

Module 4 : Overcurrent Protection

Lecture 14 : Fuse Protection

Objectives

In this lecture we will learn the following:

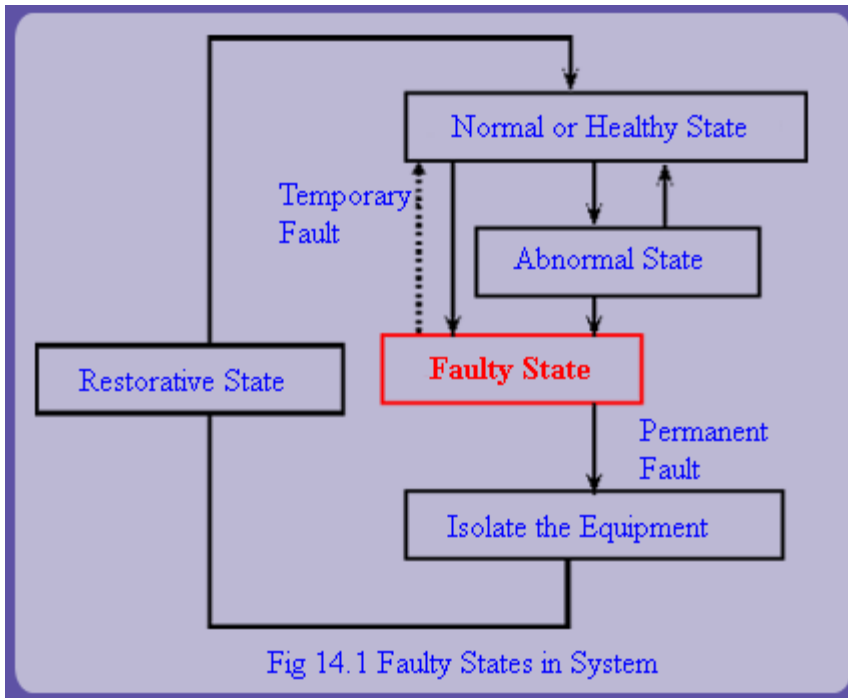
- Abnormality and faults.
- Source for fault currents.
- Fuse for overcurrent protection.
- Melting time and total clearing time of Fuse.
- Very inverse characteristic of Fuse.
- Physics of ARC interruption.
- Types of HV fuses viz, expulsion, vacuum and non-expulsion fuses and their functionality.

14.1 Abnormality and Faults

When an equipment (e.g. transmission line, transformer, generator, motor) is operating within the rated specifications (speed, voltage, current etc.), we say that it is in the normal state. Therefore, abnormal state pertains to deviation from the rated operating point. It may refer to overcurrent, under voltage, over or under frequency. If the apparatus continues to operate in this state for long enough time, it can lead to damage or reduction in life of the equipment. On the other hand, it may be also unsafe to operate in this region. A fault refers to a serious abnormality which typically requires immediate deenergization of the equipment.

Usually, faults are considered dangerous because of overcurrent that they create. This can damage the apparatus and it endangers the human safety. Three phase faults, Line to Line faults (LL), Single Line to Ground fault (SLG), Line to Line Ground faults (LLG) are some standard faults considered in our analysis. Three phase faults and Line to Line faults are also known as phase faults while Single Line to Ground and Double Line to Ground faults are also known as ground faults. However, not all faults create large overcurrents. For example, earth faults which may result due to partial insulation failure may not create large currents. However, it makes operation of the equipment unsafe from human safety perspective and further, if the fault is left unattended it can aggravate.

Fig 14.1 illustrates various aspects in this process. In the normal state, all system variables are within the normal range. Abnormal state reflects an increase in possibility of a disturbance. Severe disturbance results in a faulty state. If the fault is temporary then the system returns to normal state. Permanent fault requires isolating the equipment. Post-fault maintenance (restorative state), of the equipment can be recommenced.



Typically, power system protection, refers to fault detection and deenergization of the equipment. In contrast, condition monitoring refers to monitoring the equipment to detect possibility of equipment failure. Condition monitoring and good maintenance can reduce a number of potential faults.

14.2 Sources of Fault Current

This lecture deals with overcurrent protection for radial distribution systems. In a radial system with single source, the magnitude of fault current depends upon the following:

- Source contribution (Source voltage and impedance).
- Transformer impedance.
- Motor contribution (Back emf and impedance of induction and synchronous motors).
- Distance of fault from the source.

