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Power System Protection

Electrical Engineering

Comprehensive Theory *with* Solved Examples

Civil Services Examination

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Chapter 1

Introduction

1.1 Need for Protective Systems

An electrical power system consists of generators, transformers, transmission and distribution lines, etc. Short-circuits and other abnormal conditions often occur on a power system. The heavy current associated with short-circuits is likely to cause damage to equipment if suitable protective relays and circuit breakers are not provided for the protection of each section of the power system. Short-circuits are usually called faults by power engineers. Strictly speaking, the term 'fault' simply means a 'defect'. Some defects, other than short circuits, are also termed as faults. For example, the failure of conducting path due to a break in a conductor is a type of fault.

If a fault occurs in an element of a power system, an automatic protective device is needed to isolate the faulty element as quickly as possible to keep the healthy section of the system in normal operation. The fault must be cleared within a fraction of a second. If a short-circuit persists on a system for a longer duration, it may cause damage to some important sections of the system. A heavy short-circuit current may cause a fire. It may spread in the system and damage a part of it. The system voltage may reduce to a low level and individual generators in a power station or groups of generators in different power stations may lose synchronism. Thus, an uncleared heavy short-circuit may cause the total failure of the system.

A protective system includes circuit breakers, transducers (CTs and VTs), and protective relays to isolate the faulty section of the power system from the healthy sections. A circuit breaker can disconnect the faulty element of the system when it is called upon to do so by the protective relay. Transducers (CTs and VTs) are used to reduce currents and voltages to lower values and to isolate protective relays from the high voltages of the power system. The function of a protective relay is to detect and locate a fault and issue a command to the circuit breaker to disconnect the faulty element. It is a device which senses abnormal conditions on a power system by constantly monitoring electrical quantities of the systems, which differ under normal and abnormal conditions. The basic electrical quantities which are likely to change during abnormal conditions. are current, voltage, phase-angle (direction) and frequency. Protective relays utilise one or more of these quantities to detect abnormal conditions on a power system.

Protection is needed not only against short-circuit but also against any other abnormal conditions which may arise on a power system. A few examples of other abnormal conditions are overspeed of generators and motors, overvoltage, underfrequency, loss of excitation, overheating of stator and rotor of an alternator etc. Protective relays are also provided to detect such abnormal conditions and issue alarm signals to alert operators or trip circuit breaker.

1.2 Faults and Abnormal Operating Conditions

1.2.1 Shunt Faults (Short-Circuits)

When the path of the load current is cut short because of breakdown of insulation, we say that a 'short-circuit' has occurred. The insulation can break down for a variety of reasons. Fig. 1.1 shows a single line-to-ground fault on a transmission line due to flashover of spark gap across the string insulator.

