18 Surge arresters: applications and selection

Contents

18.1 Surge arresters 18/683
- 18.1.1 Gapped surge arresters 18/683
- 18.1.2 Gapless surge arresters 18/684

18.2 Electrical characteristics of a ZnO surge arrester 18/684

18.3 Basic insulation level (BIL) 18/687

18.4 Protective margins 18/688
- 18.4.1 Steepness (t_1) of the FOW 18/688
- 18.4.2 Effect of discharge or co-ordinating current (I_n) on the protective level of an arrester 18/688
- 18.4.3 Margin for contingencies 18/688

18.5 Protective level of the a surge arrester 18/688
- 18.5.1 Reflection of the travelling waves 18/691
- 18.5.2 Surge transference through a transformer 18/694
- 18.5.3 Effect of resonance 18/699

18.6 Selection of a gapless surge arrester 18/699
- 18.6.1 TOV capability and selection of rated voltage, V_r 18/699
- 18.6.2 Selecting the protective level of the arrester 18/703
- 18.6.3 Required energy capability in kJ/kV$_r$ 18/706

18.7 Classification of arresters 18/707

18.8 Application of distribution class surge arresters 18/708

18.9 Pressure relief facility 18/709

18.10 Assessing the condition of an arrester 18/710

Relevant Standards 18/718

List of formulae used 18/718

Further Reading 18/719

18.1 Surge arresters

When surge protection is considered necessary, surge arresters* may be installed on or near the equipment being protected. This is a device that limits the high TVs (transient voltages) generated during a system disturbance by diverting the excessive part of it to the ground and reducing the amplitude of the transient voltage wave across the equipment to a permissible safe value less than the impulse withstand level of the equipment (Tables 11.6, 14.1, 32.1(a), 13.2, and 13.3). The rate of rise of transient voltage remains the same. A surge arrester does not tame the steepness of the surge, i.e.

$$\frac{V_{t1}}{t_1} = \frac{V_{t2}}{t_1''} \text{ (curves } oa_1 \text{ and } oa_2 \text{ of Figure 17.21)}$$

thus shielding the connected equipment from dangerous voltage surges. This is achieved by providing a conducting path of relatively low surge impedance between the line and the ground to the arriving surge. The discharge current to the ground through the surge impedance limits the residual voltage across the arrester hence the equipment and the system connected to it. During normal service this impedance is high enough to provide a near-open circuit. It remains so until a surge voltage occurs and is restored immediately after discharge of the excess surge voltage.

Corollary

An arrester can be considered a replica of an HRC fuse. What a fuse is to a fault current, arrester is to a voltage surge, both limit, their severity. While a fuse is a current limiting device and protects the connected equipment by limiting the prospective peak fault currents, I_{sc} (Figure 12.18), an arrester is a voltage limiting device and protects the connected equipment by limiting the prospective peak surge voltage, V_t (curve oa_2, Figure 17.21).

Arresters or diverters are generally of the following types and the choice between them will depend upon the power frequency system voltage, characteristics of the voltage surges and the grounding system, i.e.

(i) Gapped or conventional type, and
(ii) Gapless or metal oxide type.

18.1.1 Gapped surge arresters

These are generally of the following types:

1 **Expulsion** These interrupt the follow current by an expulsion action and limit the amplitude of the surge voltages to the required level. They have low residual safe or discharge voltages (V_{res}). The arrester gap is housed in a gas-ejecting chamber that expels gases during spark-over. The arc across the gap is quenched and blown-off by the force of the gases thus produced. The enclosure is so designed that after blowing off the arc it forcefully expels the gases into the atmosphere. The discharge of gases affects the surroundings, particularly nearby equipment. The gas-ejecting enclosure deteriorates with every operation and, therefore, has only a limited operating life. Moreover, these types of arresters are of specific ratings and an excessive surge than the rated may result in its failure. They are now obsolete in view of their frequent failures and erratic behaviour and the availability of a more advanced technology in a metal oxide arrester.

2 **Spark gap** These have a pair of conducting rods with an adjustable gap, depending upon the spark-over-voltage of the arrester. Precise protection is not possible, as the spark-over-voltage varies with polarity, steepness and the shape of the wave. These arresters are also now obsolete for the same reasons.

3 **Valve or non-linear resistor** In this version, a nonlinear SiC resistance is provided across the gap and the whole system works like a preset valve for the follow current. The resistance has an extremely low value on surge voltages and a very high one during normal operations to cause a near-open circuit. It is now easier to interrupt the follow currents.

A non-linear resistor-type gapped surge arrester may generally consist of three non-linear resistors (NR) in series with the three spark gap assemblies (Figure 18.1(a)). The resistance decreases rapidly from a high value at low currents to a low value at high currents, such that $RI \simeq$ constant (Figure 18.1(b)). Hence, *V-I* is an almost flat curve, as illustrated in Figure 18.1(b). Thyrite* and Metrosil* are such materials. The purpose of non-linear resistors is to permit power frequency follow currents, after the clearance of surge voltages, while maintaining a reasonably low protective level (V_{res}). Across the spark gaps, known as current limiting gaps, are provided high-value resistors (HR) backed up with HRC fuses. The non-linear resistors have a very flat *V-I* curve, i.e. they maintain a near-constant voltage at different discharge currents. The flatness of the curve provides a small residual voltage and a low current. When the switching or lightning surge voltage exceeds the breakdown voltage of the spark gap, a spark-over takes place and permits the current to flow through the non-linear resistor NR. Due to the non-linear characteristics of the resistor, the voltage across the motor terminals (when protecting a motor) is limited to approximately the discharge commencing voltage (V_{res}), which is significantly below the 3–5 p.u. level for a motor (Table 11.6)). It may be noted that the use of resistor across the spark gap stabilizes the breakdown of the spark gap by distributing the surge voltage between the gap and the non-linear resistor. Figures 17.5(a) and (b) are oscillograms illustrating the effect of a surge arrester in arresting the surge voltages caused during a switching operation or a lightning stroke.

The current limiting gaps, as noted above, in series

*Basically they are surge diverters but conventionally are called arresters. Up to 245 kV lightning surges and beyond 245 kV switching surges are found to be more severe, Section 18.3. It is customary, therefore, to call an arrester up to 245 kV a lightning arrester and beyond 245 kV a surge arrester. For ease of reference, we have described them as surge arresters or only arresters for all types.

*Thyrite is a brand name from General Electric, USA.
Metrosil is a brand name from a GEC company in the UK.

with the non-linear resistors make it possible to adjust the protective level of the surge arrester for different values of discharge currents. They also help to maintain a near-constant voltage at around the switching surge or lightning surge spark-over-voltages during the flow of surge currents while clearing a surge. For more details and testing see IEC 60099-1.

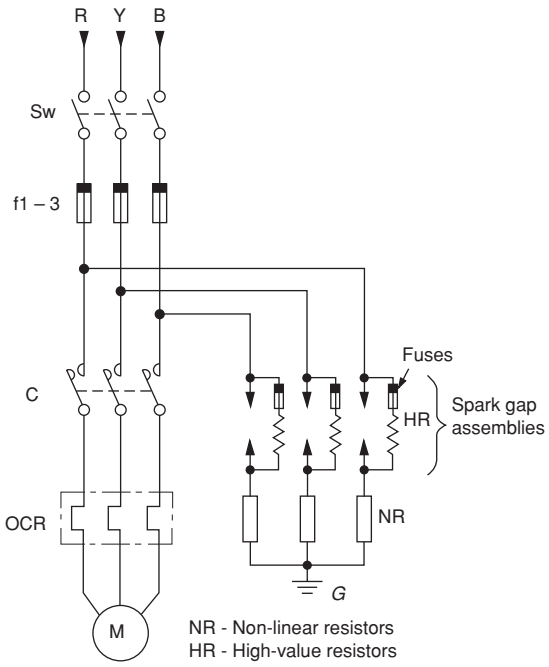


Figure 18.1(a) A typical power circuit of a non-linear resistor-type surge arrester

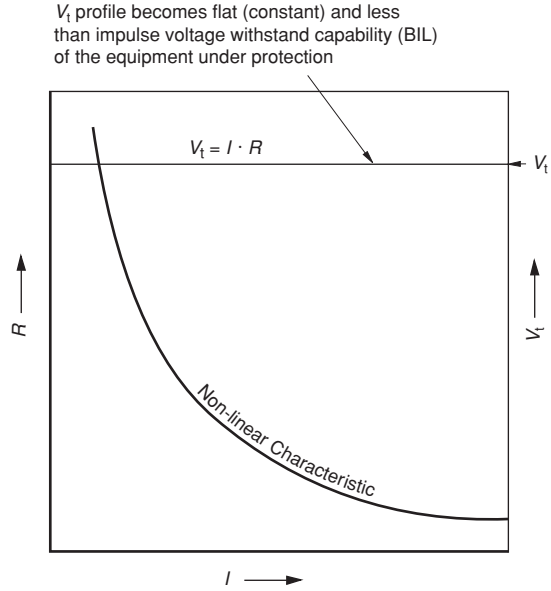


Figure 18.1(b) Characteristic of a non-linear resistor

18.1.2 Gapless surge arresters

From the above it is evident that material for non-linear resistance used in the manufacture of an efficient surge protection device must offer the least impedance during a discharge. This is to provide a free flow to the excessive discharge current to the ground, on the one hand, and to draw a negligible current under normal system conditions, to make it a low-loss device, on the other. The alternative was found in ZnO. ZnO is a semiconductor device and is a ceramic resistor material constituting ZnO and oxides of other metals, such as bismuth, cobalt, antimony and manganese. These ingredients in different proportions are mixed in powdered form, ZnO being the main ingredient. It is then pressed to form into discs and fired at high temperatures to result in a dense polycrystalline ceramic. The basic molecular structure is a matrix of highly conductive ZnO grains surrounded by resistive intergranular layers of metal oxide elements. Under electrical stress, the intergranular layers conduct and result in a highly nonlinear characteristic. For example a change of arrester current from 10^5 A to 1 A would result in a voltage change of only 54%. Since the content of ZnO is substantial (around 90%) it is popularly known as a ZnO or metal oxide elements. Surge arresters made of these elements have no conventional spark gap and call for no gap reseal and possess excellent energy absorption capability. They consist of a stack of small ZnO discs (Figure 18.2(a)) in varying sizes and cross-sections, enough to carry the discharge currents, mounted in series in a sealed porcelain or silicone (a polymer) housing (for better mechanical strength to withstand severe weather and pollution conditions) or in a metal enclosure for gas insulated switchgears (GIS) (Figure 18.2(b)). The surface area (size) of disc can be raised to make it capable of absorbing higher energy levels. The design is optimized to minimize the power loss. Figure 18.3(a)–(c) show the general arrangements of a few types and sizes of gapless surge arresters.

Under rated system conditions, its feature of high non-linearity raises its impedance substantially and diminishes the discharge current to a trickle. Under rated conditions, it conducts in μA (Figure 18.4(a)), while during transient conditions it offers a very low impedance to the impending surges and thus rises the discharge current and the discharge voltage. However, it conducts only that discharge current which is essential to limit the amplitude of the prospective surge to the required protective level of the arrester. The housing is sealed at both ends and is provided with a pressure relief valve to vent high-pressure gases, such as those caused by heavy currents during a voltage surge or a fault within the arrester, and to prevent an explosion in the event of a housing failure.

18.2 Electrical characteristics of a ZnO surge arrester

In view of the limitations in spark gap technology, as discussed earlier, the latest practice is to use gapless surge arresters. Accordingly, the following text relates to gapless arresters only. For details on gapped surge

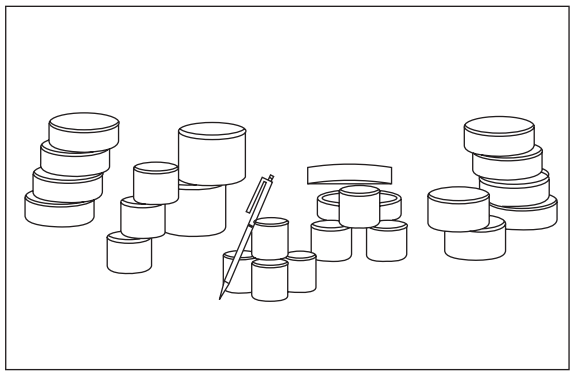


Figure 18.2(a) ZnO blocks and their small sizes

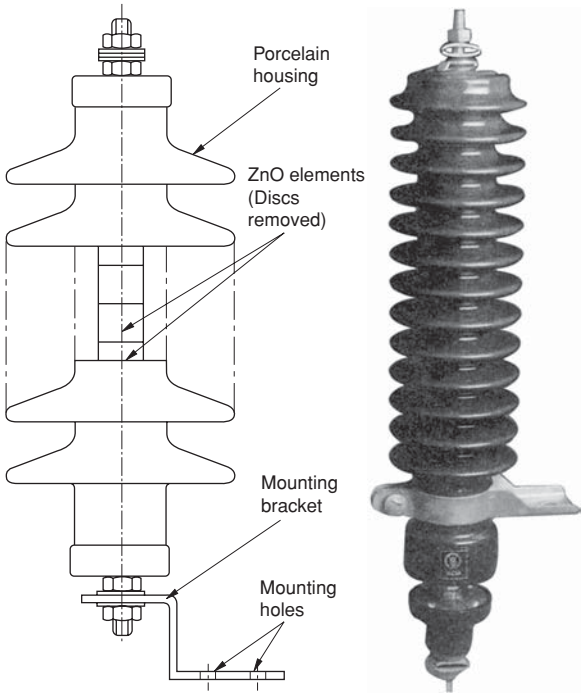


Figure 18.2(b) Distribution class surge arrester

arresters refer to ANSI/IEEE–C-62.1, ANSI/IEEE-C-62.2 and IEC 60099-5, as noted in the Relevant Standards.

ZnO blocks have extremely non-linear, current-voltage characteristics, typically represented by

$$I = K \cdot V^{\alpha} \tag{18.1}$$

where the conductance ($1/R$) in the conventional formula

$$\left(I = \frac{1}{R} \cdot V \right)$$

is replaced by K, which now represents its geometrical configuration, cross-sectional area and length, and is a measure of its current-carrying capacity. α is a measure of non-linearity between V and I, and depends upon the composition of the oxides used. Typical values are

In SiC – 2 to 6

In ZnO – it can be varied from 20 to 50.

By altering α and K, the arrester can be designed for any conducting voltage (V_{res}) and nominal current discharge (I_n). V_{res} and I_n define the basic parameters of a surge arrester, as discussed later. Figures 18.4(a) and (b) illustrate typical electrical characteristics of a ZnO arrester, suggesting that in the event of a surge voltage, with a prospective amplitude V_t, its resistance will fall rapidly to a very low and safe conducting value resulting into a residual or discharge voltage 'V_{res}' and bypass the rest '$(V_t - V_{res})$' absorbing the energy released by it. The conducting voltage will depend upon the arrester's protection level and will appear across the arrester and the equipment it is protecting. The ZnO stack possesses an excellent energy absorption capability. Some of its basic characteristics according to Figures 18.4(a) and (b), are noted below.

Electrical representation of a ZnO element

A ZnO element basically represents a capacitive leakage circuit. In its leakage current range, it may be electrically represented as shown in Figure 18.5, where I_{ZnO} is the leakage current, capacitive in nature, and I_c and I_r its capacitive and loss components, respectively. The success of an element will depend upon its low loss-component, which would mean a lower loss during continuous operation, on the one hand, and a lower temperature rise of the element on the other.

Maximum continuous operating voltage (MCOV), V_c (point 1 on the curve, Figure 18.4(a))

This is the maximum power frequency operating r.m.s. voltage that can be applied continuously ($\geq$ 2 hours) across the arrester terminals without a discharge. It continuously draws an extremely low leakage current, I_{ZnO}, capacitive in nature, due to ground capacitance. The current is in the range of a few μA. Therefore maximum continuous operating voltage,

$$V_c = \frac{V_m}{\sqrt{3}} \text{ (phase to neutral)}$$

Voltages above V_c (MCOV) may be temporary over-voltages (TOVs) or transient voltages.

Rated voltage, V_r (point 2 on the curve, Figure 18.4(a))

This is the maximum permissible r.m.s. voltage for which the arrester is designed. The arrester can withstand this voltage without a discharge for minimum 10s under continuously rated conditions (when the arrester has reached its thermal stability), indirectly indicating an in-built TOV capability of 10s. Now it also draws a current resistive in nature, in the range of a few μA. The lower this current, lower will be the loss and the heat generated during an over-voltage and hence better energy absorption capability.

Below the knee-point, in the MCOV and TOV regions particularly, the V-I characteristics (Figure 18.4(b)) is

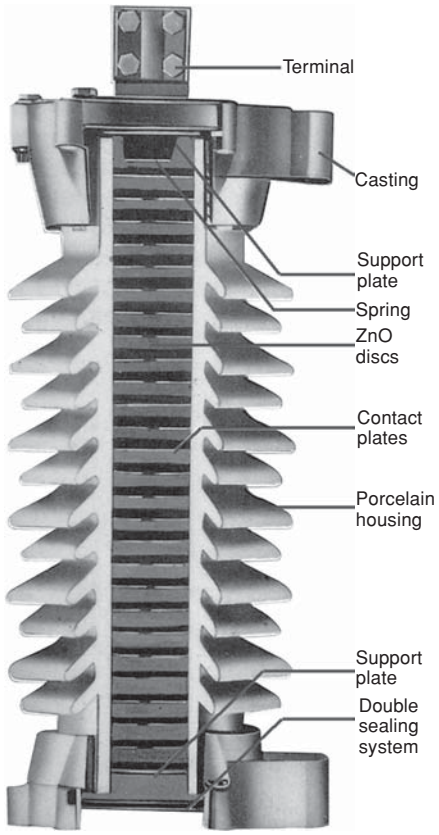


Figure 18.3(a) Sectional view of a metal oxide surge arrester (Courtesy: W.S. Industries)



Figure 18.3(b) A 420 kV surge arrester (Courtesy: Elpro (International))



Figure 18.3(c) 12–550 kV zinc oxide surge arresters (Courtesy: Crompton)

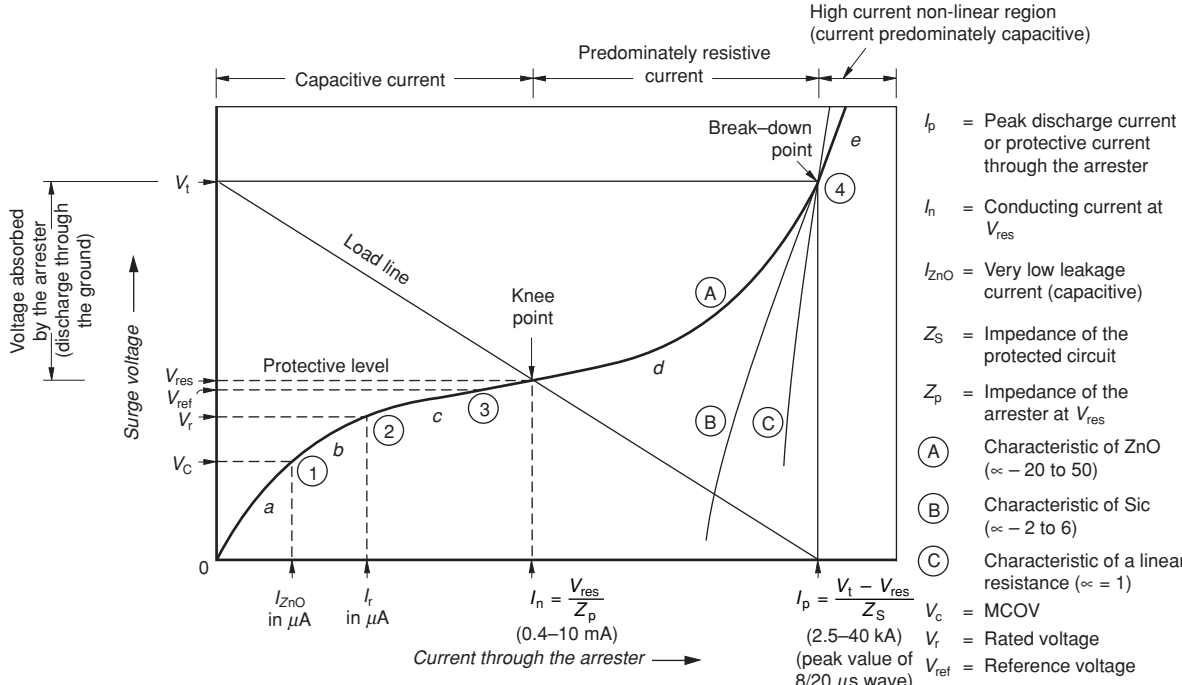


Figure 18.4(a) Characteristics of a ZnO block

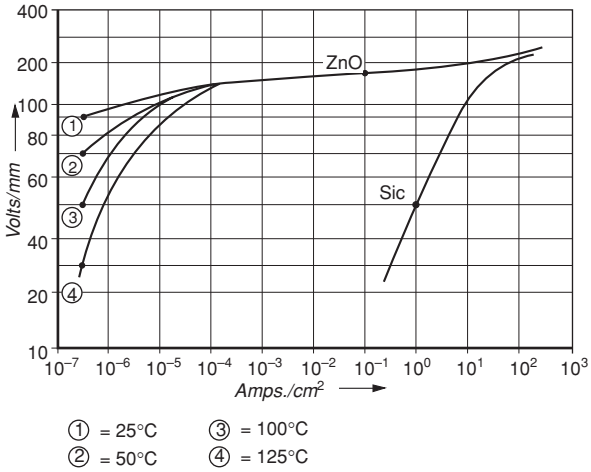
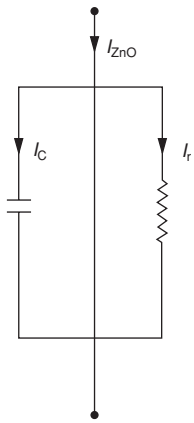


Figure 18.4(b) *V–I* characteristics of a ZnO block



Note I_r would consist of resistive as well as 3rd harmonic component.

