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OVER-VOLTAGE PROTECTION IN SUBSTATIONS USING SURGE ARRESTERS

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PURPOSE AND SCOPE

This Technical Report (TR) describes the over-voltage protection employed on the National Grid Transmission (Electricity) system and in particular, the use of metal oxide surge arresters. Surge arresters can provide essential protection of substation equipment from lightning or switching overvoltages, and also improve circuit availability and reduce operational complexity. This report justifies the move from co-ordinating gaps to surge arrester protection of key substation assets. This also supports the policy statement PS(T)021 'Surge arresters for Substations' and Technical Guidance Note TGN(T) 27 on the application of surge arresters.

PART 1 – TECHNICAL REPORT

The basic insulation level (BIL) of electrical equipment defines the material resilience or withstand capability to lightning. This parameter determines the basic design dimensions associated with HV equipment including clearances, materials and physical size.

When substation equipment is subjected to over-voltages beyond the dielectric withstand capability of the insulation, a flashover occurs. The insulation can be self restoring (like air and oil), or non self restoring in which case flashovers result in permanent damage. The repair and replacement of damaged items can incur major outages and costs. To prevent this happening in the first place, an insulation co-ordination study is necessary to identify and co-ordinate the strength of insulation material, such that the risk of damage to key or critical assets from lightning, switching surges and temporary over-voltages is significantly reduced. A study considers the technology issues, system factors and operational practices. Whilst the principles of insulation co-ordination have not changed over the last 40 years, the technology available to successfully implement over-voltage protection has improved. Sensible application of this can in turn lead to improved system performance.

Typically surge arresters have been routinely installed to protect equipment against lightning. Switching overvoltages and operational complexity have largely been managed by means of network operation such as preferred-end charging of feeder circuits or inhibiting of protection and control features. This report recognises network development requirements for greater operational flexibility and identifies how this can be achieved through the use of arresters to control switching surges and alleviate complexity.

This report will describe how surge arresters can be used to improve:

- Protection from lightning and switching over-voltages.
- Circuit and equipment availability.
- System flexibility.

1 OVERVOLTAGES

Overvoltages are short term transients and are superimposed on the network as a result of lightning or switching activity. These can stress equipment beyond its design capability and detrimentally affect system performance. This section describes the nature and characteristics of over-voltages.

1.1 Lightning Over-Voltages

Lightning is a common occurrence in the UK (up to 20 thunderstorm days/yr depending on geography). The size of the country is such that many strikes are experienced (an average of 20,000 on a big storm day). This can be interpreted into a ground flash density typically between 0.1-1.5 strikes/km²/yr, again depending on location. A typical substation size is of the order 250m x 250m (0.0625km²), so the theoretical strike frequency can be measured in tens of years. The key factor however is that the substation is surrounded by many towers which will be struck rather than the substation. From a transmission network perspective, the circuits are much more vulnerable to lightning strikes and for this reason, overhead line earth wires are installed to shield the network from most strikes. However, a percentage of strikes (10%) can evade the shield wire and terminate on a phase conductor of an overhead line. This is called a shielding failure (typically 15kA and above). Strikes of sufficient magnitude (35kA) can cause a breakdown of air insulation (flashover) at an adjacent line insulator or bushing co-ordinating gap. Lower magnitude strikes (<10kA), which 'bend' around the shield wires do not cause a flashover and are generally more onerous once within the substation.

A more severe condition, but less frequent (1%) is when a strike to the earth wire or the tower is sufficient to cause a flashover back onto the conductors across a line insulator in the immediate vicinity of the stroke. This is called a back-flashover (up to 200kA peak with typical waveshape of 2/50 µs) and can cause a double circuit outage. These current impulses with times-to-crest (T_{CR}) 1-2 µs, create a fault to earth. In either case, the circuit has to be tripped to interrupt the power frequency follow through current. Appendix A describes operational experience associated with lightning over-voltages.

