays (electronic devices), microprocessor relays (sophisticated algorithm), and digital/numerical relays (fast processor with communication facilities).

According to the characteristic they adopt Instantaneous relay, time delayed relay, and inverse time delayed relay are the best examples of this type.

1.7 Electromechanical (Electromagnetic) Relay

The earliest protective devices were fuses that were, and are, used in many situations to isolate the faulted equipment. This development was followed by the evolution of circuit breakers equipped with series trip coils. Later, first generation electromechanical relays came in the industrial market in 1901. These relays operate on the regulation of a mechanical force generated through the flow of current in windings wounded on a magnetic core and hence the name *electromechanical relay*.

Advantages

The following are the merits of electromechanical relays:

1. They are reliable in nature and still used by the utilities.
2. This relay provides isolation between the input's and output's quantities.
3. They are rugged in nature as they can withstand voltage spike due to surges and can carry substantial currents.

Disadvantages

The demerits of electromechanical relays are as follows:

1. They consist of moving parts and suffer from the problem of friction.
2. They produce low torque.
3. They suffer from the problems of high burden and high power consumption for auxiliary mechanisms.

1.7.1 Thermal Relay

Overload situation occurs many times during the operation of electrical equipment. Any electrical equipment has the ability to withstand the overload condition for a definite period of time depending on the severity of overload. Thermal relays are required to protect the equipment against the overload condition. The name *thermal relay* itself suggests that the device operates on the principle of heating effect of electrical current. The characteristic of thermal relay should match with the thermal withstanding characteristic of an equipment to be protected. Thermal relay requires a longer time (in seconds) to operate compared to overcurrent relay used for overcurrent detection, which requires a very small time (in millisecond). Figure 1.2 shows the time–current characteristic of thermal relay, overcurrent relay, and thermal withstand capability of the equipment to be protected.

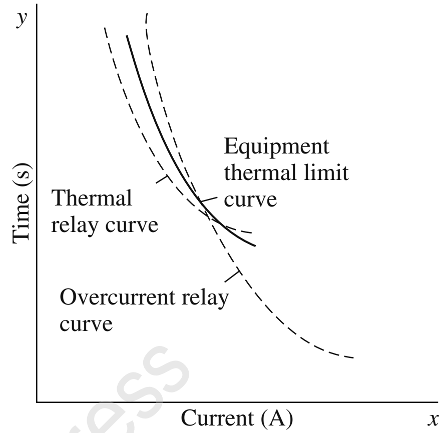


Fig. 1.2 Thermal relay characteristic

It has been observed from Fig. 1.2 that overcurrent relays cannot be used for overload protection of equipment. This is because overcurrent relays cannot fully exploit the thermal withstand capability of the equipment as it operates in the range of milliseconds. Such fast operation of overcurrent relay is not desirable for an overload condition of the equipment.

Figure 1.3 shows the replica-type thermal relay. It consists of bimetallic strips made up of nickel alloyed steel. These are heated by a heater element that absorbs the output of a current transformer in a power circuit. At one end of a bimetal strip, an insulated arm with trip contacts is provided. The arm is connected to a spring, which provides a tension against the closing of trip contacts. The characteristic of the heater element and bimetallic strips is in approximation to the heating curve of the equipment to be protected. Under normal operating condition, the bimetal strips remain in straight position against the action of spring tension. When the overload condition is detected (120% to 140% of the rated current), the bimetal strips bend and allow the trip contact to energize the trip circuit. Thermal relay is normally used for low-voltage and low-power-rating induction motor and DC motor where resistance temperature detectors (RTDs) are not generally built-in in the protected motor.

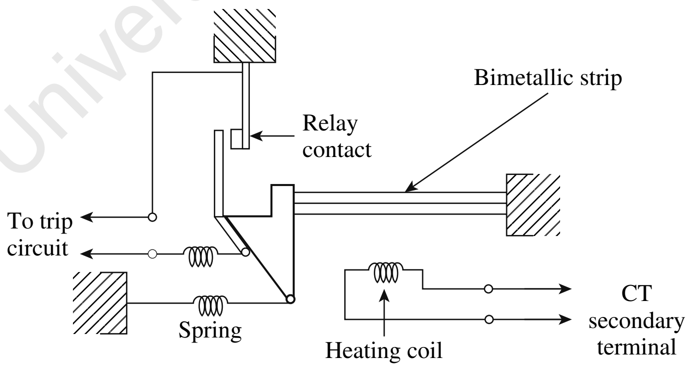


Fig. 1.3 Replica-type thermal relay

1.7.2 Attracted Armature Relay

Attracted armature relay is a simple type of protective relay, which generally consists of an electromagnet and a hinged armature or plunger/solenoid. It can be energized either by AC or DC supply. The attracted armature relay operates on the principle of electromagnetic force produced, which attracts the plunger or hinged armature. A restraining force is provided by means of a spring so that the armature returns to its original position when the electromagnet is de-energized. Whenever the force developed by the electromagnet exceeds the restraining force, the moving contact closes due to movement of the armature. Sometimes,

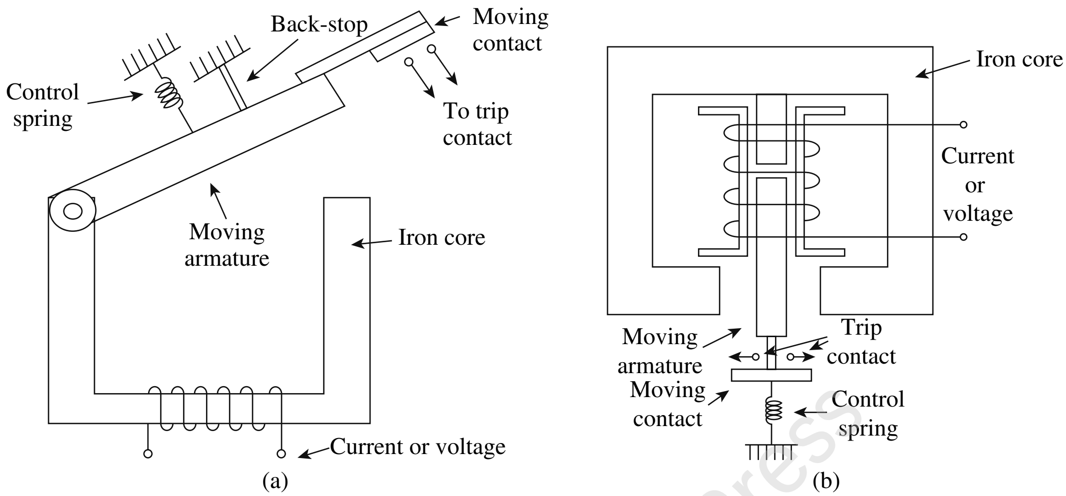


Fig. 1.4 Attracted armature relay (a) Hinged armature type relay (b) Plunger type relay

multiple contacts are mounted in parallel, which cause a single input to actuate the number of outputs. Figure 1.4 shows a hinged type (Fig. 1.4(a)) and a plunger type (Fig. 1.4(b)) attracted armature relay.

If an AC current is used, the restraining force produced by the spring is constant and the developed electromagnetic force is pulsating in nature. Hence, the relay will chatter and produce noise. To overcome this problem, the magnetic pole is split in such a way that it produces two phase-shifted fluxes in the pole such that the resultant flux is always positive and constant. These relays are fast in operation (10 and 50 ms) and fast in reset because of the small travel distance and light moving parts. Operating power, which depends on the construction, is of the order of 0.05–0.2 W. However, for a relay with several heavy duty contacts, the operating power can be as large as 80 W.

These relays are used for the protection of AC and DC equipment as an instantaneous relay that has no intentional time delay.

1.7.3 Induction Relay

The *induction relay* operates on the principle of electromagnetic induction. Hence, it is a split-phase induction motor with contacts. They are the most widely used relays for protection of lines or apparatus. Operating force is developed due to the interaction of two AC flux displaced in time and space in a movable element (rotor). Depending on the type of rotor, whether a disc or a cup, the relay is known as *induction disc relay* or *induction cup relay*.

Induction Disc Relay

Figure 1.5 shows the most commonly used shaded pole type induction disc relay. This relay is generally activated by current flowing in a single coil placed on a magnetic core having an air gap. The main air-gap flux caused because of the

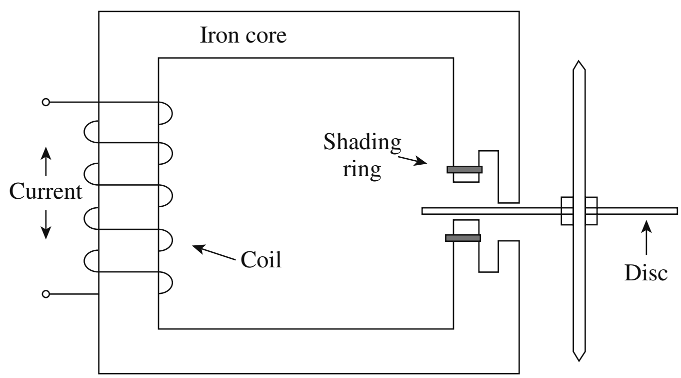


Fig. 1.5 Induction disc relay

flow of current is split into two out-of-phase components by a *shading ring*, which is made up of copper that encircles the portion of the pole face in each pole. The air-gap flux of shaded pole lags behind the flux of non-shaded pole. The rotor (made up of copper or aluminium disc) is pivoted in such a way that it rotates in the air gap between the poles. The phase angle between the two fluxes, piercing the disc, is decided at the design stage.

Induction Cup Relay

Figure 1.6 shows the constructional view of induction cup relay. In this relay, the rotating magnetic field is produced by the pair of relay coils. A rotor is a hollow metallic cylindrical cup that is arranged between two/four/eight electromagnets and a stationary iron core. The cup (looks like an induction rotor) is free to move in the gap between the electromagnet and the stationary iron core. The rotating field induces current into the cup, which then causes the cup to rotate in the same direction. The rotation depends on the magnitude of the applied AC quantities and phase displacement between them. Induction cup relay is more efficient than the induction disc relay as far as torque is concerned. Moreover, induction cup relay is faster than induction disc relay. Further, it is also used in systems where directional control is required.

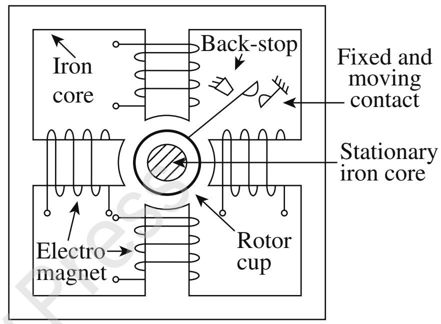


Fig. 1.6 Induction cup relay

1.7.4 Balance Beam Relay

Balance beam relay is one type of attracted armature device. As shown in Fig. 1.7, the relay with two coils surrounding the iron core is used to compare two quantities, P and Q. Operating coil produces operating torque, whereas the restraining coil produces restraining torque. These two coils are connected in such a way that their electromagnetic forces are in opposition. The electromagnetic force produced is proportional to the square of the supplied quantity (Ampere-turns). When the operating torque exceeds the restraining torque, the movement of armature closes contacts. This relay has the tendency to overreach because of a low ratio of reset to the operating current. Balance beam relay is widely used as a differential relay to compare two AC quantities.

1.7.5 Universal Torque Equation

Electromagnetic relay operates on the principle of mechanical force produced in a current conducting material because of the interaction of magnetic fluxes with their eddy currents. Figure 1.8 shows how force is produced in a part of the rotor (aluminium disc) that is penetrated by two adjacent AC fluxes. Various quantities are shown at an instant when both fluxes are directed downward and are increasing in

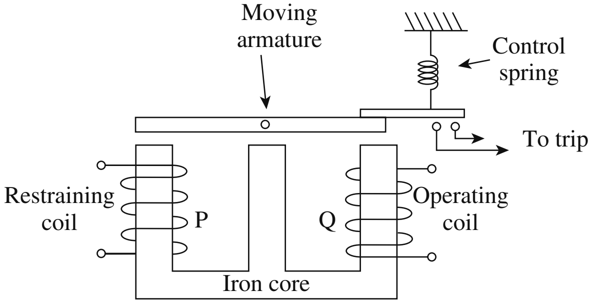


Fig. 1.7 Balance beam relay

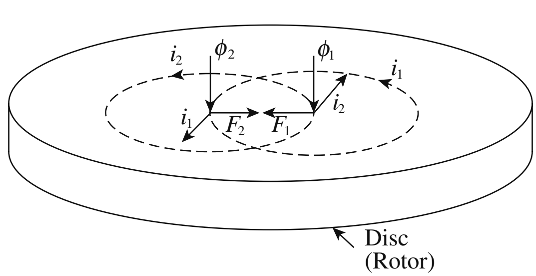


Fig. 1.8 Force production in a rotor (disc)

magnitude. Individual voltages are produced because of each flux around itself in the rotor, and currents flow in the rotor under the influence of the two voltages. The mechanical forces produced by the reaction of two fluxes act on the rotor.

