11. SURGE ARRESTERS AND PROTECTIVE GAPS

To protect generators, transformers, cables, SF_6-basses, and other devices against levels of overvoltages which could permanently destroy their non-self-restoring insulation, surge arresters are installed as close as possible to the protected device. Short connections are important to avoid the doubling effect of travelling waves on open-ended lines, even if they are short busses. Surge arresters have normally not been used for the protection of transmission lines, because one can easily recover from insulator flashovers with fast opening and reclosing of circuit breakers (self-restoring insulation). Some utilities are studying the possibility of using surge arresters on transmission lines, too, to limit switching surge overvoltages.

Protective gaps are seldom used nowadays, except in the protection of series-capacitor stations.

11.1 Protective Gaps

Protective gaps are crude protection devices. They consist of air gaps between electrodes of various shapes. Examples are horns or rings on insulators and bushings, or rod gaps on or near transformers. They do protect against overvoltages by collapsing the voltage to practically zero after sparkover, but they essentially produce a short-circuit which must then be interrupted by circuit breakers. Also, their voltage-time characteristic (Fig. 10.5) rises steeply for fast fronts, which makes the protection against fast-rising impulses questionable.

Protective spark gaps are still used to protect series capacitors. There, the sparkover does not increase the transmission line current, but actually reduces it because the line impedance increases when the series capacitor is by-passed. Since the spark gap is unable to interrupt the current, a by-pass circuit breaker must be closed to extinguish the arc in the spark gap (Fig. 11.1). This by-pass breaker must be opened again if the series capacitor is to be re-inserted. In the future, protective spark gaps may be replaced by metal-oxide surge arresters.

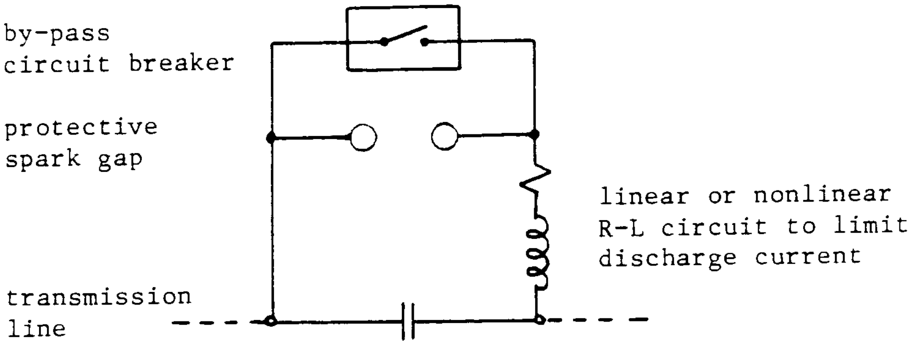


Fig. 11.1 - Series capacitor protection scheme

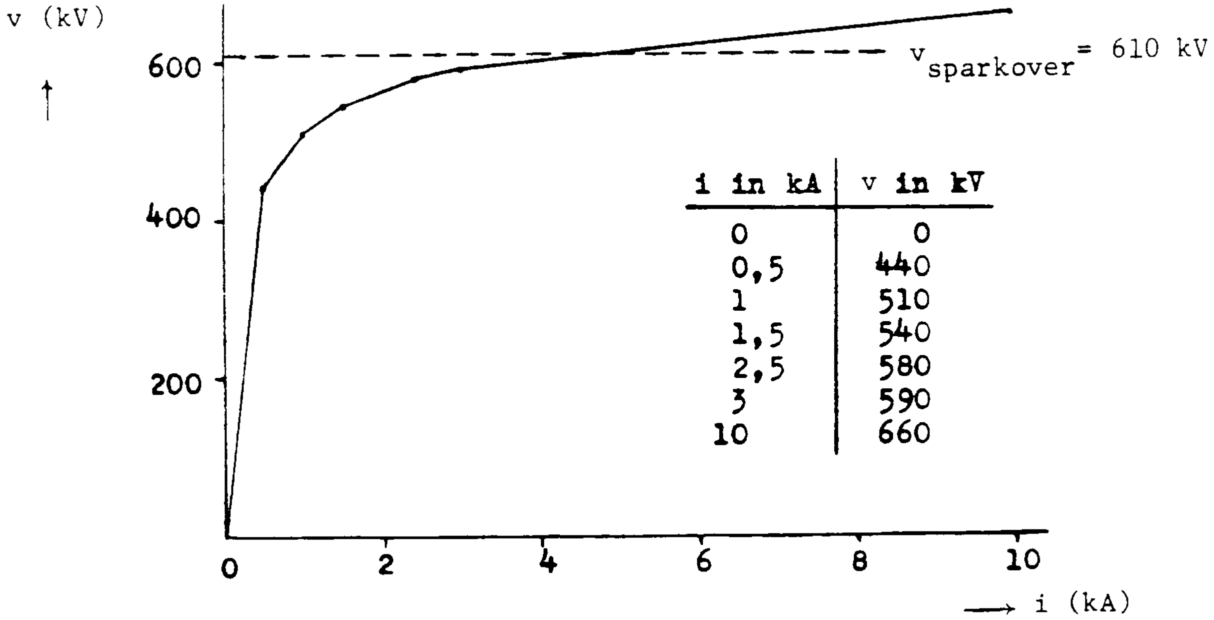
Protective gaps are simulated in the EMTP with the gap switch discussed in Section 10.1.2.