Figure 18.5 Electrical representation of a ZnO element

sharply drooping with the temperature rise causing a higher leakage current. The temperature rise may be due to continuous leakage currents and weather conditions. It is a deterrent to otherwise good performance of ZnO elements, for it means higher losses and heat under normal as well as TOV conditions. Although a very low level of leakage current has been achieved, research and improvement in the formation of ZnO compound is a continuous process by leading manufacturers to further minimize the same. It aims at optimizing the use of this material for a still better performance by attempting to flatten the voltage droop as far as possible.

Reference voltage (point 3 on the curve, Figure 18.4(a))

This is an r.m.s. voltage close to the knee-point where it commences conduction and draws a current that is resistive in nature, in the range of a few mA. Typical values are 0.4–10 mA.

This voltage is applied to the arrester to determine the peak value of the resistive component of the reference current which constitutes an important parameter to define the characteristics of an arrester (see Table 18.9).

Discharge or residual voltage 'V_{res}'

It is the voltage that appears across the arrester during the passage of discharge current – that flows through the arrester due to a surge.

Temporary over-voltage (TOV)

It is determined by its low current region (d) that is usually less than 1 A and for prospective transient voltages it is determined by its high current region (e) (2.5–20 kA, 8/20 μs current impulse).

Protective level (Figures 18.4(a))

V_{res} is the conducting voltage of an arrester during an over-voltage or transient condition and defines its protective level. It appears across the arrester, hence the equipment connected on the downstream. In a laboratory it is verified across the arrester by applying specified peak pulse current with specified waveform (see Table 18.1).

Transient voltages (V_t) (point 4 on the curve, Figure 18.4(a))

Depending upon the magnitude of V_t the operating point may shift to near point 4 or beyond and conduct a current 2.5–20 kA and more.

Energy capability (J)

Energy capability of an arrester defines its capability to absorb the surge energy (Equation (17.3), Section 17.6.5) of an impending surge, usually the long duration switching surge, being the most severe of them all (out of lightning, FOW and switching in terms of energy discharge).

Energy capability values are provided as standard by the manufacturers in their data sheets. The declared capabilities presume that multiple discharges are distributed evenly over a one minute period and a single discharge does not exceed 85% of the declared values. Allow one minute cooling period and the discharges can be repeated. One minute is considered enough for the ZnO discs to attain thermal equilibrium.

Testing of Surge Arresters

An arrester is tested as per IEC 60099-4 or ANSI/IEEE C62.11 and C62.22. For details see the said Standards.

18.3 Basic insulation level (BIL)

BIL is the basic insulation level of equipment. When the system TOVs or voltage surges exceed this level, the equipment may yield. In the latest international and national standards it is defined as follows:

1 For systems 1 kV < $V_m \leq$ 245 kV.
   (i) Rated lightning impulse withstand level (LIWL)
   (ii) Rated short time power frequency dielectric strength.

(iii) Prospective steep-rising TRVs (FOWs) that may be caused during a switching operation, as discussed in Section 17.7*.

Note
A lightning surge is considered more severe than a switching surge for assigning the BIL of an equipment or a system. Switching surge BIL is therefore not considered relevant above. But since the energy discharge by a long duration switching surge is much more than the energy discharge by a lightning surge, it is essential to check the energy absorption capability of an arrester during a switching discharge. All arresters are therefore tested for switching surge energy capability and this energy capability expressed as kJ/kVr forms an essential parameter of an arrester and mentioned in their data sheets as standard.

For motors, switchgears and bus systems see Tables 11.6, 13.2, 14.1 and 32.1(a) and for other equipment Table 13.2. For more clarity refer to Section 17.1.

2 For systems V_m > 300 kV to 765 kV;
(i) Rated lightning impulse withstand level (LIWL)
(ii) Rated short time power frequency dielectric strength.
(iii) Rated switching impulse withstand level (SIWL).
(iv) Prospective steep-rising TRVs (FOWs) that may be caused during a switching operation as discussed already or during a fast bus reclosing (Section 17.4) particularly with the line trapped charge. Refer to Table 13.3**.

The types of surges referred to above and their test waveforms are defined in Table 18.1.

18.4 Protective margins

On the BIL discussed above a suitable protective margin is considered to provide sufficient safety to the protected equipment against unforeseen contingencies. ANSI/IEEE-C62.22 has recommended certain values to account for these and they are given in Table 18.2.

$$\text{Protective margin} = \frac{\text{BIL of the equipment}}{\text{Impulse protection level of the arrester } (V_{res})} \qquad (18.2)$$

The protection level of an arrester, V_{res}, is a function of the magnitude of arrester discharge current (I_n), and the time to peak of the surge (t_1), and is influenced by the following.

18.4.1 Steepness (t_1) of the FOW

The protection level of the arrester diminishes with the steepness of the wave. As t_1 falls, V_{res} of the arrester rises, leaving a smaller protection margin across the protected equipment. Refer to the characteristics of an arrester as shown in Figure 18.7, for a 10 kA, 8/20 μs impulse wave. For a front time of, say, 0.5 μs, it will have a V_{res} of approximately 118% of its rated V_{res} at 8 μs, and hence will reduce the protection margin as in Equation (18.2).

18.4.2 Effect of discharge or co-ordinating current (I_n) on the protective level of an arrester

V_{res} rises with an increase in the discharge current through the arrester and vice versa (see Figure 18.7 having its rated V_{res} on the 10 kA characteristics on an 8 μs impulse wave). For a 15 kA discharge current, for instance, V_{res} will rise further to approximately 1.18 for an FOW of 0.5 μs, and reduce its protection margin further.

The arrester manufacturers provide the protection characteristics for different discharge currents I_n and front times, t_1, for each type of arrester to facilitate the user make an easy selection of the arrester.

18.4.3 Margin for contingencies

An additional protection margin may be considered for the contingencies noted below, depending upon the criticality of a system or its susceptibility to over-voltages:

1 Higher over-voltages than considered, during an actual fault, say, because of unfavourable grounding conditions.
2 Non-simultaneous opening (Section 19.7) or closing of the interrupting poles (Section 17.7.2).
3 More than two over-voltages occurring at the same instant such as a load rejection associated with ground and phase faults.
4 As a consideration for reduction in BIL of the protected equipment due to ageing and loading.

It is, however, recommended to select the smallest arrester as this will provide the greatest margin of protection for the insulation. A higher rating (kJ) of the arrester may prolong its life but may reduce the margin of protection. It is therefore better to strike a balance between the life of the arrester and the protection of the equipment.

18.5 Protective level of a surge arrester

This is the maximum voltage V_{res} that will appear across the arrester's terminals while discharging to the ground voltages that are in excess of it without damaging the

*There is no rated withstand levels specified in these standards for such surges. This will depend upon the system parameters as noted later and must be specified by the user to the equipment manufacturer.

Equipment may be designed for more than one BIL values as noted in the various tables referred to above for motors, switchgears and other equipment. The choice of BIL for equipment for a particular application will depend upon the extent of exposure the equipment may be subject to in normal service and the security level required by the system and the surge protection. For more details refer to Section 13.4.1(3).

**It is advisable to select the lower value of the BIL wherever possible, to save on the cost of equipment, particularly when surge protection is being provided. Equipment, however, exposed more to such onslaughts may be selected with a higher BIL. Examples are those mounted some distance from the surge arrester and have a higher protective distance leading to higher stresses (Section 18.6.2).

Table 18.1 Defining a surge for laboratory testing

Predominant surge	*Maximum system voltage V_m*	*Power system*	*Voltage shape*	*Equivalent current shape at which the arrester is tested as per ANSI/IEEE C62.11, C62.22 and IEC 60099-4*[2]	*BIL of the equipment*
Lightning	> 1 kV – 245 kV	Secondary transmission or primary distribution	1.2/50 μs	8/20 μs at different lightning impulse nominal discharge currents 'I_n' 1.5, 2.5, 5, 10, 20 kA etc. (I_n is used to classify an arrester)	See Section 18.3
	> 245 kV[1]	Mainly transmission			
Switching	> 1 kV – 245 kV	Secondary transmission or primary distribution	250/2500 μs (total time $t_2 \simeq 2750$ μs. Figure 17.2(b))	30/60 μs at different switching surge discharges or 'coordination currents'	See Section 18.3
	> 245 kV[1]	Mainly transmission		Max. system voltage V_m – kV: Coordination current A Up to 150: 500 151–325: 1000 326–800: 2000	
FOW (Switching)	> 1 kV – 245 kV	Secondary transmission or primary distribution	Rise time t_1 (Figure 17.3) may be less than 0.1 μs but total time up to 3000 μs and surge frequency 30 kHz to < 100 MHz	1/20 μs or 0.5 μs FOW. It is derived by applying a series of current wave impulses to the arrester with varying rise times to crest 1, 2, 8 μs and extrapolated for 0.5 μs, usually expressed as 1/20 μs impulse	Note 3
	> 245 kV[1]	Mainly transmission			

Notes

1 A lightning stroke may commence at around 10^2 to 10^6 Volts (1000 kV) between the clouds and the ground. By the time it reaches the ground, it loses a part of its intensity. Although it may still be around 1000 kV at ground level, it is possible that sometimes switching surges at an EHV system above 245 kV are more severe than a lightning surge, the more so because the amplitude of a switching surge rises with the rise in system voltage, while a lightning stroke remains nearly constant irrespective of the system voltage. For these voltages, the national and international Standards have prescribed separate impulse withstand levels as noted in Table 13.3 for switching as well as lightning surges. They have also classified these severities in categories 1, 2 and sometimes 3, depending upon the extent of system exposure to lightning as noted in Section 13.4.1(3).

2 In a surge arrester, it is easier to assess the severity of a voltage wave through an equivalent current wave, but it is found that the characteristic of an equivalent current wave is not exactly identical to the required voltage wave. It is noticed that the time of rise of a voltage wave is generally shorter than its equivalent current wave, and hence more severe than the current wave. The reason is the non-uniform distribution of the current through the cross-section of the conductor, because of skin effect and discontinuities as discussed earlier. Refer to Figure 18.6 explaining this. To overcome this deficiency, the actual time of rise of the test current impulses, while simulating the characteristics in a laboratory, is slightly shortened (for an 8/20 μs wave, the test wave rise time will be slightly less than 8 μs), to ensure the same severity of the test current wave as the actual voltage wave. A surge arrester is required to clear successfully all the three types of voltage surges as prescribed. It is imperative to ensure that the selected arrester is capable of clearing all such voltage surges with the same ease and safety. Accordingly, protective curves are established by the arrester manufacturers over a wide range of likely surges, in terms of lightning, switching and FOWs. They provide those to the user for ease of arrester selection (Figure 18.7).

3 For steep-rising waves (FOWs), no steepness or impulse withstand level is prescribed in these standards, as both the rise time and amplitude of such waves cannot be predefined. They will depend upon various system parameters, such as grounding method, cable or line length, other equipment installed on the system, their surge impedances, switching conditions (current chopping and restrike of interrupting contacts etc.) and the trapped charge, such as on a fast bus transfer etc. The choice of impulse level for a particular fast rising wave for equipment to be exposed to such transients is a matter of system study (such as TNA or EMTP, Section. 18.5). The user must define these to the equipment manufacturer.

terminal equipment or disrupting the continuity of the supply system. In other words, it is the breakdown (for gapped) or discharge value (for gapless) of surge arresters at which they would initiate operation and is the basic parameter that forms the basis of their selection for a particular installation.

The purpose of a surge arrester is to safeguard a system against probable transient conditions, particularly those that may exceed the safe impulse withstand level of the equipment. A brief criterion to determine the protective level of an arrester is given in Table 18.3. The spark-over-voltage refers to conventional type gapped arresters, while the residual voltage refers to gapless type surge arresters. An arrester must protect the terminal equipment against each kind of transient condition separately. Its protective level must therefore be checked separately for all such transient conditions. While for a lightning and switching surge, it would be enough to define it by its amplitude, the FOW will be defined by its amplitude and the front time, t_1.

The severity of the transient conditions can be established on the basis of past experience or data collected

Table 18.2 Recommended protection margins (Insulation coordination)

Voltage range	V_m	*Recommended minimum margins*		
	kV	*For switching surges*	*For lightning surges*	*For FOWs*
I Table 13.2	≥ 3.6–245	1.15	1.20	1.20
II Table 13.3	300–800	1.15	1.20	1.20

Note
These levels are when the arrester is mounted close to the equipment with negligible lead length. Otherwise correction for protective distance will be essential as discussed in Section 18.6.2 and corroborated in Example 18.4.

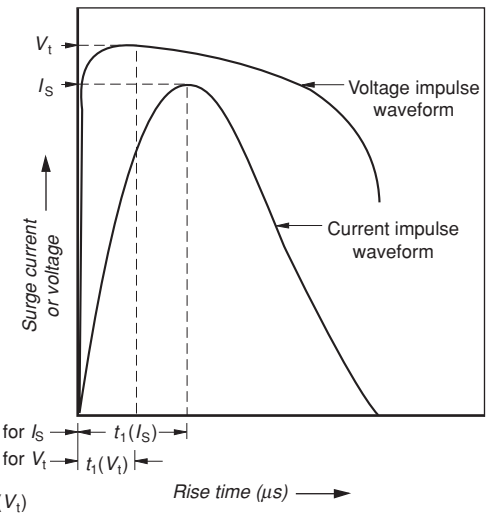


Figure 18.6 Arrester voltage and current oscillograms for 10 kA, 8/20 μs current impulse test

from similar installations. However, for large and more critical installations, such as a generating station or a large switchyard, it is advisable to carry out transient network analysis (TNA) or electromagnetic transient programme analysis (EMTP) with the aid of computers. For more details refer to Gibbs *et al.* (1989) in Chapter 17. Where this is not possible, the system may be analysed as follows to arrive at a more appropriate choice of protection level.

1 **Level of exposure**
- **When equipment is exposed to direct lightning strokes** Equipment connected directly to an overhead line, or even through a transformer, will fall into this category. Select the highest value of BIL and even then a surge protection will become necessary for critical installations.
- **When equipment is shielded** This is when it is installed indoors, like a generator or motor. Now it may be subject to only attenuated surges. One may now select a lower value of BIL. In most cases surge protection may not be essential for direct lightning strokes.
- **When equipment is exposed to severe internal disturbances** This is when equipment is exposed to switching surges, particularly when the surges are steep-fronted, as in switching of MV motors and all range-II equipment that are exposed to switching surges (Section 17.7). Now both a higher level of BIL and surge protection may be necessary.

2 **Influence of surge reflections**
3 **Influence of surge transferences**
4 **Effect of resonance**

These are only basic guidelines. It is difficult to define exposed or shielded equipment accurately. Equipment installed indoors may never be subject to lightning strokes or their transferences, but may be exposed to severe

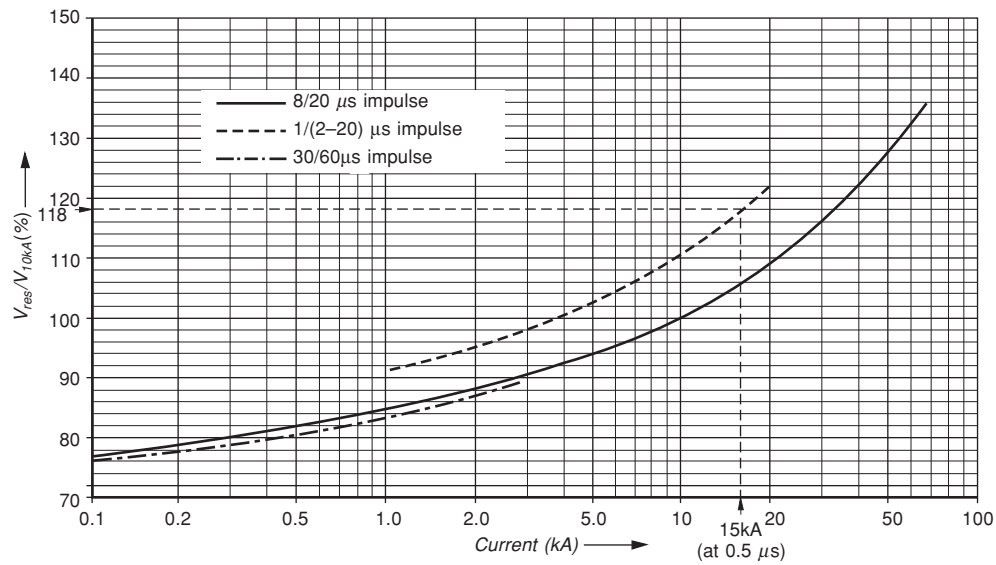


Figure 18.7 Protective characteristics for arresters type EXLIM Q (maximum residual voltage in per cent of residual voltage at 10 kA, 8/20 μs). Superposed on it are protective characteristics for the switching and FOW impulses (*Courtesy:* ABB)

Table 18.3 Establishing the protection level of a surge arrester

Transient condition as in Table 18.1	*Protection level of a gapped surge arrester*	*Protection level of a gapless surge arrester**
(1) Lightning surge	The highest lightning impulse spark-over or breakdown voltage of the arrester should be less than the lightning impulse withstand level of the equipment being protected less by the protection margin (Table 18.2)	The highest impulse residual or discharge voltage across the arrester at the nominal discharge current (item 10, Table 18.9) should be less than the lightning impulse withstand level of the equipment being protected less by the protective margin (Table 18.2)
(2) Switching surge	The highest switching impulse spark-over voltage of the arrester should be less than the switching surge impulse withstand level of the equipment being protected less by the protective margin (Table 18.2)	The highest switching impulse residual or discharge voltage across the arrester at a specified switching impulse current (item 11, Table 18.9) should be less than the switching impulse withstand level of the equipment being protected less by the protective margin (Table 18.2)
(3) Steep-fronted waves (FOWs) $t_1 \leq 1\ \mu s$ – originating from a premature interruption or multiple restrikes during a switching operation	The highest front of wave spark-over voltage of the arrester should be less than the FOW impulse withstand level of the equipment less by the protective margin (Table 18.2)	The highest FOW residual or discharge voltage across the arrester at a steep fronted impulse (1/20 μs) (item 12, Table 18.9) should be less than the FOW impulse withstand level of the equipment less by the protective margin (Table 18.2)

* Also refer to Example 18.5 and Table 18.11.