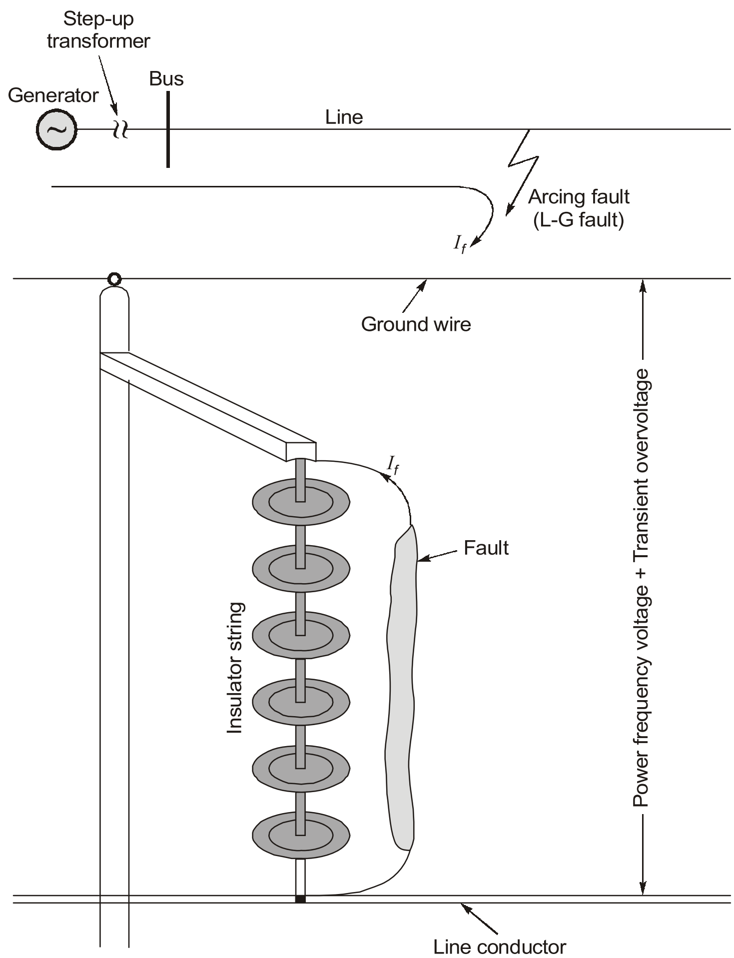

***Fig. 1.1 :** Single line-to-ground fault due to flashover of insulator string*

Such faults due to insulation flashover are many times temporary, i.e. if the arc path is allowed to deionize, by interrupting the electrical supply for a sufficient period, then the arc does not restrike after the supply is restored. This process of interruption followed by internal re-energization is known as reclosure. In low-voltage systems up to three reclosures are attempted, after which the breaker is locked out. The repeated attempts at reclosure, at times, help in burning out the object which is causing the breakdown of insulation. The reclosure may also be done automatically. In EHV systems, where the damage due to short circuit may be very large and the system stability at stake, only one reclosure is allowed.

At times the short-circuit may be total (sometimes called a dead short-circuit), or it may be a partial short-circuit. A fault which bypasses the entire load current through itself, is called a metallic fault. A metallic fault presents a very low, practically zero, fault resistance. A partial short-circuit can be modelled as a non-zero resistance (or impedance) in parallel with the intended path of the current. Most of the times, the fault resistance is nothing but the resistance of the arc that is formed as a result of the flashover. The arc resistance is highly non-linear in nature.

1.2.2 Causes of Shunt Faults

Shunt faults are basically due to failure of insulation. The insulation may fail because of its own weakening, or it may fail due to overvoltage. The weakening of insulation may be due to one or more of the following factors:

- Ageing
- Temperature
- Rain, hail, snow
- Chemical pollution
- Foreign objects
- Other causes

The overvoltage may be either internal (due to switching) or external (due to lightening).

1.2.3 Effects of Shunt Faults

If the power system just consisted of isolated alternators feeding their own loads, then the steady-state fault currents would not be much of a concern. Consider an isolated turbo-alternator with a three-phase short-circuit on its terminals as shown in Fig. 1.2. Assuming the internal voltage to be 1 p.u. and a value of synchronous impedance, $X_d = 2$ p.u., the steady-state short-circuit current would only be 0.5 p.u. which is too small to cause any worry. However considering subtransient impedance, $X_d'' = 0.1$, the subtransient current would be 10 p.u. We must not however, forget that in an interconnected power system all the generators (and even motors) will contribute towards the fault current, thus building up the value of the fault current to couple of tens of times the normal full-load current.

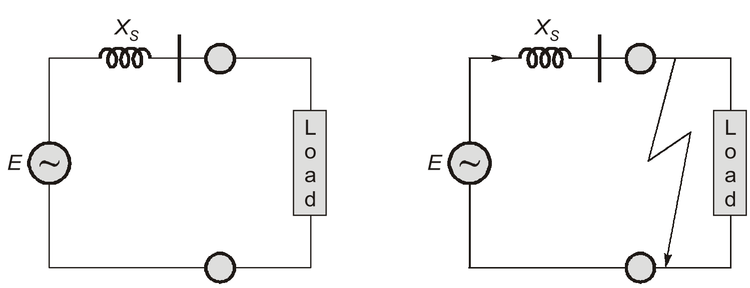

Fig. 1.2 : *(a) Isolated generator with its load (b) Three-phase fault*

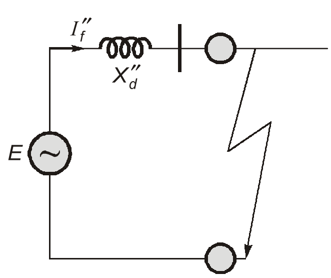

Fig. 1.3 : *Subtransient*

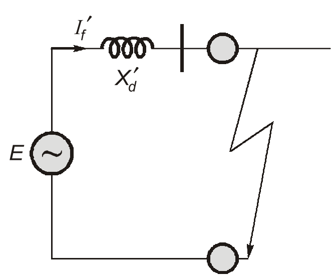

Fig. 1.4 : *Transient*

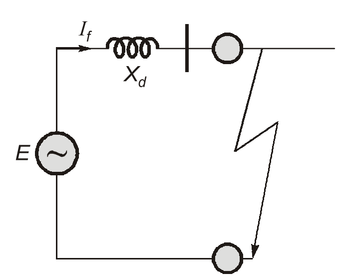

Fig. 1.5 : *Steady state*

Faults, thus, cause heavy currents to flow. If these fault currents persist even for a short time, they will cause extensive damage to the equipment that carry these currents. Over-currents, in general, cause overheating and attendant danger of fire. Overheating also causes deterioration of the insulation, thus weakening it further. Not so apparent is the mechanical damage due to excessive mechanical forces developed during over-current. Transformers are known to have suffered mechanical damage to their windings, due to faults. This is due to the fact that any two current-carrying conductors experience a force This force goes out of bounds during faults, causing mechanical distortion and damage.