11.2 Surge Arresters

There are two basic types of surge arresters, namely silicon-carbide surge arresters, and metal-oxide surge arresters. Until about 10 years ago, only silicon-carbide arresters were used, but the metal-oxide arrester is quickly replacing the older type to the extent that some manufacturers produce only metal-oxide arresters now.

11.2.1 Silicon-Carbide Surge Arrester

Silicon-carbide arresters consist of a silicon-carbide resistor with a nonlinear v-i characteristic, in series with a spark gap (Fig. 11.2). The spark gap connects the arrester to the system when the overvoltage exceeds the sparkover voltage, and the resistor limits the follow current and enables the arrester to "reseal" (interrupt the current in the gap). To facilitate resealing, so-called "active spark gaps" have been designed in which an arc voltage builds up after some time. A resistor block in series with the gap is not very high (typically 4 cm), and to produce the desired sparkover voltage and nonlinear resistance for a particular voltage level, many such blocks are stacked together in a series connection. To achieve reasonably uniform voltage distribution along the stack, parallel R-C grading networks are used, which are normally ignored in simulations.

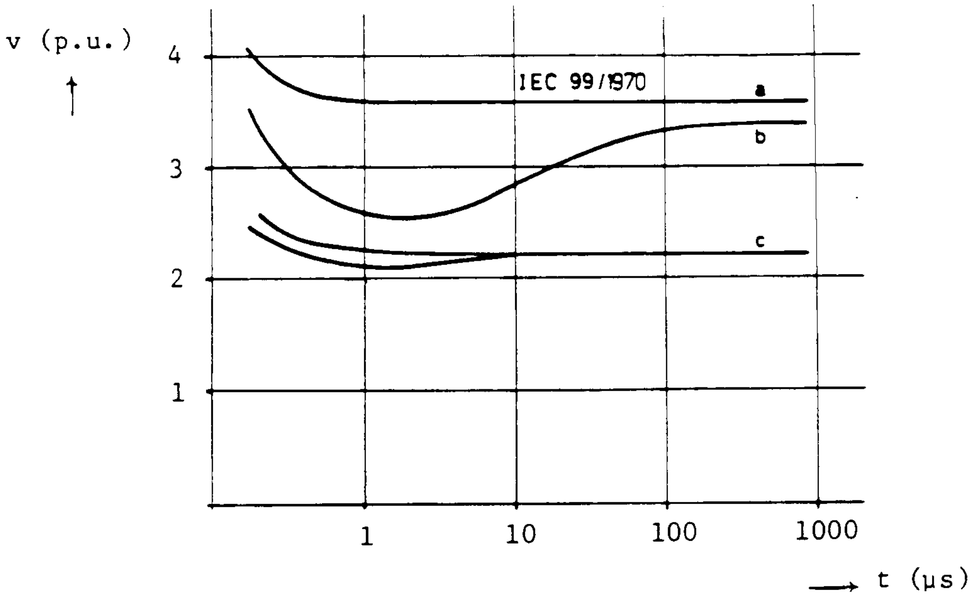


i in kA	v in kV
0	0
0,5	440
1	510
1,5	540
2,5	580
3	590
10	660

Fig. 11.2 - Nonlinear characteristic of a 220 kV silicon-carbide surge arrester

Silicon-carbide arresters are modelled in the EMTP as a nonlinear resistance in series with a gap which has a constant sparkover voltage. In reality the sparkover voltage depends on the steepness of the incoming wave, as shown in Fig. 11.3 [174]. Since surges in a system have very irregular shapes, rather than the linear rise used in the measurements of Fig. 11.3, the steepness dependence of the sparkover voltage is not easy to implement, as already discussed in Section 10.1.2. The nonlinear resistance in series with the gap is either solved with the compensation method (Section 12.1.2), or with the piecewise linear representation (Section 12.1.3).