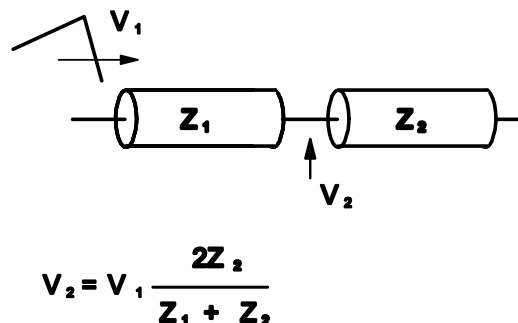


Figure 1 - Surge Voltage Magnitude at Surge Impedance Interface

The impact of a back-flashover is dependent on the equipment connected to the affected line. Electromagnetic effects can be considered as a travelling wave on the overhead line circuit. When the travelling wave reaches a discontinuity where the surge impedance changes such as a cable sealing end, open disconnector or gas/air bushing, the magnitude of the surge will be modified (figure 1). If several lines are connected to a busbar the resulting surge impedance will be reduced, as will the magnitude of the surge. Low surge impedances (such as cables) present an impedance termination and a correspondingly greater reduction of the surge will occur at the line-cable junction (where the transit time is long compared to the front-time of the surge). However, surge magnification, up to a factor of almost two, can occur where the surge impedance of the termination is higher than that of the line e.g. at an open-circuit or a transformer.

The most onerous lightning over-voltage conditions arise where the surge impedance at the termination is much higher than that of the line (e.g. transformer feeders). Wound or inductive devices connected in series with the line will present a comparatively high surge impedance termination for a line and produce similarly onerous conditions on the arrival of a steep fronted surge.

The magnitude and impact of this superimposed transient depends on the equipment connected in the vicinity. Poor tower footing resistance, high isokeraunic levels or poor substation earthing grids can affect this. The transient will apply electrical stress to the dielectric insulation. If the stress is too great a flashover will result and fault current will flow. Depending on where the strike occurs in relation to the substation, terminal equipment can experience voltage gradients of between 100-2000kV/ μ s, the later case being more aggressive and likely to result in a flashover.

Surge arresters, ideally located, can be used to mitigate the impact of lightning in substations.

1.2 Switching Over-Voltages

Switching over-voltages have a slower rate of rise than lightning with time-to-crest (T_{CR}) greater than 100 μ s (up to 250 μ s specified in IEC). These present a different threat to insulation, although the amplitude (typically 2-3 pu) and gradient of the impulse is less than lightning, the duration is significantly longer (milliseconds). These parameters result in a greater energy impulse and insulation may be exposed to thermal overload. Appendix B provides further information. The impact of switching over-voltages centres on the capability of equipment to withstand the **thermal stress** associated with heating. This can only be controlled through adequate identification of likely sources of over-voltages and appropriate specification of a surge arrester with a suitable energy absorption capability.

- a) Reactive compensation is a key source, particularly capacitor bank switching.
- b) Current chopping by circuit-breakers. The magnitude of the overvoltage is directly related to the maximum current that can be chopped. High overvoltages tend to be associated more with air blast CBs rather than modern SF₆ CBs.
- c) Shunt reactor current interruption. After interruption the reactor side oscillation can produce a high magnitude voltage.
- d) Energisation and re-energisation of circuits (particularly cables) with trapped charge. E.g. restrikes and DAR.
- e) Transformer inrush conditions, particularly remote energisation of transformers connected to long lines with mid circuit cable sections.
- f) Transformer back energisation.

Surge arresters, suitably rated, can be used to mitigate the impact of switching overvoltages.

1.3 Very Fast Transients

- a) VFTs are generated during disconnector operations, and particularly within GIS where there are very short busbar lengths in SF₆ which has a very fast breakdown. The wavefront is very fast ($<1\mu\text{s}$) but attenuation is significant, so this is a very localised effect.
- b) Disconnector and other switching in GIS.
- c) Circuit breaker reignitions during shunt reactor switching are normal for CBs without controlled switching. The consequences of these re-ignitions and the likelihood of high frequency arc interruption is heavily design dependant. Controlled opening is routinely applied to minimise the occurrence of re-ignitions.

Surge arresters have very little impact on controlling VFT.

1.4 Temporary Over-Voltages

Temporary over-voltages (TOV) are much longer duration events than lightning or switching (up to 10s), but are not continuous in nature. Typically these voltages (up to 1.4pu) will arise as a result of unbalanced system conditions, reactor switching, shunt capacitors, ferroresonance, linear resonance or harmonics. If equipment is specified without a sufficient margin between the rated voltage and any predicted TOV, the limited capability of insulation to absorb energy may result in equipment failure due to thermal overstressing. At lower voltages where the practice of solid earthing is less common, this effect is more pronounced.

