

## OVERVOLTAGE PROTECTION OF SUBSTATION EQUIPMENT

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## PURPOSE AND SCOPE

This Technical Guidance Note (TGN) addresses the application of metal oxide surge arresters to provide over-voltage protection and control of substation primary plant on the National Grid Transmission (Electricity) system. Surge arresters are deployed for the surge protection of transformers, reactors, gas insulated switchgear (GIS) substations and for some reactive compensation. This document expands on the policy statement PS(T) 021 'Surge arresters for substations', implements the recommendations made in TR(E) 409 'Over-voltage protection in substations using surge arresters' and provides further information on the requirements detailed in the policy.

This document does not cover the over-voltage protection of overhead line circuits, cable sheath voltage limiters (SVL) for cable bonding systems, HVDC converters and power electronic systems.

## PART 1 –PROCEDURAL

### 1 INTRODUCTION

The transmission system is routinely exposed to lightning and switching over-voltages. Equipment is dimensioned to withstand a certain level of transient voltage specified in international standards. However, the dielectric withstand capability of equipment insulation is can be exceeded under onerous conditions, resulting in equipment faults and damage and require a significant outage and costs to re-instate the asset.

This document describes how to apply over-voltage protection to limit the impact of these effects on critical assets within the substation arising as a result of;

- Lightning which can enter a substation through overhead lines
- Switching over-voltages due to normal and abnormal system operation.

*Note: Switching overvoltages are more onerous at transmission level than distribution, principally due to the larger quantities of energy stored in the electric and magnetic fields, which are transferred during switching and faults.*

The recommendations made in this document support the policy on surge arresters for substations PS(T) 021 and consider generic scenarios around their application. Technical report TR(T) 409 'Over-voltage protection in substations using surge arresters' describes the background for decisions and guidance in this document, while TR(E) 532 'Optimal location for surge arresters on the transmission network' provides information on the distances and protection margins offered by arresters for different configurations. The advice provided is in-line with IEC 60099-5 Surge arresters – Part 5: 'Selection and application recommendations'. This TGN provides further guidance on elements specific to NG policy. Where this document does not address an issue, guidance should be sought from Asset Policy.

This revised issue introduces three new appendices to assist the design process.

- a) Appendix A provides guidance on acceptable protection margins in open terminal substations. The complex insulation coordination has been summarised into a design guideline, which indicates via a red, amber, green (RAG) status whether the location of the arrester in relation to the item it is protecting is adequate.
- b) Appendix B provides a decision process to guide the designer towards an appropriate and compliant solution for transformer surge protection, in particular transformer replacement, however the principle can be applied in general.
- c) Appendix C illustrates some examples of surge arrester applications employed on the NG transmission system.

## 2 OVER-VOLTAGE ASSESSMENT AND CONTROL

Over-voltage control can be achieved in a number of different ways depending on the nature of the local network, existing technology employed and the required system performance. Generally, surge arresters have been installed to protect against lightning, with switching over-voltages being largely managed by means of network design and operation e.g. best-end charging of feeder circuits. A correctly applied and installed surge arrester will improve system performance and network resilience to most transient over-voltage conditions.

### 2.1 Insulation co-ordination

Insulation co-ordination (IC) is the selection of equipment dielectric strength in relation to the voltages, which can appear on the system, taking into account the characteristics of the available protective devices. There are three elements to IC, initial calculation of the expected conditions and voltages, secondly the choice of a suitable insulation level and finally the application of protective devices to the equipment to prevent damage from over-voltages.

NG specifies equipment with standard insulation levels for use at rated voltages, these are defined in TS 1. This takes into consideration the complex and integrated nature of the network and considers the worse-case over-voltages together with a protective margin (according to IEC 60071).

For critical or expensive plant items, additional protective devices and measures may be implemented to improve reliability and system security. It is not standard practice to reduce the insulation level for routine substation design purposes.

The application of surge arresters to reduce insulation withstand levels requires detailed knowledge and study. Where this is to be applied it shall be confirmed and agreed with NG at the design stage. This provides the analysis necessary to design a network (or part of

which) with adequate insulation and protective measures to ensure the safe, reliable and economic operation under all voltage conditions.

TGN 261 on Electromagnetic Transient (EMT) studies provides guidance on the modelling and types of studies to consider where insulation coordination is required to determine the nature of protection or manage a non-compliance.

TR(E) 532 '*Optimal location for surge arresters on the transmission network*' reports on a comprehensive set of EMT studies carried out to establish the margin of protection offered as the position of a surge arrester from the equipment it is protecting varies. This information has been used to inform the guidance in Appendix A and decision chart in Appendix B.