Further, in an interconnected system, there is another dimension to the effect of faults. The generators in an interconnected power system must operate in synchronism at all instants. The electrical power output from an alternator near the fault drops sharply. However the mechanical power input remains substantially constant at its pre-fault value.

This causes the alternator to accelerate. The rotor angle δ starts increasing control, the alternators will have to be tripped out. Thus, in an interconnected power system, the system stability is at stake. Therefore, the faults need to be isolated as selectively and as speedily as possible.

1.3 Classification of Shunt Faults

1.3.1 Phase Faults and Ground Faults

Those faults, which involve only one of the phase conductors and ground, are called ground faults. Faults involving two or more phase conductors, with or without ground, are called phase faults.

Power systems have been in operation for over a hundred years now. Accumulated experience shows that all faults are not equally likely. Single line to ground faults (L-G) are the most likely whereas the fault due to simultaneous short-circuit between all the three lines, known as the three-phase fault (L-L-L), is the least likely. This is depicted in Table 1.1.

Table 1.1 : Fault statistics with reference to type of fault

Fault	Probability of occurrence (%)	Severity
L-G	85%	Least severe
L-L	8%	
L-L-G	5%	
L-L-L	2%	Most severe
Total	100%	

Further, the probability of faults on different elements of the power system are different. The transmission lines which are exposed to the vagaries of the atmosphere are the most likely to be subjected to faults. Indoor equipment is least likely to be subjected to faults. The fault statistics is shown in Table 1.2.

Table 1.2 : Fault statistics with reference to power system elements

Power system element	Severity
Overhead lines	50
Underground cables	9
Transformers	10
Generators	7
Switchgear	12
CT, PT relays, control equipment, etc.	12
Total	100%

The severity of the fault can be expressed in terms of the magnitude of the fault current and hence its potential for causing damage. In the power system, the three-phase fault is the most severe whereas the single line-to-ground fault is the least severe.

1.3.2 Series Faults

Series faults are nothing but a break in the path of current. Normally such faults do not result into catastrophes except when the broken conductor touches other conductor or some grounded part. It is observed in practice that most of the open conductor faults sooner or later develop into some or the other short-circuit fault. However, there are some instances where an open circuit can have dangerous consequences. For example, the secondary circuit of a current transformer and the field circuit of a dc machine if open circuited, can have dangerous consequences.

1.4 Abnormal Operating Conditions

The boundary between the normal and faulty conditions is not crisp. There are certain operating conditions inherent to the operation of the power system which are definitely not normal, but these are not electrical faults either. Some examples are the magnetizing inrush current of a transformer, starting current of an induction motor, conditions during power swing, under frequency, under voltage, over voltage etc.

1.4.1 Should Protective Relays Trip During Abnormal Operating Conditions?

How the protective system should respond to the abnormal operating conditions needs careful consideration. It may or may not be required to take cognizance of the abnormal operating condition. Some examples of abnormal operating conditions are starting currents of motors, inrush currents of transformers and stable power swings. Magnitudewise, these currents may qualify as faults, but there is no need to provide protection from them. Thus, the protective system must be able to discriminate between the normal operating conditions, abnormal operating conditions, and faults.

1.4.2 Can Protective Relays Prevent Faults?

It can be seen from the above discussion that protective relays cannot prevent faults. To a certain extent, faults can be prevented by using the properly designed and maintained equipment. However, it is not possible to totally prevent the occurrence of faults.

1.4.3 What are Protective Relays Supposed to Do?

The protective relays are supposed to detect the fault with the help of current and voltage transformers, and selectively remove only the faulty part from the rest of the system by tripping an appropriate number of circuit breakers. This, the relay has to do with almost sensitivity, selectivity and speed. In a power system, faults are not an everyday occurrence. A typical relay, therefore, spends all of its life monitoring the power system. It must, therefore, be ready all the time in anticipation of a fault. It is said that a relay operates for more number of times during testing and maintenance than during actual fault! Thus, relaying is like an insurance against damage due to faults.

