Taking all the above into consideration, it may be concluded that, for insulation coordination of a substation and its equipment:

- Against impinging lightning surge to the station it is necessary:
  - to limit the arising station surge voltage within the **presumed largest residual voltages of the adopted arresters**
  - to realize the **withstanding insulation level of the station equipment** against the largest discharge voltage (residual voltage) for the presumed largest surge current.
- For power frequency voltages, the arrester should withstand the thermal stress of continuous leakage current caused by MCOV as well as TOV and of switching surge energy.

Figure 21.6c shows the typical TOV capability of arresters.

21.4.1.3 Classification and selection of arresters by ratings

We present here the general concept in regard to a guaranteed method for the characteristics of an arrester and the method of selection, although the detailed description of arrester standards may differ among national standards bodies.

Referring to Figure 21.6b, the arrester's essential v–i characteristics are guaranteed by the two points a and b.

Point a is the **reference voltage and current** (v_a (kVrms), i_a (mArms)) which are indicated by the supplier. It should be guaranteed that the v–i characteristics of an individual arrester at the reference current i_a (typically 1 mA) exceed the guaranteed reference voltage v_a, and the arrester has to withstand the thermal energy of the guaranteed power frequency continuous current i_a.

Point b is the **standard nominal discharge voltage and current** (v_b (kVcrest), i_b(kAcrest)). The standard nominal current i_b is specified as standard values like 1.5 kA, 2.5 kA, 5 kA, 10 kA, 20 kA, 40 kA for the purpose of arrester classification and for guaranteeing the discharge voltage characteristics. The discharge voltage of an individual arrester should be smaller than the guaranteed standard nominal discharge voltage v_b at the standard nominal discharging current i_b (tested typically with the 8/20 μs standard impulse wave current).

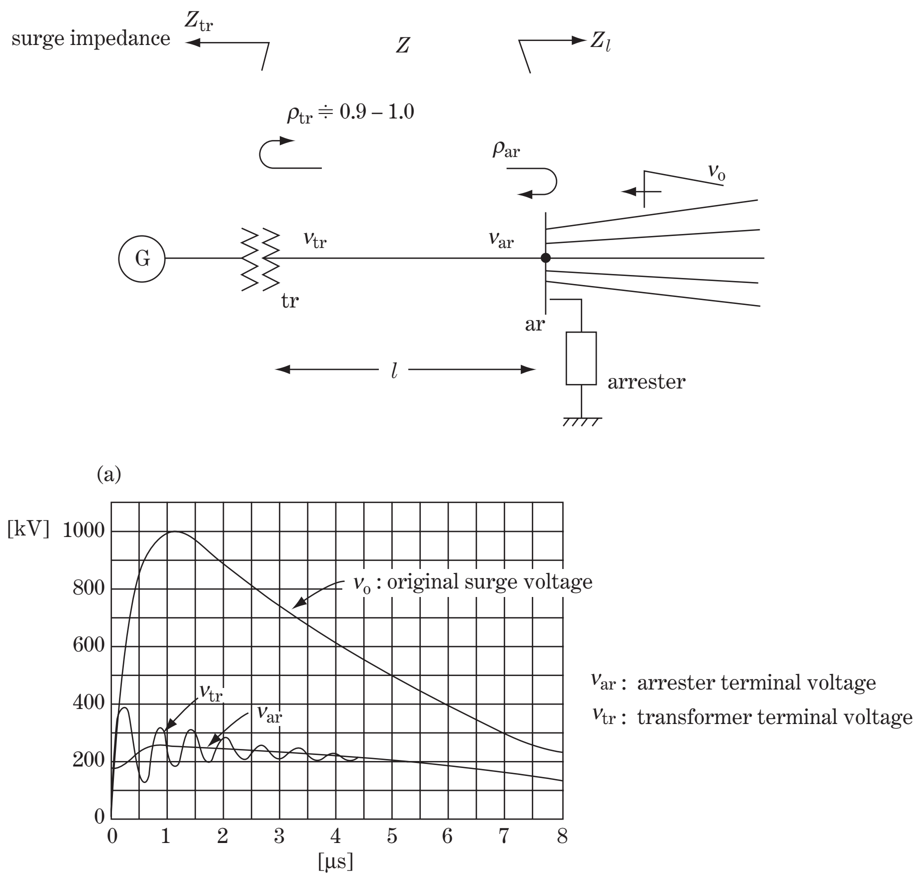
In practical engineering, individual arresters should be selected so that the guaranteed reference voltage (or the duty cycle voltage) exceeds the MCOV or the maximum TOV (U_{rp}).

High-voltage arresters of EHV/UHV classes are also assigned **switching surge durability** by the standards for the arresters, in that generally the **thermal energy absorbing capability** (kJ) at the specified discharge current is type tested. The guaranteed value can be additionally written as point c in Figure 21.6b.

In regard to switching surges, point c can be written as the guaranteed standard nominalbdischarge voltage and current (v_c (kVcrest), i_c (kA crest)) for the switching surges. The standard nominal currents for the switching surges are specified as standard values like 0.5 kA, 1 kA, 2 kAcrest. (A detailed description of the arrester's switching surge durability is omitted.)