Meshed system or a system with multiple sources require directional relays discussed in subsequent lectures. The first step in the overcurrent protection is estimation of the fault current. If the system is radial and fed from a single or equivalent source, this job is simplified. For conservative calculation, utility source impedance should be considered as zero (unlimited MVA supplying capacity). The reason for this assumption is that, changes in utility system, addition of generators, strengthening of transmission network etc. can reduce the source impedance. Consequently, the maximum fault current is limited by the impedance of the distribution transformer. In a single source radial system, typically fault current reduces as we move away from the source (an exception being a system with large motor loads at the remote ends). The transformer short circuit current can be calculated from this formula,

$$I_{sc} = [(\text{Transformer Full Load current}) \times 100 / (\% z)]$$

Any motor e.g. induction, synchronous condenser or motor etc. must be considered as a source for calculating fault current in the first few cycles. For the sake of simplicity and because of its large usage, we consider only induction motor load. Further, when calculating short circuit current it is a common practice to lump all motors that are grouped together. In other words, they are treated as if they are on a common bus. Assuming a group motor subtransient reactance (X'') of 25 %, the typical contribution is 4 times full load current.

14.3 Introduction to Fuse

Terminology 'Fuse' does not require any introduction. A 'fuse' refers to a device that opens a circuit with fusible part, which is heated and severed by current flowing through it. The fusible part is also called the "Element". When current flows in a fuse, heat is generated and the element temperature rises. If the

current is within (less or equal to) its continuous rated value, then the steady state temperature is such that the fuse does not melt. However, if the current has large enough magnitude, it will lead to the fuse element to melt before the steady state temperature conditions are achieved. After melting, an arc may be struck. The fault current will be finally interrupted when the arc is de-ionized. Thus, fuse operation involves two phases viz. melting and current interruption.

An enormous variety of fuses are available today. In terms of quantity, fuses outnumber any other over current protection devices. They provide economy in protection as well as flexibility in rating and time current characteristic. They are used for overcurrent protection of transformers, capacitors and lateral taps in distribution systems.