This is the condition, which needs to be carefully determined where the application of surge arresters is considered. Metal oxide gapless surge arresters are not rated to continuously control overvoltages. This was not a problem for the previous generation of gapped SiC arresters. Solid state devices and insulation are particularly susceptible to damage from TOVs. Typically, arresters are expected to be conducting for only a few milliseconds and longer exposure may damage the surge arrester.

2 INSULATION COORDINATION

Insulation co-ordination (IC) determines the withstand characteristics of a power system to electromagnetic stresses. IEC 60071-2 '*Insulation co-ordination: Application guidance*' can provide generic recommendations. There are two elements to IC, one is the appropriate selection and grading of equipment insulation levels, the second is the application of protective devices to the equipment to prevent damage from anticipated over-voltages. In general the designer should try to prevent the over-voltage from occurring in the first place. Where it is not possible to remove the source of the over-voltage such as lightning, controls should be employed to reduce the likelihood of flashovers. This typically would include trying to limit the steepness and amplitude of the surges.

Over-voltage control can be achieved in a number of different ways depending on the nature of the local network, electrical withstand of existing technology employed and the required levels of overall system performance.

The protection of the system against overvoltages and in particular lightning phenomena centres on the co-ordination of equipment to withstand the **electrical stress** associated with lightning. This can be implemented through either the electrical withstand voltage of the item or the electrical clearance between phases and earth. The following factors need to be considered:

- a) The basic insulation level (BIL) is also known as the lightning impulse withstand level (LIWL). This is the inherent capability of the equipment dielectric insulation to withstand lightning impulses. Suitable values for the transmission system are defined in NGTS 1. Typically this value is between 3.5 - 4 times the rated voltage. These values are based on IEC recommendations.

- b) Protective devices can be used when the equipment BIL is not sufficient to withstand the over-voltage. Such a device which operates to divert or absorb lightning and switching surges, needs to be suitably rated for all operating conditions.
- c) Tower earthwires, footing resistance and connectivity to substation earthing systems all contribute significantly to the surge severity.
- d) Operational measures such as preferred end switching or restrictions on the allowable running arrangements.
- e) Trapped charge dissipation (electromagnetic VTs can mitigate)
- f) Controlled switching (point on wave switching).

2.1 Primary Equipment

There are items of transmission plant which, in addition to their primary function, can offer some inherent over-voltage control. Equipment with significant capacitance to earth, such as a capacitor voltage transformer (CVT) or line entry cables can provide some degree of over-voltage control. Neither of these will stop or quench the steep impulse wavefront, but they may attenuate the effect. Typically both these devices provide some limited over-voltage control by reducing the rate of rise of voltage by absorbing energy into the electric field associated with the capacitance. This function however is not usually considered within the rating of the equipment.

2.2 Cables & Overhead Lines

Substation cable entries can attenuate lightning overvoltages primarily through reducing the steep-ness of the incident wave and the amplitude. This maybe true for transmission cables over say 300m, but shorter cables (particularly less than 100m) and especially at lower voltages do not affect the surge sufficiently to lessen its impact as it emerges from the cable into either a transformer or GIS transition (see fig. 1). This capacity is not considered within the rating of any cable system and is a very expensive form of voltage control. For shorter sections of cable the attenuation is not effective and equipment at the surge impedance interface is more susceptible to damage, namely the transformer or GIS.

Overhead line corona will slow down the wave front, such that a mid line strike will have a low amplitude and slower wave front than a line entry strike. Depending on where along the line the strike occurs, the resulting voltage seen in the substation can have a rise time between 100-2000kV/ μ s.

2.3 Earthing Systems

Lightning related overvoltages are usually due to strikes to the overhead line which flashover and travel into the substation along the wire. The provision of a low impedance tower footing resistance and good earth wire connectivity to the substation earth mat is one of the key elements in preventing over-voltages occurring in the first place. A high resistance can result in a higher likelihood of tower back-flashovers when lightning strikes the earth wire. The effective impedance of the grid will determine the possibility of flashovers. Tower footing resistance should aim to be less than 10Ω , and the last circuit tower should be connected to the substation earth mat, which should be a magnitude lower in impedance.

