CHAPTER 14

TRANSIENT OVER-VOLTAGES, SURGE PROTECTION AND INSULATION COORDINATION

INTRODUCTION

- Transmission and distribution lines form a large network spread over thousands of miles.
- A variety of reasons discussed here can cause abnormally high over-voltages that, unless protected properly against, can disrupt service momentarily at best, and cause prolonged outage and expensive damage to the power systems apparatus at worst.
- We will examine the causes of over-voltages and the measures that can be taken to protect against them.

CAUSES OF OVER-VOLTAGES

- Lightning strikes and
- Switching of extra-high voltage transmission lines

Lightning Strikes: Current Impulse

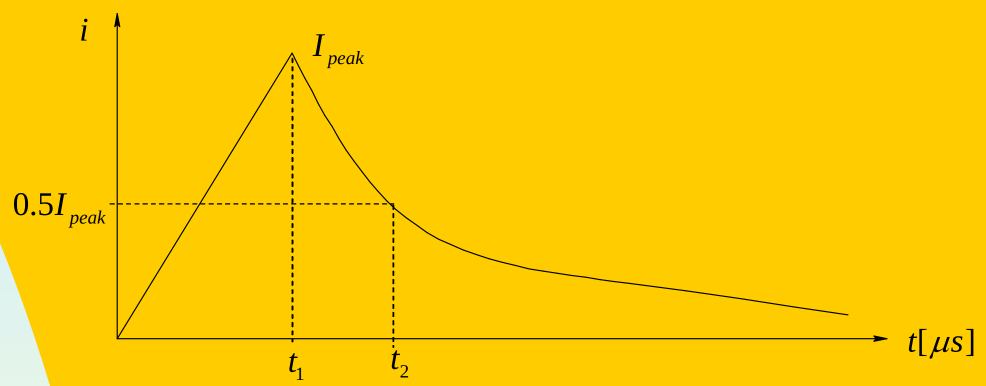
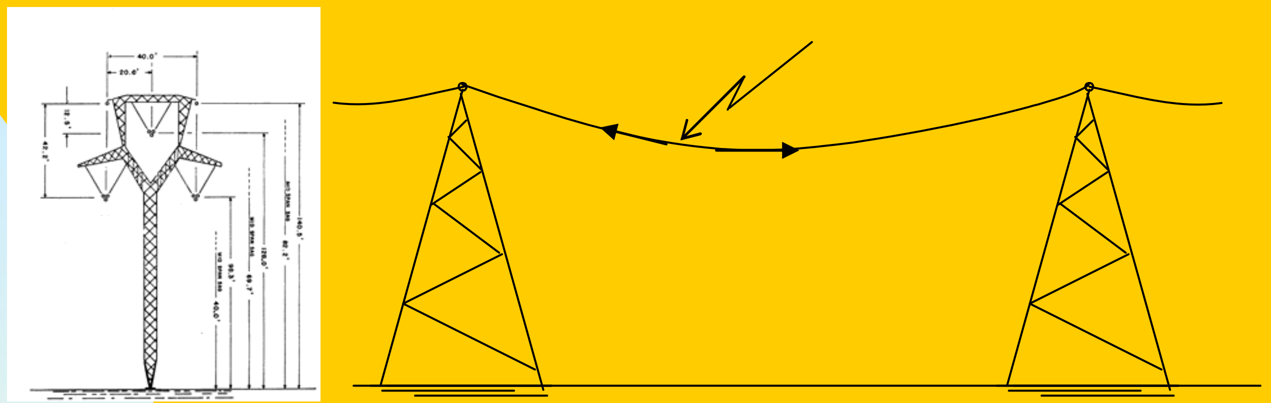


Fig. 14-1 Lightening current impulse.