The analysis also concludes that non-standard arrangements or complex circuit configurations (such as cable entries to an SGT or GIS) require a specific assessment and possible insulation co-ordination study to identify the optimum surge protection solution. The assessment should demonstrate that a minimum protective margin can be achieved between equipment withstand and probable over-voltages (minimum 15% for switching over-voltages and 25% for lightning over-voltages). Temporary over-voltage stressing shall also be considered when specifying equipment where surge arresters are applied.

Where the protective margin cannot be achieved using a single arrester, other voltage control measures can be coordinated with the operation of the surge arrester to ensure adequate protection is provided for the equipment at risk. This shall be agreed with NG at the design stage, prior to any construction going ahead.

### 3 GENERAL DESIGN CONSIDERATIONS FOR SURGE ARRESTER APPLICATION

Surge arresters are specified where the equipment insulation strength is insufficient to withstand predicted over-voltages or an increased level of transient protection is required to ensure safe and reliable operation. This is defined by either the Basic Insulation Level (BIL) also known as Lightning Impulse Withstand level (LIWL) or Switching Impulse Withstand Level (SIWL). This section explains the general issues to be considered at the design stage. The surge arrester operation should be sufficient to divert and absorb lightning and switching over-voltages such that the electrical stress seen by the plant item and network is controlled below safe limits.

#### 3.1 Design conformance

A record of the application of a surge arrester should be defined in the scheme design document or equivalent. The circumstances surrounding any site specific requirements or arrangements including designs which contradict the Policy or this TGN should also be agreed, recorded and defined at the design stage. A justification statement should be included in the scheme design document to provide a record of the decision and how the risk will be managed.

Asset Policy will only issue a deviation if the application has changed from that defined in the scheme design document. Generally, it will need to be specific to the technical behaviour of the arrester itself and not its application, with the exception of emergency transformer replacements where surge arresters cannot be installed at the time the emergency unit is installed and coordinating gaps are used.

**The recommendations of any study which contradicts this TGN or the Policy must be agreed with Asset Policy before a final design is chosen and referenced in the detail design document.**

#### 3.2 Equipment issues

When employing surge arresters the following guidelines should be followed:

- a) Surge arresters compliant with TS 3.2.3 'Metal oxide surge arresters' shall be used.

- b) Open terminal arresters are the default option (based on lower whole lifetime costs). GIS arresters should only be used where open terminal arresters cannot provide adequate protection or cannot be accommodated.
- c) A suitable energy absorption capability should be used. Generally, this will be the Station Heavy type (SH) as designated in the latest IEC standard IEC 60099-4 Issue 3. (Line discharge class 4 in the old standard), however for some applications, a higher level may be necessary to cater for switching over-voltages and lightning duty. Where a surge arrester is adjacent to long underground cables the designer shall calculate and ensure the energy handling associated with trapped charge is within the arresters capability.
- d) Phase to phase connection must be specified & assessed separately (TS 3.2.3 addresses phase to earth surge arresters).
- e) The operational impact following an overload on an arrester and the subsequent degradation of mechanical integrity must be catered for at the design & development stage.
- f) A "sacrificial" surge arrester is a unit which may become overloaded whilst protecting a key asset, because the energy absorption capability is exceeded, The unit will no longer be operational and will need to be replaced. Although arresters are designed & tested to pose minimal risk to personnel upon failure, this mode needs to be considered from a safety management perspective. Where this is specified the replacement spare and appropriate installation procedure shall be produced as part of the scheme.
- g) Any pressure relief devices associated with surge arresters should be located so as to minimise the impact of hot gases and debris on personnel and adjacent equipment.
- h) All open terminal surge arresters shall be suitable for use in site pollution severity class D as a minimum. Class E should be used for very heavily polluted sites. This will also improve thermal stability of the surge arrester under external pollution conditions.
- i) Surge arresters require specific earthing practice see TS 3.1.2.