1.5 Evolution of Power Systems

Power systems have evolved from isolated generators feeding their own loads to huge interconnected power systems spanning an entire country. The evolution has progressed from low-voltage systems to high voltage systems and low power handling capacities to high power handling capacities. The requirements imposed on the protective system are closely linked to the nature of the power system.

1.5.1 Isolated Power System

The protection of an isolated power system is simpler because firstly, there is no concentration of generating capacity and secondly, a single synchronous alternator does not suffer from the stability problem as faced by a multi-machine system. Further, when there is a fault and the protective relays remove the generator from the system, the system may suffer from a blackout unless there is a standby source of power. The steady-state fault current in a single machine power system may even by less than the full-load current. Such a fault will, however, cause other effects like speeding up of the generator because of the disturbed balance between the input mechanical power and the output electrical power, and therefore should be quickly attended to. Although, there are no longer any isolated power systems supplying residential or industrial loads, we do encounter such situations in case of emergency diesel generators powering the uninterrupted power supplies as well as critical auxiliaries in a thermal or nuclear power station.

1.5.2 Interconnected Power System

An interconnected power system has evolved because it is more reliable than an isolated power system. In case of disruption in one part of the system, power can be fed from alternate paths, thus maintaining continuity of service. An interconnected power system also makes it possible to implement an economic load dispatch.

The generators in an interconnected system could be of varied types such as turbo alternators (in coal fired, gas fired or nuclear power plants), generators in hydroelectric power plants, wind-powered generators, fuel cells or even solar-powered photovoltaic cells.

Fig. 1.6 shows a simple interconnected power system. Most of the generators operate at the voltage level of around 20 kV. For bulk transmission of power, voltage levels of the order of 400 kV or higher are used. At the receiving end, the voltage is stepped down to distribution level, which is further stepped down before it reaches the consumers.

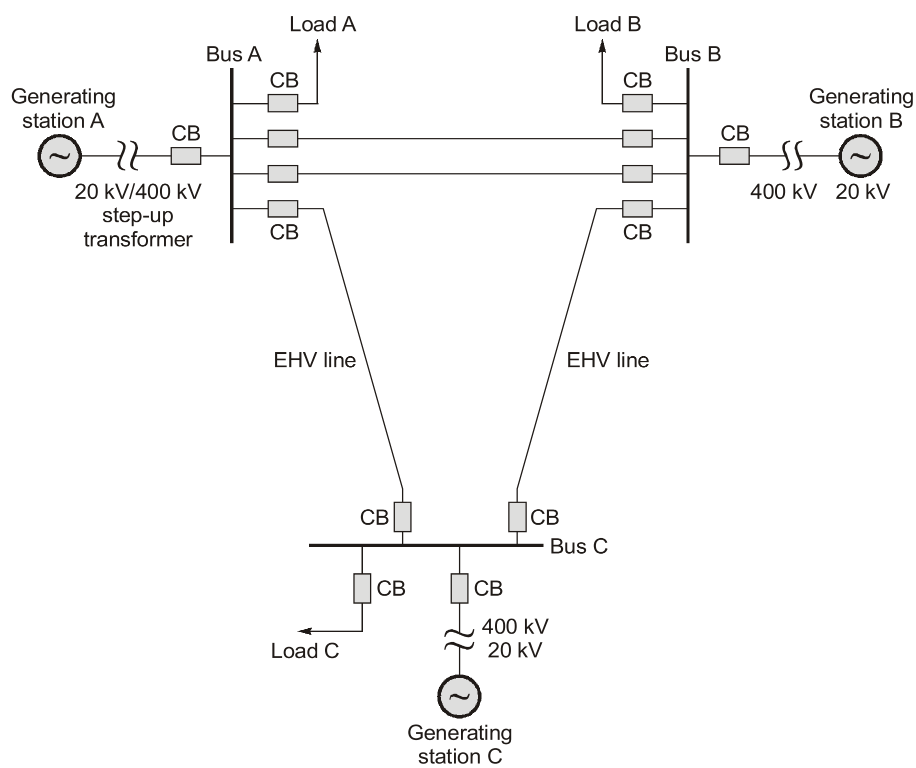

Fig. 1.6 : *Single-line diagram of a simple interconnected power system*

It can be seen that the EHV lines are the tie lines which interconnect two or more generators whereas the low voltage lines are radial in nature which terminate in loads at the remote ends.

There is interconnection at various EHV voltage levels.

1.6 System Transducers

Current transformers and voltage transformers form a very important link between the power system and the protective system. These transducers basically extract the information regarding current and voltage from the power system under protection and pass it on to the protective relays. While doing this, they insulate the low voltage protective system (both personnel and protective apparatus) from the high voltage power system.