With reference to Fig. 1.8, the two fluxes are given by

$$\Phi_1 = \Phi_{1\max} \sin \omega t$$

$$\Phi_2 = \Phi_{2\max} \sin(\omega t + \theta)$$

where θ is the angle by which Φ_2 leads Φ_1.

Now, assuming that the path in which the rotor currents flow has negligible self-inductance, the rotor currents are in phase with their voltages.

$$i_1 \propto e_1 \propto \frac{d\Phi_1}{dt} \propto \Phi_{1\max} \cos \omega t$$
$$i_2 \propto e_2 \propto \frac{d\Phi_2}{dt} \propto \Phi_{2\max} \cos(\omega t + \theta)$$

As the two forces F_1 and F_2 are in opposition, the resultant force (F) acting on the rotor is given by

$$F = (F_2 - F_1) \propto \Phi_2 i_1 - \Phi_1 i_2$$
$$F \propto \Phi_{1\max}\Phi_{2\max}\{\cos \omega t \sin(\omega t + \theta) - \cos(\omega t + \theta) \sin \omega t\} \tag{1.1}$$
$$F \propto \Phi_{1\max}\ \Phi_{2\max} \sin \theta$$

The resultant force is the same at every instant because the ωt component is not involved in Eq. (1.1). It is clear from Eq. (1.1) that the magnitude of force developed on the rotor depends on the phase angle θ between two fluxes. Greater the phase angle between the two fluxes, greater the magnitude of force on the rotor. With $\theta = 90°$, the net force is maximum. The direction of force and hence the direction of rotor depends on the flux that leads the other.

1.8 Solid State Relay

With the advent of electronic devices such as diode, transistor, ICs, chips, and many more static circuits, second generation of relays, that is, the static relays, came into operations in 1950s. The development of advanced protection schemes have been started on extensive experience in the use of electronics in simple protection systems. Over a period, these have been extended to cover other equipment such as transmission lines, motors, capacitors, and generators. The measurement of electrical quantities by static electronic devices, which are more accurate, can be performed, and the performance of the protection system has attained high reliability. The term *static* means the relay has no moving parts, and semiconductor devices such as diode, transistors, and ICs are used for data processing and also to create the relay characteristic. Static relay, in simple terms, can be viewed as an analog electronic replacement for electromechanical relay with some additional flexibility in settings and some saving in space requirements. By the use of non-moving parts, relay burden is reduced, which further reduces the requirement of output of CT/VT. In static relay, protective function is performed by static devices, and output signal may be controlled by electromechanical auxiliary relays. However, to operate all assembled electronic devices, static relays require separate DC power supply.

1.8.1 Types of Amplitude and Phase Comparator for Static Relays

The static relay senses the magnitude of voltage, current, and their phase angle to detect the fault. In static relays, amplitude or phase angle of any electrical quantity is compared with the set value of threshold to issue trip signal. Hence, the static relay has either amplitude comparator or phase comparator or both in its deriving circuit. Here, various methods of static comparators are discussed. The conversion between amplitude and phase comparator is described in Section 3.7, Chapter 3.

Amplitude Comparators

An amplitude comparator compares the magnitude of two or more quantities. It does not utilize phase angle value of input quantities. Amplitude comparator is classified into (i) bridge rectifier based comparators, (ii) averaging type comparators, (iii) phase splitting based comparator, and (iv) sampling comparators.

Bridge rectifier based comparators The overcurrent and differential relay operation is carried out by the use of bridge rectifier type amplitude comparators. In this comparator, rectified operating and restraining signals are given to the polarised relay or static integrator. The relay operates when the operating quantity exceeds the restraining quantity. Figures 1.9 (a) and (b) show the circulating current type and opposing voltage type bridge rectifier based amplitude comparators.

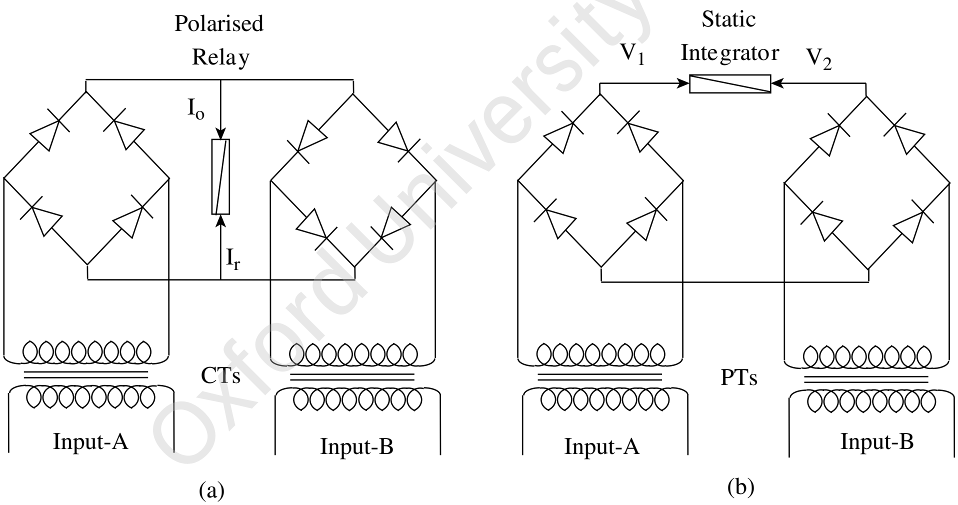


Fig. 1.9 (a) Circulating current type (b) opposing voltage type bridge rectifier based amplitude comparator

Averaging type amplitude comparator In averaging type amplitude comparator, to provide enough restrain level, the restricting quantity is rectified and smoothened to near DC value. The peak value of operating signal is compared with rectified (DC) restraining quantity. If the amplitude of operating signal exceeds the level of restrain, tripping signal is generated. Figures 1.10 (a) and (b), respectively, show the block diagram and comparison of signal for averaging type amplitude comparator.

Phase splitting type amplitude comparator In phase splitting comparator, the input quantities are divided into six components. The phase angle difference of 60°, among the six components, results in smooth rectified output. The amplitude of rectified outputs of operating and restraining signals are compared in terms of polarity detector. The phase splitting circuit and its time constant decides the operating time of

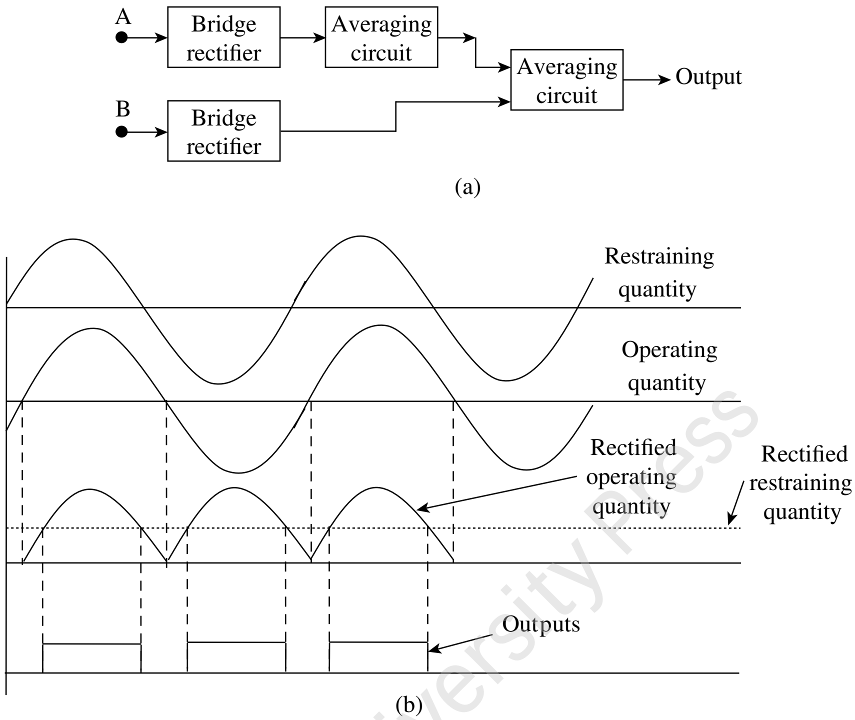


Fig. 1.10 Averaging type amplitude comparator (a) block diagram (b) comparison of signal amplitude

the comparator. Figure 1.11 shows the phase splitting of input signal and its amplitude comparator circuit.

Sampling type amplitude comparator In this comparator, one input signal is sampled and compared with instantaneous value of other input signal at a particular moment. As an example, in reactance relay, the average value of voltage is compared with the rectified current signal when it crosses zero value. Conversely, in MHO relay, the instantaneous value of current is compared with the rectified voltage signal when it crosses zero value.

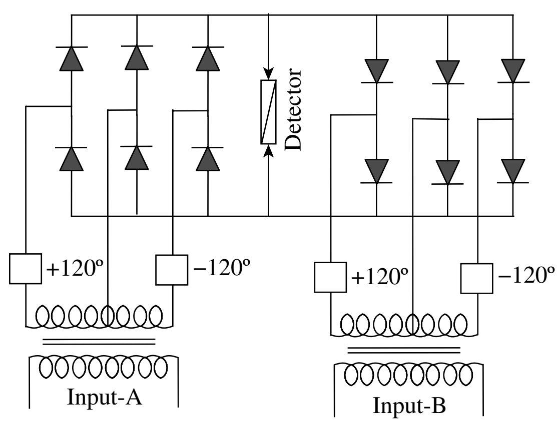


Fig. 1.11 Phase splitting type amplitude comparator

Phase Comparators

A phase comparator equates the phase angles of input signals. The output of this comparator is based on the period of coincidence of given input quantities. The phase comparator used to measure the phase difference in static relays is classified into (a) block spike type (b) phase splitting type, and (c) integrating type.

Block spike method of phase comparison Figures 1.12 (a) and (b) show the block diagram and corresponding waveform for block spike method of phase comparison. With reference to Fig. 1.12, 'α' is the period of coincidence for the given input signals A and B. These two input signals have phase angle difference of 'θ'. Hence, the period of coincidence is given by $\alpha = 180 - \theta$. The decision of trip signal is based on whether α is

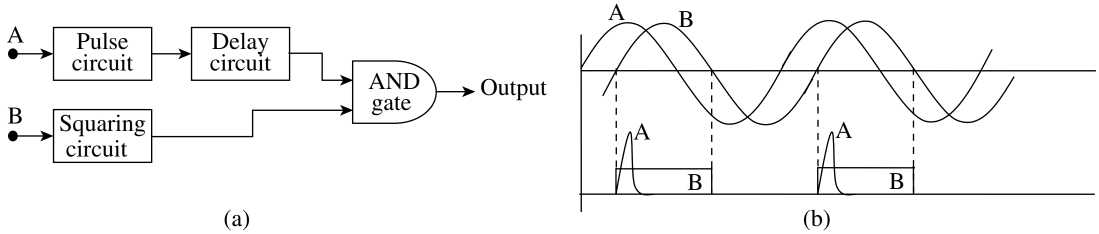


Fig. 1.12 Block spike method of phase comparison (a) block diagram (b) comparison of phase

greater or less than 90°. The output depends on the time of spike generated on coincidence of the input signals A and B. The positive rising edge of the given input signals are compared for their coincidence.

Phase splitting method In this method, as shown in Fig. 1.13 (a), the input signals A and B are divided into two components each shifted by phase displacement of ± 45° from the original. These four components are fed into the AND logic gate. As shown in Fig. 1.13 (b), the output is available only when all four inputs become simultaneously positive at any time (coincidence) in a cycle. The trip signal is obtained for $-90° < \alpha < 90°$, where α is the angle by which one signal (B) lags behind the other signal (A).