### 3.3 Design practice

- a) The surge arrester should be located as close to the item being protected as reasonably practicable (ideally within 15m). Where this is not possible due to physical constraints it may be located further away. The allowable distance is defined in Appendix A, this provides a formalised process to identify the maximum acceptable distance where the 15m rule of thumb cannot be achieved. Where the deployment meets the requirements of Appendix A, a deviation is not required.
- b) A clearance of no less than half the arrester height should be allowed around the arrester (and grading ring) to prevent distortion of the voltage profile. Where field analysis is carried to demonstrate so, this may be reduced, providing electrical clearance are adhered to.
- c) Electrical and safety clearances must take account of any voltage grading element forming part of the arrester e.g. voltage grading rings.
- d) A clearance should be provided between the surge arrester and the busbar connection to enable HVDC fingerprint testing of sections (upto 300kV) of AIS surge arresters (see section 4 for further details). This is approximately 1m (10kV/inch or 4kV/cm) for the large single unit.
- e) Where a non standard unit is specified for scheme specific reasons, it should be appropriately designed and rated to provide a 25% lightning impulse protective margin

(LIPM), a spare phase shall be provided to cater for a failure in the future. This shall be recorded and managed as a deviation by Asset Policy.

- f) In general, any co-ordinating gaps on the same section of busbar as a metal oxide gapless surge arrester should be removed and any Silicon Carbide (SiC) gapped arresters should be replaced. In the case of existing transformer/reactor installations the co-ordinating gaps are to be removed from the bushing connections when surge arresters are fitted.

*Note: Where the coordinating gap forms part of a integrated solution with the surge arrester this shall be identified in the scheme design. In this case the coordinating gap shall remain in service. This shall be recorded in the scheme design document.*

- g) The surge arrester may be located 'behind' the transformer, reactor bushing or sealing ends if there is not sufficient space between the switchgear and device to be protected to install the surge arresters. Surge arresters connections should not over-sail bushings or terminals they are not electrically connected to.
- h) Fingerprint testing (SCT 3.2.3 a) will be performed at commissioning (prior to energisation) for open terminal surge arresters. This is not practical for GIS units where isolation of the arrester, within the GIS trunking, for testing is very difficult and would introduce further intrusive commissioning work.

### 3.4 Connecting leads

- a) The connecting leads to an arrester should be electrically short. The lead should be towards the item being protected to reduce the distance between the HV terminals (see Appendix C figures 2,3 & 4). Sharp bends reduce the protective margin and should be avoided. A high frequency earth connection (dedicated earth rod) should be provided where reasonably practicable.
- b) The earth lead shall be copper and suitable for high frequency earthing (see TS 3.1.2 for further details).
- c) Where reasonably practicable, the HV connection from the busbar or line should have a shorter path to the arrester than to the asset being protected.
- d) GIS arresters should be earthed to the tank. A high frequency earth rod should also be located close by, where reasonably practicable.

## 4 APPLICATIONS IN OPEN TERMINAL SUBSTATIONS

The policy for surge arrester deployment within open terminal substations is based on the protection of individual key substation assets rather than the substation as a whole. Surge arresters provide a zone of protection, typically 10-15m in the case of fast front lightning strikes. The comparative large distance between items of equipment, in an HV open terminal substation, renders the use of a line entry arrester less effective with regard to providing lightning surge protection beyond these distances. However, it is not always practical with asset replacement of primary assets to 'squeeze' surge arresters into a bay which was never configured to house them.

The proximity of an arrester to the asset it is protecting does influence the margin of protection it affords. This is related to the nature of the over-voltage it is trying to protect against. Slow front transients which are generally associated with switching are not significantly affected by the distance, however fast front transients associated with lightning are much more sensitive to the distance. Therefore for the optimal level of protection against lightning related phenomena, a surge arrester must be close, typically within 15m of the asset it is protecting. The further away the lower the margin of protection. TR(E) 532 'Optimal

location for surge arresters on the transmission network' was commissioned to establish whether this can be extended further. The recommendations are illustrated in Appendix A which provides zones of acceptable distance that the surge arrester can be located from the asset.

The recommendation considers a range of overvoltage conditions which enables the arrester to be located further away from the device it is protecting, on the understanding that the margin of protection is reduced from 25% down to 10%. The studies are based on generic, but onerous assumptions, therefore there remains a margin built in, albeit a bit smaller. Appendix A illustrates the range of overvoltages likely as a result of lightning or switching at the terminals of the asset. The Lightning Impulse Withstand Level (LIWL) and Switching Impulse Withstand Level (SIWL) represent the dielectric capability of the asset. The residual voltage is the value appearing at the terminal of the arrester during operation.

#### 4.1 Power Transformers

Surge arresters are installed at or near the terminals of transformers to optimise protection against lightning & switching surges and prevent damage to insulation. The arrester allows the use of delayed auto-reclose (DAR) and remote end switching on transformer feeders and thereby improves system availability and flexibility.

Traditionally, transformers were protected with co-ordinating gaps and tested to withstand a chopped lightning impulse wave test +15%. New transformers are designed and tested to IEC recommendations (lightning impulse chopped wave test +10%) and are installed on the understanding that surge arresters shall be used to protect the transformer. Therefore the test requirement for coordinating gaps is no longer specified, since surge arresters are used instead of co-ordinating gaps.