Notes

1 The protective levels of the surge arresters, at different system voltages are furnished by the manufacturers in their product catalogues, Tables 18.9 and 18.11 furnish typical data for a few established manufacturers.
2 In our subsequent text, we have limited our discussions only to the more prevalent gapless surge arresters.

switching surges and require surge protection as for an exposed installation. There is no readymade formula by which such levels can be quickly established, except experience. The project engineer is the best judge of the most appropriate level of BIL, depending upon the surge protection scheme. Below we briefly discuss the effect of surge reflections and transferences on the safety of equipment to arrive at the right choice of BIL and the surge protection criteria.

18.5.1 Reflection of the travelling waves

The behaviour of a transient wave at a junction of two conductors, such as at junction *J* in Figure 18.8, is similar to that of water in a pipe, when it passes through one large-diameter pipe to another of a smaller diameter. Some of the water will flow ahead and the remainder will back-flow at the junction. Similarly, a transient wave will also reflect in part or in full at a junction between two conductors of different surge impedances, depending upon the surge impedance of the circuit ahead of the junction. This would give rise to two types of waves, i.e.

- Refracted wave: a wave that is transmitted beyond the junction.
- Reflected wave: a wave that is repelled at the joint. See Figure 18.9

To analyse this phenomenon refer to Figure 18.8,

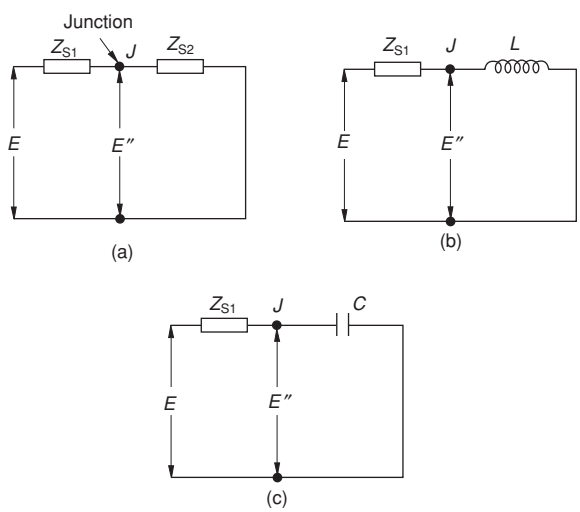


Figure 18.8 Different parameters of switching circuits

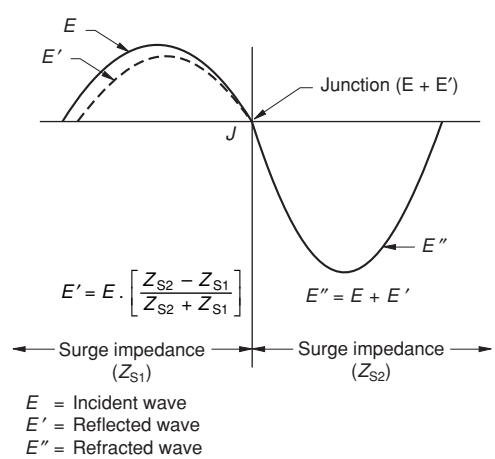


Figure 18.9 Illustration of the reflection of a transient surge at a junction

If Z_{S1} = surge impedance of the incoming circuit
Z_{S2} = surge impedance of the outgoing circuit (Figure 18.8(a))
E = voltage of the incident wave (incoming wave)
E' = voltage of the reflected wave.
E'' = voltage of the refracted (transmitted) wave.
Then the voltage of the reflected wave

$$E' = E \cdot \frac{Z_{S2} - Z_{S1}}{Z_{S2} + Z_{S1}} \tag{18.3}$$

and the voltage of the refracted wave

$$E'' = E + E'$$

$$= E + E \cdot \left(\frac{Z_{S2} - Z_{S1}}{Z_{S2} + Z_{S1}} \right)$$

$$= E \cdot \frac{2Z_{S2}}{Z_{S2} + Z_{S1}} \tag{18.4}$$

If the outgoing circuit is inductive (Figure 18.8(b)) as in a motor, transformer or an inductor coil, with an inductance L then

$$E'' = 2E \cdot \left(e^{-\frac{Z_{S1} \cdot t}{L}} \right) \tag{18.5}$$

and if it is capacitive (Figure 18.8(c)) with a capacitance C then

$$E'' = 2E \cdot \left(1 - e^{-\frac{t}{Z_{S1} \cdot C}} \right) \tag{18.6}$$

This can also be derived for a combined R, L and C circuit to obtain more accurate data. Generally, the figure obtained through Equation (18.4) is simpler, quicker and provides almost correct information for the purpose of surge analysis, and is used more in practice. Where, however, more accurate data are necessary, such as for academic interest, then the more relevant formulae may be used.

Surge impedance thus plays a significant role in determining the magnitude of the reflected wave that matters so much in adding to the TRVs. (Also refer to graphs of Figure 17.7 corroborating this analysis.)

- When the circuit is open at the junction then

  $Z_{S2} = \infty$

  $E' = E$, i.e. the travelling wave will reflect in full. The voltage at the junction

  $= E + E'$

  $= 2E$

  The incoming circuit is therefore subject to twice the system voltage and the voltage of the refracted wave

  $E'' = E + E'$

  $= 2E$

  This means that the travelling wave will transmit in full, and the system will encounter a voltage of twice the system voltage. Refer to Figure 18.10(a).
- When the circuit is shorted at the junction then

  $Z_{S2} = 0$ and

  $E' = -E$

  and voltage at the junction = 0.
  This means that the travelling wave will reflect in full but with negative polarity, thus nullifying the system voltage. The voltage of the refracted wave will also be zero, and obviously so, as there will be no refraction at the shorted end. Refer to Figure 18.10(b).

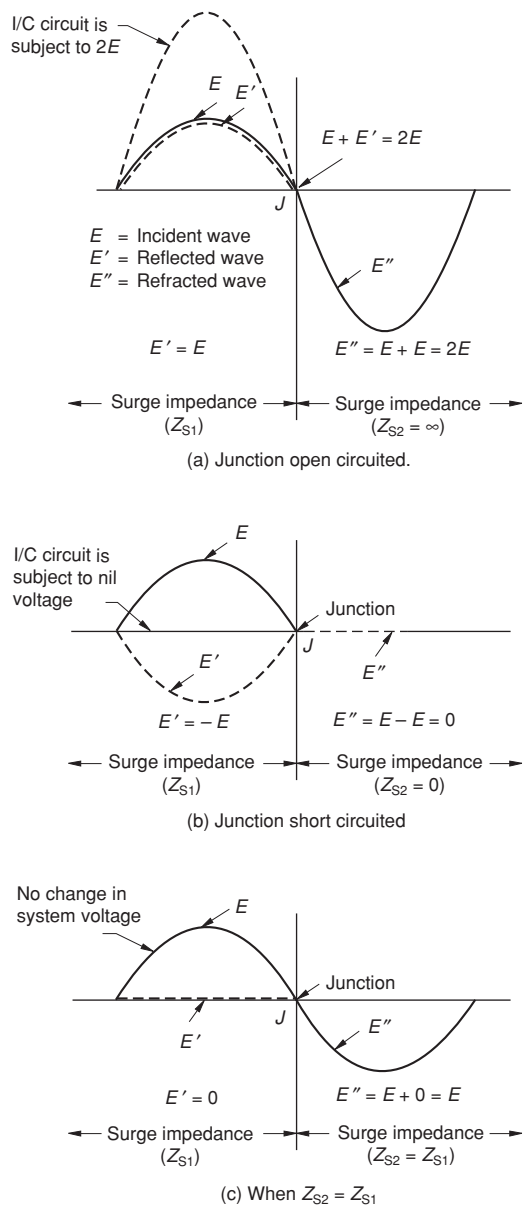


Figure 18.10 Magnitudes of refracted and reflected waves under different junction conditions

- When the travelling wave at the junction enters a circuit with equal surge impedance, such as in the cable before or after an interrupter, then $Z_{S2} = Z_{S1}$ and $E' = 0$. This means that there will be no reflection and the incidence wave will transmit in full, i.e. $E' = E$ (Refer to Figure 18.10(c)). Such a junction will cause no damage to the terminal equipment or the inter-connecting cables. Thus, the voltage wave at a junction will transmit and/or reflect in part or in full, depending upon the surge impedances as encountered by the incident and the refracted voltage waves. Each junction exposed to a travelling wave may thus be subject to severe voltage surges up to twice the incidence voltage, depending upon the surge impedances of the circuits before and after the junction. When the circuit parameters cause such high voltages, care must be taken in selecting the equipment, particularly their connecting leads and end turns as the subsequent turns will be less stressed due to an attenuated refracted wave.

Example 18.1
Consider a 33 kV overhead distribution network connected to a terminal equipment through a cable (Figure 18.11). If the surge impedance of the line is considered to be $Z_{S1} = 450\ \Omega$ and the surge is travelling into the terminal equipment through a cable having a surge impedance of $Z_{S2} = 60\ \Omega$ then,

- The voltage of the refracted wave, at junction *a*,

$$E'' = 2E \cdot \frac{60}{450 + 60}$$

$$= 0.235E$$

which is much less than even the incidence wave and hence, safe to be transmitted.

- The voltage of the reflected wave

$$E' = E \cdot \frac{60 - 450}{450 + 60}$$

$$= -\frac{390}{510}E$$

$$= -0.765E$$

Thus most of the incidence wave will reflect back with negative polarity and reduce the effect of the incidence wave. But the situation reverses as the surge travels ahead to a transformer through junction *b*, as illustrated, and encounters a higher surge impedance. The cable has a very low Z_s compared to a transformer. Now the refracted and reflected waves both are of high magnitude. The reflected wave also has a positive polarity and enlarges the incidence wave. The cable and the terminal equipment are now both subject to dangerous surges as illustrated below:

If the surge impedance of the transformer is considered as 4000 Ω, then the voltage of the refracted wave

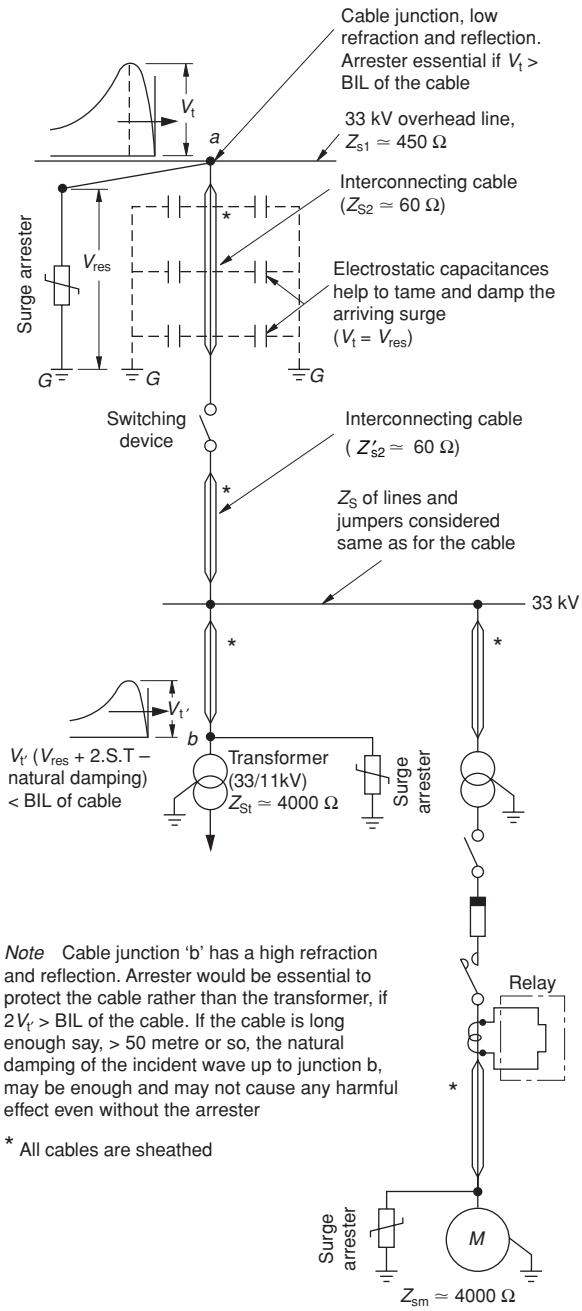
$$E'' = 2E \cdot \frac{4000}{60 + 4000}$$

$$\simeq 2E$$

and of the reflected wave

$$E' = E \cdot \frac{4000 - 60}{60 + 4000}$$

$$\simeq E$$



Note Cable junction 'b' has a high refraction and reflection. Arrester would be essential to protect the cable rather than the transformer, if $2V_{t'}$ > BIL of the cable. If the cable is long enough say, > 50 metre or so, the natural damping of the incident wave up to junction b, may be enough and may not cause any harmful effect even without the arrester

* All cables are sheathed

Figure 18.11 Surge protection of cables, transformer and motor

which will also raise the incidence wave to roughly 2*E*. Then, there will be multiple reflections between the junctions until the reflected surges will attenuate naturally. It is therefore essential to protect the cable against surges at both the ends as shown, particularly when the travelling wave is likely to be of a higher value than the BIL of the cable. It is, however, noticed that there is a natural damping of the travelling waves as they travel ahead through the power system due to the system's lumped capacitances and inductances. Even the multiple reflections tend to achieve a peak of just twice the incidence surge. It is, however, advisable to take cognisance of all such reflections and refractions while carrying out the engineering for a

surge protection scheme and deciding the location for the surge arresters.

Surges originating at some distance from the equipment are of less consequence, for they become damped as they propagate due to circuit parameters *L* and *C*. For the purpose of surge protection, each segment must be considered separately as the surges may generate at any segment and hence separate protection is essential for each segment.

18.5.2 Surge transference through a transformer (from the higher voltage side to the lower voltage side)

This is another phenomenon which can be observed on a transformer's secondary circuit. Voltage surges occurring on the primary side of the transformer, during a switching operation or because of a lightning stroke, have a part of them transferred to the secondary (lower voltage) side. This is termed 'surge transference'.

A transformer has both dielectric capacitances and electromagnetic inductances. Surge transference thus depends on the electrostatic and electromagnetic transient behaviour of these parameters as noted below.

Electrostatic surge transference

At power frequency, the effect of electrostatic capacitances is almost negligible as they offer a very high impedance ($X_c \propto 1/f$, f being too low) to the system voltage. The transformer windings behave like a simple inductive circuit, allowing a normal transformation of voltage to the secondary. A system disturbance, such as a ground fault, lightning stroke or switching sequence, however, will generate surges at very high frequencies, f_s. When such high-frequency surges impinge the windings, the lumped (electrostatic) capacitances offer a near-short-circuit to them while the electromagnetic circuit offers a near-open circuit ($X_L \propto f_s$). The transformer now behaves like a capacitive voltage divider and causes voltage surges due to capacitive coupling, in the lower voltage windings, tertiary (if provided), cables and the terminal equipment connected on the secondary side. The capacitive coupling may be considered as comprising the following:

- Capacitance between the turns of the windings
- Capacitance between higher and lower voltage main windings
- Capacitance between windings and core.

See Figure 18.12. The transformer as a voltage divider is illustrated in Figure 18.13, and transfers a substantial amount of the first peak of the incidence surge on the primary side to the secondary side. The surge voltage transfer with an open secondary can be expressed by

$$V_{tc} = \frac{C_p}{C_p + C_s} \cdot V_t \cdot p \qquad (8.7a)$$

where

V_{tc} = voltage of surge transference

C_p = lumped capacitance between the primary and secondary windings

C_s = lumped capacitance of the lower voltage side.

These values are provided by the transformer manufacturer.

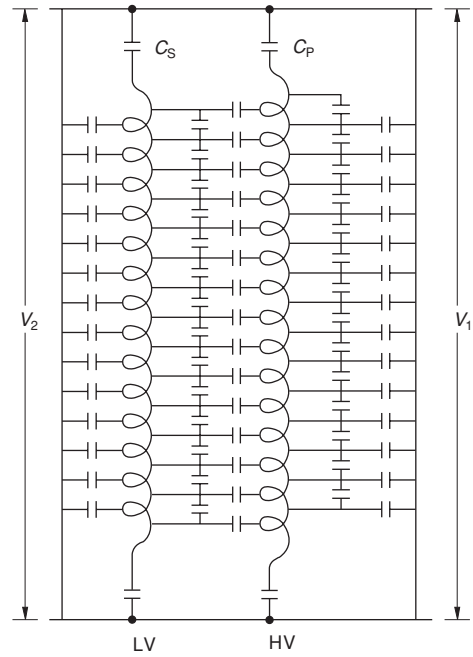
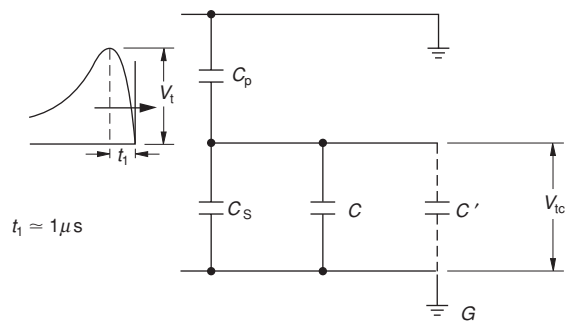


Figure 18.12 Distribution of winding inductances and leakage capacitances in a transformer shown for one winding



V_t – Surge on the primary side

V_{tc} – Surge transference on the secondary side

C_p – Lumped capacitance between the primary and the secondary windings

C_S – Lumped capacitance of the lower voltage side

C' – Protective capacitance

C – Capacitance of cable and equipment connected on the lower voltage side

Figure 18.13 A transformer as a capacitor voltage divider, drawn for one phase

V_t = Prospective voltage surge that may appear on the primary side. If an arrester is provided on the primary side, this voltage is limited to the residual voltage of the arrester (V_{res}). In both cases, consider the higher voltage such as during an FOW. In fact, the lumped capacitances will provide the arriving surge with a short-circuit path to the ground and help to dampen transference to the secondary to some extent. But these effects are not being considered to be more conservative.

p = a factor to account for the power frequency voltage already existing when the surge occurs. IEC 60071-2 has suggested a few typical figures as noted below:

(a) For a lightning surge and FOW:
For Y/Δ or Δ/Y transformers, $p \simeq 1.15$
For Y/Y or Δ/Δ transformers, $p \simeq 1.07$

(b) For a switching surge, $p \simeq 1.0$ in both the above cases.

A lightning surge and an FOW have more influence compared to a switching surge due to the former's higher surge frequencies, f_s.

Margins can be added to account for the severity of the surges, depending upon the type of installation and its criticality.

For high transformation ratios when V_1/V_2 is high, $C_p >> C_s$ and the incidence surges tend to transfer the whole of their severity to the secondary side. $C_p/(C_p + C_s)$ is the ratio of transference when the secondary is open circuited. Transference is highest when it is open circuited. This ratio will generally lie between 0 and 0.4 (IEC 60071-2), but the exact figure must be obtained from the manufacturer, when designing the protection scheme. In service, there are a number of load points connected to it, influencing the electrostatic value in the denominator. If 'C' is the capacitance of the cables and the equipment connected on the lower voltage side of the transformer, the transferred surge will be reduced to

$$V_{tc} = \frac{C_p}{C_p + C_s + C} V_t \cdot p \qquad (18.7b)$$

The front of the transferred surge will, however, be less steep and damped than on the primary side due to capacitive damping. But sometimes this may also exceed the BIL, particularly of the tertiary (if provided) and also of the secondary windings of the transformer, as well as that of the cable and the terminal equipment connected on the lower voltage side. This is especially the case when the primary side voltage is very high compared to the secondary. Protection of the secondary windings, in all probability, will be sufficient for all the cables and terminal equipment connected on the secondary side.