2.4 Network Operation

The substation configuration and operation of the system can have a big impact on the nature of switching and temporary overvoltages seen by equipment. Remote end switching on long circuits or high capacitance circuits will generate onerous conditions. Where possible this should be avoided to reduce the stress seen by equipment.

The use of point on wave switching will help to alleviate switching problems associated with reactor de-energisation. The same is true for the energisation of capacitive circuits (long cables, capacitors etc).

Tee connections may generate TOV conditions such as ferroresonance, so where possible the designer should try to install local circuit breakers for switching duties. This will also help to improve circuit flexibility.

3 SURGE PROTECTION DEVICES

This section describes the historical approach to surge protection. The different technologies are described ending up with the present designs of surge arresters.

3.1 Co-ordinating Gaps

Conventional lightning and switching over-voltage protection is provided in the form of arcing horns on the over-head line circuits and co-ordinating gaps in substations. These structures are basic in design consisting of metallic rods located close to bushings or insulators. They are designed to provide a flashover path away from the surface of bushings or insulators in order to protect the porcelain from possible physical damage in the event of a flashover to earth. The rated switching impulse withstand voltage (RSIWV) adopted in the 1970's on the 275 kV and 400kV systems was designed for a system using toroid ring co-ordinating gaps which provided adequate protection against lightning switching surges.

The gaps are co-ordinated such that mid line clearances are larger and the size tapers down to the substation ends. The reason is two-fold, most lightning strikes are mid line and are significantly attenuated by corona by the time they reach the substation. Therefore to minimise circuit outages the mid line gap is larger to reduce the frequency of flashovers. The gap is smaller in the last mile and substation to protect the key substation plant.

Co-ordinating gaps are low cost simple designs and there are no moving parts, Whilst the gaps prevent damage, by diverting the flashover, the drawback is that to limit the over-voltage, a flashover to earth occurs, which in turn operates protection to clear the fault. When the travelling wave reaches a distant discontinuity such as a transformer, a further flashover may occur at the relatively "low set" co-ordinating gap. This flashover causes a chopped-voltage-wave condition, which in the case of transformer windings, can create inter-turn voltage stresses. Additionally, mechanical stresses may be imposed due to the flow of short circuit current which ages insulation and dielectric integrity. The operational downside of tripping an earth fault is a temporary reduction in system availability and reliability. In addition to the actual damage possible as a result of a flashover, there are further shortcomings of co-ordinating gaps:

- a) The dielectric strength of the co-ordinating gap is heavily dependent on the atmospheric conditions such as humidity, temperature and altitude. Dry conditions increase the gap strength, whilst moisture reduces it so the flashover voltage is very weather dependent.
- b) Rod-rod and loop-loop type co-ordinating gaps do not provide adequate overvoltage protection against negative overvoltages with times-to-crest between 10 and 300µs where the flashover voltage for negative polarity surges is higher than for positive.
- c) The flashover voltage characteristics of both the earlier rod/rod and the later toroidal rod (screened) gap configurations do not provide effective protection for surges with times-to-crest greater than about 400µs (slow fronted switching surges).
- d) The statistical scatter in time-to-breakdown of the gap results in ineffective protection for surges with times-to-crest less than a few microseconds. Line strikes a couple of spans out will more likely have rise time in the order of 200 kV/µs, closer strikes will have fast rise times being less attenuated.

- e) Close up strikes have a fast rate-of-rise in the order of 1000 kV/ μ s and the voltage across the gap just prior to breakdown can exceed the rated lightning impulse withstand voltage (RLIWV) of protected equipment. For example, the discharge formation time in solid type insulation within transformers is shorter, and that in SF₆ insulated assemblies very much less, than that of an air gap. Hence the voltage/time-to-breakdown characteristic of an air-gap is such that protection cannot be provided for a transformer against the most severe rates-of-rise anticipated from "close-up" lightning strokes on the system. Even less effective protection is provided in the case of GIS equipment.
- f) The toroidal type co-ordinating gap exhibits a reduced polarity effect for wavefronts with times-to-crest between 10-300 μ s. This type of gap must always be used where it is required to limit overvoltages with wavefronts in this region i.e., mainly switching overvoltages.
- g) For positive polarity surges there is a very small (0.1%) probability of operation of the 400 kV gap at 770 kV (2.25 pu). The 275 kV gaps exhibit a larger margin. At both system voltages a smaller margin is provided by the earlier type co-ordinating gaps than the more recent toroidal gaps. Where long-fronted (T_{CR} 10-300 μ s) surges are anticipated with a magnitude approaching the RSIWV of plant, the use of the earlier type gaps is unacceptable.