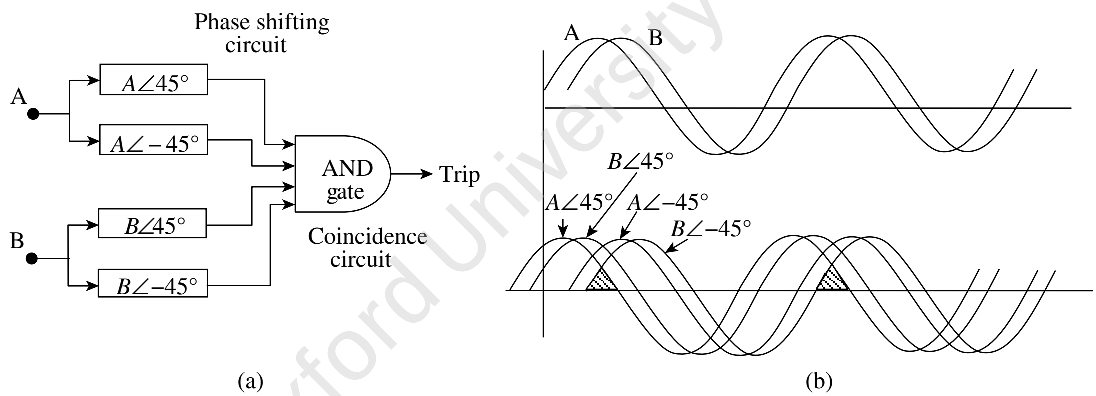


Fig. 1.13 Phase splitting comparator (a) block diagram (b) waveform of phase split input

Integrating type phase comparator In this comparator, the time of coincidence of two input signals is measured using AND logic and integrator circuit. As shown in Figs 1.14 (a) and (b), the output of AND logic is a square pulse when the two input signals (A and B) overlap in their respective positive half cycle. The integrator is R-C charging circuit whose output is given to the level detector. If the output of integrator is more than 900, the relay issues trip signal.

1.8.2 Comparison between Static and Electromagnetic Relays

The following subsections discuss the many advantages and limitations that static relays have in comparison with electromagnetic relays.

Advantages of static relays Static relays have many advantages in comparison to the corresponding electromagnetic relays. These are as follows:

1. Static relays do not contain moving parts. Therefore, they are free from problems such as contact bouncing, arcing, erosion, friction, and maintenance.
2. They have high operating torque with respect to electromechanical relays.

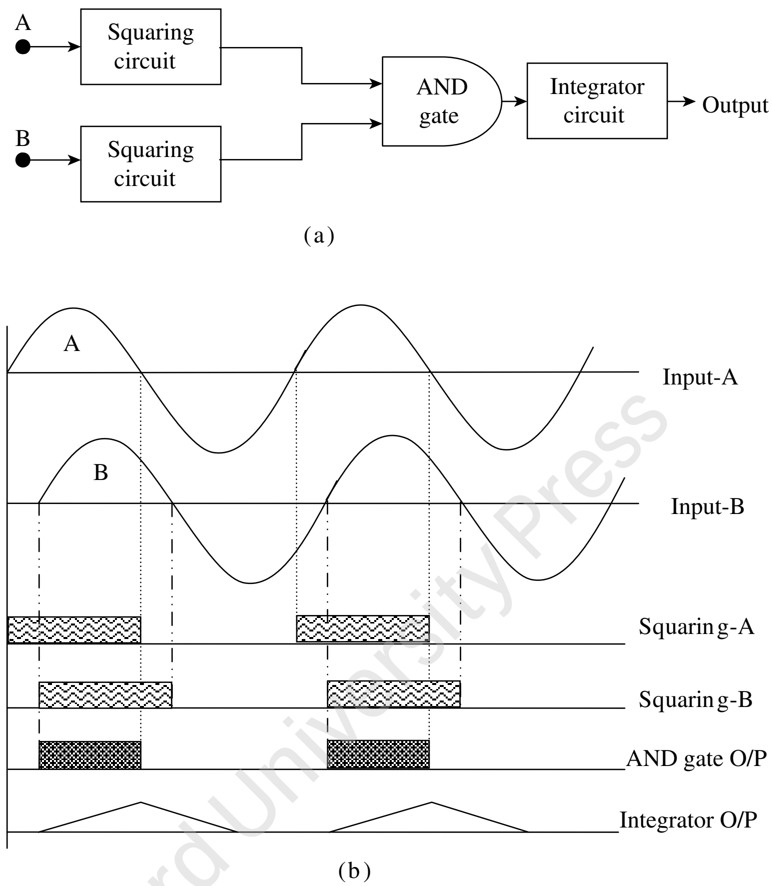


Fig. 1.14 Integrator type phase comparator (a) generalised diagram (b) input and output waveform for phase comparison

3. They place significantly less burden on instrument transformers than that placed by electromechanical relays.
4. They are compact in size.
5. They can incorporate variety of functions in a single unit.
6. Absence of moving parts in static relays leads to quick response and quick reset action. Further, they are free from the problem of overshoot owing to the absence of mechanical inertia.
7. Greater sensitivity can be obtained in static relays owing to the provision of amplification block.
8. The use of electronic devices enables achieving a greater degree of superiority in determining the operating characteristic closer to ideal characteristic as per requirement.

Limitations of static relays However, static relays also have certain shortcomings as listed here.

1. Electronic components are more sensitive to voltage spike and other transients that cause malfunctioning of static relays.
2. Auxiliary DC supply is required to operate the static relay.
3. The characteristics of electronic devices are affected by variation in temperature and ageing of semiconductor devices.
4. Static relays have low short time overload capacity compared to electromagnetic relays.

5. The reliability of static relays depends on the quality and number of small components and their electrical connection.
6. Static relays, for a particular function, are costlier compared to the corresponding electromagnetic relays.
7. Complex protective functions require highly trained persons for the servicing of static relays.

Therefore, the prime problem with electromechanical and static relays is that there is no continuous check on their operational integrity.

1.8.3 Classification of Static Relays

Various static relays have been designed by various manufacturers. They are classified according to the type of measuring unit and comparator they possess.

Electronic relays These relays use electronic valves for measuring unit and electronic tubes for comparator.

Magnetic amplifier relays (Transductor) These relays possess operating winding and controlling winding. Both are wounded on a common magnetic core. Restraining quantities are applied to the control winding, whereas relay quantities are applied to the operating winding. When operating value exceeds the magnitude of restraining value, a voltage is induced in the output winding wounded on the same core.

Rectifier bridge relays These relays make use of semiconductor devices. They consist of two rectifier bridges and a moving coil element. These are arranged in such a way that they work either as amplitude comparators or as phase comparators.

Transistor relays As transistors are able to perform amplification, summation, switching, and comparison tasks, they overcome many problems. Hence, it is possible to develop sensitive, high-speed, and precise static relays. Transistor circuit provides the necessary flexibility to outfit various relay requirements and to design various relay characteristics. These static relays are most widely used for the protection of electrical equipment and distribution feeders.

Static relays are also classified according to the protection requirement.

1. Static overcurrent relays
   (a) Static instantaneous overcurrent relays
   (b) Static definite minimum time overcurrent relays (DMT)
   (c) Static inverse definite minimum time overcurrent relays (IDMT)
2. Static directional relays
3. Static differential relays
4. Static distance relays

1.8.4 Generalized Static Time Overcurrent Relays

Different manufacturers have designed many static relays. However, due to space limitation, it is not possible to cover all the static relays here. Hence, the most widely used generalized static time overcurrent relay is discussed here.

Figure 1.15 shows the block diagram of a generalized static time overcurrent relay. This relay can be designed to achieve any characteristic such as instantaneous time overcurrent relay, DMT or IDMT.

Initially, the secondary current of CT is rectified and filtered. The filtered output of rectifier is supplied to the timing and curve shaping circuit,

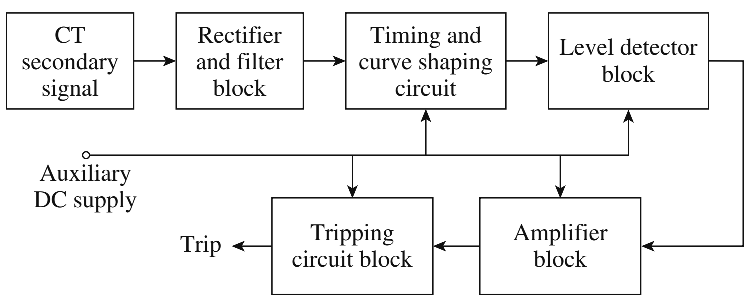


Fig. 1.15 Generalized block diagram of static time overcurrent relay

which contains non-linear resistors and RC networks to shape the time–current characteristic. The output of timing circuit is given to the level detector, which compares the relay quantities with reference quantities. If the magnitude of the relaying quantities exceeds the magnitude of the reference quantities (threshold value), it generates a voltage signal. The generated voltage signal is amplified by an amplifier block and fed to the tripping circuit. The tripping circuit may be an electromagnetic one or a static one. At last, the tripling circuit generates a tripping command, which will be given to the trip coil of circuit breaker. Suitable DC auxiliary power supply is provided to static relay from separate rectifier or from station battery.

1.8.5 Static Differential Relay

Figure 1.16 shows the basic block diagram of a simple static differential relay. The input signals (A and B) are initially scaled down to nominal value of current by current transformer. The rectifier bridge type amplitude comparator, as discussed previously, is used as a static comparator to check the difference of input signals. The output of the comparator is given to the integrator and the level detector followed by the driving circuit. The driving circuit issues a trip signal if the desired condition is fulfilled in terms of magnitude comparison.

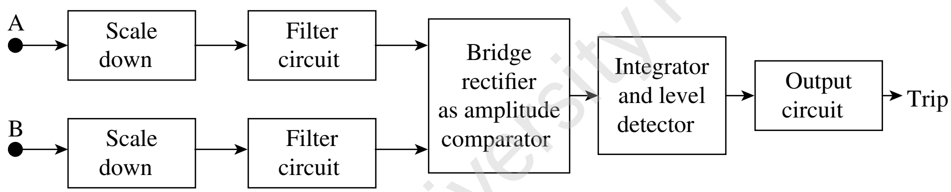


Fig. 1.16 Block diagram of static differential relay

1.8.6 Static Distance Relay

In static distance relaying scheme, both amplitude and phase comparator are used as per the requirement of distance characteristic. Figure 1.17 shows the schematic block diagram of phase comparator based static distance relay.

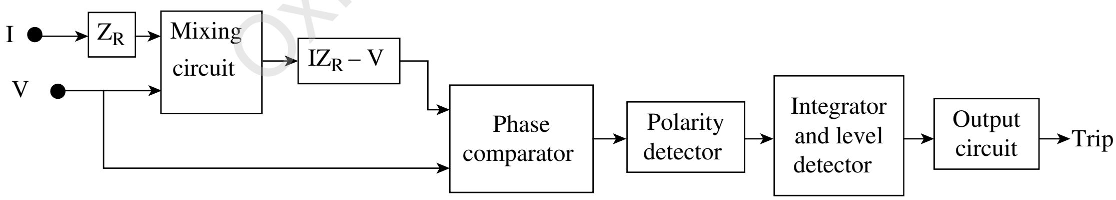


Fig. 1.17 Block diagram of static distance relay

In Mho type static distance relay, the input voltage and current from CT and PT, respectively, are scaled down and given to the mixing block. The current signal is passed through a predefined replica type impedance (Z_R). The phase comparator measures the phase angle difference (θ) between voltage signal (V) and 'IZ_R-V'. The phase comparator, used for static distance relay, follows the principle of coincidence of two input signals to detect the phase angle difference. The polarity detector detects whether θ lies within ±90°. The level detector balances whether the measured operating point falls below Z_R. If the above condition is satisfied then the output circuit immediately issues a trip signal. For discrimination of zone fault, a timer circuit is integrated into the output circuit so as to provide intentional time delay.

1.9 Digital Relaying

By 1970, advances in the very large scale integrated (VLSI) technology and software techniques led to the development of third generation microprocessor-based relays. Early designs used the fundamental approaches that were previously used in the electromechanical and solid-state relays. Though complex algorithms for implementing protection functions were developed, the microprocessor-based relays marketed till 1980s did not incorporate them. However, these relays, which performed basic functions, took advantage of the hybrid analog and digital techniques, and offered good economical solution. Though the performance of these relays was just adequate their introduction was appreciated by the highly conservative world of power system protection. Continuous advances in electronics, combined with extensive research conducted in the microprocessor-based systems, led to a few applications where multiple functions were performed by a microprocessor relay. By late 1980s, multifunction relays were introduced in the market. These devices reduced the production and installation costs drastically. Utilities are using microprocessor-based, dedicated, and economic protective modules in the protective relaying schemes.