- **This pulse is commonly represented as shown, where it reaches its peak in time $t_1$and exponentially tapers off to half its peak value at t_2.**
- **The peak current stroke of as high as 200 kA have been recorded, though generally a peak of 10 kA to 20 kA is assumed, to protect against the resulting over-voltages.**

Lightening Strike to Shield Wire and Backflash

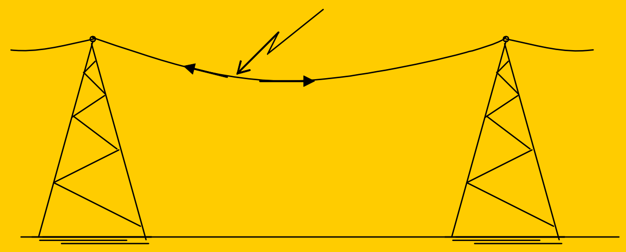


(*a*) (*b*)

Fig. 14-2 Lightening strike to the shield wire.

- Shield wires are located higher than the transmission line conductors and hence protect them from being hit directly by lightning strokes.
- They provide an approximately 30 degree protection zone.
- These shield wires are grounded through the tower to ground where it is desirable to keep the tower footing impedance as small as possible.
- It should be noted however that not all transmission systems have shield wires.

Lightening Strike to Shield Wire and Backflash



- When a current impulse due to a lightning stroke occurs to a shield wire, current flows in both direction and passes through the towers to ground.
- Due to the tower footing resistance and the effect due to the rapidly rising current-front causes the tower potential to exceed the insulation strength of the insulator string, causing it to flashover (called backflash).
- Generally, this will cause momentary power outage but soon the normal operation results, until the insulator string is seriously damaged, resulting in follow-on current which may require circuit breaker operation to interrupt it and allowing it to be self-repaired.
- Many utilities find it more economical to use surge arresters more extensively (although not at every tower) rather than employing shield wires.

Lightning Strike to the Conductor

- Another scenario is where the conductor itself is struck by lightning.
- Resulting traveling waves proceed in both directions and insulator strings may flashover, or
- When it reaches the termination, surge arresters would prevent voltage from rising to a level that can damage apparatus.

Switching Surges

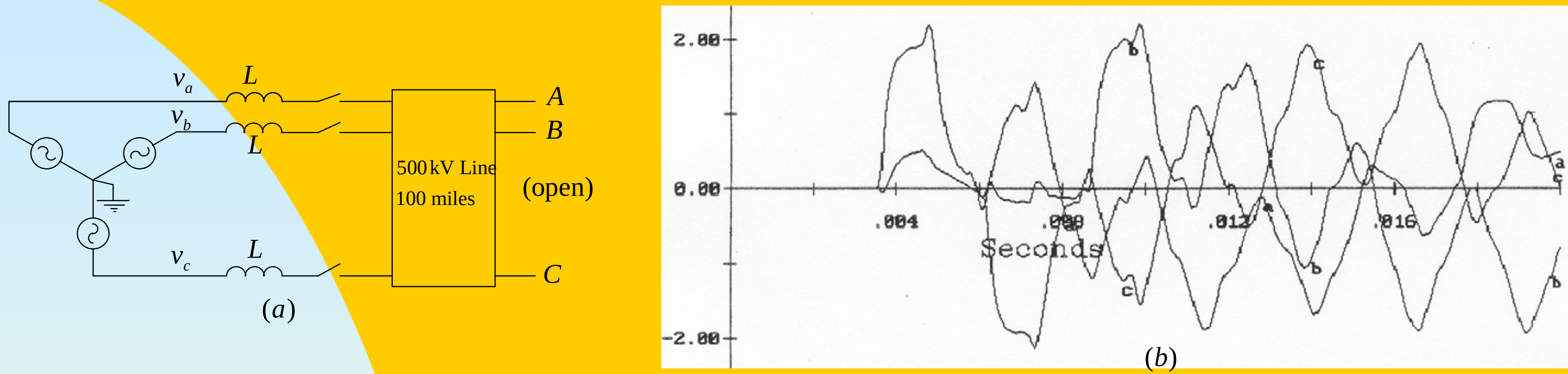


Fig. 14-3 Over-voltages due to switching of transmission lines.