Moreover, as the surge travels through the primary to the secondary of the transformer, a part will become damped due to partial discharge of the surge to the ground through the capacitive coupling and also partly through the inductive coupling of the transformer. As the surge travels forward it will encounter the system's (interconnecting cables and the terminal equipment) capacitive and inductive couplings, and will continue to attenuate in steepness as a result of electrostatic discharges, and in amplitude due to inductance of the circuit. In fact, additional surge capacitors (C') can be provided across the secondary windings as illustrated in Figure 18.13, to further dampen the arriving transferred surges. In fact, this practice is sometimes adopted.

For adequate insulation co-ordination it is mandatory to first check such transferences with the BIL of the transformer's tertiary and secondary windings. The tertiary is a crucial winding and any damage to this will mean a major breakdown of the transformer. For the purpose of protection and to be more conservative, these calculations may be carried out with the LV side open-circuited. Similarly, on the primary side, the most severe surge such as an FOW may be considered. If the transferred surge exceeds the BIL of the tertiary and secondary windings, one or more of the following protective measures may be considered:

- When the primary is provided with an arrester, select the arrester with a lower V_{res}, to shield the secondary side also.
- Consider tertiary and secondary windings with a higher BIL, if possible.
- But the tertiary must be specifically protected by the use of an additional surge arrester between each of its phases and the ground. It is possible that this arrester may discharge rather too quickly compared to the main arrester on the primary in view of larger transferences, compared to a very low voltage rating of the tertiary. If this occurs, the arrester at the tertiary may fail. The rating of the tertiary arrester, therefore, must be meticulously co-ordinated with the V_{res} of the primary arrester. The V_{res} of the tertiary arrester may have to be chosen high and so the tertiary must be designed for a higher BIL.
- Use surge capacitances across the secondary windings.
- Generally, an arrester on the primary should be adequate to protect the secondary windings. When it is not, a separate arrester may be provided between each phase and ground of the secondary windings.
- The terminal equipment connected on the secondary side of the transformer is thus automatically protected as it is subject to much less and attenuated severity of the transferred surges than the secondary windings of the transformer. Nevertheless, the BIL of the interconnecting cables and the terminal equipment must be properly co-ordinated with the BIL of the transformer secondary, particularly for larger installations, say, 50 MVA and above, to be absolutely safe. Example 18.2 will explain the procedure.

Electromagnetic surge transference

This is for systems having secondary voltages up to 245 kV and that are subject to the power frequency withstand test.

During a high-frequency (FOW) surge, the inductive impedance of the windings becomes very high and offers an open circuit to the arriving surge, and there is no inductive transference of voltage surges to the secondary. But at lower frequencies, such as during over-voltages, long-duration switching surges (250/2500 μs), and even during lightning surges, the windings acquire enough inductive continuity to transfer a part of these voltages to the secondary, depending upon the f_s of the arriving surge, in the ratio of their transformation (V_2/V_1). It is generally noticed that such transferences hardly exceed the power frequency withstand level of the windings and are thus less critical. Nevertheless they must be counter-checked while designing the surge protection scheme for the whole system. If it is higher, then

- The arrester on the primary side may be selected with a lower residual voltage (V_{res}), or

- The tertiary and secondary windings may be selected for a yet higher BIL if possible, or
- An additional arrester on the tertiary and secondary sides must be provided.

IEC 60071-2 suggests the following formula to determine such voltages:

$$V_{ti} = \text{p.q.r} \cdot \frac{V_t}{n} \tag{18.8}$$

where

V_{ti} = inductively transferred switching surge on secondary side

p = factor for power frequency voltage already existing, when an over-voltage or a long-duration switching surge occurs as noted above.

q = response factor of the lower voltage circuit to the arriving long-duration surges

(i) For power frequency transferences $q = 1$ and for FOWs $q \simeq 0$.

(ii) For secondary open-circuited, lightning surges $q \leq 1.3$, and switching surges $q \leq 1.8$.

(iii) For loaded secondary $q < 1.0$.

It is seen that normally it may not exceed 1.0 due to many factors, such as the secondary may not be open-circuited, and the circuit parameters, L and C, that the arriving surge may have to encounter with, both having a damping effect:

r = a factor that will depend upon the transformer connections, as indicated in Figure 18.14

V_t = a prospective long-duration switching surge voltage that may appear on the primary side. If an arrester is provided on the primary side, this may be substituted with the switching surge residual voltage of the arrester, V_{res}

n = transformation ratio of the transformer (V_1/V_2)

Example 18.2

Consider segment *X* of Figure 18.25 for the purpose of surge protection. The detailed working is provided in a tabular form, for more clarity, as under:

	Considerations	*Parameters*
(A)	Transformer voltage ratio	132/11 kV
	Connections	$\curlyvee/\triangleright$
	Rating	60 MVA
	Approx. surge impedance from similar graphs as of Figure 17.7(b) by extrapolation (obtain accurate value from the manufacturer)	50 Ω
	Surge travels from higher voltage side of the transformer to the lower voltage side. Consider a surge protection on the primary, with details as follows:	
	BIL of transformer from Table 13.2.	
	(Choosing a higher level, as the system being exposed to the atmosphere).	

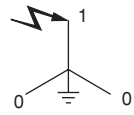
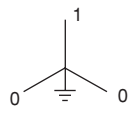
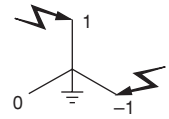
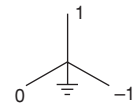
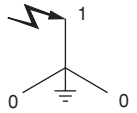
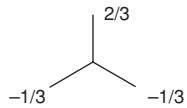
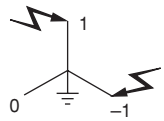
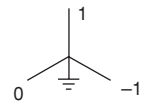
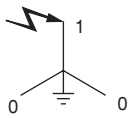
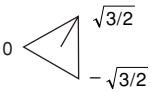
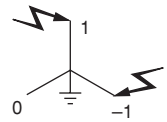
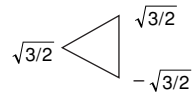
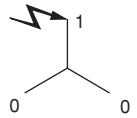
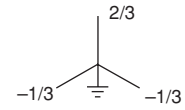
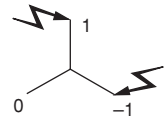
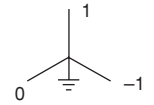
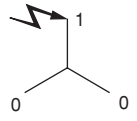
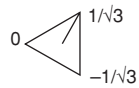
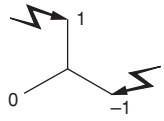
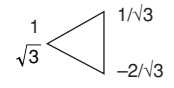
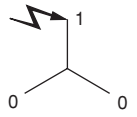
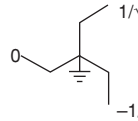
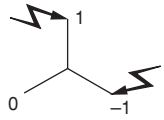
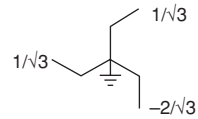
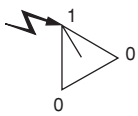
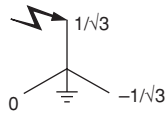
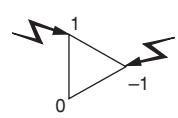
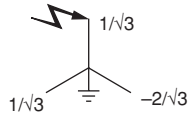
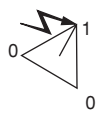
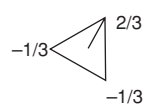
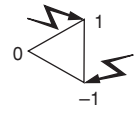
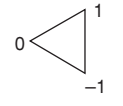
	Power frequency withstand voltage	LIWL
HV side	275 $kV_{r.m.s}$	650 kV peak
LV side	28 $kV_{r.m.s.}$	75 kV peak

Primary side	V_m	145 $kV_{r.m.s.}$
	1 p.u.	$145 \times \frac{\sqrt{2}}{\sqrt{3}} = 118$ kV
Secondary side	V_m	12 $kV_{r.m.s.}$
	1 p.u.	$12 \times \frac{\sqrt{2}}{\sqrt{3}} = 9.8$ kV
Max. continuous operating voltage, MCOV ($V_m/\sqrt{3}$);		
HV side		$\frac{145}{\sqrt{3}} = 83.7$ kV
LV side		$\frac{12}{\sqrt{3}} = 6.9$ kV

(B)	Characteristics of the arrester chosen from Table 18.9, class III; Standard rating, V_r (for detailed working and exact design parameters for selecting the arrester, refer to Example 18.3)	120 kV
	Max residual voltage (lightning) at 10 kA, V_{res} (8/20 μs)	355 kV peak
	Max. residual voltage (switching) at 1 kA, V_{res} (30/60 μs)	294 kV peak
	Max. residual voltage (FOW) at 10 kA, V_{res} (1/20 μs)	386 kV peak
	TOV capability for 10 s	203 kV peak (140% of V_m which is OK)

Considerations	*Parameters*
(C) Reflection of surges:	
Z_s of jumpers through which the surge will travel to the transformer	200 Ω
As the transformer HV side is already protected by an arrester, it is not necessary to consider the influence of refraction of surges at point A, which is quite meagre in this case.	$2 \times V_t \times \frac{50}{50 + 200}$ $= 0.4\ V_t$
The reflected wave will dampen the incidence surge by	$V_t \cdot \frac{50 - 200}{50 + 200} = -0.6\ V_t$
(D) Surge transferences through the HV side of the transformer	
(i) Capacitive transference (initial voltage spike)	$V_{tc} = \frac{C_p}{C_p + C_s} \cdot V_t \cdot p$
Assuming $\frac{C_p}{C_p + C_s} = 0.4$ $V_t = 2.5$ p.u.	
Since an arrester is provided at location A, it is appropriate to substitute V_t by V_{res} (FOW) = 386 kV peak	
$p = 1.15$ for a lightning surge in a Y/Δ transformer,	$\therefore V_{tc} = 0.4 \times 386 \times 1.15$ $= 177.6$ kV peak
which is too high compared to LV side LIWL of the transformer of 75 kV_{peak} (protective level not to be more than 75 /1.2 = 62.5 kV_{peak}, Table 18.2), and calls for either an arrester on the LV side too or provision of a few surge capacitors across the secondary windings such that, The value of C' can be calculated if values of C_p and C_s are known, which can be obtained from the transformer manufacturer.	$\frac{C_p}{C_p + C_s + C'} < \frac{62.5}{177.6}$
Note Even then a surge protection is essential for the tertiary if the tertiary is provided.	
(ii) Inductive transference	V_{ti} = p.q.r. $\frac{V_t}{n}$
Assuming, $p = 1$ for a switching surge (in inductive transference we have to consider long-duration surges only) $q = 1.8$ for a switching surge $r = \frac{\sqrt{3}}{\sqrt{2}}$ from Figure 18.14 for a Y/Δ transformer with surges of opposite polarity appearing on two phases. $n = 145/12 = 12.1$ $V_t = V_{res}$ (switching) $= 294$ kV peak	$\therefore V_{ti} = 1 \times 1.8 \times \frac{\sqrt{3}}{2} \times \frac{294}{12.1}$ $= 37.9\ kV_{peak}$ $= 28\ kV_{r.m.s.}$ or $28\sqrt{2}\ kV_{peak}$
and the power frequency withstand capacity of the LV windings	
∴ Protective margin	$= \frac{28\sqrt{2}}{37.9} = 1.04$

which is too low. It is, however, possible to make it up by selecting the arrester on the primary side with a lower switching V_{res}. Consult the arrester manufacturer for it or provide an arrester on the secondary side also. Moreover, the response factor, q is considered very high, which may not be true in actual service and an arrester at the secondary side may not be necessary in all probability. The BIL of the interconnecting cables and the terminal equipment on the secondary side must be at least equal to the capacitive and inductive transferences of the primary surges as determined above. If it is not so, the V_{res} of the primary arrester must be re-chosen or an arrester also provided on the secondary side.

S. no.	Transformer connections			Surges on one phase only $V_r = 1$ p.u, $V_y = V_b = 0$		Surges of opposite polarity on two phases $V_r = 1$ p.u, $V_y = -1$ p.u, $V_b = 0$	
	HV winding	LV winding	Tertiary winding	HV winding	Value of r for LV winding	HV winding	Value of r for LV winding
1	$Y(g)$	$y(g)$	$(-, y)$				
2	$Y(g)$	$y(i)$	$(-, y)$				
3	$Y(g)$	Δ	$(-, y, \Delta)$				
4	$Y(i)$	$y(g, i)$	$(-, y, \Delta)$				
5	$Y(i)$	Δ	$(-, y, \Delta)$				
6	$Y(i)$	$z(g, i)$	$(-, y, \Delta)$				
7	Δ	$y(g, i)$	$(-, y, \Delta)$				
8	Δ	Δ	$(-, y, \Delta)$				

g – Grounded star
i – Isolated star



Star connected windings


Zig–zag windings


Delta connected windings

Figure 18.14 Values of factor '*r*'

18.5.3 Effect of resonance

This applies to systems up to 245 kV, where inductive impedance is significant.

It is possible that at certain frequencies the capacitive and inductive couplings of the transformer may resonate ($X_C = X_L$) (Section 24.4) during the course of a long-duration surge and give rise to yet higher voltage transferences. For critical installations it is advisable to identify (e.g. by TNA) the likely surges and their frequencies that may cause such a phenomenon to help take corrective steps or modify the parameters C and L of the transformer at the design stage.

An arrester basically is for equipment protection and must be installed at all main equipment heads that are exposed to internal or external surges and whenever the amplitude of such surges, V_t, is expected to exceed the BIL of the equipment.

Figure 18.15 shows a power network with generation, transmission and distribution of power, illustrating the influences of the different kinds of surges that may appear in the system and which must be taken into account, while engineering a surge protection scheme for such a system or a part of it.

18.6 Selection of a gapless surge arrester

To provide the required level of surge protection for equipment or a power system against possible transient frequency voltage surges, ZnO gapless surge arresters are the latest in the field of insulation co-ordination. We provide below a procedure to select the most appropriate type and size of a ZnO surge arrester for the required insulation co-ordination. Based on the discussions above, the following will form the basic parameters to arrive at the most appropriate choice:

1 ***Service conditions:*** As for other equipment (e.g. motors, transformers or switchgears) a surge arrester too is influenced by unfavourable operating conditions such as noted in Table 18.4.

   Unfavourable operating conditions will require a derating in the rating of a surge arrester or special surface treatment and better clearances. Refer to the manufacturer for the required measures and/or deratings.

2 ***Mechanical soundness:*** Such as strength to carry the weight of conductor and the stresses so caused, pressure of wind and, in extremely cold climates, the weight of ice.

3 ***Maximum continuous operating voltage (MCOV) V_c (rms):*** This voltage is selected so that the highest system voltage, V_m, as in column 2, Tables 13.2 or 13.3, when applied to the arrester is less than or equal to the arrester MCOV, that is, $V_c \geq V_m / \sqrt{3}$.

4 ***The BIL of the equipment being protected*** (Section 18.3).

5 ***The arrester's nominal discharge current (I_n):*** This classifies an arrester and is the peak value of a lightning current impulse wave (8/20 μs) that may pass through the arrester for which it is designed. It may be one of the following:

   1.5, 2.5, 5, 10 and 20 kA

18.6.1 TOV capability and selection of rated voltage, V_r

TOV is considered only to select the MCOV and the rated voltage, V_r, of the surge arrester. This is a reference parameter to define the operating characteristics of an arrester. It plays no part in deciding the protective level of the arrester, which is solely dependent on the transient conditions of the system, as discussed later. V_r is used to make the right choice of an arrester and its energy absorption capability to ensure that it does not fail under the system's prospective transient conditions.

To determine the level of TOVs and their duration, it is essential to analyse all the possible TOVs the system may generate during actual operation, and then decide on the most crucial of them, as shown in Table 18.5. Surge arrester manufacturers provide their TOV capability curves in the shape of TOV strength versus duration of the TOV. A few typical TOV capability curves are shown in Figure 18.16(a) for distribution class and Figure 18.16(b) for station class surge arresters. They indicate the ratio between V_c and V_r which may vary from manufacturer to manufacturer and is termed the TOV strength factor K. For curve 18.16(b) it is typically

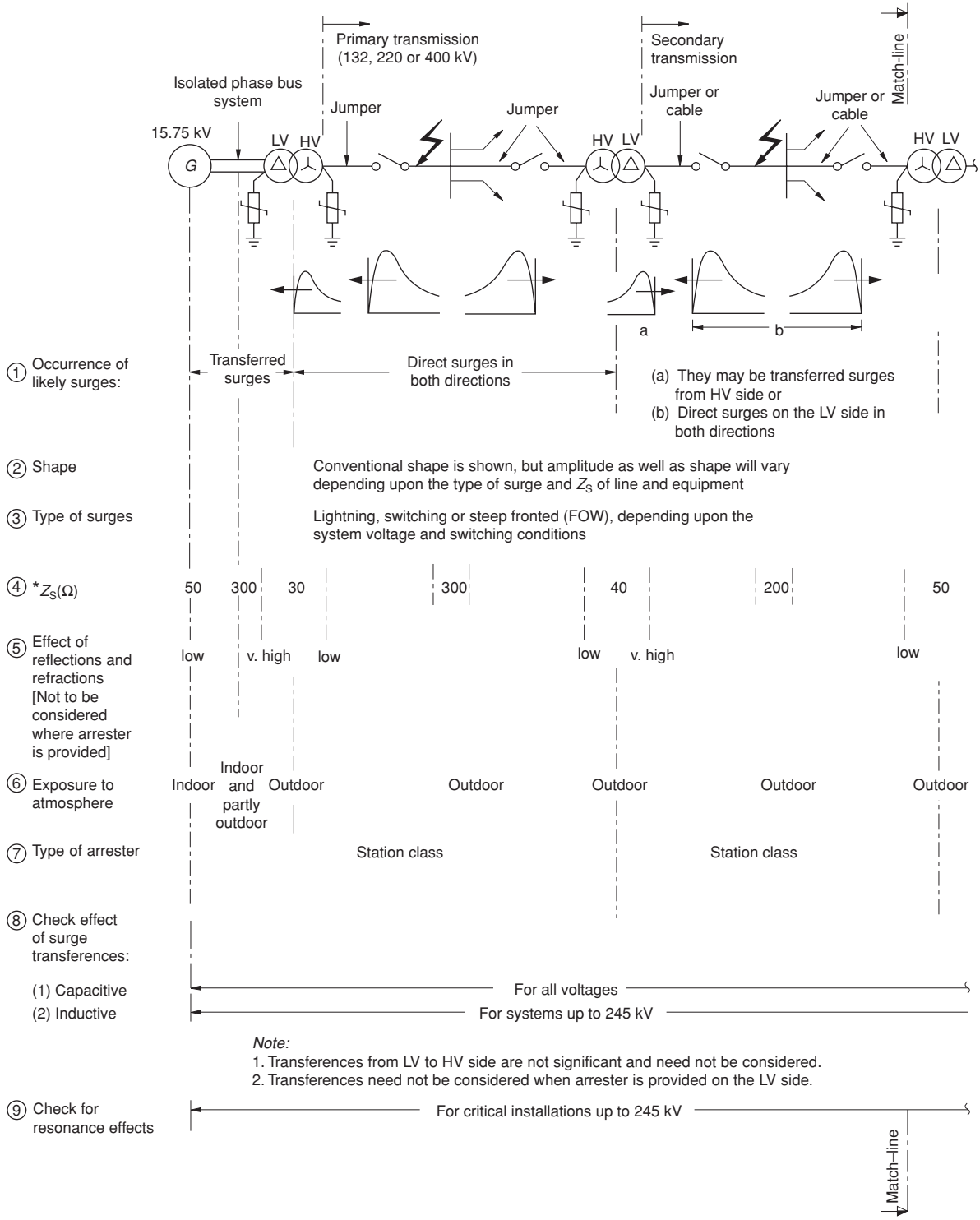
$$V_c = 0.8\ V_r$$

Table 18.4 Standard operating conditions

	Parameters	*Standard conditions*
1	Ambient temperature[1]	–40°C to +40°C
2	System frequency	48–62 Hz
3	Altitude[2]	1000 m
4	Seismic conditions	Locations prone to experience an earthquake of magnitude $M = 5$ or a ground acceleration of 0.1 g and more (Section 14.6)
5	Pollution/contamination[3]	Due to excessive rain, humidity, smoke, dirt and corrosive surroundings etc., which may influence the arrester's porcelain housing outer surface, hence the insulating properties of the arrester

Notes

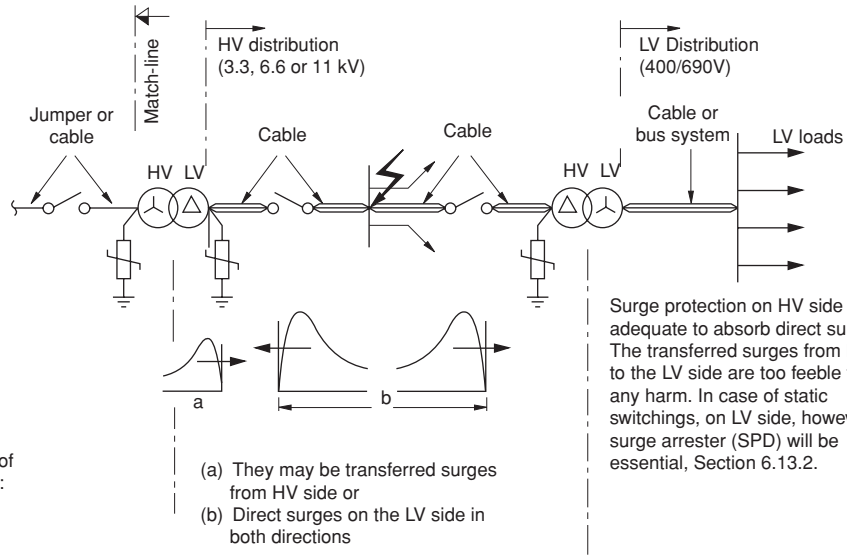
1. Higher ambient temperature would mean higher leakage current and higher losses (Figure 18.4(b)). Consequently it would call for deration of ZnO blocks and the arrester. The manufacturer is the best guide.
2. For higher altitudes extra clearances may be required in the design of the arrester housing. For every 100 m above 1000 m arrester clearances may be increased by roughly 1%. Now also the manufacturer is the best guide.
3. During periodic inspections the atmospheric contamination can be controlled by cleaning the housing by hot-washing the arrester with de-ionized water or applying non-conducting, non-tracking, water repellent grease. Contact the manufacturer for procedure.