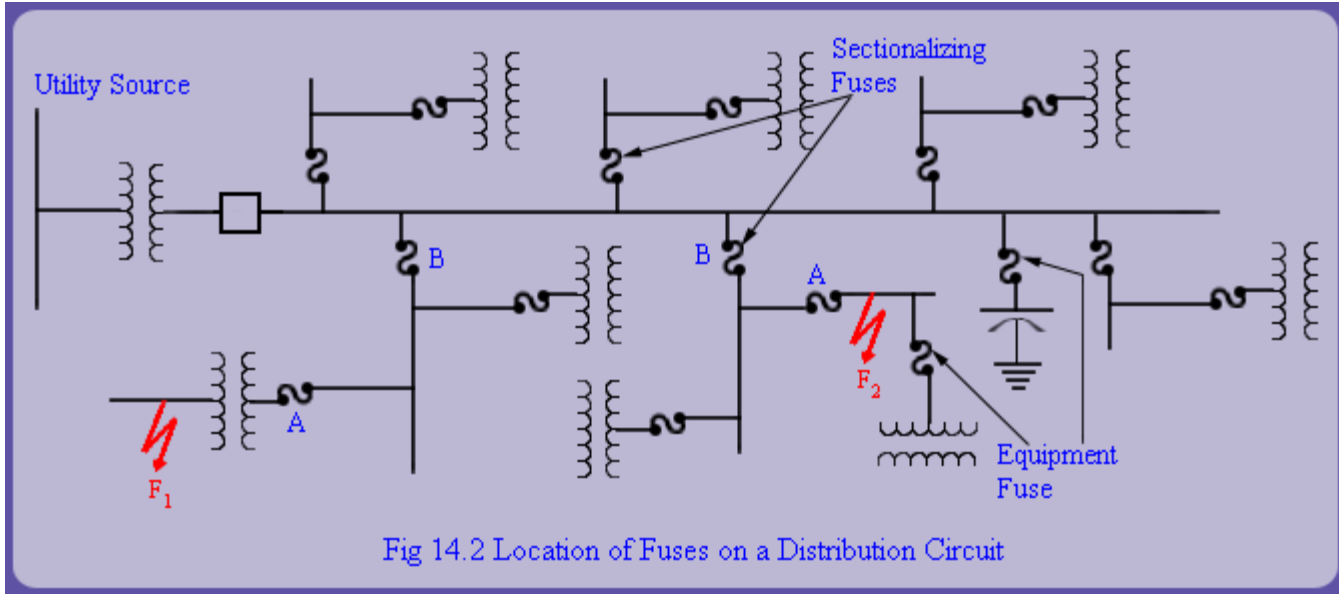


Fig 14.2 Location of Fuses on a Distribution Circuit

Fig 14.2 shows location of fuses in a distribution system. Each transformer and capacitor bank has fuse protection to selectively disconnect the device in case of a fault in the device. Transformer fuses can also provide overload protection. The sectionalizing fuses are used to divide the system into smaller sections which can be then isolated from the rest of the system. For the fault F_1 or F_2 it is the responsibility of fuse A to operate. Thus, only customers connected to this line are affected. In absence of fuse A, fuse B would have to be operated but this would lead to a interruption in service to larger number of customers. Role of reclosers will be discussed in later lectures.

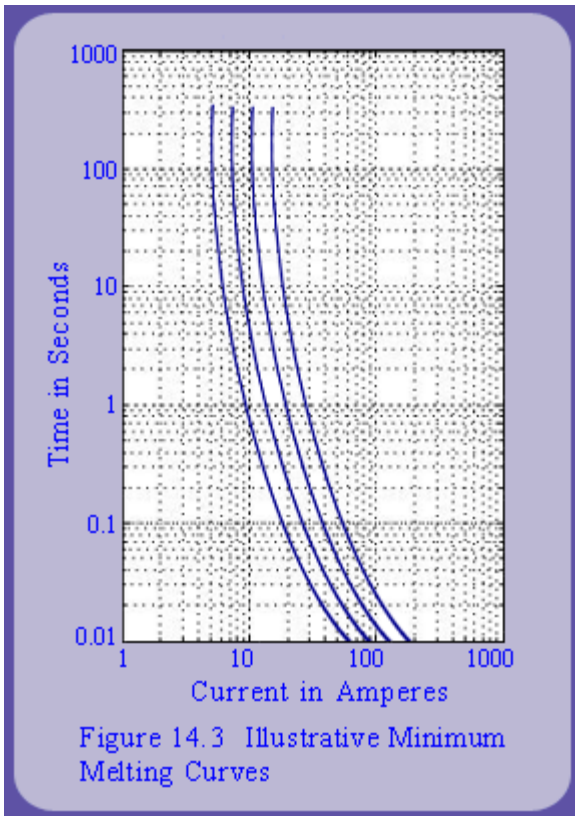
14.4 Fuse Characteristics

Fuses are characterized by 'thermal' and 'interrupting' characteristics. Thermal characteristic are quite intuitive and relate to the following:

- Current rating.
- Melting characteristics.
- Interrupting characteristics refer to the following:
- Voltage rating.
- Interrupting rating.

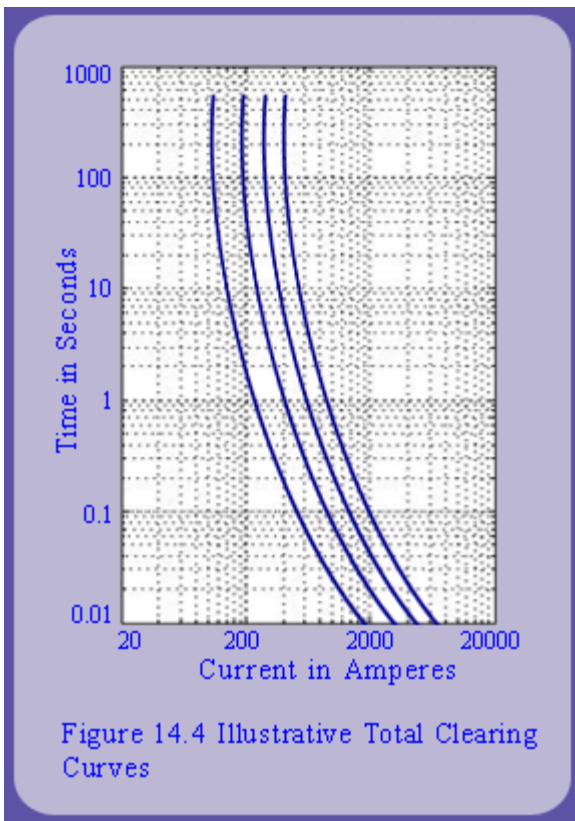
14.4.1 Thermal Characteristics

As the magnitude of the current increases, melting time reduces. It should be obvious that larger magnitude currents will lead to higher power dissipation (I^2R) in