3.2 Surge Arresters

A surge arrester is a protective device with a non-linear characteristic, which can safely control over-voltages and absorb the energy associated with them. During normal operation, these units provide a very high impedance to the system and are essentially invisible, but for over-voltages above the defined protective level the impedance significantly drops to conduct the impulse current away from the device it is protecting. The response time of the surge arrester is much quicker (nanoseconds) than that of co-ordinating gaps and is the only device suitable for over-voltage protection of GIS.

A key benefit is that there is no earth fault developed when the arrester operates. During operation, the arrester retains a residual voltage across itself, which allows the circuit to function without interruption and does not introduce the near-instantaneous collapse of voltage associated with the operation of a co-ordinating gap. The energy associated with the impulse is then absorbed in the resistive blocks, essentially heating the block up. These properties enable the arrester to provide better operational characteristics and a greater degree of over-voltage control and system protection than co-ordinating gaps.

There are two designs of surge arrester, the older gapped design using silicon carbide and the gapless metal oxide arrester. Both designs provide effective protection to all types of insulation for all surge wave shapes likely to be encountered on the system. However SiC technology is now obsolescent.

3.2.1 Silicon Carbide (SiC) Gapped Surge Arresters

This design of arrester was manufactured and installed on the network up to the mid 1980's. The technology is based on non-linear SiC resistors with a series controlled spark gap. The spark gap is in a controlled environment and provides the trigger to activate the arrester into operation. Although effective, this design is now obsolete and no longer manufactured due to developments in technology. Metal oxide gapless technology has replaced the SiC resistors. The internal structure of a SiC arrester and spark gap is quite intricate compared to modern metal oxide gapless arresters. There are still a number of these units in operation on the network, mostly associated with early GIS substations.

Surge counters were installed with these devices to indicate the number of times the spark gap had operated. This enabled excessive operation and possible deterioration of the gap to be identified and addressed.

A strategy for the replacement of co-ordinating gaps with gap type silicon carbide arresters (TPS8/6 -1960) was established. Due to concerns regarding the pollution performance, poor mechanical reliability (e.g. poor seals, internal corrosion etc) and difficulty of monitoring the condition of the series gaps, the strategy was not widely implemented at 275 and 400 kV.

The performance characteristics of SiC gapped devices is quite different to that of gapless devices and as such, where new equipment is being installed adjacent to existing SiC, the SiC units should be replaced with metal oxide units.

3.3 Metal Oxide Gapless Surge Arresters

The gapless metal-oxide design of surge arrester (which uses zinc oxide blocks) is now specified for all new installations because of superior performance and availability (fig.2). The protective characteristic (residual voltage) is improved and exhibits less dispersion than the sparkover voltage of silicon carbide surge arresters. Typically, manufacturers indicate that the residual voltage for the higher rates-of-rise anticipated in service (corresponding to a $1/2\mu\text{s}$ current wave residual voltage test) is about 8% higher than that for a standard lightning impulse voltage wave ($1.2/50\mu\text{s}$). Laboratory tests suggest that even for times-to-crest in the region of 30ns the increase in residual voltage of the blocks alone is about 5% only (approximately 13% in total).



Figure 2 - Zinc Oxide Blocks

These devices are permanently connected to the network and energised at the system voltage. Since they are gapless and have a limited energy absorption capability, care must be taken to limit their exposure to temporary overvoltages (TOV). Additionally they are more sensitive to external pollution than SiC units. This is resolved at the arrester specification stage by adopting a rated voltage as high as practicable and the resulting increased continuous operating voltage will also improve pollution withstand. The arrester rated voltage must be above that of **any** anticipated temporary or long-term over-voltage (TOV) conditions experienced in the vicinity of the arrester.