- At extra-high voltage levels, switching of transmission lines can result in over-voltages that can exceed that by lightning strikes.
- These switching surges are of longer duration than those caused by the lightning impulse; the length of the over-voltage duration, in addition to its amplitude, also influences the requirement of the needed insulation.
- These switching over-voltages can be minimized by the use of pre-insertion resistors where switching-in a transmission line, a resistor in series is inserted which is later bypassed for normal operation.

TRANSMISSION LINE CHARACTERISTICS AND REPRESENTATION

- We will assume a transposed three-phase line and make use of the discussion dealing with transmission lines in steady state.

$$Z_c = \sqrt{\frac{L}{C}} \qquad L = 2\times 10^{-7} \ln \frac{\sqrt[3]{D_{12}D_{23}D_{31}}}{r} \quad H/m$$

$$c = \sqrt{\frac{1}{LC}} \qquad C = \frac{2\pi \times 8.85\times 10^{-12}}{\ln \frac{\sqrt[3]{D_{12}D_{23}D_{31}}}{r}} \quad F/m$$

$$c = 3\times 10^{8}\, m/s$$

Transmission Line Impedances

- The transient disturbances are usually not balanced, for example only one of the transmission-line phases is normally subjected to lightning impulse. Therefore, the zero-sequence path involving ground return must be carefully included in modeling to get correct over-voltages.
- Similarly, transmission lines are not perfectly balanced and most lines are not transposed, and hence may require to be represented as un-transposed. Moreover, associated with these transient phenomena, we are no longer dealing with a steady state line frequency of 60 or 50 Hz; rather the transient operation that involves very high frequencies.