1.6.1 Current Transformer

The current transformer has two jobs to do. Firstly, it steps down the current to such levels that it can be easily handled by the relay current coil.

The standard secondary current ratings used in practice are 5 A and 1 A. This frees the relay designer from the actual value of primary current. Secondly, it isolates the relay circuitry from the high voltage of the EHV system. A conventional electromagnetic current transformer is shown in Fig. 1.7. Ideally, the current transformer should faithfully transform the current without any errors. In practice, there is always some error. The error creeps in both in magnitude and in phase angle. These errors are known as ratio error and phase angle error.

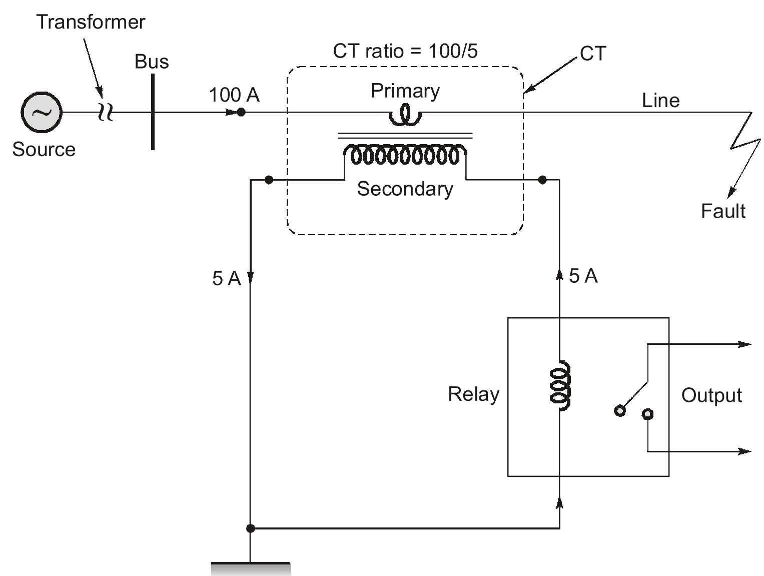

Fig. 1.7 : *Current transformer*

It may be pointed out here, that current transformer are used for metering purposes as well. However, there is a very important difference between a metering CT and a protection CT. A metering CT is a so designed (proportioned) that in case of faults, it will saturate and thus save the instrument connected to its secondary from damage due to excessive current. On the other hand, a protective CT is designed to faithfully reproduce the largest fault current. The operating points, on the excitation characteristics, for the two types of CTs are shown in Fig. 1.8.

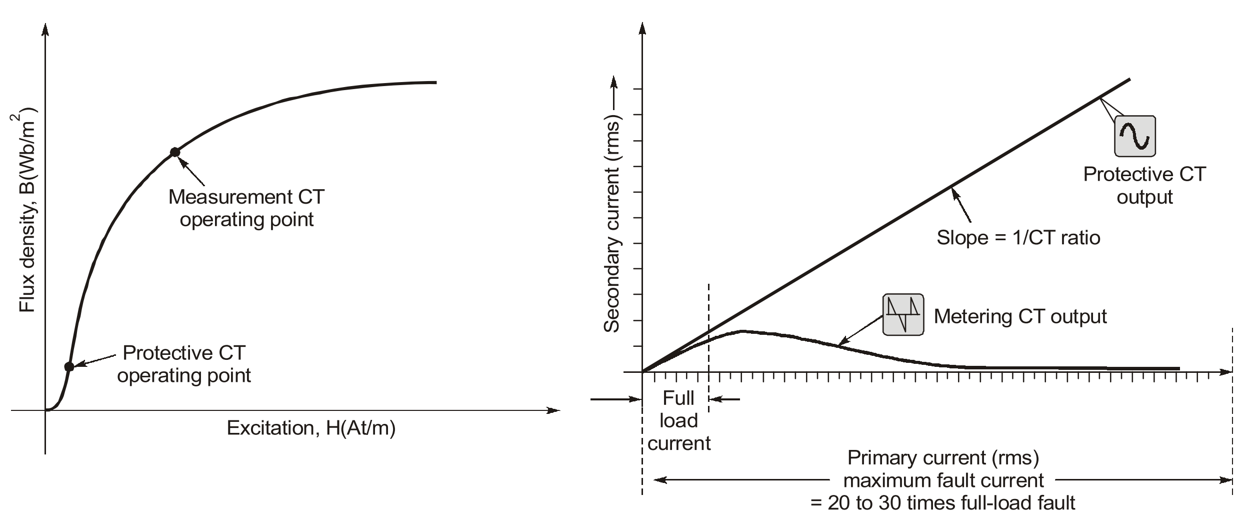

Fig. 1.8 : *Protective CT vs measurement CT*

1.6.2 Voltage Transformer

The voltage transformer steps down the high voltage of the line to a level safe enough for the relaying system and personnel to handle. The standard secondary voltage on line-to-line basis is 110 V. This helps in standardizing the protective relaying equipment irrespective of the value of the primary EHV adopted. A PT primary is connected in parallel at the point where a measurement is desired, unlike a CT whose primary is in series with the line in which current is to be measured. A conventional electromagnetic VT is shown in Fig. 1.9. The VT also suffers from ratio and phase angle errors. Another type of VT that is commonly used in EHV systems is the Capacitive Voltage Transformer or CVT.

