Module 1 : Fundamentals of Power System Protection

Lecture 1 : Introduction

Objectives

In this lecture:

- We will provide an overview of electrical energy systems.
- Make a case for protection systems.
- Describe necessity of apparatus and system protection.
- Define a relay element.
- Discuss evolution of relays from electromechanical to numerical relay.
- Describe functioning of a circuit breaker.

1.1 Overview of Electrical Energy Systems

Electrical energy systems consists of various equipments connected together. Typically, power is generated at lower voltages (a few kV) (3-phase ac voltage source) which is stepped up by a transformer and fed into a transmission grid. Thermal power should be generated at pit heads and hydro power at reservoirs. A transmission grid is a meshed network of high voltage lines and transformers. It can have multiple voltage levels like 400 kV, 220 kV, etc. The power is delivered to load centers which may be far off (even thousands of km's apart).

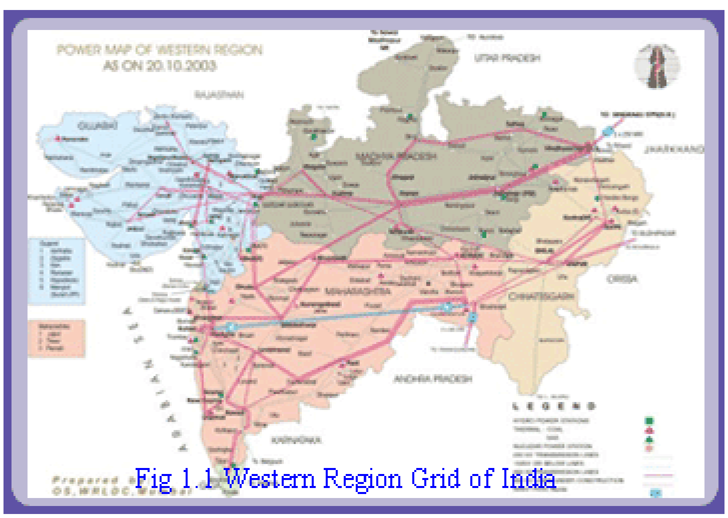

Fig 1.1 Western Region Grid of India

Fig 1.1 shows the western region grid of India. It can be seen that large amount of generation is concentrated in the eastern end while large load centers are concentrated in the western end. The power is transferred through the ac network and HVDC lines. At load centers, voltage levels are stepped down by step down transformers in multiple stages and finally power is delivered to the end user by a distribution system which is mostly radial (no loops) in nature.

A unique feature of electrical energy systems is its *natural* mode of synchronous operation. It implies that during steady state the electrical frequency is same all through the system irrespective of the geographical location. This closely knits the system together.

We can perceive all generators acting in tandem like the ballet dancers in a dance.

1.1 Overview of Electrical Energy Systems

They may occupy different angular positions, but all machines rotate at the same electrical speed. This close knitting implies an embedded interaction of generators through the transmission network which is governed by the differential and algebraic equations of the apparatus and interconnects. This aspect is referred to as the system behavior. This system has to be protected from abnormalities which is the task of protection system.

1.2 Why do we need Protection?

Electrical power system operates at various voltage levels from 415 V to 400 kV or even more. Electrical apparatus used may be enclosed (e.g., motors) or placed in open (e.g., transmission lines). All such equipment undergo abnormalities in their life time due to various reasons. For example, a worn out bearing may cause overloading of a motor. A tree falling or touching an overhead line may cause a fault. A lightning strike (classified as an act of God!) can cause insulation failure. Pollution may result in degradation in performance of insulators which may lead to breakdown. Under frequency or over frequency of a generator may result in mechanical damage to it's turbine requiring tripping of an alternator. Even otherwise, low frequency operation will reduce the life of a turbine and hence it should be avoided.