Frequency Dependence of Transmission Line Parameters

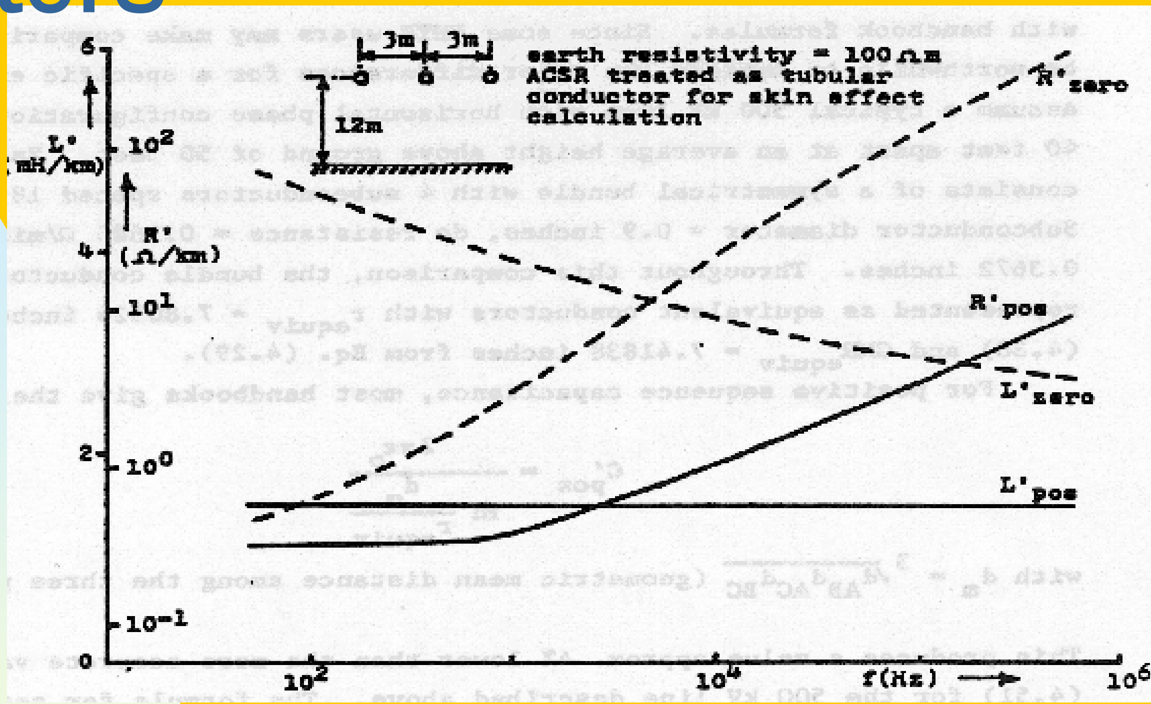


Fig. 14-4 Frequency dependence of the transmission line parameters [Source: 2].

Fig. above illustrates the frequency dependence of the line parameters for positive (and negative) sequence quantities and the zero-sequence quantities as well, and this dependence should also be included.

Calculation of Switching Over-Voltages on Line 1-3 in the Example 3-Bus Power System

Fig. 14-5 Calculation of switching over-voltages on a transmission line.

INSULATION TO WITHSTAND VOLTAGES

- Power systems apparatus is designed with insulation to withstand a certain amount of voltages. The insulation level to withstand voltages depends on factors such as the shape of the voltage wave and its duration, condition of the insulation in terms of its age, humidity and the contamination levels.
- Power systems apparatus can be categorized into having two types of insulations:
  - self-restoring and
  - non-self-restoring.
- Insulator strings on transmission lines represent self-restoring type of insulation which can be allowed to breakdown occasionally and restores itself after the resulting fault clears.
- However, insulation for transformers, generators etc is of non-self-restoring type, which if allowed to fail at any time will result in a severe and permanent damage that will be very expensive to repair.

Insulation Considerations

- For self-restoring insulation such as the insulator string of transmission lines, it is cost-prohibitive to insulate against all expected over-voltages and hence a statistical approach is used where certain probability of failure is acceptable. On the other hand, the non-self-restoring insulation of transformers, for example, is protected against failure using surge arresters, as discussed later in this chapter.
- As mention earlier, the withstand voltage capability of insulation depends on the shape of the voltage wave and its duration, which differs based on lightning or switching surges. These voltage levels that a given insulation can withstand are defined in subsequent slides.

Standard Voltage Impulse to Define Basic Insulation Level (BIL)

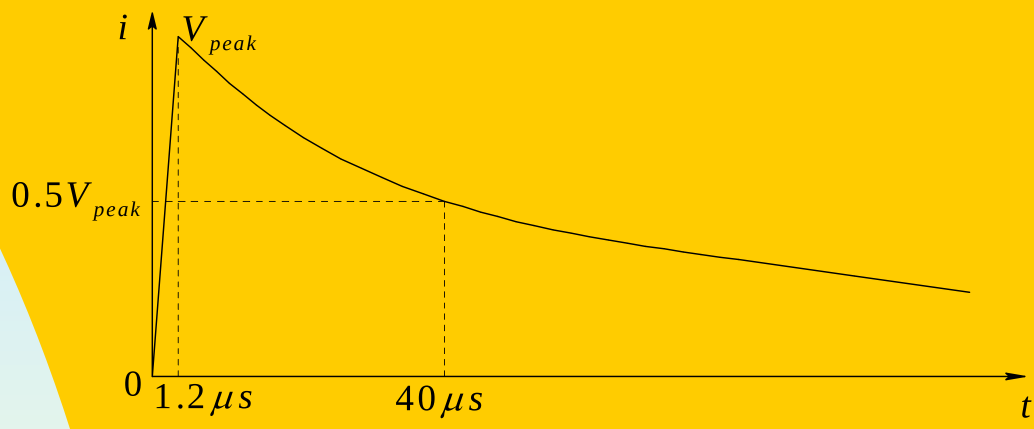


Fig. 14-6 Standard Voltage Impulse Wave to define BIL.