14.4 Fuse Characteristics

14.4.2 Interrupting Characteristics



14.4.3 Very Inverse Melting Characteristic

Fuse melting time characteristic is usually described in literature as “very inverse”. To understand this, we need to address the physics of the problem. When overcurrents are smaller in magnitude, rate of heat generated in the element is low and only slightly higher than rate of dissipation. As a consequence,

the fuse and hence faster rise in temperature of the element. This would imply that melting time of the fuse should be inversely proportional to magnitude of square of current. The relationship between the magnitude of the current that causes melting and the time needed for it to melt is given by the fuse's melting time current characteristics (TCC). To cover a wide range of currents and operating time, TCC is plotted on a log-log paper.

The current is the symmetrical current. The current on x-axis is the symmetrical current. It does not involve dc offset current. Further, fuse does not carry initial current and ambient temperature is between 20°C and 30°C (IEEE Std 37.41-1994). Since, the melting time vary in a range, minimum melting time curve is plotted as shown in fig 14.3.

The severing of fuse element is a primary consequence of thermal effect. It does not depend upon mechanical forces, inertia etc. Thus there is no limit on how short the melting time can be. This extremely small melting (fast operation) of a fuse at very high currents tends to distinguish it from most other protective devices.

It is important to realize that power apparatus and systems contain inductive elements. Hence, melting of a fusing element is not sufficient to interrupt the current. Consequently, there is always some period of arcing before the current is interrupted. During this period, fuse must withstand any immediate transient voltage condition and subsequent steady state recovery voltage. Addition of melting time and this arcing overhead gives the total clearing time.

Total clearing TCC curve (fig 14.4) describes this information. For lower currents, melting time can be large and arcing time small because of lower stored energy $\frac{1}{2}LI^2$ in induction circuit. In contrast, for large currents, melting time is small but the arcing time is large. Hence, TCC for melting time and total clearing time diverges as $|I|$ increases.

Both of these characteristics are required to coordinate back up fuse or overcurrent relay or any other protective devices. Back up device should provide sufficient 'opportunity window' (time) to primary fuse to clear the fault. This ensures selectivity. Recall that selectivity minimizes loss of service.

temperature of the element increases gradually. As the current increases, melting time reduces at a rate which is more than expected increased rate of heat generation (I^2R). This is because, heat which is generated in reduced cross section and/or centre of element, cannot be removed as fast as it is produced. This gives fuse a **very inverse characteristics**. At very short melting times, no heat is lost from the smaller cross section of the element.

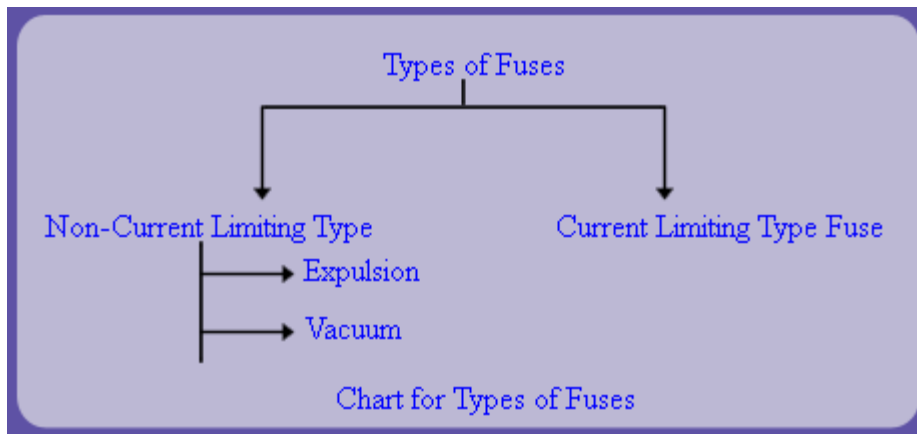
14.4 Fuse Characteristics

14.4.4 Voltage Rating

So far we have not broached the subject of voltage rating of a fuse. However, even a fuse has a maximum rated voltage. It is the highest voltage at which fuse is designed to operate and it is important that a fuse should not be asked to interrupt current above this voltage. Faults can be line to ground or line to line. When applied phase to ground on three phase systems, the voltage rating of the fuse should equal or exceed the phase to ground system voltage. When applied in the line on the same system, the conservative approach is to choose the fuse voltage to be equal to system phase to phase voltage. Sometimes, for a fuse both maximum and minimum interrupting currents are specified.

