DESIGNED FOR SAFETY

Modeling insulation in high-voltage substations

The goal of insulation coordination is to determine the dielectric strength of transformers and other substation equipment in relation to overvoltages that can appear on the system. Once insulation characteristics have been assessed, the designer can choose an appropriate protection scheme that reduces or eliminates the chances of surge-induced failure.

Overvoltages in power systems can be caused by a variety of events. These events can be represented in the frequency domain, in line with international standards for insulation coordination (IEC 60071 series), and are mainly characterized by their magnitude, rise time and frequency.

The main topic of this article is high-frequency phenomena. These are classified as fast-front transients. Such transients are usually caused by lightning surges and can result in overvoltages with values five times or more the rated operating voltage.

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Properly rated and well-located surge arresters (such as the ABB Polim series) are very effective at limiting excessive overvoltages. Although their application is straightforward, there are several aspects that must be addressed during the surge arrester selection process.
Of these aspects, the evaluation of overvoltage protection during transient conditions is the most complex.

In the past, it was impossible for engineers to perform the complex studies that would provide a better understanding of transient phenomena. Nowadays, electromagnetic transient (EMT) simulation software comes to the aid of designers and is even considered as indispensable for the investigation of certain cases.

**Modeling lightning strike effects**

Lightning strikes are inevitable when an high voltage (HV) substation is supplied by overhead transmission lines. The lightning can hit either the phase wire (direct stroke) or the shield wire, causing backflash over the insulator string. Voltage magnitudes can reach values as high as several megavolts at frequencies in the range of 50 kHz to 10 MHz.

The lightning-generated current magnitudes and waveshapes that are used for EMT studies are selected according to international standardization committee guidelines (IEC, CIGRE) that have been established over many years of measurements. Despite the unpredictable nature of lightning phenomena, such an approach ensures a satisfactory level of lightning current approximation.

**Protect your substation**

When a direct strike or backflash occurs, an overvoltage wave is generated that propagates along the phase conductor to the substation. Limitation of such overvoltages is crucial for the safe and reliable operation of substation equipment, especially transformers, which are the most expensive components of the power system. Overvoltage mitigation can be achieved thanks to the nonlinear characteristics of surge arresters based on zinc oxide. These surge arresters consume negligible current in the steady state and very high current (kA range) when faced with surges due to events such as lightning discharges.
Thanks to this characteristic, overvoltages are clipped below the maximum permissible levels.

→3 shows the voltage behavior during a so-called 8/20 µs lightning surge, with respect to Uc, the maximum continuous operating voltage (MCOV).

The general rule is to keep the surge arrester as close as possible to the equipment that it is meant to protect.

The 8 and 20 refer to the rise time of the current crest and current tail off time, respectively, in µs, of the impulse curve. The 8/20 is one of several standard discharge current waveshapes that have been in use for many years. It is often used, even though it does not accurately represent all lightning surges.

Simulating lightning overvoltages
Insulation coordination studies must assume that the worst possible conditions will arise and all at the same time. Planning for this eventuality necessitates the verification of several critical aspects of the application – such as lightning current crest and steepness, substation topology, overhead line layout, presence of HV cables, tower structure and the ratings and location of surge arresters. These aspects can be deliberated upon using a typical HV network modelled in EMTP-ATP (Electromagnetic Transients Program – Alternative Transients Program) software. The network studied here consists of a 380 kV overhead line, an HV cable that supplies the gas-insulated switchgear in the substation and a power transformer →4.

Examples of simulation results for lightning strikes on the phase conductor (direct stroke) and shield wire (backflash) are presented in →5–6. It can be seen that the application of surge arresters results in a decrease of the maximum overvoltage peak value to below the permissible limits of the basic insulation level (BIL), which, according to the IEC 60071 standard, is 1,425 kV (peak value) for 400 kV networks. This standard also proposes a so-called safety factor, kS, of 1.15. Some customers have their own standards, where the kS factor is set at 1.20 or even 1.25. This higher margin of error implies stricter requirements in the surge arresters’ specifications.
02 EMT simulation of a lightning strike on a tower structure according to CIGRE WG 33.0.

02a Tower structure and lightning strike locations.

02b Typical lightning current surges.

02c Typical voltages generated by a lightning strike.

03 Nonlinear characteristic of ABB’s PEXLIM surge arrester.

04 Simplified diagram of the 380 kV system under study.

\[ U_{\text{res}} \text{ - residual voltage during a } 8/20 \mu s \text{ lightning surge} \]
\[ U_c \text{ - maximum continuous operating voltage} \]
**Do not forget about…**

Besides the surge arresters themselves, there are also other factors that have to be considered — eg, the lengths of the leads that interconnect the surge arresters. Here, the general rule is to keep the surge arrester as close as possible to the equipment that it is meant to protect (transformer, cable or switchgear). Overlong connections lead to a decrease of the surge arrester’s overvoltage damping capabilities, especially at higher frequencies. This effect is due to the inductive reactance of the connections playing a more significant role during high-frequency transients than during 50 Hz or 60 Hz steady-state conditions →7–8.

In other words, an additional voltage drop occurs during the lightning event, which may increase overvoltage values and cause BIL levels to be exceeded.

Therefore design engineers should keep surge arrester leads as short as possible. This is especially important on HV and ultra-HV systems, where leads are usually long.

Another factor that must be considered is the ability of the surge arrester to handle the large amounts of energy generated by surges. Surge arresters are assigned a line discharge rating from class 1 (lowest) to 5 (highest) that reflects their energy handling ability.

Class 2 devices may be selected for less hazardous areas where lightning activity is infrequent and switching operations are occasional. Class 5 has to be delivered for high lightning activity areas or for installations where switching operations are frequent (daily) →9. Sometimes designers use a device of a class higher than is strictly necessary to provide an additional safety margin.

**Customer-oriented approach**

In every project in which ABB carries out engineering, installation and commissioning of HV gas-insulated switchgear, the suitability of the proposed surge arresters, must be verified. Most customers are keen on having studies made based on the latest relevant international standards, such as:

- The IEC-60071 series
- IEEE standard C62.82.1 (revision of IEEE 1313.1 and 1313.2).

The customer expects ABB to comply with these standards in its high-frequency transient studies.
Moreover, some customers have their own project technical specification (PTS) that must be considered and referenced in the final report. It is of extreme importance to be able to find agreement if there are deviations from the end client’s requirements. In certain cases, it is necessary to consider a special approach that is not fully specified by the international standards.

The customer always has the right to review the insulation coordination study report to clarify any uncertainty. Such full transparency and openness to discussion ensure that the results delivered are correct and comply with all the customer requirements.

Of course, a lightning overvoltage study is only one aspect of substation design. It is worth adding that ABB also provides an insulation coordination simulation service in other relevant domains – for example, analyses related to switching events when circuit breakers or disconnectors are operated, at all voltage levels.

Voltage magnitudes can reach values as high as several MV at frequencies in the range of 50 kHz to 10 MHz.