- **For the lightning impulse, the level of insulation is specified as the Basic Insulation Level (BIL), which is the peak of the withstand voltage of a standard lightning impulse voltage wave.**
- **This lightning impulse wave, as shown in Fig. 14-6, is assumed to rise to its peak value, and tapers off exponentially to one-half the peak value as shown.**

Basic Insulation Level (BIL)

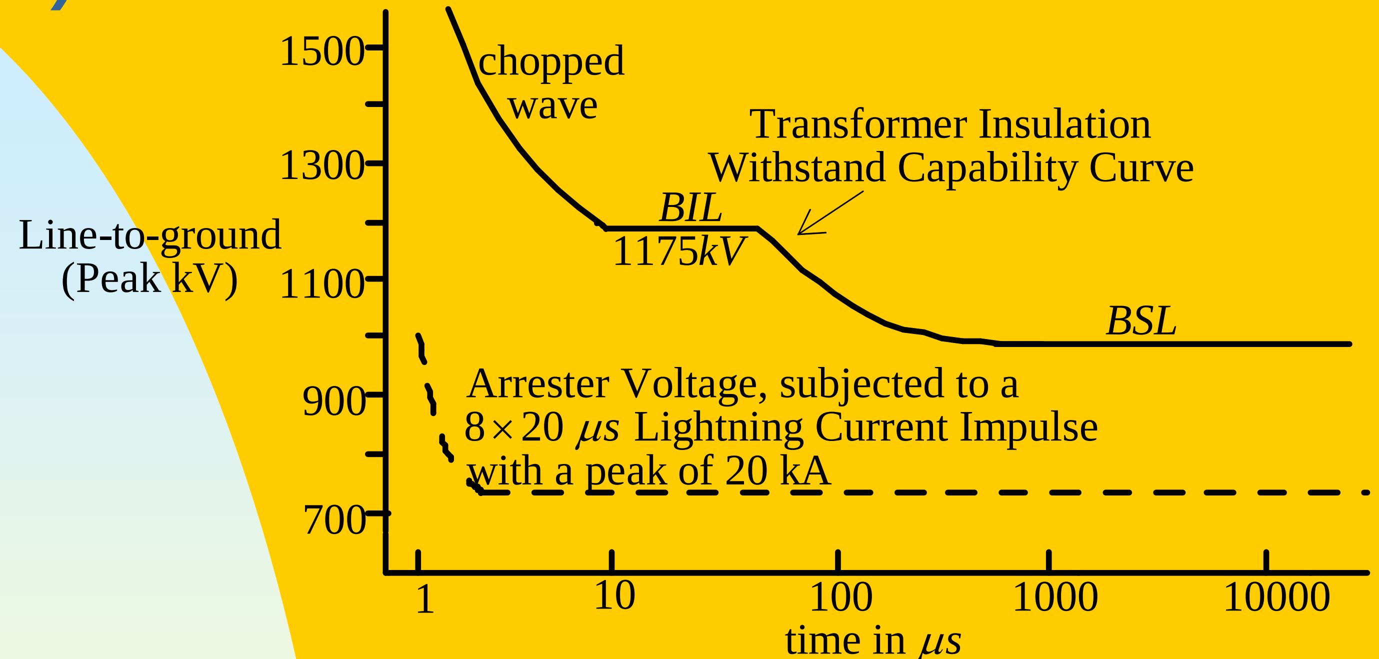


Fig. 14-7 A 345-kV transformer voltage insulation levels.