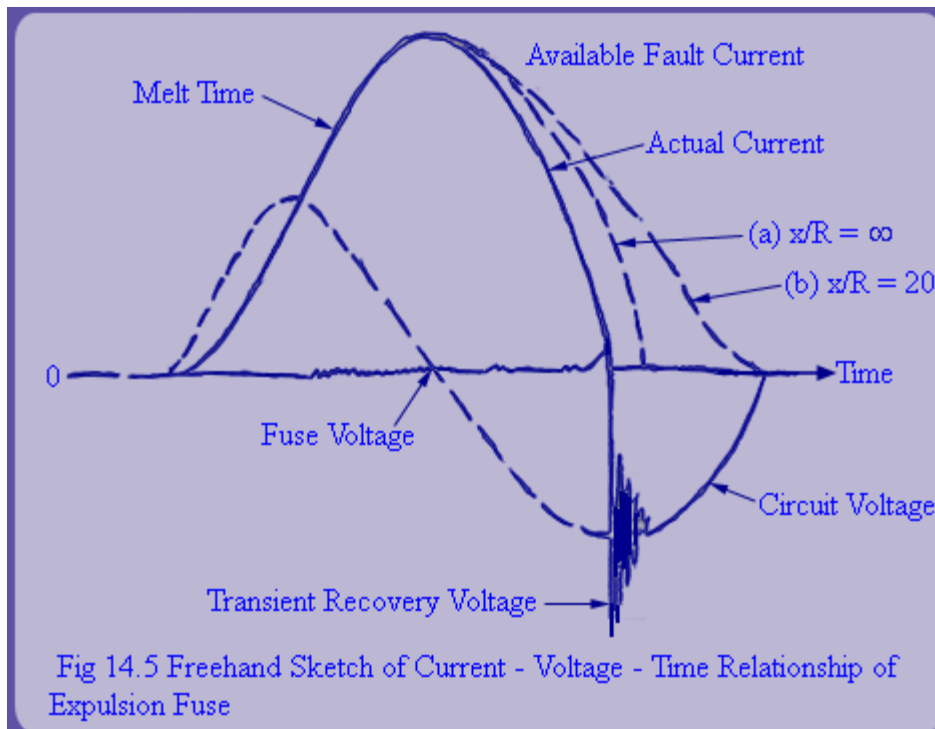
14.5 Types of Fuses

Fuse can be classified into two types (see the chart below)



14.5 Types of Fuses

1. Non-Current Limiting Fuses (Expulsion type)



The expulsion type fuse is used where expulsion gases cause no problem such as in overhead circuits and equipment. These fuses can be termed as current awaiting types; and the function of interrupting medium is similar to that of an ac circuit breaker. The temperature of arc is of the order of 4000-5000K. At this temperature special materials located in close proximity to fuse element rapidly create gases. Preferred gas generating materials are fiber, melamine, boric acid and liquids such as oil or carbon tetrachloride. These gases help to create a high pressure turbulent medium surrounding the arc, thus when the current does reach to zero and the arc channel reduces to a minimum; the ablated gases rapidly mix with remaining ionized gas and thereby deionize them as well as remove them from 'arc area'. In turn, this leads to rapid build up of dielectric strength that can withstand the transient recovery voltage (TRV) and steady state power system voltage.

TRV for expulsion fuse is shown in fig 14.5. Note that in an inductive circuit, current zero occurs at 90° lag to voltage i.e. when voltage is at maximum value. The action of interrupting medium causes TRV to be seen in this region.