Note:
1. Transferences from LV to HV side are not significant and need not be considered.
2. Transferences need not be considered when arrester is provided on the LV side.

* Values are only indicative to illustrate the likely reflections at different junctions. Obtain accurate values from the equipment manufacturers.

Figure 18.15 (*Contd.*)



① Occurrence of likely surges:

(a) They may be transferred surges from HV side or
(b) Direct surges on the LV side in both directions

② Shape — Conventional shape is shown, but amplitude as well as shape will vary depending upon the type of surge and Z_S of line and equipment.

③ Type of surges — Lightning, switching or steep fronted (FOW), depending upon the system voltage and switching conditions.

④ *$Z_S(\Omega)$ — 50 | 100 | 2000

⑤ Effect of reflections and refractions [Not to be considered where arrester is provided] — low | high | v. high

⑥ Exposure to atmosphere — Outdoor | Outdoor | Outdoor or indoor | Indoor

⑦ Type of arrester — Station class | Distribution class

⑧ Check effect of surge transferences:

(1) Capacitive — For all voltages
(2) Inductive — For systems up to 245 kV

Note
1. Transferences from LV to HV side are not significant and need not be considered.
2. Transferences need not be considered when arrester is provided on the LV side.

⑨ Check for resonance effects — For critical installations up to 245 kV

Match–line

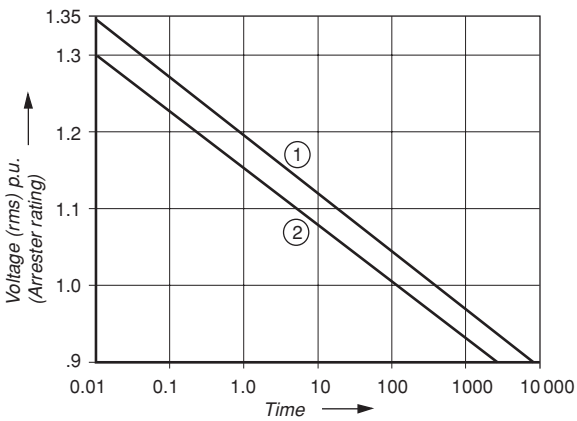
* Values are only indicative to illustrate the likely reflections at different junctions. Obtain accurate values from the equipment manufacturers.

Figure 18.15 A power generation, transmission and distribution network and strategic locations for the surge arresters

Table 18.5 Determining TOV

TOVs	*Cause of TOV*	*OV factor*	*Tripping time*[a]	*TOV factor K from Figure 18.16(b) for a particular brand of surge arrester*
TOV_1	Ground fault			
	(i) for a solidly grounded system	≤ 1.4	1 or 3 seconds	1.16 – for 1 second 1.13 – for 3 seconds
	(ii) For an isolated neutral system	1.73	10 seconds to a few hours and more	1.10 – for 10 seconds 0.93 – for 2 hours
TOV_2	Load rejection	1.1	1 second	1.16

[a] The higher the duration of fault, the higher will be the TOV factor of the arrester (Figure 18.16(b)) and the lower will be the protective margin and vice-versa. Depending upon the system operating conditions and criticality of the system and the equipment the arrester is protecting, one should choose a more appropriate fault clearing time that the arrester shall have to withstand to provide a safe surge protection to the equipment and the system.



Curve – 1, No prior energy.
Curve – 2, With prior energy.

Figure 18.16(a) TOV capability of a distribution class arrester

Generalizing this for different conditions of TOV and make of surge arrester,

$$V_c = K \cdot V_r$$

For each kind of TOV and its duration, a corresponding factor (K) is obtained and with this is determined the required rating, V_r of the arrester. The most crucial TOV may be selected as the rating of the arrester. If it is not a standard rating as in the manufacturer's catalogue as shown in Tables 18.9 and 18.11, one may select the next higher rating available. A simple procedure is outlined in Table 18.5 for a quick reference.

To determine TOV

The main causes of TOV, as discussed above, may be one or more of the following:

- Load rejection (Section 24.6.2).
- Resonance and ferro-resonance effects (Sections 24.4 and 20.2.1(2)).

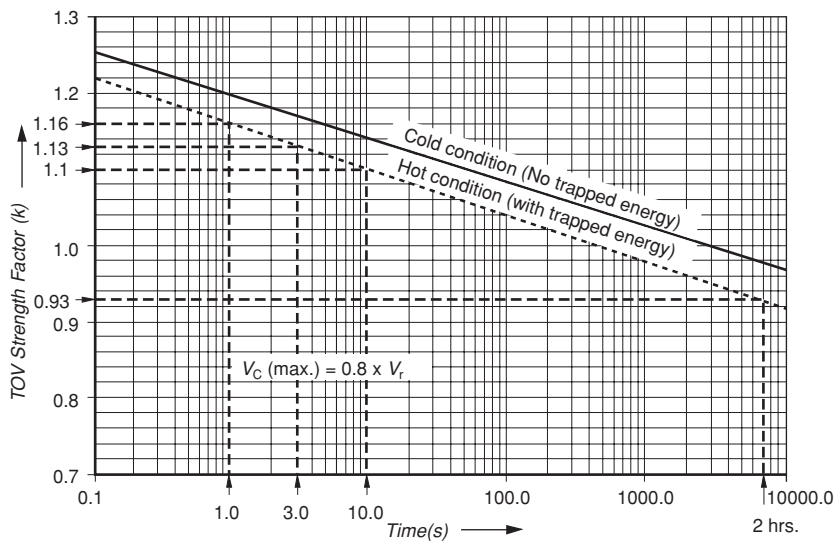


Figure 18.16(b) Typical TOV capability of a station class arrester

- Ground fault: Section 20.1. It is essential to know the grounding conditions to determine the OV factor as below:
- Amplitude: As discussed in Section 20.1, grounding conditions, besides influencing the ground fault current, also raise the system voltage in the healthy phases. It is established that for an isolated or resonant grounded system this can rise to 1.73 times and for a solidly grounded system up to 1.4 times the rated voltage. When system parameters such as R_0, X_0 and X_1 are known a more accurate assessment of this factor can be made by using OV curves as shown in Figures 18.16(a) and (b).
- Duration: This will depend upon the ground fault protection scheme adopted and may be considered as follows:

  (a) For a solidly grounded system: 1–3 seconds (normally, generation and transmission systems are provided with a longer tripping time of up to 3 seconds, and a distribution system still longer, say, up to 10 seconds).

  (b) For an isolated, impedance or resonant grounded system: from a few minutes to several hours (when it is 2 hours or more, it may be considered continuous for the purpose of selection of an arrester).
- Short-circuit condition (Section 13.4.1(6)).

Based on these discussions and experience from different installations, the likely power frequency overvoltage (TOV) over a long period of operation for different voltage systems can be determined. For a more accurate value at a particular installation, it is advisable to carry out a system study. Generally, not more than one contingency may occur at a time. However, depending upon the type of system, which may be critical and more sensitive to load variations, a fault condition or frequent switchings, more than one contingency may also be considered.

Example 18.3
For a 400 kV system

V_m = 420 kV and

$$V_c = \frac{420}{\sqrt{3}} = 243 \text{ kV}$$

and minimum rated voltage V_0 = 243/0.8 = 304 kV, when the system is not subject to any TOV. Consider a solidly grounded system, with a protective scheme of 3 seconds and the eventuality of load rejection, which may occur simultaneously:

$\therefore$ Total TOV = $1.4 \times 1.1 = 1.54$

From Figure 18.16(b), the TOV factor, K = 1.13 for 3-second tripping.

$$\therefore \text{ Required } V_r = \frac{1.54 \times 243}{1.13}$$

$$= 331 \text{ kV (which is higher than 304 kV)}$$

From the reproduced protective characteristics of this arrester, as in Table 18.11, the nearest next higher rating available is 336 kV for a 420 kV system voltage. This is the basic rating of the arrester which must be further checked for

- Whether its protective level can protect the BIL of the system and/or the equipment it is protecting, and
- its energy capability to clear safely the long-duration prospective voltage surges.

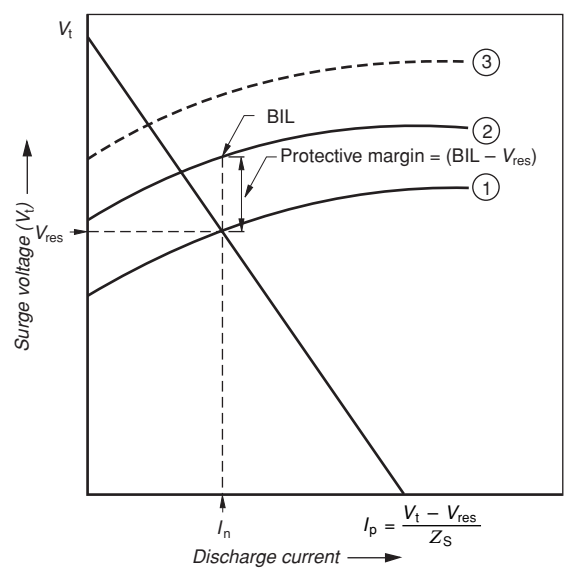
Note
Increasing the TOV level, i.e. choosing a higher protective level (V_{res}) of the arrester, may increase the life of the arrester but will reduce the margin of protection for the protected equipment. Selection therefore should be done judiciously bearing all these aspects in mind.

18.6.2 Selecting the protective level of the arrester

For prospective voltage surges, as described in Table 18.1, which may arise in the system during normal operation the protective characteristics of the surge arrester must be well below the BIL of the equipment at all points. For a minimum protective margin refer to Table 18.2. It is the basic parameter of a surge arrester that defines its protective level. This is the voltage that will appear across the arrester terminals and thus also across the equipment being protected during a current discharge on the occurrence of a voltage surge. It should be well below the BIL of the equipment under protection. Refer to the load diagram shown in Figure 18.17, for more clarity.

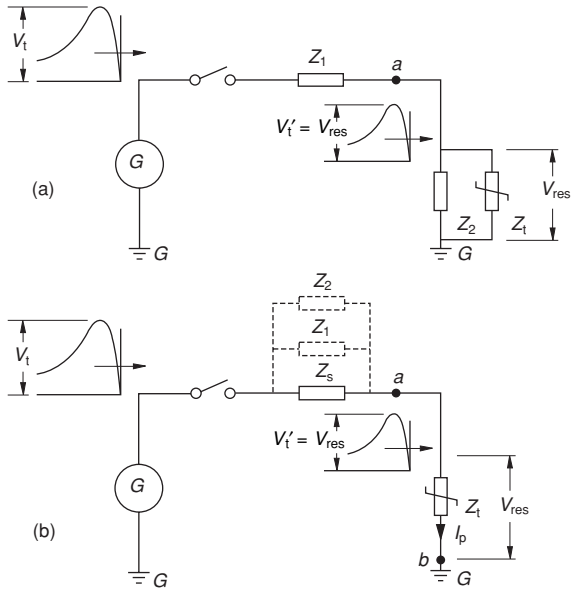
To determine this, consider the simple power circuit diagram of Figure 18.18(a), where

Z_1 = surge impedance of the line on which is connected the equipment to be protected from the source of supply up to the arrester
Z_2 = surge impedance of the equipment to be protected
Z_t = surge impedance of the arrester at V_t



1. Surge arrester protective characteristics.
2. BIL of the equipment.
3. Actual voltage surge.

Figure 18.17 Load diagram



Z_1 = Source impedance
Z_2 = Impedance of equipment being protected
Z_t = Impedance of surge arrester. At V_t, it is negligible

Figure 18.18 Equivalent circuit applying Thevenin's theorem

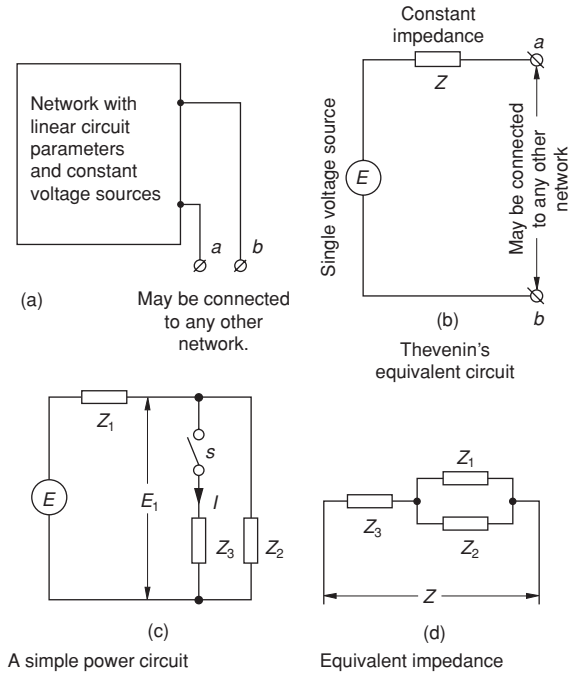


Figure 18.19 Thevenin's theorem

Then applying Thevenin's theorem,* the equivalent circuit can be represented as shown in Figure 18.18(b). On application of a voltage surge, the arrester will start conducting at a certain voltage and carry a certain discharge current. The voltage at which the conduction will start is the impulse protective level of the arrester and is termed the residual voltage (V_{res}) of the arrester. By a manufacturer it is determined for each particular arrester to establish its protective level. It is established by drawing its elements' $I \propto V^{\alpha}$ characteristics as shown in Figure 18.17 and drawing a load line on it to represent the characteristic of the prospective surge. It is drawn with V_t as the ordinate and the current through the equipment I_s (had there been no arrester) as the abscissa:

$$\text{Then } I_s = \frac{V_t}{Z_s}$$

and the protective current through the arrester on a discharge

$$I_p = \frac{\text{Voltage absorbed or the voltage that is discharged to ground}}{\text{Impedance of the line and the equipment}}$$

$$= \frac{V_t - V_{res}}{Z_s}$$

where

V_t = prospective surge voltage
V_{res} = residual surge voltage across the surge arrester (the impulse protective level of the arrester) which must be below the equipment BIL, with a sufficient protective margin,
and Z_s = equivalent impedance of Z_1 and Z_2. (the impedance of arrester, being too small, is ignored)

***Thevenin's theorem:** This is one of the many theorems deduced mathematically to solve intricate circuits. This theorem has established that it is possible to replace any network with linear parameters and constant phasor voltage sources, as viewed from terminals, *a* and *b*, Figure 18.19(a), by a single phasor voltage source *E* with a single series impedance *Z*, Figure 18.19(b). The voltage *E* is the same that would appear across the terminals *a* and *b* of the original network when these terminals are open circuited, and the impedance *Z*, is that viewed from the same terminals when all voltage sources within the network are short-circuited. This can be illustrated by the following example.

Consider the simple switching circuit of Figure 18.19(c). If we wish to find the current through the impedance Z_3, on the closure of the switch, *S*, then;

$$I = \frac{\text{Voltage across this circuit } (Z_3) \text{ before closing the switch, } E}{\text{Equivalent impedance, } Z, \text{ of the remaining circuit as seen from this switch (Figure 18.19d)}}$$

$$= \frac{E}{Z_3 + \dfrac{1}{\left(\dfrac{1}{Z_1} + \dfrac{1}{Z_2}\right)}}$$

$$= \frac{E}{Z_3 + \dfrac{Z_1 \cdot Z_2}{Z_1 + Z_2}}$$

and the voltage across this circuit

$$E_1 = \frac{E \cdot Z_3}{Z_3 + \dfrac{Z_1 \cdot Z_2}{Z_1 + Z_2}} \quad \text{etc.}$$

The criteria to determine the safe protective level of an arrester are the BIL of the equipment, as shown in Table 11.6 for motors, Tables 13.2 or 14.1 for switchgears, Table 32.1(a) for bus systems, and Tables 13.2 and 13.3 for all other systems. Motors have a comparatively lower BIL, but they are not connected directly on an outdoor overhead line, and are also reasonably shielded by the line transformer, switchgear and cables. Switchgear and the bus systems, which may or may not be as shielded as the motors, have comparatively a higher BIL than a motor. Their prescribed impulse withstand level for more exposed installations is given in Table 13.2, list II or III, while for shielded installations, it is lower and given in list I. One may notice that list I is still higher than a motor. On this BIL is considered a suitable protective margin to provide sufficient safety to the protected equipment as in Table 18.2.

Protective characteristics of an arrester

The protective characteristic of a surge arrester is defined by its V_{res}, as a function of its nominal current (I_n) and the time of rise, t_1, in the impulse region as noted above. It is seen that the characteristic of an arrester varies with the front time of the arriving surge. Steeper (faster rising) waves raise the protective level (V_{res}) of an arrester, as illustrated in Figure 18.20, and reduce the protective margin for the equipment it is protecting. Refer to Figure 18.17 for more clarity. Figure 18.20 gives typical characteristic curves of a leading arrester manufacturer, drawn for different magnitudes of current waves (I_n = 3–40 kA), V_{res} versus t_1. From these curves can be determined the revised V_{res} during very fast-rising surges to ensure that the arrester selected is suitable for providing an adequate protective margin during a fast-rising surge.