With the advent of digital computing technology, digital relaying is a very promising area of thought. In 1969, Rockefeller came out with his landmark paper on the use of digital computer for protection purposes. Since then, digital relays also have gone through revolutionary changes, thanks to the advent of low-cost, high-performance, high-density, large-scale integrated digital circuits, particularly microprocessor and related devices. With the change in technology, it became evident that a single computer for the protection of all the equipment in a substation was not an efficient approach in view of the presently available computer hardware. A probable solution to this problem is to use a number of microprocessors dedicated to individual equipment relaying tasks with an inter-computer data exchange facility. The concept of digital computer relaying has grown rapidly as digital computers have become more powerful, cheaper, and sturdier. It is to be noted that digital relays can realize some very useful functions, which are not possible with electromechanical or analog circuits such as mathematical functions, long-term storage of pre-fault data, and, they also inherit all the features of microprocessor-based relays. However, these computer relays do not have successful solutions to cumbersome problems such as high fault resistance, mutual coupling, remote infeed, time delay, and so on, which have been bothering relay engineers for many years. The fourth generation of relays, that is, digital relays, came into the market in the 1990s. Let us now discuss some features of these relays.

1.9.1 Merits and Demerits of Digital Relay

Digital/numerical relays have many advantages over electromechanical/static relays:

1. They provide many functions such as multiple setting groups, programmable logic, adaptive logic, sequence-of-events recording, and oscillography.
2. Digital relays have the ability of self-monitoring and self-testing, which were not available in electromechanical/static relays.
3. Digital relays have the ability to communicate with other relays and control computers.
4. The cost per function of digital/numerical relays is lower as compared to the cost of their electromechanical and solid-state counterparts. The digital relays include all the relay characteristics in one group. For example, in IDMT relay, digital relay includes normal inverse, very inverse, extremely inverse, and many more characteristics in one group. On the other hand, in case of electromechanical/static relays, one has to purchase a separate unit for each characteristic.
5. A major feature of digital/numerical relays, which was not available in previous technologies, is the ability to allow users to develop their own logic schemes, including dynamic changes in that logic.
6. Digital/numerical relays place significantly less burden on instrument transformers than the burden placed

by the relays of the previous technologies.

7. Digital protection systems require significantly less panel space than the space required by electromechanical and solid-state systems that provide similar functions.
8. Reporting features, including sequence-of-events recording and oscillography, are another feature of digital relays.

However, digital/numerical relays have certain shortcomings:

1. Digital/numerical devices, including the protection systems, have short life cycles. While each generation of microprocessor-based systems increases the functionality compared to the previous generation, the pace of advancements makes the equipment obsolete in shorter times. This makes it difficult for the users to maintain expertise with the latest designs of the equipment.
2. Another variation of this shortcoming is in the form of changes in the software used on the existing hardware platforms. Sometimes, these changes effectively generate newer relay designs. This requires that a software tracking system be used for each device owned by a utility.
3. Electromechanical relays are inherently immune to electrical transients such as electromagnetic interference (EMI) and radio frequency interference (RFI). Early designs of solid-state relays were susceptible to incorrect operations owing to transients, but later designs included adequate countermeasures. Because of a better understanding of the problems, digital/numerical relays were designed in a manner that provided excellent reliability under the said conditions as long as they conform to the IEEE Standard C37.90 or IEC 61000 series of standards. However, digital/numerical relays will always remain more susceptible to such problems because of the nature of the technology compared to the systems built with the electromechanical technology.
4. Many digital/numerical relays, which are designed to replace the functions of several electromechanical and static relays, offer programmable functions that increase the application flexibility compared to the fixed function relays. The multifunction digital/numerical relays, therefore, have a significant number of settings. The increased number of settings may pose problems in managing the settings and in conducting functional tests. Setting-management software is generally available to create, transfer, and track the relay settings. Special testing techniques, specifically the ability to enable and disable selected functions, are generally used when digital/numerical relays are tested. This increases the possibility that the desired settings may not be invoked after testing is completed. Proper procedures must be followed to ensure that correct settings and logic are activated after the tests are completed.

1.9.2 Generalized Block Diagram of Digital Relay

Figure 1.18 shows the basic block diagram of a digital relay. Analog signals, such as currents and voltages acquired from the power system network, are processed by a signal conditioning device, which consists of isolation transformer, surge protection circuit, and anti-aliasing filter (AAF). Isolation transformer provides the electric isolation, whereas surge protection circuit gives protection to the digital component against transients and spikes. AAF is a low pass filter that blocks the unwanted frequency component. Further, it also avoids aliasing error. According to Nyquist criterion, the sampling frequency must not be less than two times the maximum frequency contained in original signal.

$$f_s \geq 2 \times f_m \tag{1.2}$$

where,

f_s = sampling frequency and f_m = maximum significant frequency within the signal sample.

It is to be noted that this processing is true if conventional transducers are used. On the other hand, these input signals can be given directly to the central processing unit (CPU) if electronic CTs and CVTs

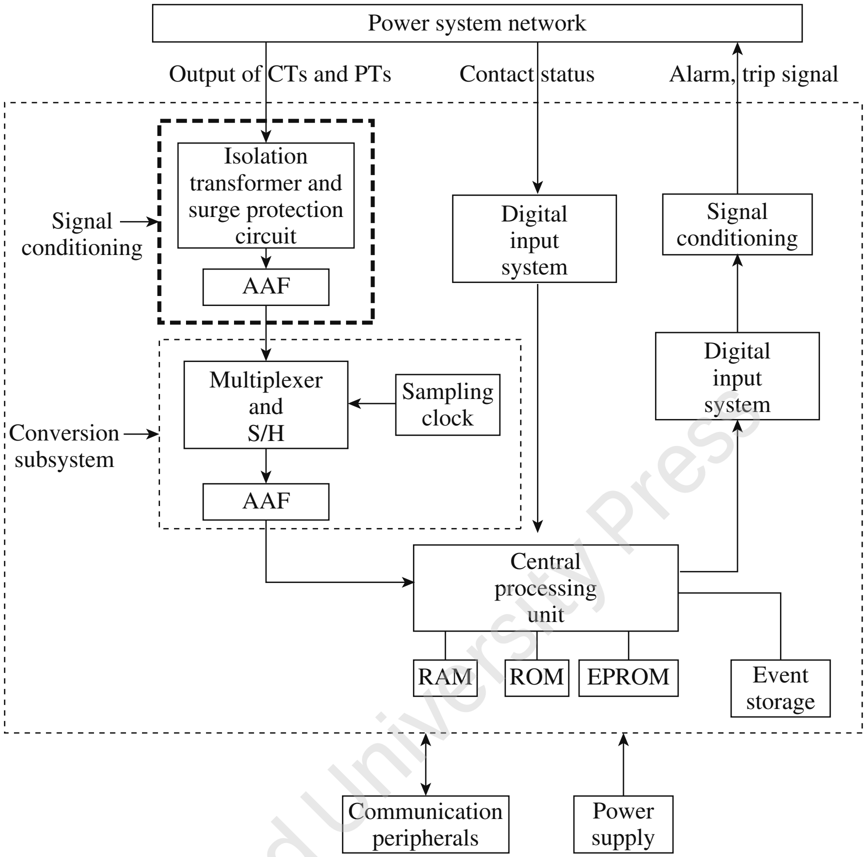


Fig. 1.18 Basic block diagram of digital relay

are used. These signals are given to the CPU through multiplexer and analog to digital converter (ADC), which samples, combines, and converts the analog signal into digital form. The input signals are frozen by sample and hold circuit to achieve synchronized sampling between all the acquired signals. The digital input, such as status of circuit breaker contacts, status of local and remote end relays, and reset signals are acquired by the digital input system and transferred to the CPU. CPU is the core component of digital relay, where all processes regarding different logics/algorithm have been carried out. CPU executes the relay programme with a different characteristic, maintains different timing function, and communicates with external devices.

Several memory units are allocated for data storage and data processing purposes. The random access memory (RAM) stores the input sample data temporarily and buffer data permanently. Further, the stored data in RAM is processed during the execution of relay algorithm. The read only memory (ROM) is used to store the relay algorithm permanently. EPROM is used to store certain parameters such as relay setting. These parameters may change in case of change in external system conditions. The event storage block is used for storing historical data such as fault related data, transient data, and event time data.

The digital output system provides the tripping, alarm, and other control signals to activate the external devices in the power system. A self-diagnosis software available in the digital relay checks integrity of the relay at regular intervals. This feature allows the relay to remove itself from service when a malfunction occurs and to alert the control centre. Relay setting, data uploading, and event data recording are done through the various peripheral communication ports. A common communication protocol IEC 61850 has been adopted by relay manufacturers to increase the interoperability of the relays among the local and remote substations.

The digital relays are usually powered from the station battery, which is provided with a battery charger. This ensures that the relays will operate during outages of the station AC supply.

1.9.3 Sampling and Data Window

The process of converting a continuous analog signal into a discrete-time signal is known as *sampling*. This task is carried out by ADC along with sample and hold circuit. Certain fixed interval is used to acquire the next (new) value of sample (quantity). This interval is known as *sampling interval*. The reciprocal of sampling interval is referred to as the *sampling frequency*.

Figure 1.19 shows the simple circuit of acquiring samples of a continuous analog signal. For a fixed sampling interval, the switch S operates using a periodic pulse and remains in closed condition. During the sampling interval, the capacitor is charged at a level of instantaneous value of the signal. This value is known as the *sampled value of the quantity* (e.g., voltage) for a particular period during which the switch S remains in closed condition. The switch S is opened at the desired instant. The quantity (e.g., voltage) is then fed to the ADC, which gives the digital value depending upon the value of sampled signal.

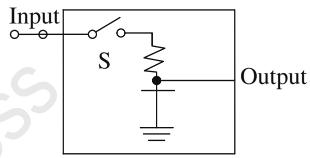


Fig. 1.19 Basic circuit of sampling

This entire process is known as *sampling and quantizing*. This can be obtained by two different approaches.

1. One approach is to acquire a sample at every sampling interval. In this approach, the necessary computations are carried out by algorithms before the next sample is acquired.
2. The other approach is to acquire a set of samples at a particular time, store them in a buffer, and thereafter, perform necessary computations by algorithms before the next set of samples are acquired.

Now, assuming the fundamental frequency of 50 Hz, the sampling frequency is given by

$$f_s = f \times n \tag{1.3}$$

where,

f_s = sampling frequency (Hz)
f = fundamental frequency (Hz)
n = number of samples/cycle

Data window is the window having a set of acquired samples that are used to obtain an estimate of the acquired signal/quantity. Figure 1.20 shows the concept of data window, which uses three samples at a time in a window. It is to be noted that in each data window, the number of samples remain constant (three samples in the case). Therefore, when the next sample is acquired, the previous sample is discarded. Whenever a new sample is taken, the data window advances, that is, slides ahead. Hence, this concept is also known as *sliding window* concept.

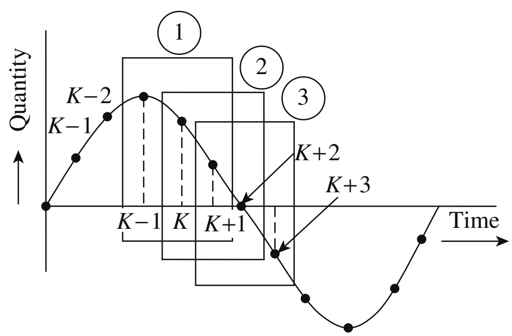


Fig. 1.20 Concept of data window

1.10 Adaptive Relaying

Conventionally, the relays are provided with setting switches and other means that can be selected/adjusted by the operator, depending on the operating condition of the system. Since changes and events occur quite rapidly in a power system, human intervention to change setting switches to cope with every system change is not possible. Therefore, the settings are usually selected on the basis of the worst case and changed only when a major change in the system configuration is made. This requires high degree of professionalism on the part of the user to decide as to when and what changes to make in the settings. Furthermore, the relay settings that are selected for the worst case would generally give slow speed, low sensitivity, or poor selectivity on other conditions in the protected system. Last, but not the least, a fixed operating characteristic of a given relay may not be able to give the requisite speed, selectivity, and sensitivity on all the operating conditions of the protected system. Relay engineers have dreamed that relay could adapt to the system changes. With the development of high-speed microprocessors, new tools for signal processing and digital communication techniques, this dream is fast turning true. With the use of programmable devices in digital relays, it is possible to design a relay such that it changes its settings, parameters, or even the characteristic automatically and appropriately in accordance with the changed condition of the system protected by it. A relay having such a feature is called an *adaptive relay*. The idea of modifying relay settings to correspond to changing system conditions, as a preventive action to improve system stability, was first proposed by DyLiacco in 1967. Thereafter, different researchers have given different definitions of adaptive protection. All these definitions narrate the same facts in different forms. Therefore, adaptive relaying is defined as 'changing relaying parameters or functions automatically depending upon the prevailing system condition or requirements'. The adaptive relaying philosophy can be made fully effective only with computer-based relays.