14.5 Types of Fuses

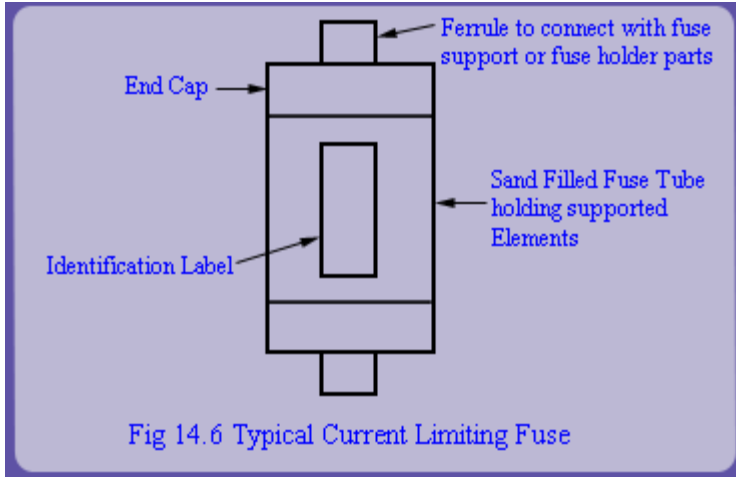
2. Vacuum Fuse

Vacuum fuse is a non expulsive fuse but still a current zero awaiting type. The design, operation and current-voltage-time relationship of this fuse closely matches with that of an expulsion fuse. The main difference is that it is a completely sealed unit and no expulsion action. Interruption occurs because of rapid dielectric build up that occur in a vacuum after current zero is reached.

3. Current Limiting Fuse

Suppose that an overcurrent protective element could insert a large resistance in series during fault current. This would then improve the power factor in the fault circuit which otherwise is more or less inductive. Thus, the zero crossing of the current and voltage would be in phase. This implies that when the arc is extinguished temporarily at current zero, the applied voltage across it will also be zero. This should be contrasted with expulsion type or current awaiting type fuse where typically, $I(t) = 0, V = V_m$. (90° phase lag in an inductive circuit). If at current zero, $V(t) = V_m$, then the presence of a large electric field does not help in quick de-ionization. In contrast, when the current zero and voltage zero are in phase, then when the temporary arc is extinguished, the dielectric medium will be quickly de-ionized. (This also reduces TRV. Inclusion of higher resistance also reduces peak value of current.)

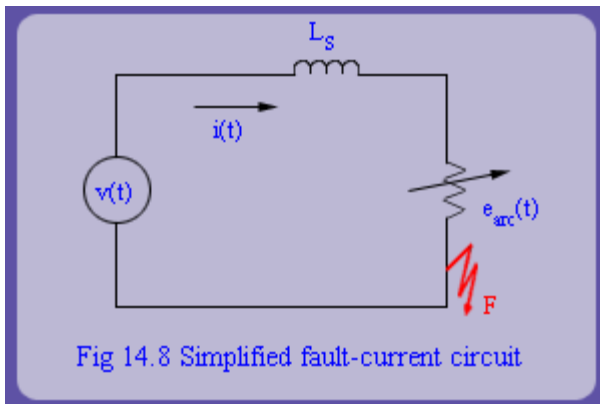
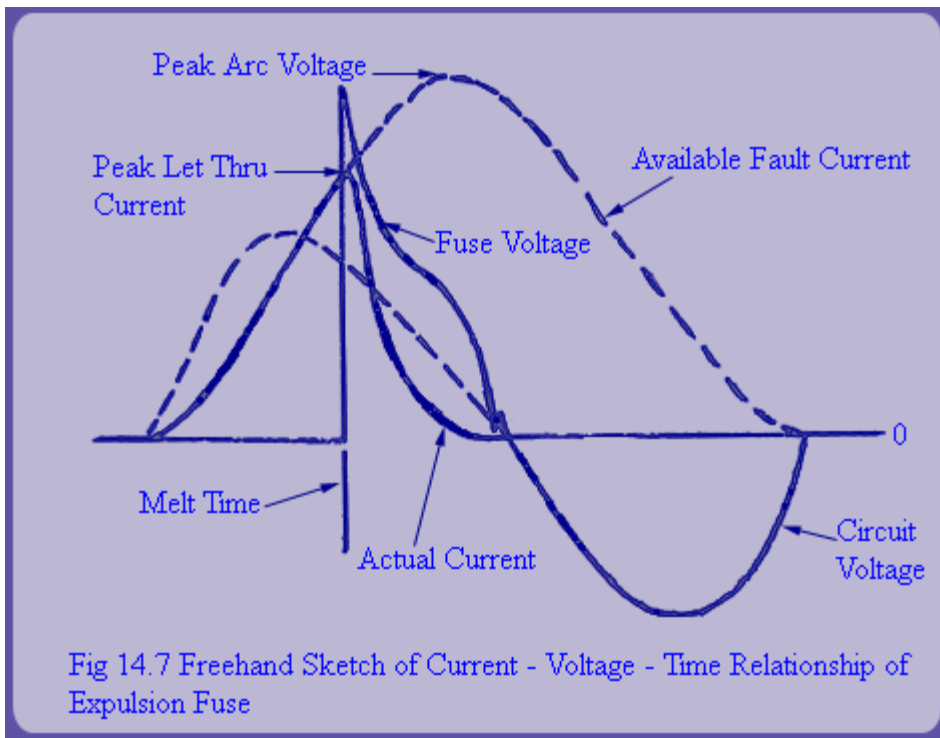
This leads to speeding in fuse action. The primary question however, is how to insert the high resistance in series. Basically, the current limiting fuses attempt to constrict the arc and it is cooled by sand.