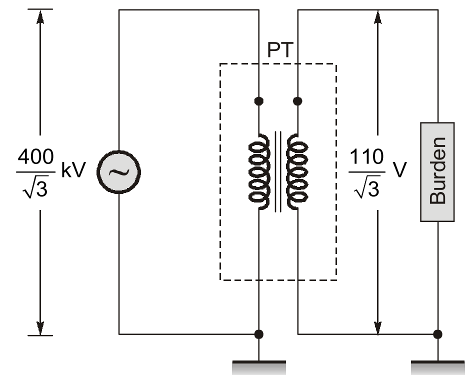

***Fig. 1.9 :** Potential (voltage) transformer (PT or VT)*

1.6.3 Circuit Breaker

The circuit breaker is an electrically operated switch, which is capable of safely making, as well as breaking, short-circuit currents. The circuit breaker is operated by the output of the associated relay. When the circuit breaker is in the closed condition, its contacts are held closed by the tension of the closing spring. When the trip coil is energized, it releases a latch, causing the stored energy in the closing spring to bring about a quick opening operation.

1.6.4 Trip Circuit of a CB

The circuit breaker contacts are in a closed position by the force of a spring. Energy is stored in the spring during the closing operation. In order to trip the circuit breaker, it is necessary to release a latch either manually or by energizing the trip-coil of the circuit breaker. The trip-battery supplies energy to the trip-coil for this operation. The relay output contact is wired in series with the trip-battery and the trip-coil. Thus when the relay operates, the trip-coil gets energized and the circuit breaker quickly parts its contacts. The mechanical arrangement is quite complicated and only its essence is depicted in Fig.1.10.

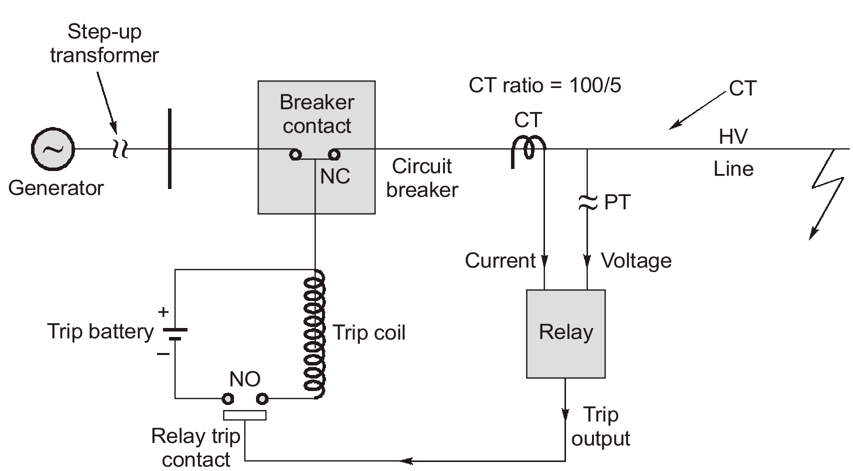

***Fig. 1.10 :** Trip circuit of a circuit breaker*

1.6.5 Organization of Protection

The protection is organized in a very logical fashion. The idea is to provide a ring of security around each and every element of the power system. If there is any fault within this ring, the relays associated with it must trip all the allied circuit breakers so as to remove the faulty element from the rest of the power system. This 'ring of security' is called the zone of protection. This is depicted in Fig. 1.11 with the help of a simple differential relay for the protection of a transformer. Without going into the detailed working of the differential relaying scheme, we can make the following statements.