1.11 Tripping Mechanism of Relay

The relay is always connected in the secondary circuit of CT and potential transformer (PT) irrespective of the type of relay. The main function of any type of relay is to detect or sense the inception of fault, whereas the tripping task is carried out by the auxiliary relay and circuit breaker. Since the relay only does the function of sensing, the speed of the relay is increased, and hence, it operates at a very high speed. *Auxiliary relay* is a relay that carries high value of trip coil current during a fault. Moreover, it also gives signals to perform certain other functions associated with relays such as alarms and interlocking. Figure 1.21 shows the basic tripping circuit of any type of relay.

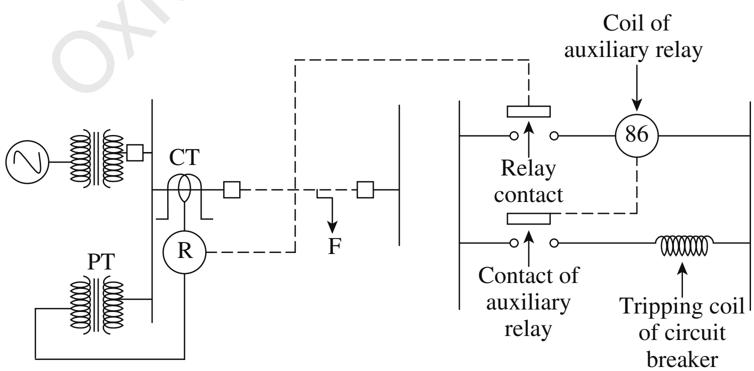


Fig. 1.21 Power circuit and control circuit of operating mechanism of any relay

If single input relay is used (current-based relay or voltage-based relay), then the relay receives a signal from the secondary of CT or PT only. Conversely, for two input relays, it receives signals from the secondary of both CT and PT. As shown in Fig. 1.20, the relay R senses the fault F within a fraction of second (in millisecond) and gives signal to the auxiliary relay through its contact. The contact of auxiliary relay closes owing to energization of the coil of auxiliary relay. This will further energize the trip coil of the circuit breaker.

1.12 Digital Filters

A digital filter is a device which executes mathematical operations on a discrete-time signal to decrease/increase definite aspects of that signal. Filtration of signals is important in protective relaying schemes for the evolution of signal whether it has such information or not like CT saturation, Magnetising inrush, Power swing, Harmonic and noise analysis etc. For filtering a signal in digital relaying schemes, various types of digital filters are utilized. Also, there is a wide difference between analog and active filters.

Normally, filters are formed by utilizing combinations of resistance, inductance, and capacitance. Figures 1.22 (a) and (b) show the basic circuit of low pass and high pass filter, respectively. These filters are known as analog filters. If the output of analog filter is added with amplifier then this filtering circuit is known as active or digital filters. The circuit of digital filter is shown in Fig. 1.22 (c) in which X_n is the input signal and Y_n is the output signal.

Some of the limitations of analog filter are as follows.

1. Due to the large space requirement of inductor, analog filters are bulky in size. Hence, they become expensive due to the requirements of highly precise components.

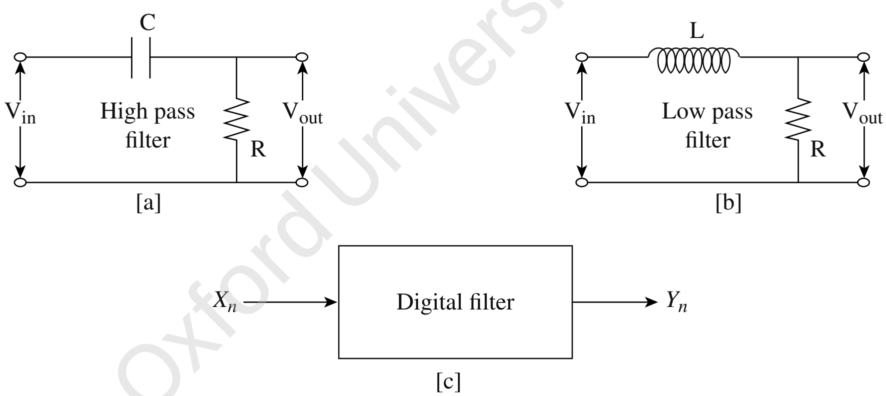


Figure 1.22 (a) High pass filter (b) Low pass filter (c) Digital filter

2. Characteristic drifts also occur in analog filter with respect to temperature and time. Even for low frequency filtration, it requires a large valued component which is impractical.
3. Analog filters do not have the ability to change their characteristics with respect to input signals. Hence, they are not adaptive and programmable.

A digital filter rectifies all the above problems of analog filters. They do not even require highly precise R, L, and C components. The basic hardware required for all types of digital filters are an anti-aliasing filter with sample and hold (S/H) circuit, analog to digital (ADC) and digital to analog (DAC) converter with digital processor, and a reconstruction filter for smoothing the signals. The simplified representation of a digital filter is shown in Fig. 1.23. As shown in Fig.1.23, anti-aliasing filter is always placed before the sample and hold (S/H) circuit to prevent the detrimental effect widely known as aliasing. Then, the signal is processed through S/H circuits in which analog to digital conversion is carried out by the processor. Finally, it converts the digital value to analog value. Since the output of DAC is like a staircase the smoothing filter is required.

As shown in Fig. 1.23, $x[n]$ is the continuous time signal whereas $y[n]$ is the processed discrete time signal. Moreover, $x_a(t)$ and $y_a(t)$ are the continuous and discrete time equivalent of the signal, respectively.

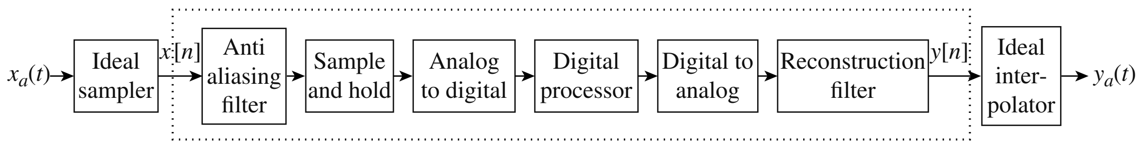


Fig. 1.23 Simplified representation of digital filter

The several benefits of digital filters include easy to change filter characteristics through programming, immune to ageing and drift against time and temperature variations, and no maintenance and tuning.

Digital filters are classified as follows

1. Low pass filters
2. High pass filters
3. Finite Impulse Response (FIR) filters
4. Infinite Impulse Response (IIR) filters

1.12.1 Simple Low Pass Filter

A low pass filter is a device which allows signal with a frequency lower than a definite cutoff frequency and attenuates signals with frequencies higher than the cutoff frequency. The operation of a low pass filter depends on the running average of the last two samples. The internal structure of a digital low pass filter is shown in Fig. 1.24 (a). In this filter, the R-C circuit behaves as a filtering circuit and its output is given to the amplifier. 'A_n' is the sample for filtration and 'B_n' is the filtered output.

The filtered output of low pass filter is given by Eq. (1.4),

$$B_n = \frac{A_n + A_{n-1}}{2} \tag{1.4}$$

The frequency against amplitude characteristic of a low pass filter is shown in Fig. 1.24 (b). In this figure, 'F_H' indicates pass band which filters higher frequency signal. The region between pass band and stop band is known as transition region.

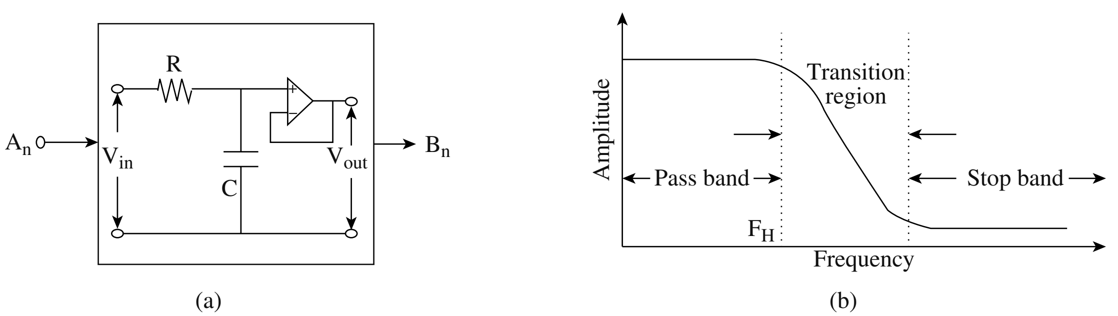


Fig. 1.24 (a) Internal structure of low pass filter (b) Frequency vs amplitude characteristic

The output of a low pass digital filter is shown in Fig. 1.25. As shown in Fig. 1.25, the second sample at the input of the digital low pass filter has a large magnitude and has positive polarity, whereas the third sample has an equal magnitude but opposite polarity. Here, as noise signal is considered as a high frequency signal it rides over the low frequency signal. However, as the output of digital low pass filter is formed by taking the running average of last two samples, the effect of positive spike cancels the effect of negative spike and hence, a smoother output signal, as shown in Fig. 1.25, is achieved.

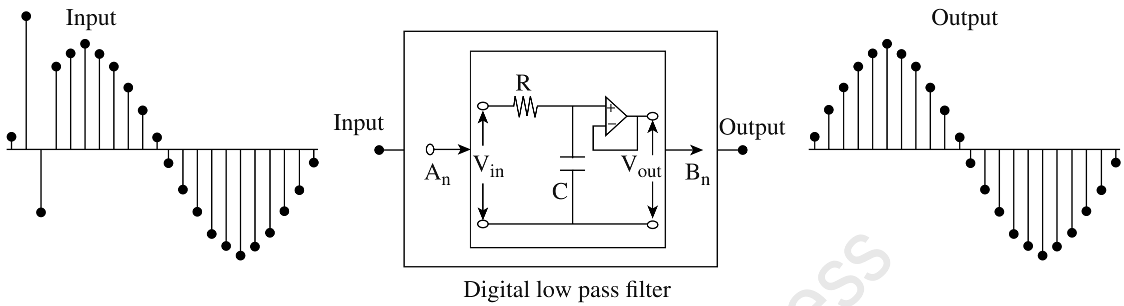


Fig. 1.25 Output of low pass filter

1.12.2 Simple High Pass Filter

A high pass filter is an electronic filter that allows signals with a frequency higher than a certain cutoff frequency. At the same time, it also attenuates signals with frequencies lower than the cutoff frequency. The amount of attenuation for each frequency depends on the design of filter. Figure 1.26 shows the internal

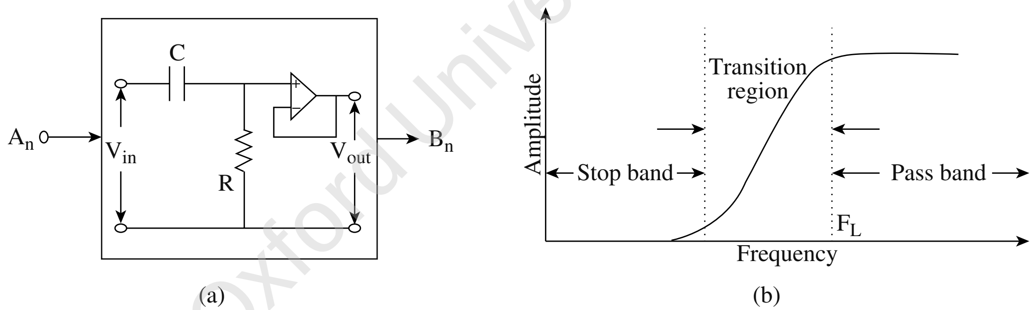


Fig. 1.26 (a) Internal structure of high pass filter (b) Frequency v/s Amplitude characteristic

structure of a high pass filter along with its amplitude and frequency characteristics. The cutoff frequency is shown as F_L, in Fig 1.26 (b). This means that the filter allows signal which has frequency more than the cutoff frequency. The high pass filter filters signals by taking a running difference of samples. Mathematically, it is given by Eq. (1.5).

$$B_n = \frac{A_n - A_{n-1}}{2} \tag{1.5}$$

Figure 1.27 shows the output of a high pass digital filter. In case of a sudden change in input signal, the high pass filter amplifies the sample by taking the difference of results. As shown in Fig. 1.27, the second sample with positive polarity and the third sample with negative polarity having higher frequencies are visible in input signals. After filtering, only high frequency signals are highlighted in the output.