21.4.2 Separation effects of station arresters

In regard to surge phenomena, the induced time-changing overvoltage of an arbitrary point is different from that of any other point in the same substation. Accordingly, the voltage at the transformer terminal (or at any other equipment) is different from that of the station arrester terminal. Generally we need to consider that the voltage at the protected insulation may possibly be higher than that at the arrester



(b) surge voltages at a arrester point and a transformer terminals. (simulation)

(c) Typical values of surge impedances

overhead lines	: 300–500 Ω
cable lines	: 20–60 Ω
transformers	: 1000–10 000 Ω
rotating machinery	: 500–1500 Ω

Figure 21.7 Separation effects of arresters

terminals due to the travelling distance on connecting leads and the conductor circuit. This rise in voltage is called the **separation effect of an arrester**. This effect obviously lessens the surge protection performance of arresters. Referring to Figure 21.7a, the separation effects can be explained as the behaviour of travelling waves which is deeply linked with (1) the increasing rate of rise of incoming surge μ (kV/μs), (2) the distance l between the arrester and protective equipment (a transformer), and (3) the reflection factor ρ_{tr} of the equipment. The phenomena can be roughly calculated by the equation below, referring to Figures 21.7a, b and c.

We image that the transmitted lightning surge voltage at the arrester point with the time front $T_{front} \fallingdotseq 1.2\mu$ s and the initial steepness of α (kV/μ s typically 200–500 kV/μ s) appears on $t = 0$, so the voltage during the initial small time interval of $0 < t < T_{front}$ ($\fallingdotseq 1.2\mu$ s) can be written $V_{ar}(t) = \alpha \cdot t$(kv). The surge voltage begins to travel to the transformer terminal (distance l) on $t = 0$ and arrive on $t = l/u \equiv T$, so that the surge voltage at the transformer terminal (reflection factor ρ_{tr}) appears on $t = l/u$ (that is $t' = t - l/u = 0$) as is the voltage form of $V_{tr}(t') = (1 + \rho_{tr}) \cdot \alpha \cdot t'$ (kV), where attenuation is neglected.

Assuming $l = 60\,\text{m}, u = 300\,\text{m}/\mu\,\text{s}$, namely $T = 60/300 = 0.2\,\mu\,\text{s}$ for one way traveling.
$Z_1 = 300\,\Omega$ (for station conductors), $Z_2 = 5000\,\Omega$ (for a transformer)

$$\rho_{tr} = (5000–300)/5000+300) = 0.9 \text{ (reflection factor)}$$

$$V_{ar}(t) = \alpha \cdot t\,(\text{kV}) \quad \text{for } 0 < t < 2T = 0.4\ \mu\,\text{s}$$

$$V_{ar}(t') = (1+\rho_{tr}) \cdot \alpha \cdot t'\ (\text{kV}) = 1.9\,\alpha \cdot t'\ (\text{kV}) \quad \text{for } 0 < t' < 2T = 0.4\mu\,\text{s}$$

The equation shows that the transformer terminal voltage $V_{tr}(t')$ build up by $1+\rho_{tr} = 1.9$ times of steepness from that of the arrester terminal voltage $V_{ar}(\text{tr})$ during the initial time of up to $2T = 0.4\mu$ s.

Furthermore, V_{ar} continues to increase the magnitude until the interval of $t = T_{front} = 1.2\,\mu$ s and reaches the maximum residual voltage, so that $V_{tr}(t')$ also continues to increase the magnitude for the interval of wave front $1.2\,\mu$ s, while the waveform would become oscillatory mode after $t > 2T = 0.4\mu$ s because the negative reflection waves soon come back from the arrester point. As the result, the transformer terminal voltage $V_{tr}(t)$ could become totally larger magnitude than the arrester terminal voltage V_{ar} and be oscillatory mode by almost doubled steepness.

The above results indicate that the overvoltage stress to the transformer may be more severe than the arrester's protective level because of the separation effect by large destance l or by the large traveling time $T = 1/u$. On the contrary, if the distance l is small, such a severe stress would not appear at the transformer terminal, because the negative reflected waves would soon come back from the arrester point and the V_{tr} and V_{ar} become almost the same.

In practical engineering, the arresters installed very close to the junction tower of a transmission line are quite meaningful as gateway barriers to protect entire substations against lightning surges from the transmission lines. However, these arresters may not be able to protect properly the transformers or any other facilities because of the separation effects.

This is the reason why important transformers or other equipment (including cables) at large stations are preferably protected by exclusively and closely installed **bespoke arresters**. Such arresters for individual transformers would also be very effective at reducing the overvoltage stresses caused by repeated switching surges or rare cases of direct lightning strikes on the station.

Figure 21.8 shows a typical example of GIS for a 500 kV out-door substation with double bus system, the breakers of which are of one-point-breaking type. The arresters are installed at each main transformer terminals as well as at transmission line feeding points.

21.4.3 Station protection by OGWs, and grounding resistance reduction

21.4.3.1 Direct lightning strike on the substation

Surge arresters are generally installed at the gateway point of the substation very close to the first tower of each feeding transmission line and well protect the substation against impinging lightning surges from the transmission lines. However, direct lightning strikes on the substation may be