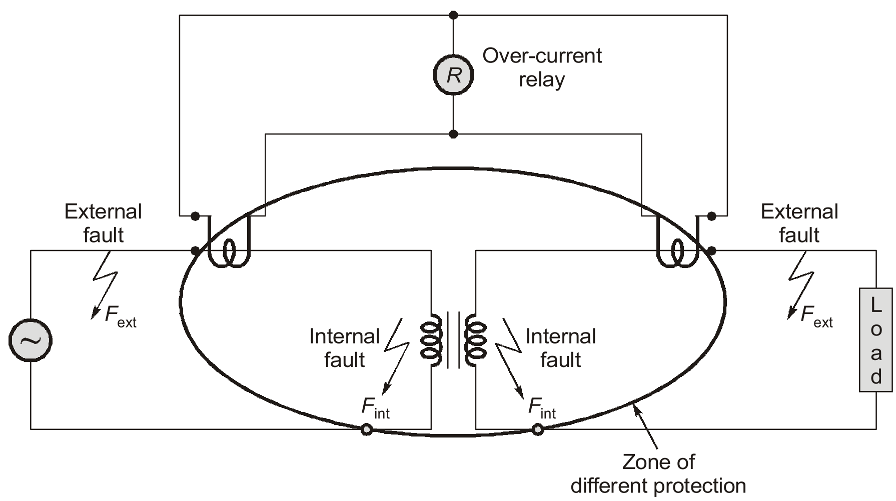

***Fig. 1.11 :** Zone of protection, external and internal faults*

Faults within the zone are termed internal faults whereas the faults outside the zone are called external faults. External faults are also known as through faults. Ideally, a relay looking after the protection of a zone should operate only for internal faults. It should restrain from operating for external faults. The farthest point from the relay location, which is still inside the zone, is called the reach point. The distance between the relay location and the reach point is termed the reach of the relay.

It might be mentioned here, in passing, that though the zone of protection, as a notion, is a very clearly marked out area, in practice, it may become fuzzy and keep on expanding and contracting. How far the zone is crispy carved out depends upon the relaying principle used. In general, it can be said that the differential relaying gives a much more crispy carved out zone than over-current or distance relaying. Directional relaying creates a zone with infinite reach in the tripping direction.

1.6.6 Zone of Protection

Various zones, for a typical power system, are shown in Fig. 1.12. It can be seen that the adjacent zones overlap, otherwise there could be some portion which is left out and remains unprotected. At the same time, it must be realized that if the fault takes place in the overlapped portion, more than the minimum number of circuit breakers will trip, causing a major dislocation to the system. Each of the zones may be implemented using a different relaying principle. All the zones, in practice, may not be as well marked out as they are shown in the figure and may contract or expand depending upon the various system conditions.

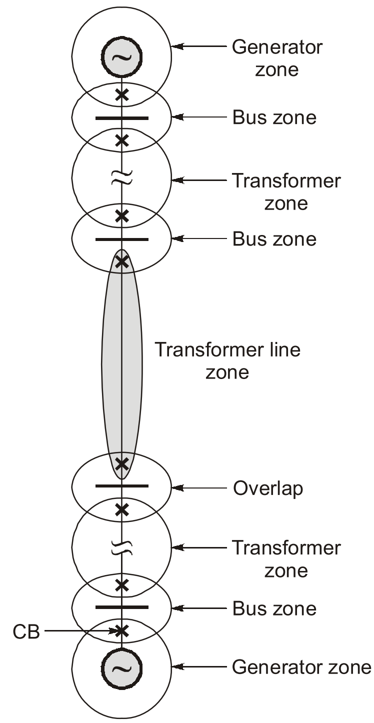

Fig. 1.12 : *Various zones of protection for a power system*

1.6.7 Primary and Back-up Protection

As already mentioned there are times when the primary protection may fail. This could be due to failure of the CT/VT or relay, or failure of the circuit breaker. One of the possible causes of the circuit breaker failure is the failure of the trip-battery due to inadequate maintenance. We must have a second line of defence in such a situation. Therefore, it is a normal practice to provide another zone of protection which should operate and isolate the faulty element in case the primary protection fails. A little thought will convince the reader that the back-up protection should not have anything in common with the primary protection. It should also preferably be located at a place different from where the primary protection is located. Further, the back-up protection must wait for the primary protection to operate, before issuing the trip command to its association circuit breakers. In other words the operating time of the back-up protection must be delayed by an appropriate amount over that of the primary protection. Thus, the operating time of the back-up protection should be equal to the operating time of primary protection plus the operating time of the primary circuit breaker. Consider the radial system shown in Fig. 1.13. Relay *B*, in conjunction with circuit breaker CB_B, provides primary protection to the line section B-C. Relay A with circuit breaker CB_A provides back-up protection to the section B-C. Consider a fault in section B-C as shown in Fig. 1.14.