The combination of low pass filter and high pass filter behaves as a band pass filter. The characteristic of band pass filter is shown in Fig. 1.28. The frequency spectrum is bounded by the limit $F_L > F > F_H$. This indicates that the filtering must be carried out between F_L (lower frequency limit) and F_H (higher frequency limit).

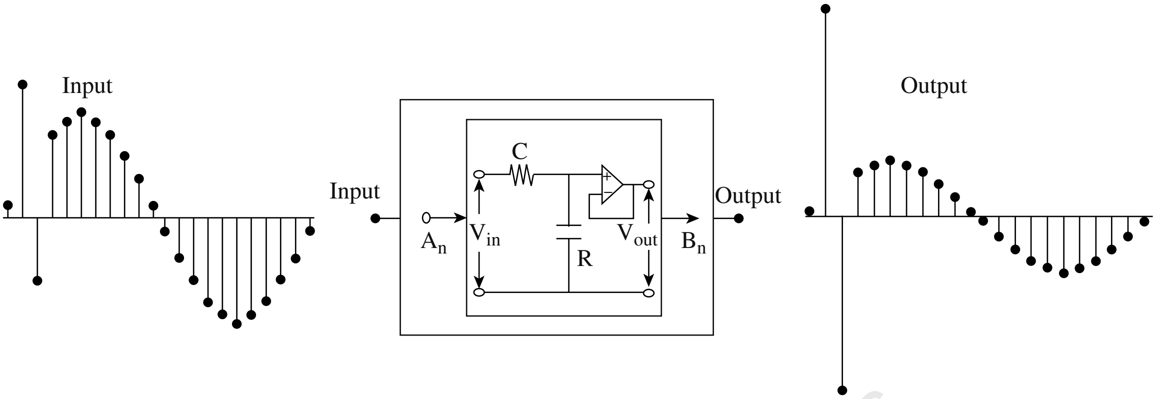


Fig. 1.27 Output of high pass digital filter

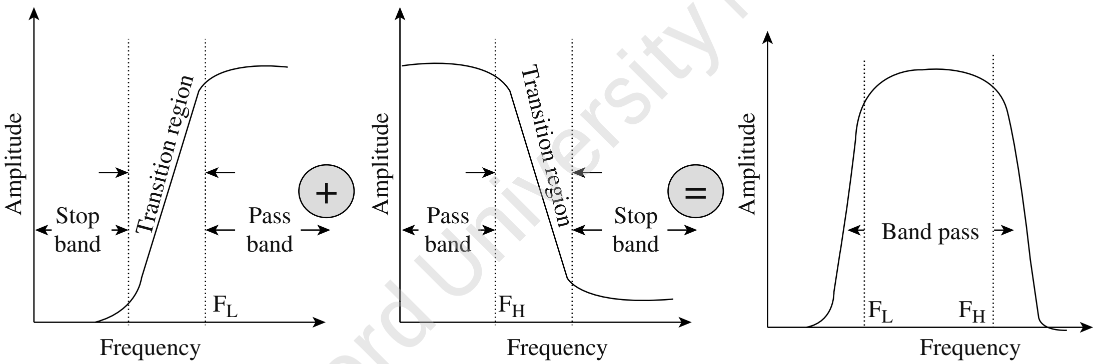


Fig. 1.28 Band pass filter as combination of low and high pass filter characteristics

1.12.3 Finite Impulse Response Filter

When the impulse response is followed by a finite number of terms it is known as finite impulse response (FIR) filter. The standard FIR filter is also known as *transversal filter*. Figure 1.29 shows the input–output response of a digital FIR filter. The output samples are formulated by filtering the weighted sum of the input samples and a limited number of previous input samples. Hence, samples of the impulse response are important for analysing and decision-making of the system. Thus, the output of FIR filter with length 'm' is

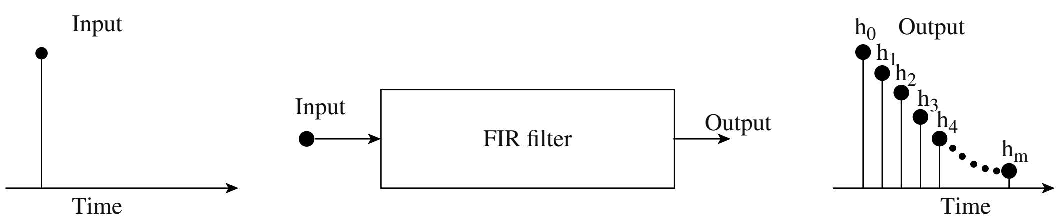


Fig. 1.29 FIR filter input–output results

given as an incoming sequence of samples with impulse response of the filter. The simplified representation of an FIR filter in the form of a block diagram is shown in Fig. 1.30.

The n^{th} output is given by Eq. (1.6)

$$B_n = h_0 A_n + h_1 A_{n-1} + \dots\dots + h_m A_{n-m} \qquad (1.6)$$

In order to store m samples and $(m + 1)$ numbers of coefficients, the memory requirement should be sufficient.

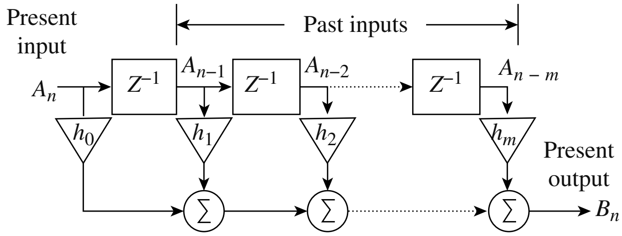


Fig. 1.30 Block diagram and simplified representation of FIR filter

The frequency response of FIR filter is given by Eq. (1.7)

$$f(j\omega) = \sum_{n=0}^{m} e^{(-j\omega n \Delta t)} . h_m \qquad (1.7)$$

where Δt = sampling inverter, h_m = set of co-efficients, ω = frequency.

From Eq.(1.7), it is clear that the frequency response depends on the frequency of input signal, sampling interval, and the set of coefficients. Also, the Fourier transform of the impulse response and periodic function having 2π/Δt period is considered to achieve good frequency response.

The transfer function of filter in Z-domain is given by Eq (1.8),

$$\frac{B_n}{A_n} = \frac{h_0 z^m + h_1 z^{m-1} + h_2 z^{m-2} + \dots\dots + h_m}{z^m} \qquad (1.8)$$

1.12.4 Infinite Impulse Response Filter

The infinite impulse response (IIR) filter is characterized by n^{th} number of samples in which the output is derived using both previous input and output values. The coefficients h_0, ….., h_m are similar as that of FIR filter, whereas the coefficients i_1, …., i_k form the recursive part of the filter. Figure 1.31 shows the block diagram of input–output signals of an IIR filter. Many alternative ways are available for the implementation of IIR filter. Figure 1.32 shows the basic circuit diagram of an IIR filter.

The output with n samples is given by,

$$\begin{aligned} B_n &= h_0 A_n + h_1 A_{n-1} + \dots\dots\dots + h_m A_{n-m} \\ &+ i_1 B_{n-1} + i_2 B_{n-2} + \dots\dots\dots + i_k B_{n-k} \end{aligned} \qquad (1.9)$$

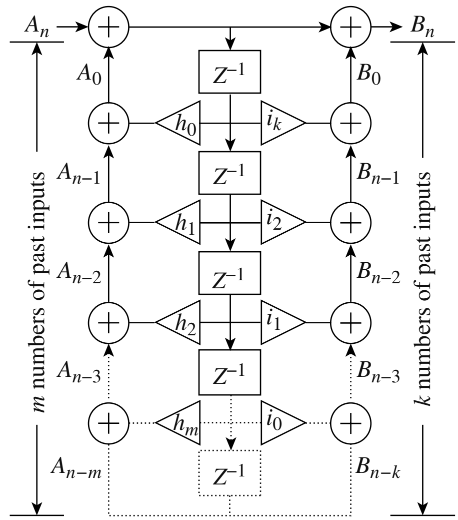


Fig. 1.31 Block diagram of IIR filter

The output at any instant is a function of m number of past inputs and k number of past outputs. Due to the presence of closed loop feedback, this filter is known as *recursive filter*.

The transfer function of IIR filter in Z-domain is given by,

$$\frac{B_{(Z)}}{A_{(Z)}} = \frac{h_0 + h_1 Z^{-1} + h_2 Z^{-2} + \dots\dots\dots + h_m Z^{-m}}{1 - i_1 Z^{-1} - \dots\dots\dots\dots - i_k Z^{-k}} \qquad (1.10)$$

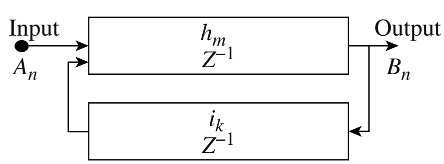
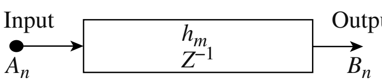
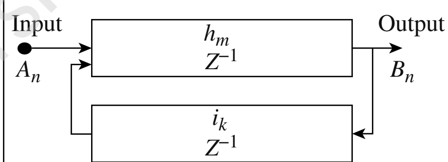
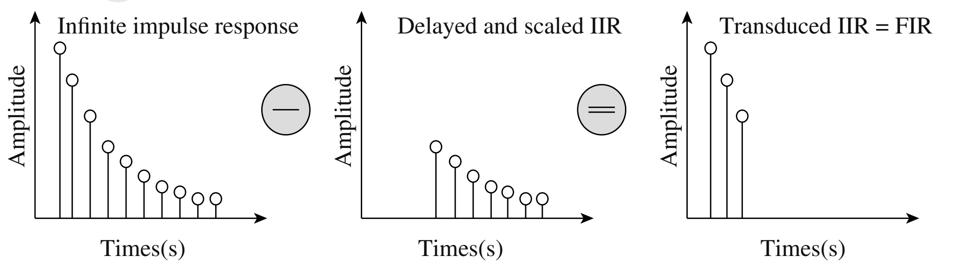


Fig. 1.32 Basic circuit diagram of IIR filter

1.12.5 Comparison Between FIR and IIR Filters

Base of comparison	FIR filter	IIR filter
Output	Non-recursive	Recursive
Response	Finite impulse response	Infinite impulse response
Stability	Always stable since there is no feedback	Because of feedback, possibility of instability exists
Coefficients	Less	More than FIR
Transfer function	Has only numerator terms	Both numerator and denominator terms
Order of filter required for a given frequency response	Higher order	Lower order
Response characteristics	Linear	Non-linear
Simplicity for implementation	Very simple	Complex compared to FIR filter.
Basic circuit diagram	 	
Equation	$B_n = h_0 A_n + h_1 A_{n-1} + \ldots\ldots + h_m A_{n-m}$	$B_n = h_0 A_n + h_1 A_{n-1} + \ldots\ldots + h_m A_{n-m} + i_1 B_{n-1} + i_2 B_{n-2} + \ldots\ldots + i_k B_{n-k}$
Transfer function	$\frac{B_n}{A_n} = \frac{h_0 z^m + h_1 z^{m-1} + h_2 z^{m-2} + \ldots\ldots + h_m}{z^m}$	$\frac{B_{(Z)}}{A_{(Z)}} = \frac{h_0 + h_1 Z^{-1} + h_2 Z^{-2} + \ldots\ldots + h_m Z^{-m}}{1 - i_1 Z^{-1} - \ldots\ldots - i_k Z^{-k}}$
Conversion of FIR filter from IIR filter	 	

1.13 Different Relay Algorithms

Protection of transmission lines is a very important area. Owing to the increase in demand, the lines are heavily loaded, because of which the margin between load and fault currents is often small. Sometimes, the magnitude of fault current may be less than the maximum full load current in the line.