Protective distance

The protective level as determined above is true only when the surge arrester is mounted directly on the protected equipment (Figure 18.21). But this is seldom possible, as there is usually a gap between the surge arrester and the equipment, due to arrester height, connecting leads and the working gap required between the mounting of the arrester and the protected equipment. On the occurrence of a voltage surge, while the arrester will conduct and absorb the part of surge voltage that is in excess of its protective level (V_{res}), the residual voltage, V_{res}, will travel ahead with the same steepness (r.r.r.v.) until it reaches the equipment under protection. It may regain a sufficient surge voltage to endanger the BIL of the equipment. Since the voltage will continue to rise as it travels ahead, as illustrated in Figure 18.22, the equipment will be subject to higher stresses than the protective level considered for the surge arrester. The distance between arrester and the equipment and the r.r.r.v. will determine the excess stress to which the equipment will be subject to. This can be determined by

$$V_s = V_{res} + S.2.T \qquad (18.9)$$

V_s = actual surge voltage at the equipment
S = r.r.r.v. of the incoming wave in kV/μs

The factor 2 is considered to account for the reflection of the incident surge at the equipment (Equation (18.3)):
T = travelling time of the surge to reach the equipment from the arrester terminals.

If l is the distance in metres from the arrester terminals to the equipment, then

$$T = \frac{l \times 10^{-3}}{0.3}\ \mu s$$

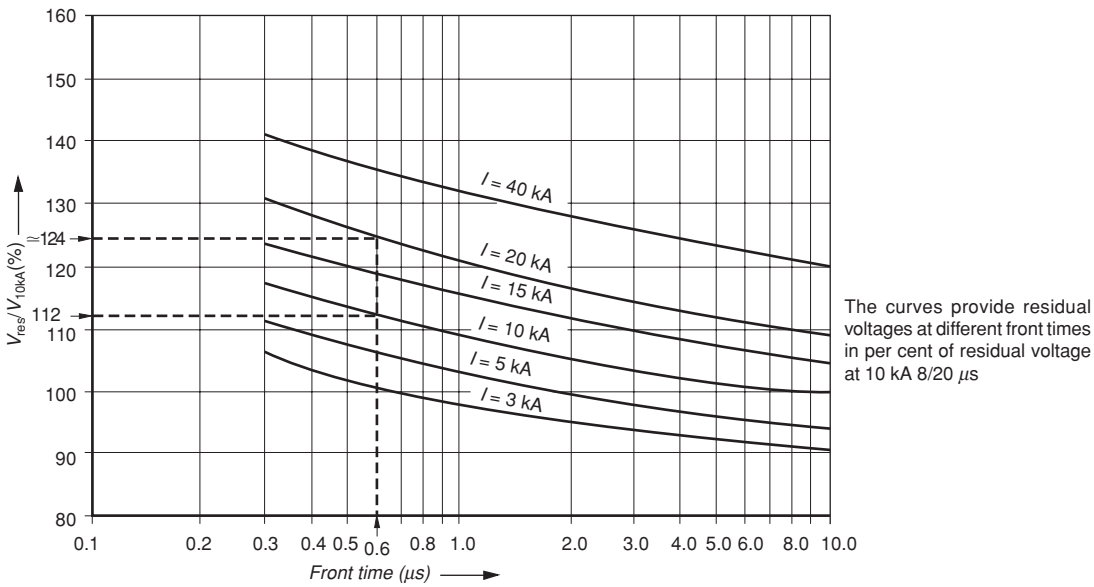


Figure 18.20 Variation in protective level of an arrester with front time

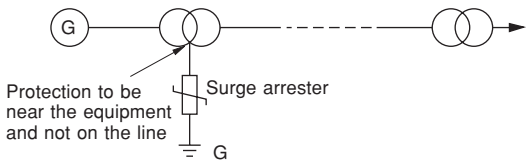


Figure 18.21 Ideal location of a surge arrester

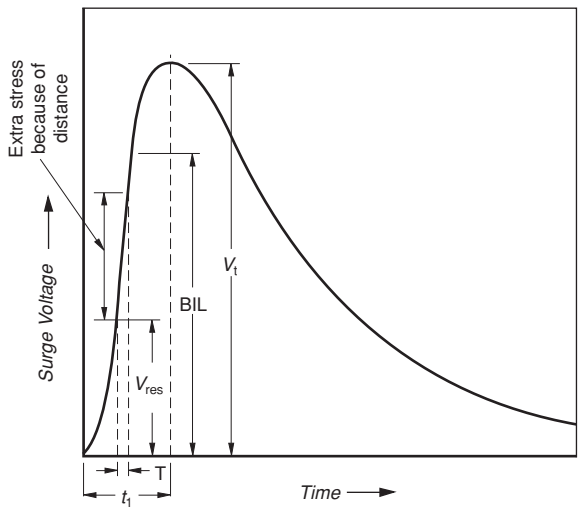


Figure 18.22 Effect of distance on the protective level

(considering the propagation of surge in the overhead lines at 0.3 km/μs, Section 17.6.6).

The longer the distance, l, the greater will be the severity of the oncoming wave which would reduce the protective margin of the arrester dangerously. Safe protective distances are normally worked out by the arrester manufacturers and may be obtained from them for more accurate selection of an arrester.

Example 18.4
For the arrester of the previous example,

V_m = 420 kV,
V_r = 336 kV
V_{res} = 844 kV for a lightning surge protective margin at 20 kA discharge current, from the manufacturer (Table 18.11)

It we consider the lightning surge with a steepness of 2000 kV/μs, then for a total distance of, say, 8 m from the arrester to the equipment

$$V_s = 844 + \frac{2000 \times 2 \times 8 \times 10^{-3}}{0.3}$$

$$= 844 + 107$$

$$= 951 \text{ kV}$$

If we maintain a protective margin of 20%, then the minimum BIL that the equipment under protection must have

$$= 1.20 \times 951$$

$$= 1141.2 \text{ kV}$$

which is much below the BIL of the equipment (1300 kV) as in Table 13.3. One can therefore safely select the arrester with a higher rated voltage, V_r, at 381 kV and a V_{res} at 957 kV.

Note
A lightning surge protective level is found to be more stringent than the switching surge or FOW protective levels. Hence, it is sufficient to check the protective distance requirement for the lightning surge alone,

In such cases, care must be taken to reduce the protective distance, l, if possible, otherwise at some installations equipment with a higher BIL may have to be selected or an arrester with a lower V_{res}, considered. Alternatively one may have to provide two arresters in parallel, which is also an acceptable practice.

18.6.3 Required energy capability in kJ/kV$_r$

This is the energy the arrester has to absorb while clearing a switching surge. It also depends upon the distance of the arrester from the equipment it is protecting, as discussed above. The basic parameters that will determine the required energy capability (I^2Rt), are current amplitude, steepness, duration and number of likely consecutive discharges. The energy capability of an arrester depends upon the size of the ZnO blocks. By resizing these blocks, an arrester of a higher energy capability can be designed. Hence, an arrester with a higher kJ/kV$_r$ capacity will be larger than one with a lower kJ/kV$_r$. ZnO blocks can generally absorb much higher energies at low currents with long durations (i.e. power frequency stresses under normal operation) than higher currents for short durations (i.e. surge voltage capacitive discharges). To select the right type of arrester the energy capability of the arrester in kJ must be determined by what it has to absorb on every discharge. System studies through TNA or EMTP and past experience of similar other installations can be a good guide for the likely number of consecutive discharges an arrester may have to perform at a time and the likely energy release during a switching operation. A computer modelling can predict the arrester discharge capabilities to match the arrester for the system switching conditions. Generally, two consecutive discharges are considered to be adequate. Like other equipment, a surge arrester becomes too heated too during normal service, even when it is not conducting, due to its continuous charging current, I_{ZnO} (Figure 18.4(a)) however small the loss content. When the arrester is conducting, the level of discharge current (I = kV$^{\alpha}$) is a function of the protective level of the arrester, V_{res}, and the rest of the severity of the voltage surge is absorbed by the arrester.

The rating of an arrester is therefore defined in terms of its energy capability to absorb at least the required energy on each discharge and the number of discharges the arrester may have to perform in quick succession. IEC 60099-4 has prescribed the minimum energy capability that an arrester must possess, at each discharge. The graphs in Figure 18.23 indicate these levels for different classes. It may be noted that an arrester with a higher energy capability level will mean less strain or risk of failure for the arrester, but at a higher cost. A brief procedure to determine the energy level that the arrester may have to absorb on each discharge is given below.

Of the three types of surges noted earlier (Table 18.1)

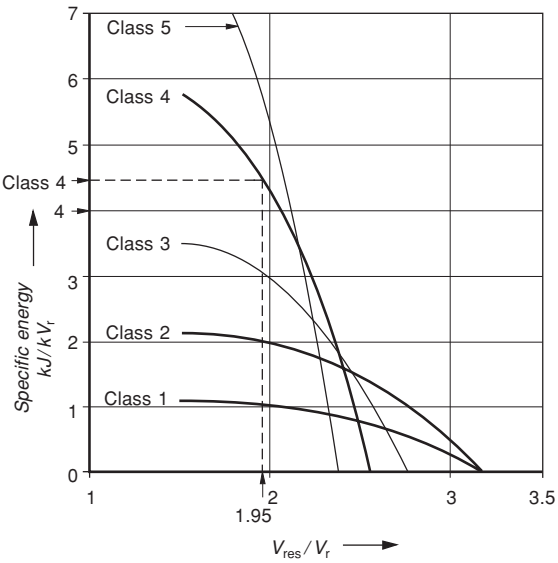


Figure 18.23 Classification of arresters in terms of specific energy kJ/kV$_r$ versus V_{res}/V_r as in IEC 60099–4

which the arrester may have to sustain and absorb, the switching surge energy would be the maximum that would exist for the longest duration, compared to lightning or very steep-fronted FOWs (Section 17.3) which are of very short duration. Normally, therefore, a switching surge alone is considered for this purpose. During the operation of a surge arrester, a part of the surge, equivalent to the protective level of the surge arrester, will conduct and appear as the residual voltage across the arrester in terms of its protective level and the rest would be absorbed by it. What is absorbed would determine its absorption capability. For a switching circuit, as shown in Figure 18.18(a), this can be theoretically determined by:

$$W = \frac{(V_t - V_{res})}{Z_s} \cdot V_{res} \cdot 2T \cdot n \times 10^{-3} \qquad (18.10)$$

where

W = energy absorbed in kWs or kJ (1 W = 1 J/s)
V_t = prospective switching surge crest voltage (kV)
V_{res} = Switching surge residual voltage of the arrester (kV)

Note
As in IEC 60099-4, the lowest value of V_{res} must be considered which occurs at a lower switching surge discharge current, such as a switching surge, V_{res}, at 1 kA, 2 kA, 3 kA, etc. Tables 18.9 and 18.11 illustrate this.

Z_s = surge impedance of the affected line.
T = travelling time of the switching surge from the arrester to the equipment in μs. The factor 2 is considered to account for the reflection of the incident switching transient wave at the equipment (Equation (18.3)). The virtual duration of the surge peak, considered in Table 18.6, also corroborates this.
n = number of consecutive discharges. The energy capability of an arrester is its capability to discharge three such switching surges at an interval of 50–60 seconds each (IEC 60099-4). But since the thermal time constant of ZnO blocks is high (in the range of 60–100 minutes) the time interval of 50–60 seconds does not really matter, and it may be considered as three consecutive discharges for all practical purposes. It is, however, seen that in service, even two consecutive discharges are rare and three may never occur. It is, therefore, sufficient to consider two consecutive discharges for selecting an arrester. The normal practice by leading manufacturers is to specify only the total energy capability for which their arresters would be suitable during consecutive discharges.

Table 18.6 Typical parameters of a transmission line

Line discharge current (kA)	*Line discharge class of arrester*	*Surge impedance of the line $Z_s(\Omega)$*	*Virtual duration of peak $2.T^a(\mu s)$*	*Approx. surge amplitude $V_t(kV)$*
10	1	4.9 V_r	2000	3.2 V_r
10	2	2.4 V_r	2000	3.2 V_r
10	3	1.3 V_r	2400	2.8 V_r
20	4	0.8 V_r	2800	2.6 V_r
20	5	0.5 V_r	3200	2.4 V_r

Based on IEC 60099-4
[a] These are the line discharge test values to test an arrester, as recommended by IEC and have been considered here for the purpose of selection of an arrester. Refer to Example 18.5.

Apparently a higher level of V_{res} would mean a lower level of energy absorption by the surge arrester in terms of V_r. For an excessive level of W required, it is better to select a higher V_r. If it jeopardizes the required protection level, then select another type of surge arrester with a higher energy capability.

To determine W from the above it is essential to know the system parameters. Based on system studies of different voltage systems (transmission lines particularly) many data have been collected. Typical data as suggested by IEC 60099-4 are provided in Table 18.6 for a general reference. For secondary transmission or primary distribution networks up to 245 kV too, where a lightning surge forms the basis of selection for the protective level (V_{res}) of the arrester, only the switching surge must be considered to determine energy capability.

Example 18.5 in Section 18.10 illustrates the procedure to determine the energy capability requirement of an arrester for a particular system. The ultimate selection of an arrester is a compromise between its protective level, V_{res}, TOV capability and energy absorption capability.

18.7 Classification of arresters

These are classified by their nominal discharge currents I_n (8/20 μs) and surge energy absorption capability during a discharge (kJ/kV$_r$). Each discharge current is assigned a system voltage according to IEC 60099-4, as noted in

Table 18.7 Classification of arresters

Arrester line discharge class		*Nominal discharge current at lightning impulse* (8/20/μs) *kA*	*Rated voltage* V_r	*Typical energy capability of arresters produced*
As in ANSI	*As in IEC 60099-4*		*as in* IEC 60099-4 *kV*	*kJ/kV*$_r$
Station class	1	10[a]	$3 \le V_r \le 362$	Generally more than recommended as in graphs of Figure 18.23
	2	10[a] up to 420 kV		
	3	10[a]		
	4	20[a]	$362 < V_r \le 765$	
	5	20[a] 765 kV and above		
Distribution class	–	5	up to 11	Not significant for the purpose of arrester selection
	–	2.5[c]	up to [b]	
	–	1.5[c]		

Notes
[a]Selection of any arrester will depend upon the duty it has to perform (light duty for indoor and heavy duty for outdoor installations) and the required energy absorption capability.
[b]Yet to be defined by IEC 60099-4, but generally for low-voltage systems. Not often in use for power system applications.
[c]The application of such arresters is noted in Section 18.8.

Table 18.7. The energy capability of an arrester will vary with the over-voltage conditions of the system. It is therefore essential to ensure that the arrester chosen has sufficient capability to sustain the required system TOV and surge conditions during long years of operation. IEC 60099-4 has also recommended the line discharge classes of arresters, based on the required energy level in kJ/kV$_r$ and the ratio of V_{res}/V_r (Figure 18.23). The energy capability of a normal arrester produced by leading manufacturers is generally higher than recommended by the IEC for a particular class of arrester. The last column of Table 18.7 and Figure 18.23 recommend the minimum energy capability of different classes of arresters. The class of arrester for a system, particularly for heavy duty, can be easily chosen with the help of these figures for a required level of kJ/kV$_r$ and a ratio of V_{res}/V_r. Arresters classes 1 to 5 are regarded as heavy duty and classified as station class by ANSI/IEEE-C62.11. For light duty, a distribution class may be selected to economize on cost. The nominal current, rated voltage, V_r, level of protection, V_{res}, and energy capability for such arresters are indicated in Table 18.8 for a particular manufacturer.

The subsequent Example 18.5 will provide a simple step-by-step procedure to select an arrester for a particular application >245 kV.

The application and rating of an arrester is a matter of system study and systematic insulation co-ordination, likely discharge current during a possible lightning discharge at the location of the installation and experience gathered from similar installations. Different countries may adopt different practices, depending upon the stability of their networks and the type of surges that may arise during the course of operation. Hence, only broad guidelines can be given to choose an arrester. The rest is a decision by the application engineer and his experience of power networks.

18.8 Application of distribution class surge arresters

The application of these arresters is guided by their following basic characteristics:

Gapped Surge Arresters

1. The gapped arresters possess a low-energy handling capability and hence cannot be applied for installations and equipment that may be subject to long-duration (250/2500 μs) switching surges such as motors requiring high-energy handling capability. They are, however, suitable to withstand an FOW or a transferred surge, as this requires a very low energy handling capability which such arresters can handle.
2. They also pose limitations for installations that connect a number of cables, reactors and capacitor banks, as these also require a higher energy handling capability.
3. They offer a relatively higher V_{res} and may generally not be suitable for protection of equipment that have a low BIL. The BIL of rotating machine or a dry type transformer for instance, may fall lower than the V_{res} of the arrester chosen as per the V_r and the equipment may remain unprotected, unless the arrester is custom-built to suit the BIL of a motor. For clarity see Example 17.5.
4. Basically they are light-duty arresters and must be installed at locations that are not directly exposed to lightning strokes.

These arresters are therefore employed for surge protection of installations and equipment that are not so critical as to cause a shutdown of the power system. Likely applications may be small distribution networks and equipment such as distribution transformers, feeding residential or small industrial loads, not directly exposed to the atmosphere and hence to direct lightning strokes.

Table 18.8 Technical data of metal oxide distribution and station class lightning arresters (MOVs)

	Parameters		*Distribution class*	*Station class*[a] (*for motor protection*)	
1	Rated maximum system voltage (V_m) (50 Hz)	kV r.m.s.	–	7.2	3.6
2	**Rated voltage**	kV r.m.s.	9	**6**	3
3	Nominal discharge current (8/20 μsec.)	kA peak	5	10	10
4	MCOV	kV r.m.s.	7.65	5.5	2.8
5	Max. residual voltage V_{res} (kV peak) at:				
	(a) Lightning current impulse (8/20 μs) peak				
	(i) 2.5 kA		29	–	–
	(ii) **5 kA**		30	**17.7**	9.31
	(iii) 10 kA		33	19.0	10.0
	(iv) **20 kA**		36	**21**	11.5
	(b) **Switching surge residual voltage (1.0 kA, 30/60 μs)**	kV peak	30	**15.3**	8.1
	(c) **Steep current impulse (1/2 μs)**	5 kA peak	33	–	–
		10 kA peak	40	**21.5**	11.5
6	Long duration discharge class: (defines the energy capability)[c]				
	(a) Current	A peak	75	–	–
	(b) Virtual duration of peak	μs	1000	–	–
7	High current (4/10 μs)[d]	kA peak	65	100	100
8	Temporary power frequency over-voltage capability	(kV r.m.s.),			
	(i) 0.1 second		10.5	[b]	
	(ii) 1.0 second		10	[b]	
	(iii) 10.0 seconds		9.5	[b]	
	(iv) 100.0 seconds		9.2	[b]	

Courtesy: Elpro International

Notes

[a]For 11 kV motors refer to Table 18.9.

[b]TOV capability of the arrester is provided by the manufacturer as standard practice, either in the form of voltage versus time data, as given in column 1, or a graph. A typical graph is shown in Figure 18.16(a).

[c]To assess the loss parameter of the arrester, under normal operating conditions (power frequency), the following data, typical (for the above arresters) may also be obtained from the manufacturer. Also refer to Section 18.2.

Reference current: 1.0 mA

Leakage current at MCOV,

(i) Resistive 3.0 mA

(ii) Capacitive 0.8 mA

[d]To identify the suitability of the arrester on direct lightning strokes.

Such installations are reasonably shielded, as when installed within a city. Even 5 kA gapped distribution class arresters may not be suitable for distribution lines running through long open terrains, such as for rural electrification and are therefore exposed to direct lightning strokes and their higher severities.

Therefore, for power applications that are adequately shielded minimum 5 kA surge arresters are in practice. 1.5 and 2.5 kA arresters hardly have any application due to their frequent discharges and rapid failures and most manufacturers have since discontinued the manufacture of the same.