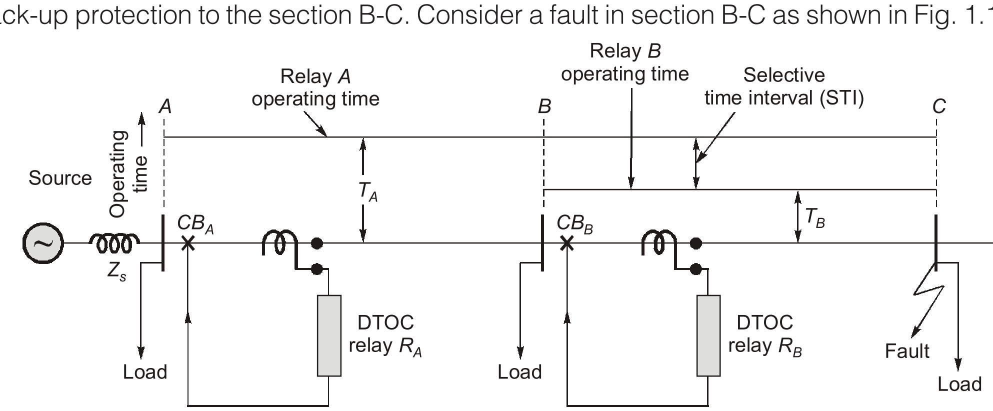

Fig. 1.13 : *Primary and back-up protection*

When a fault takes place, both the primary relay R_B and the back-up relay R_A, start operating simultaneously. In case the primary protection (provide by $R_B + CB_B$) operates successfully, the line B-C gets de-energized but the loads on buses A and B remain unaffected. Therefore, the back-up protection (provided by $R_A + CB_A$) resets without. However, in case the primary protection fails to operate, the back-up which is already monitoring the fault, waits for the time in which the primary would have cleared the fault and then issues the trip command to its allied circuit breakers. When the back-up operates, the time for which the fault persists is longer and disruption to the loads also lasts longer.

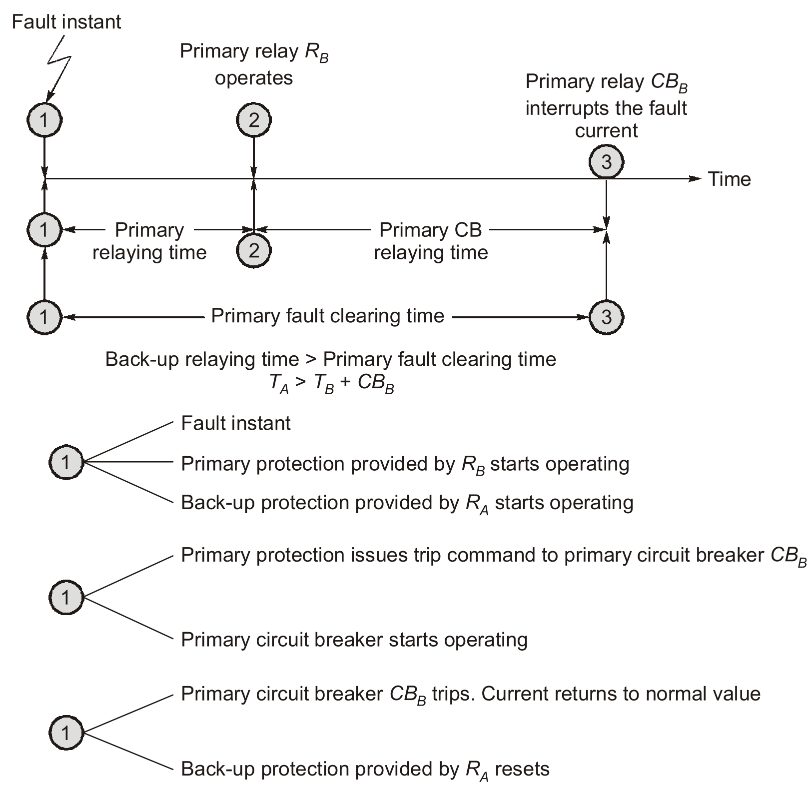

Fig. 1.14 : *Primary and back-up protection, sequence of events, normal operation*

Example - 1.1 What is meant by primary protection and backup protection?

Solution:

The main protection is the first line of defence and ensures quick acting and selective clearing of faults within the boundary of the circuit section or element it protects. Main protection as a rule, is provided for each section of an electrical installation.

Backup protection is the name given to a protection which backs up the main protection whenever the latter fails in operation or is cut out for repairs etc.

Backup protection is important to the proper functioning of a good system of electrical protection since per cent reliability not only of the protective scheme but also of the associated CTs, PTs and circuit breakers cannot be guaranteed. It is the second line of defence which functions to isolate a faulty section of the system in case the main protection fails to function properly.