Long EHV (extra high voltage) and UHV (ultra high voltage) lines are protected by the modern digital/numerical relay that contains hardware and software as two main parts. The software part includes a digital algorithm that is based on a set of mathematical equations. It basically involves the estimation of line parameters in frequency domain, time domain, or both domains by monitoring the voltage and current at the relaying point. These estimated parameters are compared with their preselected thresholds, and a trip decision is taken. A number of algorithms for the digital protection of transmission lines have been proposed in the literature. On the basis of special applicability and domain of analysis used, these algorithms can be classified into four groups:

1. Algorithms assuming pure sinusoidal relaying signal
2. Algorithms based on the solution of system differential equations
3. Algorithms applicable to distorted relaying signals
4. Algorithms based on travelling wave approach

In the following sections, these algorithms are discussed in detail. In the said four categories, each algorithm contains many algorithms. However, we have discussed only one or two main algorithms. Besides the development of algorithms, efforts have been made by different researchers to study the applicability of the said algorithms on the basis of speed of convergence of the estimated values of parameters to their post fault values and accuracy. It has been found that high-speed algorithms have poor accuracy in the presence of distortion in signals due to transients. On the other hand, the algorithms giving more accurate results tend to be slower because of the larger data window and complex computations involved.

1.13.1 Algorithms Assuming Pure Sinusoidal Relaying Signal

This was the first approach used by the researchers to compute apparent real and imaginary parts of the impedance from current and voltage samples. As the inputs to the relay are assumed to be pure sinusoidal, this approach has certain advantages.

1. The sampling process is not required to be synchronized with the phase position of the sine wave being measured.
2. Shorter data window is sufficient.
3. Owing to low computational requirements, the decision process is fast.

On the other hand, as the relaying signals contain DC offset, harmonics, and noise, especially during a few cycles following the fault inception, this approach lacks accuracy.

This algorithm is derived as follows:

As the relaying signals are assumed to be pure sinusoidal, at any sampling instant k, the current, i_k, is given by

$$i_k = I_P \times \sin \omega t \tag{1.11}$$

The rate of change of the current with time, i'_k, is given by

$$i'_k = w \times I_P \times \cos \omega t \tag{1.12}$$

Therefore, the peak I_P, and the phase angle, ϕ_i, of current can be expressed as

$$I_P^2 = i_k^2 + \left(\frac{i'_k}{w}\right)^2 \text{ and } \phi_i{}^2 = \tan^{-1}\left(\frac{\omega i_k}{i'_k}\right)^2 \tag{1.13}$$

The derivative at any sampling instant can be calculated from

$$i'_k = \frac{i_{k+1} - i_{k-1}}{2h} \tag{1.14}$$

where, h is the sampling interval.

Here, in this algorithm, digital filtering technique, namely, averaging of samples over a short span, is used to attenuate harmonics. For the suppression of decaying DC offset, series R–L circuit across CT is used.

1.13.2 Algorithms Based on Solution of System Differential Equations

Transmission line is modelled by a set of first order linear differential equations. It is given by

$$v(t) = R \times i(t) + L\frac{\mathrm{d}i(t)}{\mathrm{d}t} + E(t) \tag{1.15}$$

where, $v(t)$ and $i(t)$ are instantaneous value of voltage and current measured by the relay, and $E(t)$ is the error.

This equation is solved for R and L using numerical techniques, and relaying decisions are taken accordingly. For a solution of this model, different algorithms have been proposed by different researchers. However, we have given only one algorithm.

In order to determine the parameters of line, that is, R and L, we have to take the derivation of the current signal. This can be achieved by two methods. The first method is to use the derivative approximation using the input signal samples. It is given by

$$v(t_k) = R \times i(t_k) + L \times i'(t_k) + \Delta E(t_k) \tag{1.16}$$

where, $v(t_k)$ and $i(t_k)$ are the input voltage and current samples and $i'(t_k)$ is the derivative approximation in the t_k time. The derivative of current ($i'(t_k)$) is expressed using backward or forward or central difference approaches.

$$\left.\begin{aligned} i'(t_k) &= \frac{i(t_k) - i(t_{k-1})}{h} \text{ using backward approach} \\ i'(t_k) &= \frac{i(t_{k+1}) - i(t_k)}{h} \text{ using forward approach} \\ i'(t_k) &= \frac{i(t_{k+1}) - i(t_{k-1})}{2h} \text{ using central approach} \end{aligned}\right\} \tag{1.17}$$

The second method uses integration to eliminate the derivative approximation. It is given by

$$\int_{t_1}^{t_2} v(t)\,\mathrm{d}t = R\int_{t_1}^{t_2} i(t)\,\mathrm{d}t + L \times [i(t_2) - i(t_1)] + \int_{t_1}^{t_2} \Delta E(t)\,\mathrm{d}t \tag{1.18}$$

In order to evaluate the said equation, which involves digital integration, trapezoidal approach is used. This is given by

$$\int_{t_1}^{t_2} X(t)\,\mathrm{d}t = \sum_{K=n-N}^{n-1} \frac{(X_k + X_{k+1})}{2}\, h \tag{1.19}$$

where,

N = number of samples per cycle, n and $n - N$ are samples corresponding to the times t_2 and t_1, and are given by,

$t_1 = (n - N) \times h$ and $t_2 = n \times h$

where, h is the sampling interval.

Now, neglecting the error term (ΔE) in Eq. (1.18) and using two equations over two successive time periods, we get the following two equations.

$$\int_{t_0}^{t_1} v(t)\,\mathrm{d}t = R\int_{t_0}^{t_1} i(t)\,\mathrm{d}t + L \times [i(t_1) - i(t_0)] \tag{1.20}$$

$$\int_{t_1}^{t_2} v(t)\,\mathrm{d}t = R\int_{t_1}^{t_2} i(t)\,\mathrm{d}t + L\times\left[i(t_2) - i(t_1)\right] \tag{1.21}$$

Using Eq. (1.21), we obtain the following two equations.

$$\frac{h}{2}\left(v_k + v_{k-1}\right) = R\,\frac{h}{2}\left(i_k + i_{k-1}\right) + L\left(i_k + i_{k-1}\right)$$

$$\frac{h}{2}\left(v_k + v_{k-2}\right) = R\,\frac{h}{2}\left(i_{k-1} + i_{k-2}\right) + L\left(i_{k-1} + i_{k-2}\right)$$

Therefore, the line parameters R and L are estimated by

$$R = \frac{\left(i_{k-1} - i_{k-2}\right)\left(v_k + v_{k-1}\right) - \left(i_k - i_{k-1}\right)\left(v_{k-1} + v_{k-2}\right)}{\left(i_k + i_{k-1}\right)\left(i_{k-1} - i_{k-2}\right) - \left(i_{k-1} + i_{k-2}\right)\left(i_k - i_{k-1}\right)} \tag{1.22}$$

$$L = \frac{h}{2}\times\frac{\left(i_k + i_{k-1}\right)\left(v_{k-1} + v_{k-2}\right) - \left(i_{k-1} + i_{k-2}\right)\left(v_k + v_{k-1}\right)}{\left(i_k + i_{k-1}\right)\left(i_{k-1} - i_{k-2}\right) - \left(i_{k-1} + i_{k-2}\right)\left(i_k - i_{k-1}\right)} \tag{1.23}$$

1.13.3 Algorithms Applicable to Distorted Relaying Signals

Owing to switching and faults, the voltage and current signals to the relay get distorted. The algorithms discussed in this section assume that the relaying signals can be modelled by an expression containing the fundamental frequency, high frequency, and DC components. All the algorithms discussed in this section use data from one half/full cycle of the fundamental frequency. Hence, these techniques are also known as *long window techniques*. Most of the modern digital relays use different phasor estimation algorithms depending upon the requirements and applications such as discrete Fourier transform (DFT), least square error, and Walsh function.

Fourier Analysis-based Algorithm

In this algorithm, the acquired quantities (voltage and current) are transformed into the frequency domains, which are then used to obtain the apparent value of impedance from the relaying point to the fault point.

Assumption As this algorithm does not reject DC and even harmonics completely, digital filtering is required to pre-process the signals for removal of DC offset and harmonics before the extraction of fundamental frequency components.

Any periodic function (say voltage or current) $f(t)$ can be represented by the Fourier series as

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + \sum_{n=1}^{\infty} b_n \sin n\omega_0 t \tag{1.24}$$

where,

$\omega_0 = 2\pi f_0$ = angular fundamental frequency

$n\omega_0 = n^{\text{th}}$ harmonic angular frequency

$T = \dfrac{1}{f_0}$ = time interval of fundamental component

If the periodic function $f(t)$ is assumed as a current quantity, then using Eq. (1.24), it is given by

$$i(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + \sum_{n=1}^{\infty} b_n \sin n\omega_0 t \tag{1.25}$$

The coefficients of the current wave are given by

$$a_n = \frac{2}{T} \int_{t_1}^{t_1+T} i(t) \cos n\omega_0 t \, \mathrm{d}t \tag{1.26}$$

where n starts from 0, 1, ….

$$b_n = \frac{2}{T} \int_{t_1}^{t_1+T} i(t) \sin n\omega_0 t \, \mathrm{d}t \tag{1.27}$$

where $n = 1, 2, \ldots$.

Full-cycle algorithm Extraction of fundamental component of current and voltage quantity during fault is the main theme of this algorithm. This is achieved by correlating one cycle of faulted waveform of current or voltage with stored reference sine and cosine waves.

Let us assume that I_x and I_y are the real and imaginary parts of the fundamental component of the faulted current waveform $i(t)$.

Using Eqs (1.26) and (1.27), I_x and I_y are given by

$$I_x = a_1 = \frac{2}{T} \int_{t_0}^{t_0+T} i(t) \cos \omega_0 t \, \mathrm{d}t \tag{1.28}$$

$$I_y = b_1 = \frac{2}{T} \int_{t_0}^{t_0+T} i(t) \sin \omega_0 t \, \mathrm{d}t \tag{1.29}$$

where,

t_0 = time under consideration

If M is the number of samples per cycle of fundamental component and h is the sampling time interval, then

$t_k = k \times h$ = the time of the k^{th} sample, and

$T = M \times h$ = the period of fundamental component.

From these expressions, Eqs (1.28) and (1.29) can be evaluated as follows:

$$I_x = \frac{2}{Mh} \begin{bmatrix} i(t_0) \cos \omega_0 t_0 + i(t_1) \cos \omega_0 t_1 + \cdots + i(t_k) \cos \omega_0 t_k + \\ \cdots + i(t_{M-1}) \cos \omega_0 t_{M-1} + i(t_M) \cos \omega_0 t_M \end{bmatrix} h$$

$$I_x \cong \frac{2}{M} \sum_{k=0}^{M} i_k \cos\left(\frac{2\pi k}{M}\right) = \frac{2}{M} \sum_{k=0}^{M} W_{xk} i_k \tag{1.30}$$

where,

$i_k = i(t_k)$ is the k^{th} sample of current waveform

W_{xk} and W_{yk} are weighting factors of the k^{th} sample.

This expression is given by

$$W_{xk} = \cos \omega_0 t_k = \cos \frac{2\pi}{T} kh = \cos(2\pi k/M) \tag{1.31}$$

where, $k = 0, 1, \ldots, M$

$$W_{yk} = \sin \omega_0 t_k = \sin \frac{2\pi}{T} kh = \sin(2\pi k/M) \text{ , where, } k = 0,\ 1,\ \ldots,$$

$$I_y = \frac{2}{Mh}\left[\begin{matrix} i(t_0)\sin\omega_0 t_0 + i(t_1)\sin\omega_0 t_1 + \cdots + i(t_k)\sin\omega_0 t_k \\ \cdots + i(t_{M-1})\sin\omega_0 t_{M-1} + i(t_M)\sin\omega_0 t_M \end{matrix}\right.$$

$$I_y \cong \frac{2}{M}\sum_{k=0}^{M} i_k \sin\left(\frac{2\pi k}{M}\right) = \frac{2}{M}\sum_{k=0}^{M} W_{yk} i_k$$

Figure 1.33 shows the frequency response of a full-cycle algorithm. It is to be noted that if the full-cycle window algorithm uses k samples, then only $\left(\frac{k}{2}-1\right)$ harmonics can be estimated. To reduce higher frequency harmonics, an initializing filter is required.