It is necessary to avoid these abnormal operating regions for safety of the equipment. Even more important is safety of the human personnel which may be endangered due to exposure to live parts under fault or abnormal operating conditions. Small current of the order of 50 mA is sufficient to be fatal! Whenever human security is sacrificed or there exists possibility of equipment damage, it is necessary to isolate and de-energize the equipment. Designing electrical equipment from safety perspective is also a crucial design issue which will not be addressed here. To conclude, every electrical equipment has to be monitored to protect it and provide human safety under abnormal operating conditions. This job is assigned to electrical protection systems. It encompasses apparatus protection and system protection.

1.3 Types of Protection

Protection systems can be classified into apparatus protection and system protection.

1.3.1 Apparatus Protection

Apparatus protection deals with detection of a fault in the apparatus and consequent protection. Apparatus protection can be further classified into following:

- Transmission Line Protection and feeder protection
- Transformer Protection
- Generator Protection
- Motor Protection
- Busbar Protection

1.3.2 System Protection

System protection deals with detection of proximity of system to unstable operating region and consequent control actions to restore stable operating point and/or prevent damage to equipments. Loss of system stability can lead to partial or complete system blackouts. Under-frequency relays, out-of-step protection, islanding systems, rate of change of frequency relays, reverse power flow relays, voltage surge relays etc are used for system protection. Wide Area Measurement (WAM) systems are also being deployed for system protection. Control actions associated with system protection may be classified into preventive or emergency control actions.

1.3.2.1 Analogy with Functioning of a Human being

A human being is a complex system that performs through various apparatus like legs, hands, eyes, ears, heart, bones, blood vessels etc. The heart is analogous to an electrical generator and stomach to the boiler. The eating process provides raw material to generate calories. The power generated is pumped by heart through a complex network of blood vessels. The primary transmission is through arteries and veins. Furthermore, distribution is through fine capillaries. The system operator is the brain which works on inputs of eyes, ears, skin etc. Diagnosing abnormality in any of these organs and taking remedial measures can be thought of as job of "apparatus protection". However, does this cover the complete gambit of anomalies? Are fever, infection etc, a specific apparatus problem? Why does it cause overall deterioration in functioning of the human being?

The answer lies in the fact that the system which encompasses body has also abstraction like the mind. Overall health is not just an aggregation of apparatus. It is something much more complex. It involves complex process and associated dynamics (biological, chemical, mechanical etc.) and control. Thus, protecting a system is not just apparatus protection but something much more. Since we cannot define this "much more" clearly, it is complex and challenging. Monitoring of system behavior, taking corrective measures to maintain synchronous operation and protecting the power system apparatus from harmful operating states is referred as **system protection**.

1.4 What is a Relay?

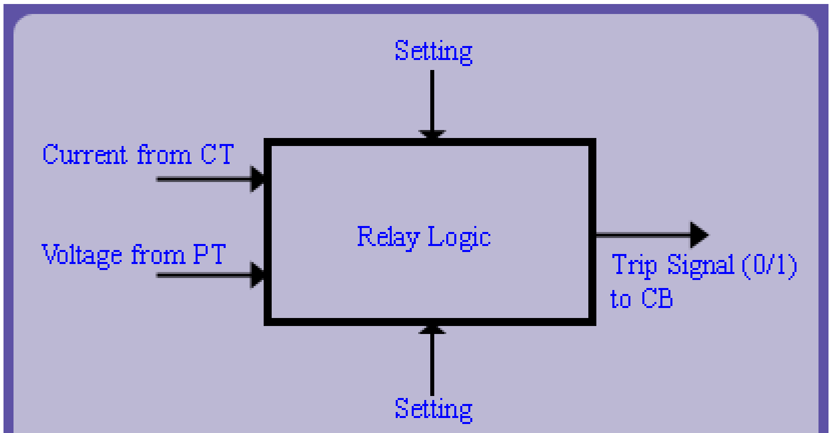

Fig 1.2 Conceptual Diagram of Relay

Formally, a relay is a logical element which processes the inputs (mostly voltages and currents) from the system/apparatus and issues a trip decision if a fault within the relay's jurisdiction is detected. A conceptual diagram of relay is shown in fig 1.2.