Gapless metal oxide varistors (MOVs)

These are heavy-duty distribution class surge arresters and possess high energy absorption capability and suitable for distribution systems discussed above. Tables 18.8 and 18.8(a) provide typical data up to 11 kV surge arresters, widely employed for the distribution of power that can be through an overhead or an underground distribution network. For higher ratings one may consult the manufacturer or their data sheets. These arresters are suitable for protection against lightning surges as well as switching surges. Since distribution is not below 11 kV these arresters too have little application below 11 kV except on the secondary side of a sub-distribution transformer 33 or 11 kV/ 3.3 or 6.6 kV feeding utilities and other loads at 3.3 or 6.6 kV such as to protect furnaces, capacitors, reactors and rectifier circuits even motors from transferred surges.

18.9 Pressure relief facility

A surge arrester is a sealed unit to save it from all atmospheric hazards. It is normally filled with air. Explosions of surge arresters have been noticed during service. Explosion of a porcelain housing is dangerous, as the shell splinters can cause great damage to nearby bushings, insulators and other equipment and also maintenance personnel if working in the vicinity.

It is possible that ZnO elements may break down with

Table 18.8a Technical data of 5kA gapless metal oxide distribution class surge arresters (MOVs)

Rated voltage (V_r)		*(kV rms)*	*3*	*5*	*6*	*9*	*10*	*12*
Maximum continuous operating voltage (MCOV)		(kV rms)	2.55	4.25	5.1	7.65	8.5	10.2
Maximum residual voltage (V_{res}) at lightning current impulse 8/20 μs	2.5kA	(kV peak)	8.6	14.3	17.3	25.9	28.8	34.6
	5kA	(kV peak)	9.4	15.7	18.8	28.2	31.3	37.6
	10kA	(kV peak)	10.3	17.2	20.7	31.0	34.4	41.3
Maximum steep current impulse residual voltage at 5 kA 1/20 μs impulse		(kV peak)	10.3	17.2	20.7	31.0	34.4	41.3
Insulation withstand at 1.2/50 μs impulse		(kV peak)	95	95	95	95	95	95
Long duration discharge current at 1000 μs impulse		(A)	75	75	75	75	75	75
Energy absorption capability at 4/10 μs impulse		(kJ/kVr)	2.8	2.8	2.8	2.8	2.8	2.8

Courtesy: Alstom (Now Areva)

time due to thermal cracking as a result of system TOVs occurring frequently or existing for long durations, or while clearing a lightning or a switching surge and even subsequent to that. Breakdown of ZnO elements into splinters may collide with the main porcelain housing. But most damage is caused by a flashover between the ZnO elements and the side walls of the housing, which may result in puncture or crackdown. It may lead to a cascading effect and cause an eventual short-circuit within the housing and result in a very heavy ground fault current $(V_l/\sqrt{3} \cdot Zg)$ through it.

The fault current may cause a flashover and rise in the internal temperature and pressure of the housing. It is extremely important to make provision to release this pressure, otherwise it may lead to an explosion of the housing, scattering splinters like bullets in the vicinity. This is dangerous and must be avoided. The pressure relief capacity must be such that there will be no violent explosion of the housing during a failure. Although it may shatter, the arrester's fractured pieces should not fall beyond a circle of a radius equal to its height, somewhat similar to the properties of safety glass wind screens used in a car. International specifications recommend that on a pressure build-up, the hot gases will escape through the pressure relief diaphragm or the housing may simply collapse as a result of thermal shock. An arrester that is vented must be quickly replaced.

This is achieved through a pressure relief system in the form of a pressure relief diaphragm at the top of the housing. The pressure relief system is designed for the system fault level. To test the pressure relief system, IEC 60099-4 and IEC 60099-1 have also specified the test current of the same magnitude as the fault current of the system, but for a very short duration, of the order of 0.2 second or so. This brief period is enough to burst or shatter the housing of the arrester, hence a longer duration is of no relevance.

The practice for heavy-duty arresters is to eliminate the causes of internal flashover between the ZnO elements and the housing at the manufacturing stage. Different manufacturers have adopted different methods for achieving this. One such method is providing a barrier of an insulating material not affected by heat and arcing, such as an FRP (fibre reinforced plastic) tube between the housing and the ZnO elements.

18.10 Assessing the condition of an arrester

To ensure adequate safety for a system and its terminal equipment against over-voltages and voltage surges it is essential to ascertain the soundness of the arrester at regular intervals. It should be possible to do this when it is in service without taking it off from the lines with the help of available instruments noted next. If deterioration of the ZnO elements is detected it may need more frequent future services or replacement of the arrester. It can now be planned well in advance. The requirement is similar to ascertaining the condition of power capacitors when in service (Section 26.2). Like a capacitor, an arrester deteriorates too with time due to degradation of the dielectric strength of its ZnO elements.

ZnO is a highly non-linear resistor element. The success of an arrester will depend upon its low, continuous resistive leakage current Figure 18.4(a) to maintain low loss and low heating over years of continuous operation. When the ZnO blocks start to deteriorate which is a slow process as discussed earlier, the leakage current starts rising from its original level. The rise in current is rich in third harmonic component due to the non-linear characteristic of the ZnO blocks. Other reasons for degradation in the dielectric properties and a rise in current may be one or more of the following:

- Ingress of moisture through the seals, although Silicagel is provided beneath the arrester sealing to absorb the moisture.
- Failure of ZnO elements during or after clearing a few surges.
- Premature ageing of the ZnO elements.
- Temperature variations. The rise in I_r is rapid at higher operating temperatures (Figure 18.4(b)).
- Frequent system voltage variations.
- Being continuously energized.

A rise in leakage current is not desirable and is indicative of deterioration of the ZnO blocks, which may lead to failure besides extra losses till such period the arrester remains in service. It is therefore necessary to monitor the leakage current and detect a possible failure beforehand and take corrective steps in advance. The maximum safe leakage current is specified by the arrester manufacturer as a relation between I_r and its third harmonic component, I_{3r}. I_{3r} is expressed in terms of I_{ZnO} as discussed later. It varies with deterioration of the arrester and is used as a reference parameter to assess the arrester's condition. As the actual leakage current measured through I_{ZnO} starts rising and approaches the maximum leakage current in healthy condition closer monitoring of the arrester becomes essential, to avoid an abrupt failure or explosion. Refer to Table 18.10 to monitor the condition of the arrester. To measure I_r, let us analyse the basic circuit of an arrester as considered in Figure 18.5, where

I_r = loss component and is about 5–20% of I_c under normal operating conditions. Any change in its value will contain a third harmonic component because of its non-linearity. It will vary with system voltage and operating temperature.

I_c = leakage capacitive component leads I_r by 90°. It also depends upon the system voltage and the

Table 18.9 Protective characteristics of gapless station class surge arresters for a nominal discharge current of 10 kA[a]

1	System voltage (50 Hz) kV	420	245	245	***145***	123	72	36	36	24	12	12
2	Rating of surge arrester (at the reference current) kV	390	216	198	***120***	96	60	36	30	18	12	9
3	Discharge class	III	III	III	***III***	III	II	II	II	I	I	I
4	Energy dissipation capability cumulative operation (kJ/kV_r)	10	10	10	6.5	6.5	4.5	4.5	4.5	2.5	2.5	2.5
5[b]	High current impulse withstand of 4/10 μs wave shape kA	100	100	100	100	100	100	100	100	100	100	100
6	Reference current of the arrester at ambient temperature mA	5	5	5	3.25	3.25	2.25	2.25	2.25	1.5	1.5	1.5
7	Components of the continuous leakage current at COV											
	Resistive μA peak	400	400	400	400	400	400	400	400	400	400	400
	Capacitive μA peak	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
8	Watt loss at MCOV per kV of rated voltage W/kA	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
9	Maximum continuous operating voltage kV r.m.s.	303	178	168	102	81	52	30.5	25.5	15	10	7.65
10	Max. residual voltage at lightning impulse of 8/20 μs wave kV peak											
	5 kA	860	567	518	333	249	162	103	85	60	38	33
	10 kA	900	602	550	***355***	264	175	110	90	65	40	35
	20 kA	957	668	610	390	304	202	128	104	75	46	41
11	Maximum residual voltage at switching current impulse of 30/60 μs, 1 kA	780	496	457	***294***	221	138	87	71	52	32	28
12	Maximum residual voltage at steep-fronted impulse (1/20 μs, IEC 60099-4) at 10 kA	1050	654	600	***386***	288	202	124	101	73	45	40
13	Temporary power frequency overvoltage capability											
	(a) 0.1 second kV peak	705	397	364	220	156	97	58	48	29	19	14
	(b) 1.0 second kV peak	580	382	350	212	149	93	56	46	28	18	14
	(c) 10.0 seconds kV peak	565	367	336	203	142	89	53	44	26	17	13
	(d) 100.0 seconds kV peak	550	305	280	169	135	84	51	42	25	16	12

Courtesy: Elpro International

[a] These are typical figures and can be varied by the manufacturer to suit an application.
[b] To identify the suitability of the arrester on direct lightning strokes.

Table 18.10 Logbook to monitor the condition of an arrester when in service

Date of measurement	*Healthy* $I_{ZnO(h)\ max.}$[a] *provided by the arrester manufacturer* μA	*Actual measurement of* $I_{ZnO(a)}$ *at site*[b]		*Likely condition of the arrester*
		μA	*As % of* $I_{ZnO(h)}$	
1st year	250	70	28	Good
3rd year		90	36	Good
5th year		115	46	Good
7th year (December)[c]		160	64	Sign of deterioration
8th year (May)[c]		220	88	Sign of rapid deterioration Recommended for servicing around this time
8th year, (November)[c]		300	120	Requires servicing or replacement

[a] $I_{ZnO(h)}$ = maximum leakage current in normal conditions.
[b] $I_{ZnO(a)}$ = actual leakage current measured at site.
[c] Closer monitoring recommended.
The above figures are purely hypothetical.

Note
Monitoring by such an instrument can be carried by installing it permanently or by using it as a portable instrument. Even when connected permanently, the measurements are taken at long intervals for short durations for periodic checks of the arrester. The table suggests only likely check periods, which may vary with environmental conditions and the quality of the system voltage. Higher discharges or frequent switchings of the line breakers, for instance, may deteriorate the ZnO blocks more quickly and require more frequent readings than for systems having lower discharges or switchings.

operating temperature. It is, however, independent of I_r and remains almost unaffected by the deterioration of ZnO blocks, i.e. change in I_r.

I_{ZnO} = Total leakage current of the arrester. It also rises with system voltage and operating temperature. Under healthy conditions this current is very low (in the range of μA).

Ideally, measuring the variation in I_{ZnO} should be enough to determine the condition of an arrester. But it is not so, as it does not provide a true replica of I_r for the following reasons:

- **System voltage harmonics** With deterioration of the arrester, I_r rises and so does its third harmonic component, because of non-linearity of the ZnO blocks. I_{ZnO} therefore also measures the harmonics present in the system voltage, particularly the third harmonic. The system harmonics are also magnified by the leakage capacitances of the arrester. Since an arrester is connected between a phase and the ground, the third harmonic of the system finds its path through the grounded arrester and distorts the third harmonic of the ZnO blocks caused by their deterioration.
- **Uneven distribution** of *C* along the arrester (Lundquist *et al.,* 1989)
- **Pollution by the surroundings**, such as by dirt and ingress of moisture. In normal conditions this also raises I_c and I_{ZnO} and
- **Corona effect** All such factors may influence the I_r and I_{ZnO} in different proportions and be detrimental in assessing the actual variation in I_r through I_{ZnO}. I_{ZnO} therefore cannot be regarded as a true replica of I_r. Monitoring of I_{ZnO} may not accurately assess the actual condition of the arrester. To use I_{ZnO} to assess the condition of an arrester, it is essential to separate I_r from it.

The greatest effect of ageing is reflected by the variation in its resistive current, which is rich in the third harmonic. Variation in I_r is used in assessing the condition of an arrester. By conducting laboratory tests to determine the characteristics of an arrester, we can establish a ratio between the total leakage current, I_{ZnO} and the content of I_r, to assess the condition of the arrester. If we can monitor this current, we can monitor the condition of the arrester. Below we discuss briefly one such method by which this component can be separated out.

Leakage current monitor

(A diagnostic indicator of metal oxide surge arresters in service).

Note
Instruments operating only during discharges are basically surge counters and can only indicate the number of discharges. They provide no information on the condition of the arrester.

To measure the resistive leakage current, I_r, alone is a complex subject. However, there are a number of methods to determine this. IEC 60099-5 mentions a few methods by which the resistive leakage current, I_r, can be measured through I_{ZnO}. The main problem faced in all these methods is the presence of a system voltage third harmonic that finds its way through the grounded arrester and shows up in I_{ZnO}. Therefore, unless the system voltage third harmonic is eliminated from I_{ZnO}, it will not provide a true replica of the arrester's condition. Below we discuss one better recognized method (See Lundquist *et al.,* 1989) by which an attempt is made to separate out the system voltage third harmonic from I_{ZnO}. The method is based on extraction of I_r by third-order harmonic analysis of I_{ZnO}. This is achieved by providing an electric field probe located at the grounding end of the arrester. The probe compensates

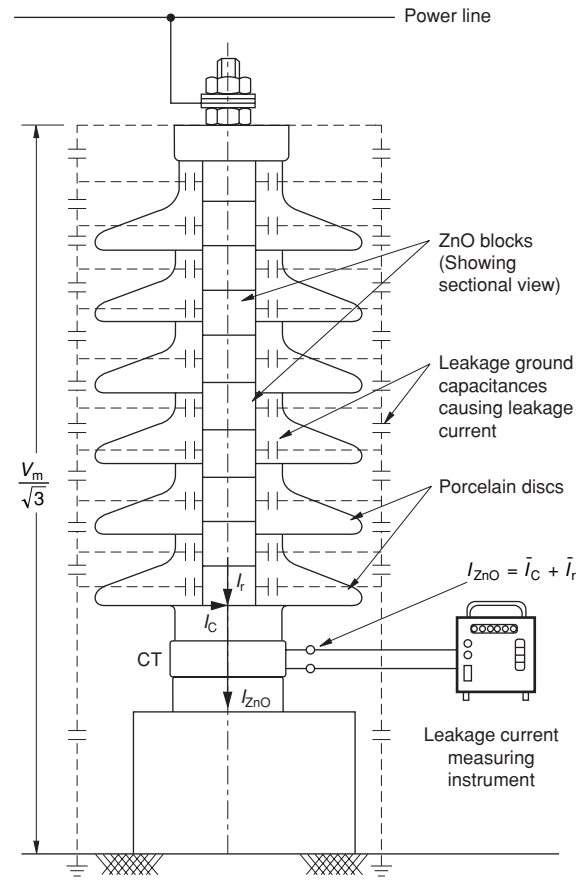
the third harmonic present in the system voltage so that the current measured at the ground end of the arrester contains only the third harmonic of I_r. Harmonics, other than the third even if they are present in the system or I_{ZnO}, are of little relevance, as the instrument analyses only the third harmonic.

The instrument separates out I_r and I_c and provides a direct reading of I_r and hence the condition of the arrester. Refer to Table 18.10 providing a brief procedure to monitor the condition of an arrester through such a monitor.

A typical layout of such an instrument and its accessories is shown in Figure 18.24(a). It consists of:

- ***Leakage current monitor*** – this can be connected permanently for continuous reading or periodic monitoring. The normal practice is to measure only periodically for a short period to take average measurements on an hourly, daily, monthly or yearly basis. When not connected permanently, the instrument can also be used as a portable kit to monitor the condition of other arresters installed in the vicinity.
- ***Field probe*** – to compensate the third harmonic of the system voltage to make the I_{ZnO} free from the third harmonic of the system voltage. This method of I_r measurement therefore provides more accurate and closer monitoring of the arrester.
- ***Clip-on CT*** – to measure I_{ZnO} and is mounted at the grounding end of the arrester.
- ***Current probe*** – to measure the third harmonic component of I_r. It is then converted to actual I_r from the ZnO characteristic data provided by the arrester manufacturer, I_r versus I_{3r}, corrected to the site operating temperature and voltage. The value of I_r is then used to assess the condition of the arrester.
- ***Adapter (connector)*** – to connect the CT with the instrument.

Figure 18.24(b) illustrates the use of a leakage current



I_{ZnO} – Surge arrester leakage current free from system voltage 3rd harmonic
I_C – Free from system voltage 3rd harmonic
I_r – With 3rd harmonic current component

Figure 18.24(b) Measuring leakage current through an arrester

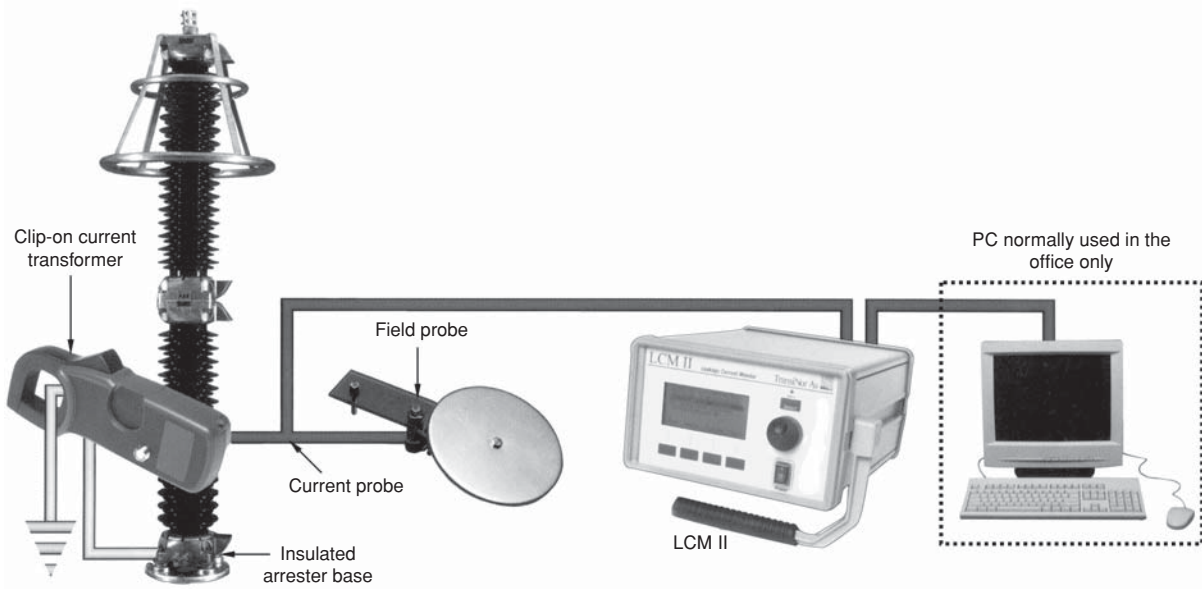


Figure 18.24(a) General arrangement of a Leakage Current Monitor (LCM) (*Courtesy:* TransiNor As)

monitor. The instrument can be used to display or monitor on a computer remotely and store data at intervals as required to provide diagnostic information. Now it is easier to take corrective measures in time. The instrument can also be programmed to give an alarm at a preset value of I_r when the actual operating conditions exceed this.

Example 18.5

Step-by-step selection of a surge arrester for the protection of equipment mounted on a 400 kV transmission line as in Figure 18.25.

Considerations	*Data*	
Nominal system voltage (V_l)	400 kV (r.m.s.)	
Maximum system voltage (V_m)	420 kV (r.m.s.)	
In per unit (p.u.)	1 p.u. = $420 \times \frac{\sqrt{2}}{\sqrt{3}}$ = 343 kV	
Maximum continuous operating voltage (MCOV), $\frac{V_m}{\sqrt{3}} = V_c$	$\frac{420}{\sqrt{3}}$ = 243 kV (max.)	
Temporary overvoltages (TOVs) as in Table 18.5	OV factor	tripping time
(i) Due to a ground fault for a solidly grounded system with a GFF of 1.4 TOV_1	1.4	3 sec
(ii) TOV due to load rejection TOV_2	1.1	1 sec
(iii) TOV due to a short-circuit fault TOV_3	1.3	0.5 sec

Considering conditions (i) and (ii) occurring at the same instant,

$\therefore$ total TOV = $1.4 \times 1.1 = 1.54$ for 3 seconds

TOV factor as in Figure 18.16(b), $K = 1.13$

$$\therefore\ V_r = \frac{1.54 \times 243}{1.13} = 331 \text{ kV}$$

For this voltage, we have selected a Class 4 arrester, which has the nearest next higher rating as in Table 18.11 as

$V_r = 336$ kV

As regards the primary selection of the arrester, it is complete at this stage. But this selection must be checked for its adequate protective level and the energy absorption capability.