A typical current limiting fuse is shown in fig 14.6. In this case, the fusible element is very long. The element is completely surrounded with filler material, typically silica sand, to contain the arc as well as maintain a very high pressure in the long restricted arc area caused by the practically simultaneous melting of the full length of element. This then allows the fuse to produce a very high resistance in the circuit in a very short period of time (typically hundreds of μsec).

14.5 Classification of Fuses

3. Current Limiting Fuse



The current – voltage time relationship is shown in fig 14.7. We now conclude this lecture, by briefly discussing the physics of arc interruption. Simplified fault current circuit is shown in fig 14.8.

$E_{arc}(t)$ is the arc voltage and $V(t)$ is the source voltage, then differential equation governing the circuit is:

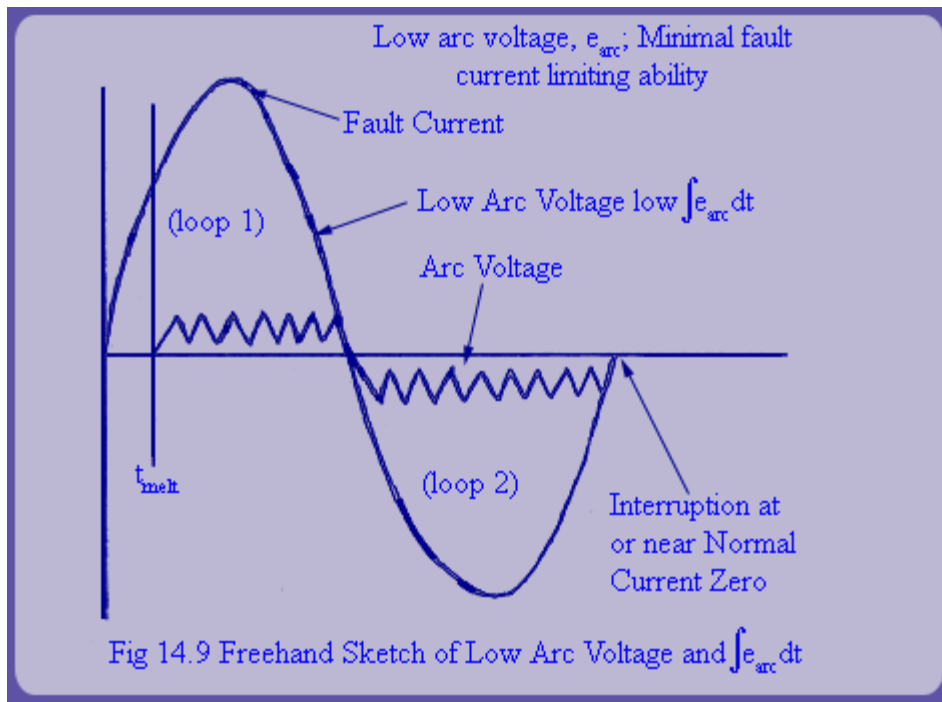
$$v(t) - e_{arc}(t) = L \left(\frac{di}{dt} \right)$$

$$i(t) = \frac{1}{L} \int (v(t) - e_{arc}(t)) dt$$

14.6 Physics of Fuse Interruption

The equation brings out the following concepts;

1. The current is proportional to the area under the difference of source and arc voltage. The inductance provides a stored energy and the necessary voltage to sustain the current even if the instantaneous arc voltage of the fuse momentarily exceeds the source voltage.
2. Thus, a higher source voltage will adversely affect the interruption of current.
3. Conversely, a high fuse arc voltage, sustained over time will help in greater limitation of the fault current.
4. Lower the inductance, higher the available prospective fault current.