- **The basic insulation level (BIL), as an example, for a 345-kV transformer is shown in Fig. 14-7 as 1175 kV, which is the peak line-to-ground voltage.**

Switching Insulation Level (BSL)

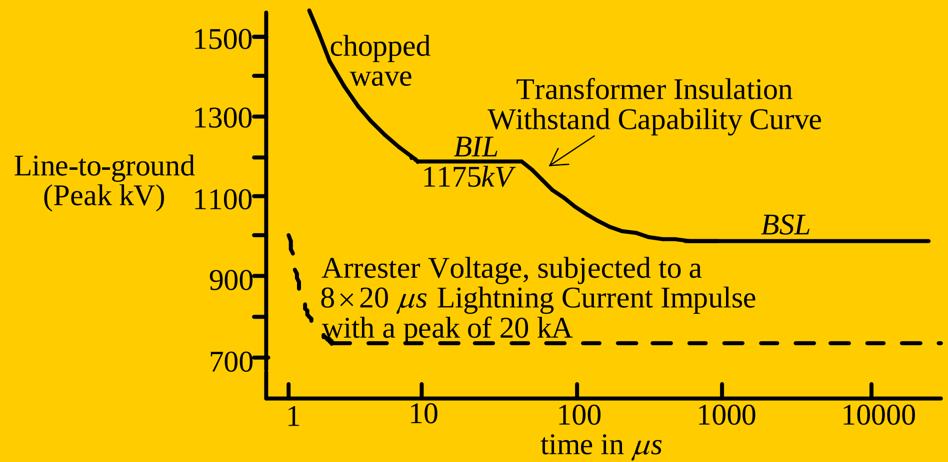


Fig. 14-7 A 345-kV transformer voltage insulation levels.

- Switching surges do not have as steep a front as those resulting from lightning impulse; these switching surges are also of longer duration.
- The standard switching impulse voltage wave is assumed to rise to a peak value in 250 microseconds and tapers off exponentially to one-half the peak value in 2,500 microseconds.
- The withstand insulation level for the peak of such as switching surge is called the basic switching insulation level (*BSL*).
- As shown in Fig. 14-7, an apparatus with a particular BIL has a lower withstand capability to switching surges, that is, it has a lower BSL than BIL due to the fact that switching surges are of longer duration.

Chopped Wave Insulation Level

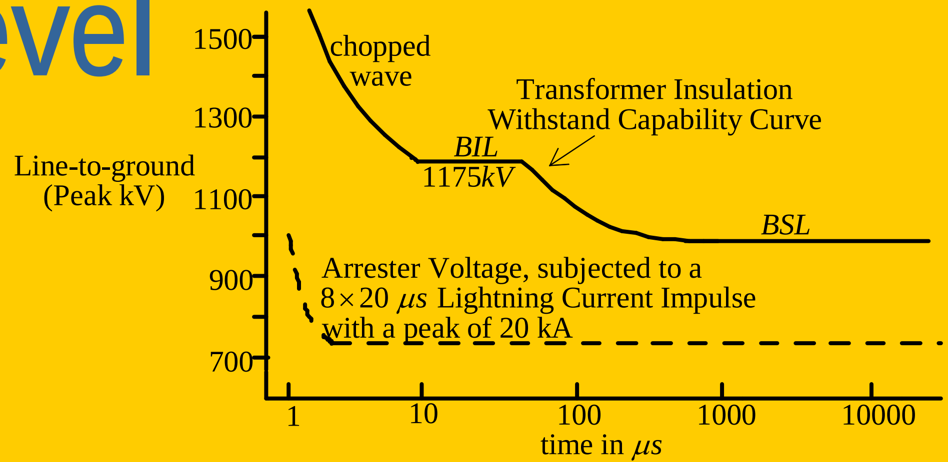


Fig. 14-7 A 345-kV transformer voltage insulation levels.

- As shown in Fig. 14-7, the same apparatus insulation can withstand higher voltages than BIL if the voltage impulse beyond the peak is chopped to bring it to zero in 3-4 microseconds.