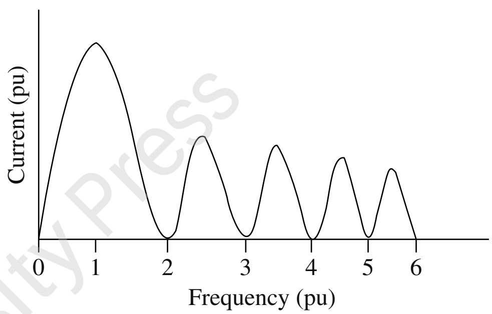


Fig. 1.33 Frequency response of a full-cycle algorithm

Half-cycle algorithm This algorithm uses information corresponding to one half cycles in contrast to the one cycle information used by the full-cycle algorithm. If *Ix, hc* and *Iy, hc* are the real and imaginary parts of the fundamental component of the phasor derived from a half-cycle window, then their expressions are given by

$$I_{x,hc} = \frac{2}{(T/2)} \int_{t_0}^{t_0+T/2} i(t)\cos\omega_0 t \, dt \qquad (1.32)$$

$$I_{y,hc} = \frac{2}{(T/2)} \int_{t_0}^{t_0+T/2} i(t)\sin\omega_0 t \, dt \qquad (1.33)$$

Following the same procedure as done in Eq. (1.30) of full-cycle algorithm, we get

$$I_{x,hc} = \frac{4}{M}\sum_{k=1}^{M/2} W_{xk} i_k \qquad (1.34)$$

$$I_{y,hc} = \frac{4}{M}\sum_{k=1}^{M/2} W_{yk} i_k \qquad (1.35)$$

Figure 1.34 shows the frequency response of a half-cycle Fourier algorithm.

The main advantages of this algorithm over the full-cycle algorithm are as follows:

1. It is faster than full-cycle algorithm.
2. It can easily remove odd harmonics.

However, the prime limitation of the half-cycle algorithm is the increase in error due to even harmonics.

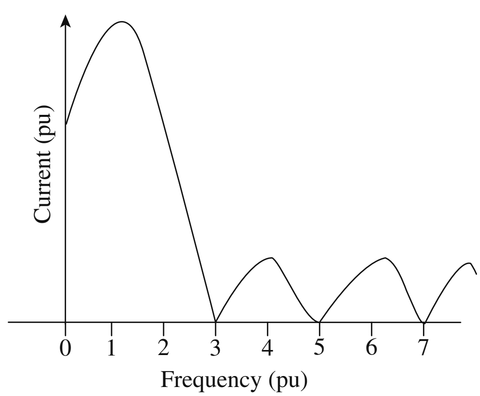


Fig. 1.34 Frequency response of half-cycle algorithm

Walsh Function Technique

The fundamental part of odd and even square waves is added to harmonically related square waves to obtain the *Walsh function.* This is correlated with the fault signal to extract the fundamental frequency components.

Any periodic function, say current between an interval of t_1 to $t_1 + T$, can be expanded using Fourier series.

$$i(t) = F_0 + \sum_{n=1}^{\infty}\left(\sqrt{2}F_{2n-1}\ \sin n\omega_0 t + \sqrt{2}F_{2n}\ \cos n\omega_0 t\right) \tag{1.36}$$

where,

$$\begin{aligned} F_0 &= \frac{1}{T}\int_0^T i(t)\ \mathrm{d}t,\ F_{2n-1} = \frac{\sqrt{2}}{T}\int_0^T i(t)\sin n\omega_0\ \mathrm{d}t,\ \text{and} \\ F_{2n} &= \frac{\sqrt{2}}{T}\int_0^T i(t)\cos n\omega_0 t\ \mathrm{d}t \end{aligned} \tag{1.37}$$

Here, F_0 is the DC component, whereas F_{2n} and F_{2n-1} are the real and imaginary components of n^{th} harmonic, respectively. Equation (1.36) can be further extended by using Walsh series as

$$i(t) = \sum_{k=0}^{\infty} W_k\ W_{al}\left(k,\ \frac{t}{T}\right) \tag{1.38}$$

where, W_k is the k^{th} Walsh coefficient and is given by,

$$W_k = \frac{1}{T}\int_0^T i(t)\ W_{al}\left(k,\ \frac{t}{T}\right)\mathrm{d}t, k = 0,\ 1,\ 2, \ldots \tag{1.39}$$

With M as the number of samples per cycle, Walsh coefficient $W_k(\mathrm{s})$ is given by

$$W_k(\mathrm{s}) = \frac{1}{M}\left[\frac{1}{2}f_{\mathrm{s}} + f_{1+\mathrm{s}} + \ldots + f_{j+\mathrm{s}} + \ldots + f_{M-1+\mathrm{s}} + \frac{1}{2}f_{M+\mathrm{s}}\right] \tag{1.40}$$

The fundamental frequencies of sine and cosine components in terms of Walsh coefficients for a sampling rate of $M = 16$ are given by

$$\begin{aligned} F_{\mathrm{s}} &= 0.9W_1 - 0.373W_5 - 0.074W_9 \\ F_{\mathrm{c}} &= 0.9W_2 + 0.373W_6 - 0.074W_{10} \end{aligned}$$

where, W_{s} represents the Walsh coefficients.

Least Error Square Technique

Least square fitting technique estimates the impedance from the relaying point to the fault point, which includes fundamental component, decaying DC offset component, and certain harmonics of fault current and voltage wave.

Any signal (either voltage or current) that includes the decaying DC offset component, fundamental component, and harmonics can be given by

$$f(t) = K_1 e^{-t/\tau} + \sum_{m-1}^{M}\left(k_{2m}\ \cos m\omega_0 t + k_{2m+1}\ \sin m\omega_0 t\right) \tag{1.41}$$

where,

$K_1, K_2, \ldots, K_{2M+1}$ are the unknown constants

M = the highest harmonic considered
τ = time constant of the decaying DC component
ω_0 = angular frequency of the fundamental component

Now, to determine the constants $K_1, K_2, \ldots, K_{2M+1}$, the integral of error is given by

$$S = \int [v(t) - f(t)]^2 \ \mathrm{d}t \tag{1.42}$$

$$S = \int \left[v\ (t) - K_1 e^{-t/\tau} - \sum_{m-1}^{M} k_{2m} \left(\cos m\omega_0 t + k_{2m+1} \sin m\omega_0 t \right) \right]^2 \ \mathrm{d}t$$

In order to achieve the necessary condition for S to be a minimum, take the partial derivation of S. Therefore,

$$\frac{\mathrm{d}s}{\mathrm{d}k_i} = 0 \left(i = 1,\ 2 \text{ and } 2M + 1 \right)$$

$$\frac{\mathrm{d}s}{\mathrm{d}k_i} = 0 = -2 \int_{t_1}^{t_1+T} \left[v(t) - K_1 e^{-t/\tau} - \sum_{m-1}^{M} \left(k_{2m} \cos m\omega_0 t + k_{2m+1} \sin m\omega_0 t \right) \right] \times \ e^{-t/\tau} \ \mathrm{d}t$$

$$\frac{\mathrm{d}s}{\mathrm{d}k_{2m}} = 0 = -2 \int_{t_1}^{t_1+T} \left[v(t) - K_1 e^{-t/\tau} - \sum_{m-1}^{M} \left(k_{2m} \cos m\omega_0 t + k_{2m+1} \sin m\omega_0 t \right) \right] \cos m\omega_0 t \ \mathrm{d}t$$

$$\frac{\mathrm{d}s}{\mathrm{d}k_{2m+1}} = 0 = -2 \int_{t_1}^{t_1+T} \left[v(t) - K_1 e^{-t/\tau} - \sum_{m-1}^{M} \left(k_{2m} \cos m\omega_0 t + k_{2m+1} \sin m\omega_0 t \right) \right] \sin m\omega_0 t \ \mathrm{d}t$$

These three equations can be further simplified and are given as

$$K_1 = \int_{t_1}^{t_1+T} v(t)\, e^{-t/\tau} \ \mathrm{d}t$$

$$K_{2m} = \frac{2}{T} \int_{t_1}^{t_1+T} v(t) \cos m\omega_0 t \ \mathrm{d}t \tag{1.43}$$

$$K_{2m+1} = \frac{2}{T} \int_{t_1}^{t_1+T} v(t) \sin m\omega_0 t \ \mathrm{d}t$$

Using trapezoidal method, Eq. (1.43) can be written as

$$K_1 = W_{11} s_1 + W_{1N} s_N + \sum_{n=2}^{N-1} 2 W_{1N} s_N \tag{1.44}$$

where,

W_{1N} = weighting factor of the i^{th} sample
N = number of samples per cycle

$$K_{2m} = \frac{1}{N} \left[W_{2m,1}\, s_1 + W_{2m,N}\, s_N + \sum_{n=2}^{N-1} 2 W_{2m,n} s_n \right] \tag{1.45}$$

$$K_{2m+1} = \frac{1}{N}\left[W_{2m+1,1}s_1 + W_{2m+1,N}s_N + \sum_{n=2}^{N-1} 2W_{2m+1,n}s_n\right] \tag{1.46}$$

where, $W_{2m,n}$ and $W_{2m+1,n}$ are the weighting factors of the n^{th} sample.

Finally, the impedance is estimated by

$$Z = \frac{K_{2V} + jK_{3V}}{K_{2I} + jK_{3I}} \tag{1.47}$$

where, K_{2V}, K_{2I} and K_{3V}, K_{3I} are the real and imaginary parts of the fundamental component of voltage and current.

Recapitulation

- Speed, selectivity, discrimination, and time of operation are the prime requirements of protective devices.
- Unit protection is based on absolute selectivity, whereas non-unit protection is based on relative selectivity.
- In primary protection relays operate in the first line of defence, whereas in backup protection relays work as the second line of defence.
- Relays have progressed from electromechanical, static, and microprocessor, to digital/numerical.
- It is very important to examine the technology used in modern digital/numerical relays and analyse their application in the protection of power systems.
- Sampling frequency in digital relays is decided using Nyquist criterion, $f_s \geq 2 \times f_m$.
- Sampling frequency is given by $f_s = f \times n$.
- The analytical approach of different relay algorithms such as Fourier analysis-based algorithm, Walsh function technique, and least error square technique used in practice have immense importance in designing digital relaying schemes for particular protection functions.

Multiple Choice Questions

1. Unit protection is based on the concept of
(a) absolute selectivity (c) both (a) and (b)
(b) relative selectivity (d) none of the above

2. Blind spot is a point in zones of protection where
(a) partial protection is available
(b) complete protection is available
(c) no protection is available
(d) none of the above

3. The function of anti-aliasing filter is
(a) to remove high frequency components
(b) to remove both low and high frequency components
(c) to allow low frequency components
(d) to remove low frequency components

4. Which relay is more susceptible to electromagnetic interference?
(a) Digital relay (c) Static relay
(b) Electromechanical relay (d) All of the above

5. The operating time of modern digital relay is of the order of
(a) 20–30 ms (c) 400–600 ms
(b) 10–20 ms (d) 1–10 s

6. Which type of backup protection scheme is widely used in the field?
(a) Relay backup (c) Remote backup
(b) Breaker backup (d) None of the above

7. As the sampling frequency increases, the computational requirements
   (a) increase
   (b) remain constant
   (c) decrease
   (d) none of the above
8. Distance relay is the best example of
   (a) unit protection scheme
   (b) non-unit protection scheme
   (c) independent protection scheme
   (d) none of the above
9. The function of trip isolation circuit is
   (a) to avoid maloperation of relay during periodic testing of relay
   (b) to trip the circuit breaker
   (c) to trip the main relay
   (d) none of the above
10. The function of auxiliary relay is
   (a) to carry high fault current
   (b) to sense the inception of fault
   (c) to provide backup
   (d) none of the above

Review Questions

1. Explain how the protection zone of various types of equipment is decided.
2. Enlist the various requirements of protection systems.
3. Explain the concept of unit and non-unit protection.
4. What do you mean by primary and backup protection of power system?
5. What is the function of a bimetallic strip in a thermal relay?
6. Explain how thermal relay is used for the protection of equipment against overloading condition.
7. Why can an overcurrent relay not be used in place of a thermal relay for the protection of equipment against overloading condition?
8. Why is induction cup relay superior to induction disc relay?
9. Discuss the advantages and disadvantages of static relays compared to electro-mechanical relay.
10. Explain the working of a generalized static relay.
11. Discuss the various components of digital relays used in power systems.
12. Explain the function of the following with reference to digital relay.
   (a) Anti-aliasing filter
   (b) Analog-to-digital converter
   (c) Isolation transformer
   (d) Surge protection circuit
   (e) Signal condition device
   (f) Digital output system
13. Discuss various merits and demerits of digital relays, with reference to electro-mechanical and static relays.
14. Explain the concept of adaptive relaying.
15. What are the different types of structures/equipment required to implement the concept of adaptive relaying?
16. Discuss half-cycle and full-cycle discrete Fourier transform algorithms.

Answers to Multiple Choice Questions

1. (a) 2. (c) 3. (d) 4. (a) 5. (a) 6. (c) 7. (a) 8. (b) 9. (a) 10. (a)