In fig 1.3, a relay R_1 is used to protect the transmission line under fault F_1. An identical system is connected at the other end of the transmission line relay R_3 to open circuit from the other ends as well.

To monitor the health of the apparatus, relay senses current through a current transformer (CT), voltage through a voltage transformer (VT). VT is also known as Potential Transformer (PT).

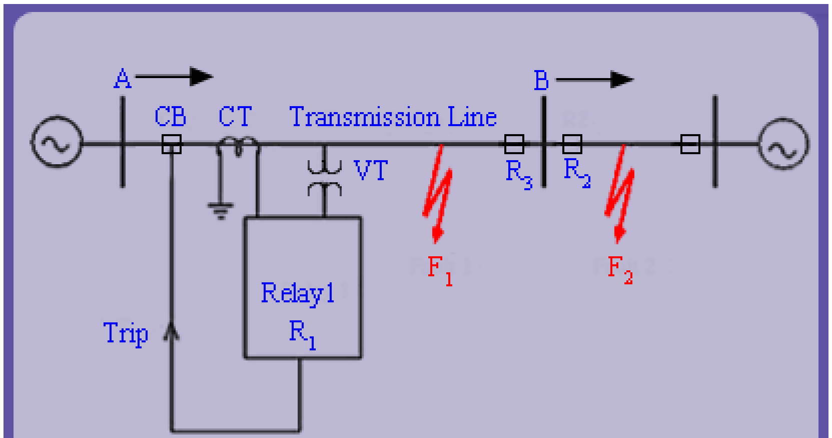

Fig 1.3 Typical Relaying System

The relay element analyzes these inputs and decides whether (a) there is a abnormality or a fault and (b) if yes, whether it is within jurisdiction of the relay. The jurisdiction of relay R_1 is restricted to bus B where the transmission line terminates. If the fault is in it's jurisdiction, relay sends a tripping signal to circuit breaker(CB) which opens the circuit. A real life analogy of the jurisdiction of the relay can be thought by considering transmission lines as highways on which traffic (current/power) flows.

If there is an obstruction to the regular flow due to fault F_1 or F_2, the traffic police (relay R_1) can sense both F_1 and F_2 obstructions because of resulting abnormality in traffic (power flow). If the obstruction is on road AB, it is in the jurisdiction of traffic police at R1; else if it is at F_2, it is in the jurisdiction of R_2. R_1 should act for fault F_2, if and only if, R_2 fails to act. We say that relay R_1 backs up relay R_2. Standard way to obtain backup action is to use time discrimination i.e., delay operation of relay R_1 in case of doubt to provide R_2 first chance to clear the fault.

1.5 Evolution of Relays

If we zoom into a relay, we see three different types of realizations:

- Electromechanical Relays
- Solid State Relays
- Numerical Relays

1.5.1 Electromechanical Relays

When the principle of electromechanical energy conversion is used for decision making, the relay is referred as an electromechanical relay. These relays represent the first generation of relays. Let us consider a simple example of an over current relay, which issues a trip signal if current in the apparatus is above a reference value. By proper geometrical placement of current carrying conductor in the magnetic field, Lorentz force $F = Bil \sin\theta$ is produced in the operating coil.

This force is used to create the operating torque. If constant 'B' is used (for example by a permanent magnet), then the instantaneous torque produced is proportional to instantaneous value of the current. Since the instantaneous current is sinusoidal, the instantaneous torque is also sinusoidal which has a zero average value. Thus, no net deflection of operating coil is perceived.

On the other hand, if the B is also made proportional to the instantaneous value of the current, then the instantaneous torque will be proportional to square of the instantaneous current (non-negative quantity). The average torque will be proportional to square of the rms current. Movement of the relay contact caused by the operating torque may be restrained by a spring in the overcurrent relay. If the spring has a spring constant 'k', then the deflection is proportional to the operating torque (in this case proportional to I_{rms}^2). When the deflection exceeds a preset value, the relay contacts closes and a trip decision is issued. Electromechanical relays are known for their ruggedness and immunity to Electromagnetic Interference (EMI).