14.6 Physics of Fuse Interruption

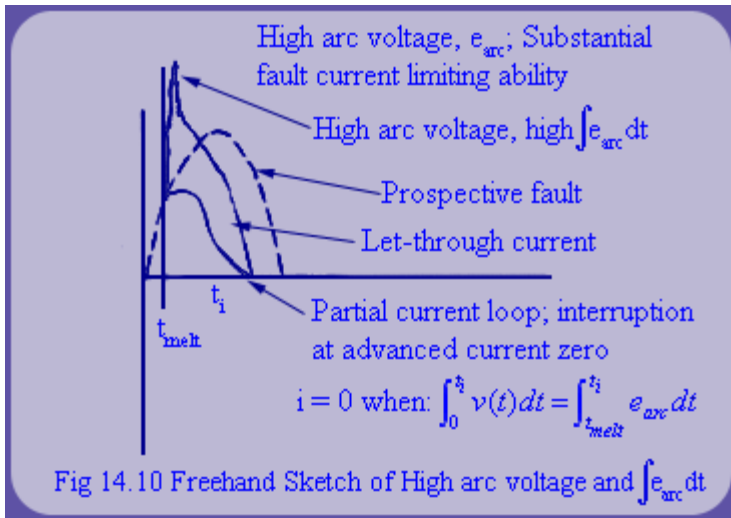


Fig 14.9 and fig 14.10 shows the function of expulsion type and current limiting fuses. Notice that in expulsion type fuses, arc voltage is low, the peak first cycle current is not limited and current is interrupted after one or two loops at near nominal current zero. In contrast, in current limiting fuse, high arc voltage resulting in substantial current limiting capacity with advanced current zero. This condition is achieved at time t_i , when $\int v dt = \int E_{arc} dt$

14.7 Power class and Distribution class fuses :

Fuses can also be classified by their domain of application. Based on this approach they are classified into following types:

- Power class.
- Distribution class type.

Power fuses are tested to TRVs and X/R ratio values more likely to be encountered in or near the generating station or substation for three phase circuits. Distribution fuses have specifications more closely matched to distribution system which is further away from source or substation on a single phase or three phase system.

Review Questions

1. Differentiate between abnormal state and faulty state.
2. What are the advantages and disadvantages of fuse?
3. Define the following terms:

- a) Available fault current.
 - b) Interrupting rating.
 - c) Voltage rating.
4. Explain the physics of arc interruption in a fuse.
 5. Explain how does a current limiting fuse, insert a high series resistance in the fault circuit? What benefits does it achieve?

Recap

In this lecture we have learnt the following:

- **Available Fault Current:** This is the maximum rms short circuit current that flows to a faulted node or point. The magnitude is limited by the ac impedance to that specific point. The impedance is the sum of the utility source impedance and the in-plant circuit impedance.
- **Continuous Current Rating:** As with all overcurrent devices, most fuses are limited to a continuous loading of 80% of their label rating. This is due to the mutual heating between switch, fuse and adjacent devices.
- **Current limiting Fuse:** First generation fuses, e.g. expulsion type, only limit the duration (time) of the fault. The modern current-limiting fuse, however, not only limits the duration of the fault, but also limits the magnitude of the fault.
- **Interrupting Rating:** This is the maximum current that overcurrent device can safely interrupt at a stated voltage, frequency, and short circuit power factor. Interrupting ratings are expressed in rms symmetrical amperes. It is common for a device rated 200 000 A to have an abbreviated marking such as 200 KA IR.
- **Voltage Rating:** The rms alternating current voltage at which the fuse is designed to operate. Fuses of the 600 V class will always function safely on a lesser voltage. For example 600 V fuses are typically used on 480 and 208 V.

Congratulations, you have finished Lecture 14. To view the next lecture select it from the left hand side menu of the page