In silicon-carbide surge arresters with current-limiting gaps, a voltage builds up across the gap after 200 to 400 μs, which is best modelled as an inserted ramp-type voltage source [175], as shown in Fig. 11.4. This ramp voltage source is not part of the EMTP arrester model now, but it can easily be added as an extra voltage source, after one trial run to determine when sparkover occurs. This gap voltage is only important in switching surge studies. In lightning surge studies, it can be ignored because of the time delay of 200 to 400 μs. Useful IEEE guidelines for modelling silicon-carbide arresters are found in [175].



a = medium voltage
b = high voltage, lightning surge protection
c = high voltage, lightning and switching surge protection

Fig. 11.3 - Arrester sparkover voltage-time characteristic for wavefronts with linear rise [174]. Reprinted by permission of Plenum Publishing Corp. and Brown Boveri Oerlikon

It is doubtful whether very sophisticated models with dynamic characteristics, such as the "type-94 modern-style SiC surge arrester" based on [176] in the BPA EMTP, are useful, because it would be almost impossible to obtain the required data. Brauner [177] has developed a model with dynamic characteristics with special reference to GIS insulation coordination, which appears to require less data than the type-94 arrester.

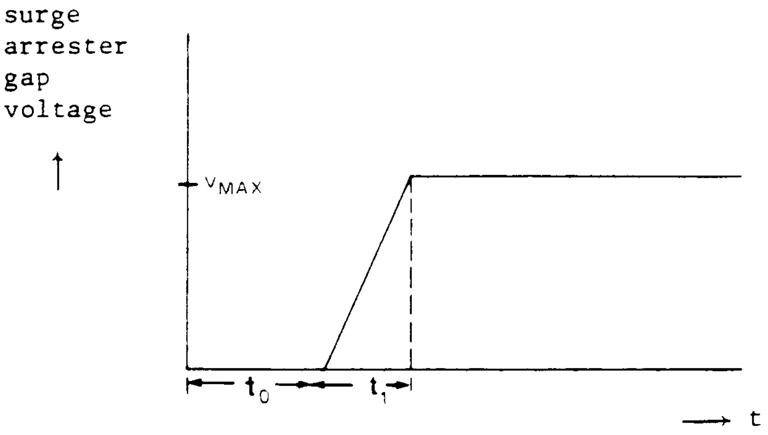


Fig. 11.4 - Arrester gap characteristic

11.2.2 Metal-Oxide Surge Arrester

Metal-oxide or zinc-oxide surge arresters are highly nonlinear resistors, with an almost infinite slope in the normal-voltage region, and an almost horizontal slope in the overvoltage protection region, as shown in Fig. 11.5. They were originally gapless, but some manufacturers have re-introduced gaps into the design. Its nonlinear resistance is represented by a power function of the form

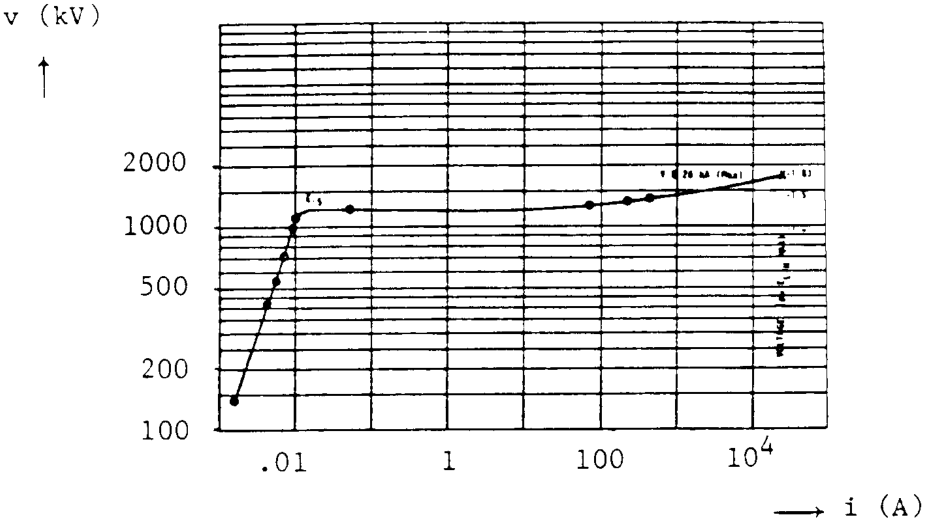


Fig. 11.5 - Voltage-current characteristic of a 1200 kV gapless metal-oxide surge arrester [183]. © 1982 IEEE

$$i = p \left(\frac{v}{v_{ref}} \right)^{q} \tag{11.1}$$

where p, v_{ref} and q are constants (typical values for q = 20 to 30). Since it is difficult to describe the entire region with one power function, the voltage region has been divided into segments in the BPA EMTP, with each segment defined by its own power function. In the UBC EMTP, only one function is allowed so far. For voltages substantially below v_{ref}, the current is extremely small (e.g., $i = p \bullet 0.5^{30} = p \bullet 10^{-9}$ for $v/v_{ref} = 0.5$), and a linear representation is therefore used in this low voltage region. In the meaningful overvoltage protection region, two segments with power functions (11.1) are usually sufficient.