Transformer surge protection is the most common application for surge arresters. Space can be a problem particularly for transformer replacements where the old units had coordinating gaps which were the standard form of surge protection, before surge arresters were developed. Therefore where possible the following should be applied:

- a) Each individual transformer needs to be protected, especially where units are banked, since a transformer internal single phase fault could generate an overvoltage which could in turn damage its neighbour.
- b) During SGT replacement works, where the existing bay footprint does not cater for a surge arrester, there may be insufficient space between the transformer and the disconnector. Providing the overall distance is still within the margins set out in Appendix A, it is acceptable to locate the surge arrester on the busbar side of the disconnector, providing the transformer cannot be energised from the HV side without the arresters in service. This is also highlighted in TGN 286 with regard to the replacement of transformers.
- c) The middle phase surge arrester is often a limiting factor in determining clearances etc. The arresters do not all have to be the same distance from the transformer bushings, providing the requirements of Appendix A are met.
- d) An existing gantry or new build gantry can be used, such that the arresters can be hung, inverted, close to the transformer (figure 4 Appendix C illustrates). The arresters (especially porcelain units) should not be hung directly above the transformer bushings due to the possibility of collateral damage if the arrester fails or is overstressed and mechanically fails during operation.

##### 4.1.1 New transformer bays

All new power transformers (this includes SGTs, compensator, inter-bus, generator, traction supply and converters) shall have surge arresters installed on the HV and LV terminals.

- a) The design and construction of a new transformer bay shall include adequate space and equipment necessary to satisfactorily accommodate surge arresters within 15m of the transformer.

*Informative: Appendix B shall only be applicable where space is limited and the additional costs or risks are disproportionate.*

- b) Where space is limited, one option maybe transformer tank mounted surge arresters using brackets. The manufacturer of the transformer must approve the application and a risk assessment must be carried out at the design stage to prove the transformer tank integrity is not compromised. A clearance of approximately half the length of the arrester should be maintained between the HV end of the arrester and the bushing. These arresters must be earthed to the transformer tank. There is no need to engineer their own dedicated earth connection to the earth mat. Avoid sharp corners or loops in the connection.
- c) Surge arresters shall be installed on both the HV and LV terminals such that transferred surges from an unprotected terminal cannot enter the transformer. This is particularly relevant for slow front switching surges.
- d) Surge arresters should be located close to the air/oil bushing in-line with the advice in this document, but not so close as to mechanically stress the unit.
- e) Where the tertiary winding is loaded, surge arresters should only be installed to protect the tertiary load as mandated in the Policy or this TGN. A transformer tertiary winding has a high BIL (typically much higher than the tertiary load equipment) and does not require arresters specifically for its protection. Surge arresters however, can be installed to protect the switchgear or tertiary connected equipment, where the policy statement or this document refers.
- f) Surge arresters shall be used to protect the feeder (overhead line) side of all transmission transformers at points of supply with banked transformers on the same feeder. In such cases the temporary loss of supply caused by the simultaneous operation of co-ordinating gaps on both transformers cannot be accepted. Where new transformer capacity is being installed resulting in a banked pair of transformers, surge arresters shall be installed on both units.
- g) Where a cable is terminated directly into an SGT bushing from an overhead line and the surge arresters cannot be installed at the terminals of the transformer, then surge arresters should be installed at the line & cable sealing end. Where a standard unit cannot be employed, the rating of these units will need to be identified through an insulation co-ordination activity and agreed with Asset Policy (assessment guidelines are provided in section 2.1). Where short cables (less than 100m in length) are used, a remote arrester will be less effective, so surge protection is required at the transformer in the form of either a dedicated surge arrester or coordinating gaps if arresters cannot be accommodated at the line/cable interface.

#### 4.1.2 Replacement transformers

The installation of a new transformer on an asset replacement scheme, will require surge arresters. However the unit being replaced is likely to have had coordinating gaps. Installation may prove difficult as there may not be space readily available for arresters. Where this is the case, the risk assessment process based on the flow chart in Appendix B establishes the suitable criteria necessary to determine the appropriate level of protection for the replacement transformer. TGN 286 Appendix F 'Technical guidance and deviations for single asset replacements' also covers this issue and should be considered in conjunction with this TGN. The design priority should be in the following order;

- a) Install free standing surge arresters as close as possible to the transformer between the transformer and the disconnector (Appendix B - Solution A)