(A) Checking for the protective level

For this rating, the arrester protection levels are:

- V_{res}(max) for a switching impulse wave of 1 kA for the purpose of energy capability = 654 kV.
- For switching impulse protective margin at 2 kA = 676 kV = V_t (switching).
- V_{res}(max) for a 20 kA lightning impulse (8/20 μs) = 844 kV.
- V_{res}(max) for a 0.6 μs FOW from Figure 18.20 = $1.24 \times 844 = 1047$ kV = V_t (FOW).
  BIL of the equipment to be protected, from Table 13.3 list I (considering the lower side to save on the cost of equipment)
- For switching surges = 950 kV
- For lightning surges = 1300 kV
- For very fast-rising surges (FOWs) = 1300 kV (assumed). This value must be obtained from the manufacturer of the equipment to be protected.

Table 18.11 Protective characteristics of a gapless station class surge arrester for (1) Line discharge class 4, and (2) Single impulse energy capability = 7 k.J/k.V_r

System voltage	*Rated voltage*	*Max. cont. operating voltage (MCOV)*	*MCOV as in ANSI tests*	*TOV capability for*		*Maximum residual voltage with current wave*						
						Switching surges[a]			*Lightning surges 8/20 μs*			
$kV_{r.m.s}$	$kV_{r.m.s}$	$kV_{r.m.s.}$	$kV_{r.m.s}$	1s $kV_{r.m.s}$	10 s $kV_{r.m.s}$	1 kA kV_{peak}	2 kA kV_{peak}	3 kA kV_{peak}	5 kA kV_{peak}	10 kA kV_{peak}	20 kA kV_{peak}	40 kA kV_{peak}
420	330	264	267	383	363	642	664	680	718	759	829	911
	336	267	272	390	370	***654***	***676***	693	731	773	***844***	928
	360	267	291	418	396	701	724	742	783	828	***904***	994
	372	267	301	432	409	724	748	767	810	856	934	1027
	378	267	306	438	416	736	760	779	823	870	949	1044
	381	267	308	442	419	741	766	785	829	877	***957***	1052
	390	267	315	452	429	759	784	804	849	897	979	1077
	396	267	318	459	436	771	796	816	862	911	994	1093
	420	267	336	487	462	817	845	866	914	966	1055	1160

[a]Any impulse with a front time longer than 30 μs.
Courtesy: ABB

To check the protective margins

	Type of surge	*Margins recommended as in Table 18.2*	*Margin available*	*Suitability of the arrester*
(i)	For switching surges	1.15	$\frac{950}{676} = 1.40$	OK
(ii)	For lightning surges	1.20	$\frac{1300}{844} = 1.54$	OK
(iii)	For FOWs	1.20	$\frac{1300}{1047} = 1.24$	OK

Notes

1 The above selection of the arrester may be considered as having taken account of reflections at the terminals.
2 When such an arrester is installed on the system, it takes care of switching, lightning or steep to very steep rising surges, irrespective of their amplitudes.
3 It is presumed that the protective distance (distance of the protected equipment from the arrester) is short and within safe limits. It too must be checked before a final selection of the arrester, as explained in Section 18.6.2. The above selection, however, seems to be appropriate for a distance up to 8–10 m as considered in Example 18.4.
4 The arrester selected has protective margins much greater than the minimum required. In fact even considering a protective distance up to 8–10 m, it would be possible to select the arrester with the next higher rating, V_r and V_{res} to enhance the life of the arrester without jeopardizing the safety of the equipment.

(B) Checking for the energy capability

It is sufficient to check this for systems of range II (>245 kV) alone, as the energy requirements for systems of range I may be moderate. The lightning surges are found to be more severe than the switching surges. But since the lightning surges are of short duration, they dissipate very low energy and a normal arrester is capable to absorb much more than this. The energy capability for long duration switching surges is checked in the following paragraphs

W (for each discharge)

$$= \frac{V_t - V_{res}}{Z_s} \cdot V_{res}.2.T.\ 10^{-3}\ \text{kJ} \qquad (18.10)$$

To assess the energy capability of the arrester more realistically, let us consider the established system parameters as in Table 18.6 to determine the maximum energy discharge through the arrester,

where

$V_t = 2.6 V_r$
$= 2.6 \times 336$
$= 874$ kV

$V_{res} = 654$ kV (for $I_n = 1$ kA as per IEC 60099-4)

$Z_s = 0.8 V_r$
$= 0.8 \times 336$
$= 269\ \Omega$

$2.T = 2800\ \mu s$

Note

The time of travel from the point the lightning strikes on the overhead lines to the arrester, considering a line length of approximately 420 km and speed of propagation of the surge as 0.3 km/μs,

$$T = \frac{420}{0.3} = 1400\ \mu s$$

Accounting for reflections, the total time must be considered as 2×1400 or 2800 μs. Accordingly, 2800 μs is specified by IEC 60099–4 for the testing of the arrester under the worst conditions. The arrester must also have the capability to successfully discharge the prospective surge under such conditions.

$$\therefore\ W = \frac{(874 - 654)}{269} \times 654 \times 2800 \times 10^{-3}\ \text{kJ}$$

$$= \frac{220}{269} \times 654 \times 2800 \times 10^{-3}$$

$$= 1498\ \text{kJ or } \frac{1498}{336} = 4.46\ \text{kJ/kV}_r$$

Say, 4.5 kJ/kV$_r$

The arrester chosen has a total energy capability of 7 kJ/kV$_r$ (from the manufacturer's catalogue). The single energy discharge of 4.5 kJ/kVr is also within 85% of the energy capability of the arrester as stipulated under energy capability of the arrester (Section 18.2). In service the arrester will be required to discharge much less energy than this as the distance of the arrester from the point of surge origination may be much smaller than considered.

Line arrester class can also be selected quickly from Figure 18.23, corresponding to V_{res}/V_r. In the above case, it is 654/336, i.e. 1.95, corresponding to which also the class of arrester works out as '4', as considered by us, and which will have an energy absorption capability of more than 4.5 kJ/kV$_r$ per discharge. If we consider the arrester with two consecutive discharges, this arrester may prove marginal. In which case select another arrester with a higher energy capacity or refer the matter to the manufacturer for a more accurate selection of the arrester.

(C) Checking for reflections and transferences

We have considered protection of both 400 kV transformers, one for primary transmission and the other for secondary transmission. We will now analyse as in Table 18.12 the influence of surge reflections and transferences of a surge occurring on the 400 kV primary transmission bus as shown in Figure 18.25 and its effects on segments *A* and *B*.

Table 18.12 Analysis for surge reflections and transferences

		Segment A	*Segment B*
Basic parameters		$Z_{s1} = 300\ \Omega$ $Z_{s2} = 30\ \Omega$	$Z_{s1} = 300\ \Omega$ $Z_{s2} = 40\ \Omega$
(a) Reflection of surges: As the arresters are being provided at the primary of each transformer, this aspect need not be considered		Low	Low
(b) Surge transferences to the LV side			
(i) **Capacitive transference** (initial voltage spike)		$Vt_c = \dfrac{C_p}{C_p + C_s} V_t \cdot p$	
Assuming	$\dfrac{C_p}{C_p + C_s}$	0.4 The actual value may be much less than this when obtained from the transformer manufacturer	
p for a Y/Δ transformer		1.15	
	$V_{t(FOW)}$	1047 kV peak	
	$\therefore V_{tc}$	$= 0.4 \times 1047 \times 1.15$ $= 481.62$ kV peak	
BIL (lightning) of the transformers' LV sides from Table 13.2		for 15.75 kV LV (V_m = 17.5 kV) = 95 kV peak	for 132 kV LV (V_m = 145 kV) = 650 kV peak
Minimum protective level required *which is too low compared to V_{tc} and requires an arrester on the LV side or provision of surge capacitors across the secondary windings, such that $\dfrac{C_p}{C_p + C_s + C'} < \dfrac{79.2}{481.62}$ The value of C' can be calculated if values of C_p and C_s are known. *Note* Even then a surge protection will be essential for the tertiary, if a tertiary is provided.		95/1.2 = 79.2* kV peak	650/1.2 = 541.7 kV peak Protective margin available $= \dfrac{650}{481.62} \simeq 1.35$ which is adequate and no more protection is necessary
Note The above analysis also corroborates that surge transferences are more severe in high ratio transformers than low ratio ones (Section 18.5.2)			
(ii) **Inductive transference**		V_{ti} = p.q.r. V_t/n	
Assuming		$p = 1$ for a long-duration switching surge for inductive transference $q = 1.8$ for a long-duration switching surge	
		$r = \sqrt{\dfrac{3}{2}}$ from Figure 18.14 for a Y/Δ transformer with surges of opposite polarity appearing on two phases	
		$n = \dfrac{420}{17.5} = 24$	$\dfrac{420}{145} = 2.9$
	$V_t = V_{res}$ (switching)	676 kV peak	676 kV peak
	$\therefore V_{ti}$	$= 1 \times 1.8 \times \sqrt{\dfrac{3}{2}} \times \dfrac{676}{24}$ = 43.9 kV peak	$= 1 \times 1.8 \times \sqrt{\dfrac{3}{2}} \times \dfrac{676}{2.9}$ = 363 kV peak
Power frequency withstand capacity of the LV windings from Table 13.2		38 kV r.m.s.	275 kV r.m.s
∴ Protective margin		$= \dfrac{38\sqrt{2}}{43.9}$ = 1.22	$= \dfrac{275\sqrt{2}}{363}$ = 1.07
		This is adequate and no additional surge protection is necessary	This is too low. But it is possible to make it up by selecting the arrester at the primary with a lower switching V_{res}, if possible, or provide an arrester at the secondary. Moreover, the response factor, q, is considered very high, which may not be true in actual service and an arrester at the secondary may not be necessary in all probability. The design engineer can use a more realistic factor based on his past experience and the data available from similar installations.

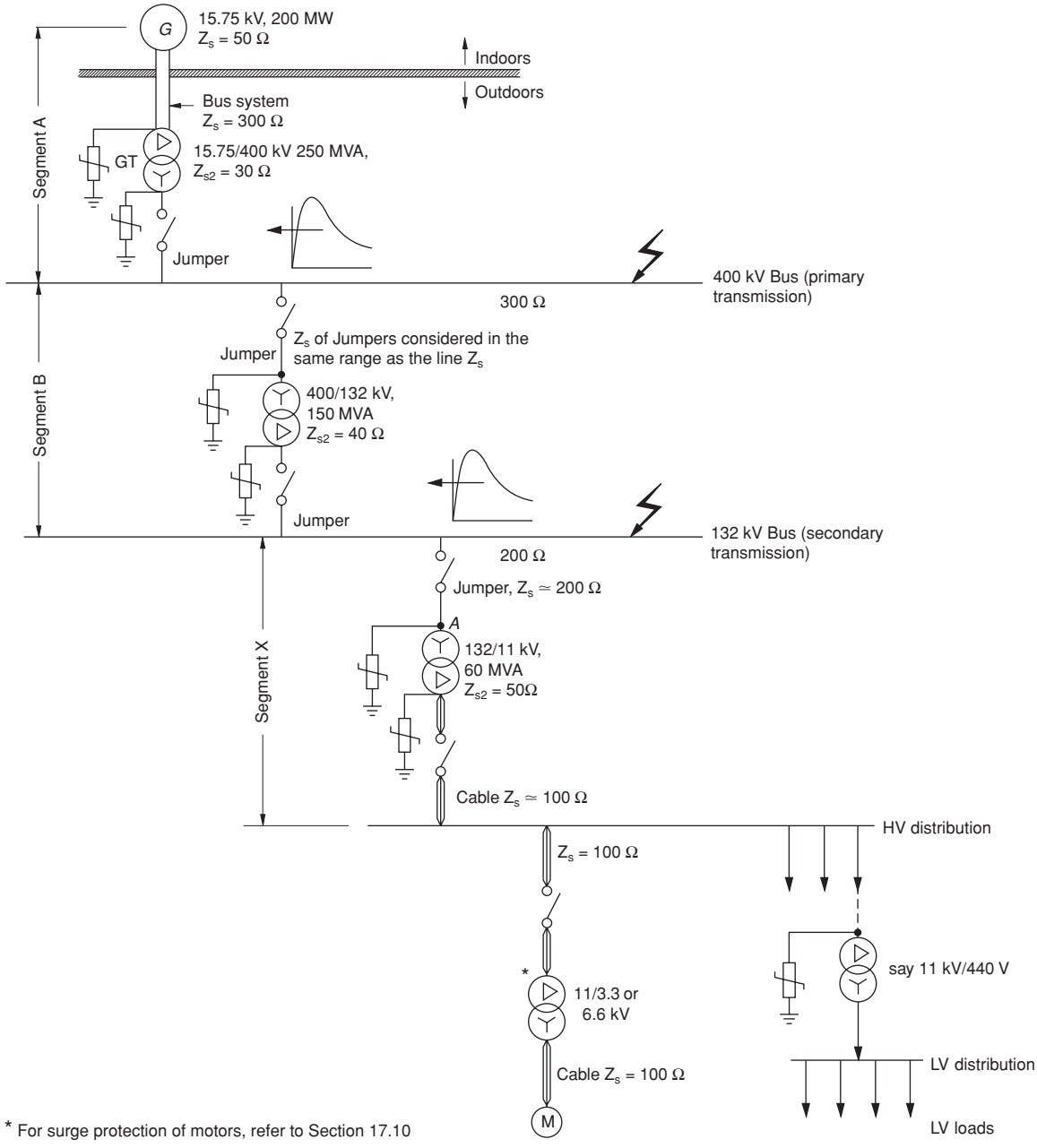


Figure 18.25 Surge protection analysis of potential locations for the network illustrated in Figure 18.15

Relevant Standards

IEC	*Title*	*IS*	*BS*	
60071-1/1993	Insulation coordination phase to earth – Principles and rules. Insulation coordination phase to phase – Principles and rules.	2165-1/2001, 2165-2/2001	BS EN 60071-1/1997	–
60071-2/1996	Insulation coordination – Application guide.	3716/2001	BS EN 60071-2/1997	–
60099-1/1999	Surge arrester – Non linear resistor type gapped surge arresters for a.c. systems.	15086-1/2001	BS EN 60099-1/1994	–
60099-3/2004	Surge arresters – Artificial pollution testing.	15086-3/2003	BS EN 60099-4/2004	–
60099-4/2004	Surge arresters – Metal oxide without gaps for a.c. power circuit.	–	BS EN 60099-4/2004	–
60099-5/1999	Surge arresters – Selection and application recommendations.	15086-5/2001	BS EN 60099-5/1997	–
61024-1/1990	Protection of structures against lightning – General principles.	2309/2000	DD ENV 61024-1/1995, BS 6651/1999	–
61643-1/1998	Surge protective devices connected to low voltage power distribution systems – performance requirements and testing methods.	–	–	–
62271-100/2003	High voltage alternating current circuit breakers.	13118/2002	BS 5311/1996	–

Relevant US Standards ANSI/NEMA and IEEE

ANSI/IEEE-1313.1/1996	Insulation coordination – Definitions, principles and rules.
ANSI/IEEE-C62.1/1994	Standard for gapped silicon carbide surge arresters for a.c. power circuits.
ANSI/IEEE-C62.2/1994	Guide for application of gapped silicon carbide surge arrester for a.c. systems.
ANSI/IEEE-C62.11/1999	Metal oxide surge arresters for a.c. power circuits.
ANSI/IEEE-C62.22/1997	Guide for the application of metal oxide surge arresters for a.c. systems.
NEMA/LS-1/1992	Low voltage surge protection devices.

Notes

1 In the table of relevant Standards while the latest editions of the Standards are provided, it is possible that revised editions have become available or some of them are even withdrawn. With the advances in technology and/or its application, the upgrading of Standards is a continuous process by different Standards organizations. It is therefore advisable that for more authentic references, one may consult the relevant organizations for the latest version of a Standard.
2 Some of the BS or IS Standards mentioned against IEC may not be identical.
3 The year noted against each Standard may also refer to the year it was last reaffirmed and not necessarily the year of publication.

List of formulae used

Electrical characteristics of a ZnO surge arrester

Characteristic of a ZnO block

$$I = K \cdot V^{\propto} \tag{18.1}$$

K = depends upon geometrical configuration, cross-sectional area and length of ZnO Block
$\propto$ = is a measure of non-linearity between V and I

Protective margins

$$\text{Protective margin} = \frac{\text{BIL of the equipment}}{\text{Impulse protection level of the arrester } (V_{res})} \tag{18.2}$$

Reflection of the travelling waves

Voltage of the reflected wave

$$E' = E \cdot \frac{Z_{S2} - Z_{S1}}{Z_{S2} + Z_{S1}} \tag{18.3}$$

Z_{S1} = surge impedance of the incoming circuit
Z_{S2} = surge impedance of the outgoing circuit

Voltage of the refracted wave,

$$E'' = E + E' = E \cdot \frac{2 \cdot Z_{S2}}{Z_{S2} + Z_{S1}} \tag{18.4}$$

E = voltage of the incident wave (incoming wave)
E' = voltage of the reflected wave
E'' = voltage of the refracted (transmitted) wave

When the outgoing circuit is inductive,

$$E'' = 2E \cdot \left(e^{-\frac{Z_{S1} \cdot t}{L}} \right) \tag{18.5}$$

L = inductance of the circuit

When the outgoing circuit is inductive,

$$E'' = 2E \cdot \left(1 - e^{-\frac{t}{Z_{S1} \cdot C}} \right) \tag{18.6}$$

C = capacitance of the circuit

Surge transference through a transformer

(i) Electrostatic surge transference

$$V_{tc} = \frac{C_p}{C_p + C_s} \cdot V_t \cdot p \qquad (18.7a)$$

V_{tc} = voltage of surge transference
C_p = lumped capacitance between the primary and the secondary windings
C_s = lumped capacitance of the lower voltage side
V_t = prospective voltage surge on the primary side
p = a factor to account for the power frequency voltage already existing when the surge occurs

Damped surge transference

To account for the capacitance C of cables and terminal equipment.

$$V_{tc} = \frac{C_p}{C_p + C_s + C} V_t \cdot p \qquad (18.7b)$$

(ii) Electromagnetic surge transference

$$V_{ti} = p \cdot q \cdot r \cdot \frac{V_t}{n} \qquad (18.8)$$

p = factor for power frequency voltage
q = response factor of the lower voltage circuit to the arriving long-duration surges
r = a factor that will depend upon the transformer connections
n = transformation ratio of the transformer (V_1/V_2).

Selecting the protective level of an arrester

Protective distance

$$V_s = V_{res} + S \cdot 2 \cdot T \qquad (18.9)$$

V_s = actual surge voltage at the equipment
S = r.r.r.v. of the incoming wave in kV/μs
T = travelling time of the surge, to reach the equipment from the arrester terminals

Energy capability

$$W = \frac{(V_t - V_{res})}{Z_s} \cdot V_{res} \cdot 2T \cdot n \times 10^{-3} \qquad (18.10)$$

W = energy absorbed in kW-s or kJ
V_t = prospective switching surge crest voltage – kV
V_{res} = switching surge residual voltage of the arrester – kV
Z_s = surge impedance of the affected line
T = travelling time of the switching surge in μs
n = number of consecutive discharges

Further Reading

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