SURGE ARRESTERS AND INSULATION COORDINATION

$$i = 2500\left(\frac{V}{V_{ref}}\right)^{26} A$$

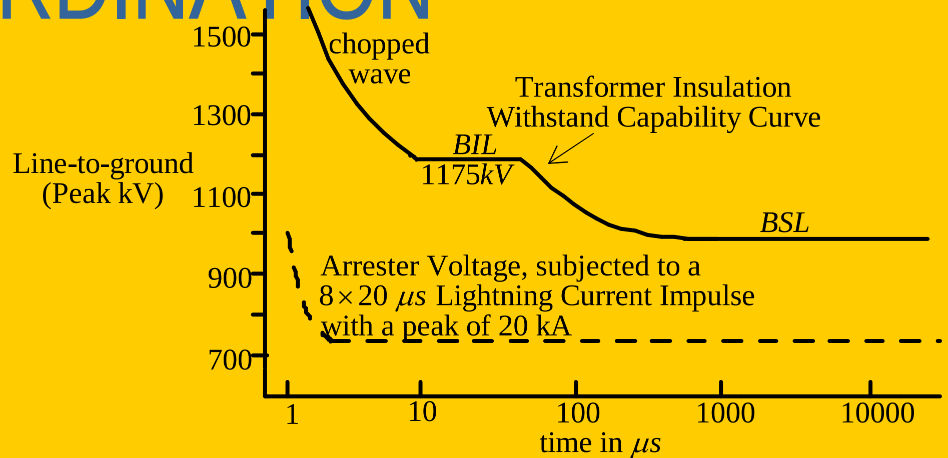


Fig. 14-7 A 345-kV transformer voltage insulation levels.

- In power systems apparatus, their insulation is protected against voltage impulses by means of surge arresters. The role of surge arresters is similar to that of Zener diodes in low power electronic circuits. Surge arresters appear as open-circuit at normal voltages and draw almost negligible current. However, they allow whatever current that needs to flow, of course within their rating, thus "clamping" the voltage across the device being protected to a threshold voltage plus a small *IR* current-discharge voltage, as shown in Fig. 14-7.
- The surge arrester should also be able to dissipate the associated energy without damage to itself, thus allowing quick return to the normal operation where it should once again appear as an open-circuit. In power systems, modern practice is to use ZnO arresters which have a highly nonlinear *i-v* characteristic, for example, as given by the relationship above.

SURGE ARRESTERS AND INSULATION COORDINATION

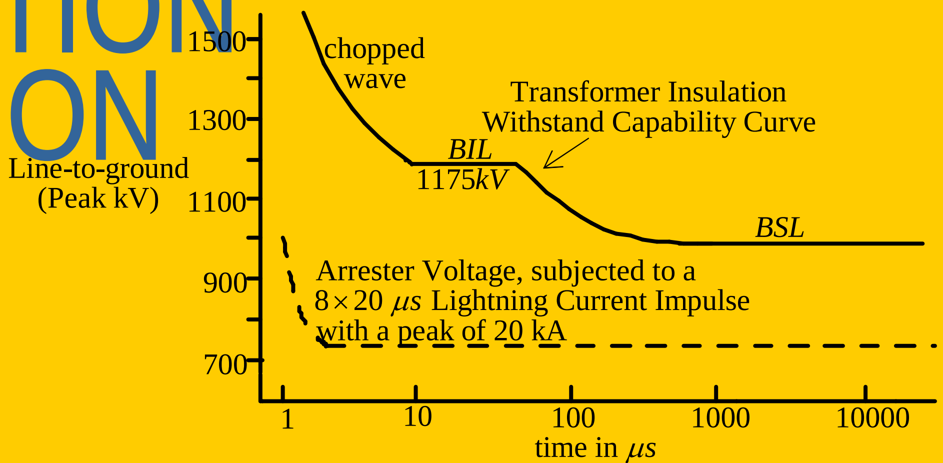


Fig. 14-7 A 345-kV transformer voltage insulation levels.

- The arrester discharge voltage level should be sufficiently below the apparatus insulation level this arrester is to protect, and provide a margin of at least 15-20%. Insulation coordination requires coordinating and selecting BIL and BSL of various apparatus and the ratings of the arresters to protect them.

Summary Protection of Power Systems

- Protection against Short-Circuit Faults
- Causes of Over-Voltages
- Insulation to Withstand Faults
- Surge Arresters and Insulation Coordination