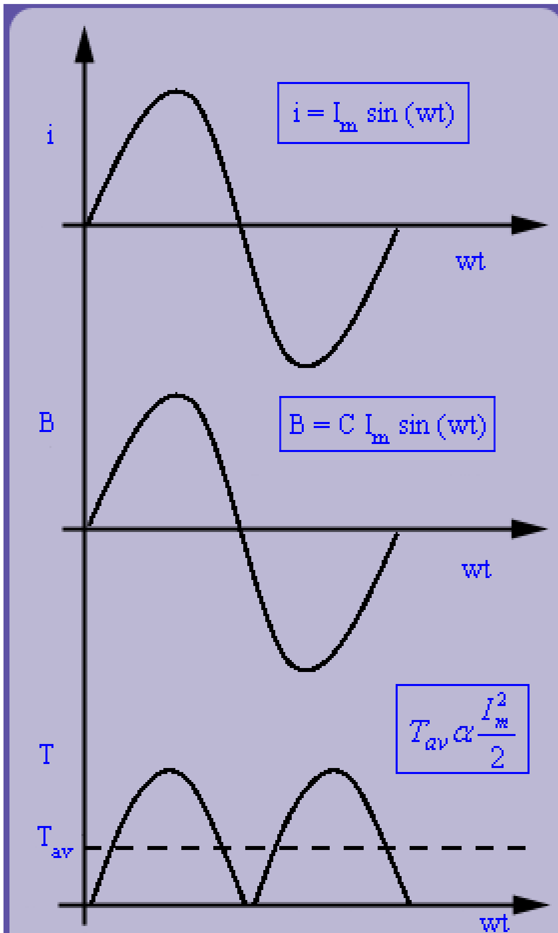

Fig. 1.4 Torque and Current Relationship in Attracted Armature Relay

1.5 Evolution of Relays

1.5.2 Solid State Relays

With the advent of transistors, operational amplifiers etc, solid state relays were developed. They realize the functionality through various operations like comparators etc. They provide more flexibility and have less power consumption than their electromechanical counterpart. A major advantage with the solid state relays is their ability to provide self checking facility i.e. the relays can monitor their own health and raise a flag or alarm if its own component fails. Some of the advantages of solid state relays are low burden, improved dynamic performance characteristics, high seismic withstand capacity and reduced panel space.

Relay burden refers to the amount of volt amperes (VA) consumed by the relay. Higher is this value, more is the corresponding loading on the current and voltage sensors i.e. current transformers (CT) and voltage transformers (VT) which energizes these relays. Higher loading of the sensors lead to deterioration in their performance. A performance of CT or VT is gauged by the quality of the replication of the corresponding primary waveform signal. Higher burden leads to problem of CT saturation and inaccuracies in measurements. Thus it is desirable to keep CT/VT burdens as low as possible.

These relays have been now superseded by the microprocessor based relays or numerical relays.

1.5.3 Numerical Relays

The block diagram of a numerical relay is shown in fig 1.5.

It involves analog to digital (A/D) conversion of analog voltage and currents obtained from secondary of CTs and VTs. These current and voltage samples are fed to the microprocessor or Digital Signal Processors (DSPs) where the protection algorithms or programs