The static characteristic of Eq. (11.1) can be extended to include dynamic characteristics similar to hysteresis effects, through the addition of a series inductance L, whose value can be estimated once the arrester current is approximately known from a trial run [10]. A metal-oxide surge arrester model for fast front current surges with time to crest in the range of 0.5 to 10 μs was proposed and compared against laboratory tests by Durbak [178]. The basic idea is to divide the single nonlinear resistance into m parallel nonlinear resistances, which are separated by low pass filters, as illustrated in Fig. 11.6 for two parallel nonlinearities, which is usually sufficient in practice. The R_1-L_1 circuit is the low pass filter which separates the two nonlinear resistances defined by $i_0(v_0)$ and $i_1(v_1)$. The inductance L_0 represents the small but finite inductance associated with the magnetic fields in the immediate vicinity of the surge arrester, while R_0 is used only to damp numerical oscillations (see Section 2.2.2). C is the stray capacitance of the surge arrester. The model of Fig. 11.6 can easily be created from existing EMTP elements. If three such models were connected to phases a, b, c, then the six nonlinear resistances would have to be solved with the compensation method with a six-phase Thevenin equivalent circuit.

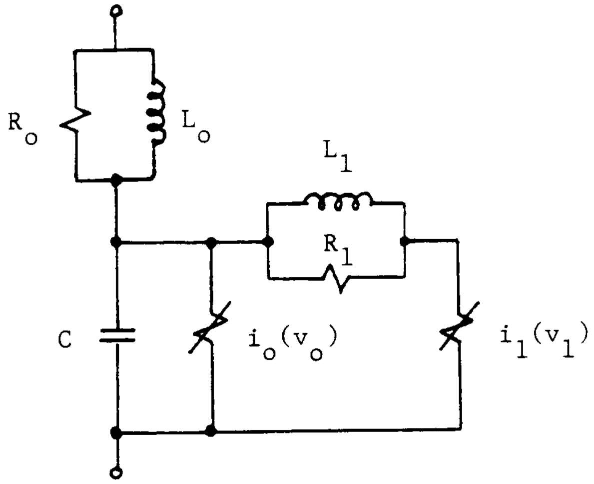


Fig. 11.6 - Two-section surge arrester model for fast front surges [178]

A somewhat different model (Fig. 11.7) has been proposed by Knecht [179]. It consists of a nonlinear resistance R(v), a more or less constant capacitance C, and a linear, but frequency-dependent impedance Z(ω).

No IEEE guidelines have yet been published for the modelling of metal-oxide surge arresters. The energy absorbed in them is an important design factor, and should therefore be computed in whatever type of model is used. Since energy absorption may change as the system is expanded, it is important to check whether ratings which were appropriate initially may possibly be exceeded in future years. Energy absorption capability is probably more of a limitation for switching surges than for lightning surges. The sharp change from the almost vertical to the almost horizontal slope, which limits overvoltages almost ideally at the arrester location, could produce oscillations with overshoot at locations some distance from the arrester, especially in substations with long bus runs. This may be another factor worth watching for.

Metal-oxide surge arresters are generally solved with the compensation method in the EMTP, with iterations using Newton's method as explained in Section 12.1.2. The piecewise linear representation is less useful because the highly nonlinear characteristic of Eq. (11.1) is not easily described by piecewise linear segments.

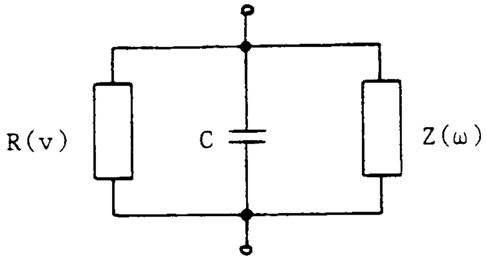


Fig. 11.7 - Alternative surge arrester model

If the surge arrester is equipped with a shunt spark gap, as illustrated in Fig. 11.8, then it is still represented as a nonlinear resistance in the solution process except that the function for that resistance will change abruptly from $R_1(i) + R_2(t)$ before sparkover to $R_2(i)$ after sparkover. If the surge arrester is equipped with a series spark gap, then a very high resistance is added to $R_1(i) + R_2(i)$ to represent the series gap before sparkover.

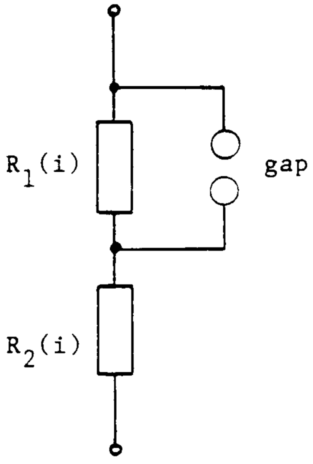


Fig. 11.8 - Metal oxide surge
arrester with shunt spark gap