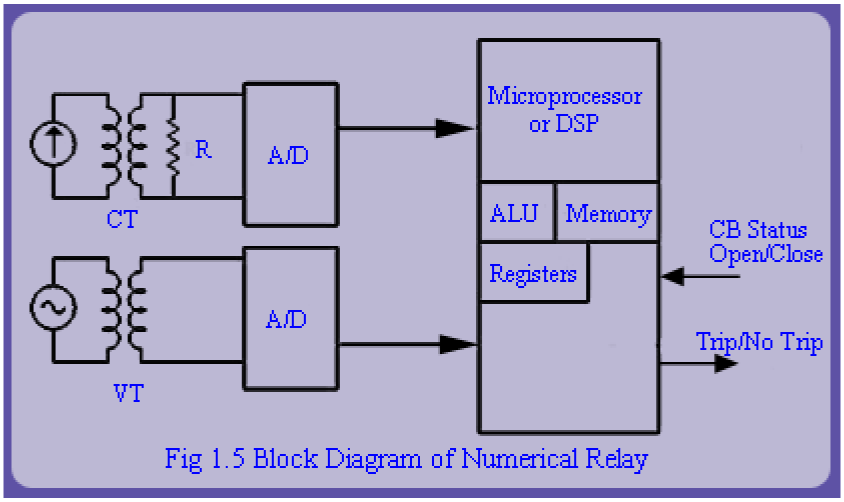

Fig 1.5 Block Diagram of Numerical Relay

process the signals and decide whether a fault exists in the apparatus under consideration or not. In case, a fault is diagnosed, a trip decision is issued. Numerical relays provide maximum flexibility in defining relaying logic.

1.5 Evolution of Relays

1.5.3 Numerical Relays

The hardware comprising of numerical relay can be made scalable i.e., the maximum number of v and i input signals can be scaled up easily. A generic hardware board can be developed to provide multiple functionality. Changing the relaying functionality is achieved by simply changing the relaying program or software. Also, various relaying functionalities can be multiplexed in a single relay. It has all the advantages of solid state relays like self checking etc. Enabled with communication facility, it can be treated as an Intelligent Electronic Device (IED) which can perform both control and protection functionality. Also, a relay which can communicate can be made adaptive i.e. it can adjust to changing apparatus or system conditions. For example, a differential protection scheme can adapt to transformer tap changes. An overcurrent relay can adapt to different loading conditions. Numerical relays are both "the present and the future". Hence, in this course, our presentation is biased towards numerical relaying. This also gives an algorithmic flavour to the course.

1.6 What is a Circuit Breaker?

A Circuit Breaker (CB) is basically a switch used to interrupt the flow of current. It opens on relay command. The relay command initiates mechanical separation of the contacts. It is a complex element because it has to handle large voltages (few to hundreds of kV's) and currents (in kA's). Interrupting capacity of the circuit breaker is therefore expressed in MVA.

Power systems under fault behave more like inductive circuits. X/R ratio of lines is usually much greater than unity. For 400 kV lines, it can be higher than 10 and it increases with voltage rating. From the fundamentals of circuit analysis, we know that current in an inductive circuit (with finite resistance) cannot change instantaneously. The abrupt change in current, if it happens due to switch opening, will result in infinite di/dt and hence will induce infinite voltage. Even with finite di/dt, the induced voltages will be quite high. The high induced voltage developed across the CB will ionize the dielectric between its terminals. This results in arcing. When the current in CB goes through the natural zero, the arc can be extinguished (quenched). However, if the interrupting medium has not regained its dielectric properties then the arc can be restruck. The arcing currents reduce with passage of time and after a few cycles the current is finally interrupted.

Usually CB opening time lies in the 2-6 cycles range. CBs are categorized by the interrupting medium used. Minimum oil, air blast, vacuum arc and SF_6 CBs are some of the common examples. CB opening mechanism requires much larger power input than what logical element relay can provide. Hence, when relay issues a trip command, it closes a switch that energizes the CB opening mechanism powered by a separate dc source (station battery). The arc struck in a CB produces large amount of heat which also has to be dissipated.

Review Questions

1. What are the two types of protection?
2. Why is system protection required?
3. What are the functions of a relay and a circuit breaker?
4. Describe various generation of relays.
5. In fig 1.5, why is a resistor connected across CT secondary?

Recap

In this lecture we have learnt the following:

- Necessity of a protection system.

- Three generations of relays.

- Role of Circuit Breaker.

- Types of protection i.e. apparatus protection and system protection.