Company Directive

STANDARD TECHNIQUE : TP21S/1

Relating to Application of Surge Arresters to Grid Transformers

This Standard Technique defines how surge arresters shall be applied to grid transformers. It covers surge arrester positioning and associated earthing arrangements.

Author: **Simon Scarbro**

Implementation Date: **May 2009**

Approved by P J Weir

Policy Manager

Date: 12-05-09

1.0 **INTRODUCTION**

1.1 This Standard Technique defines how surge arresters shall be applied to grid transformers. It covers surge arrester positioning and associated earthing arrangements. The content is aimed at project engineers and designers. See EE SPEC: 84 for surge arrester specification.

1.2 At the time of writing a programme of surge arrester installation at grid transformers is underway. This is intended to improve grid transformer protection from damage caused by lightning overvoltages. This document defines how to apply surge arresters for optimum performance and details the reasoning involved.

2.0 **SCOPE**

2.1 ST:TP21B/1, by citing EE SPEC: 89, defines the basic earthing requirements for the general application of surge arresters at major substations.

2.2 This document, ST: TP21S/1, provides additional guidance and explanation specific to surge arrester positioning and earthing for the protection of grid transformers.

3.0 **REQUIREMENTS**

3.1 **Arrester Position - Mounting Arrangements and Connection Lengths**

3.1.1 There are two basic surge arrester mounting arrangements as shown in Figure 1 and Figure 2:

a) Turret-mounted (preferred option)
b) Post-mounted.

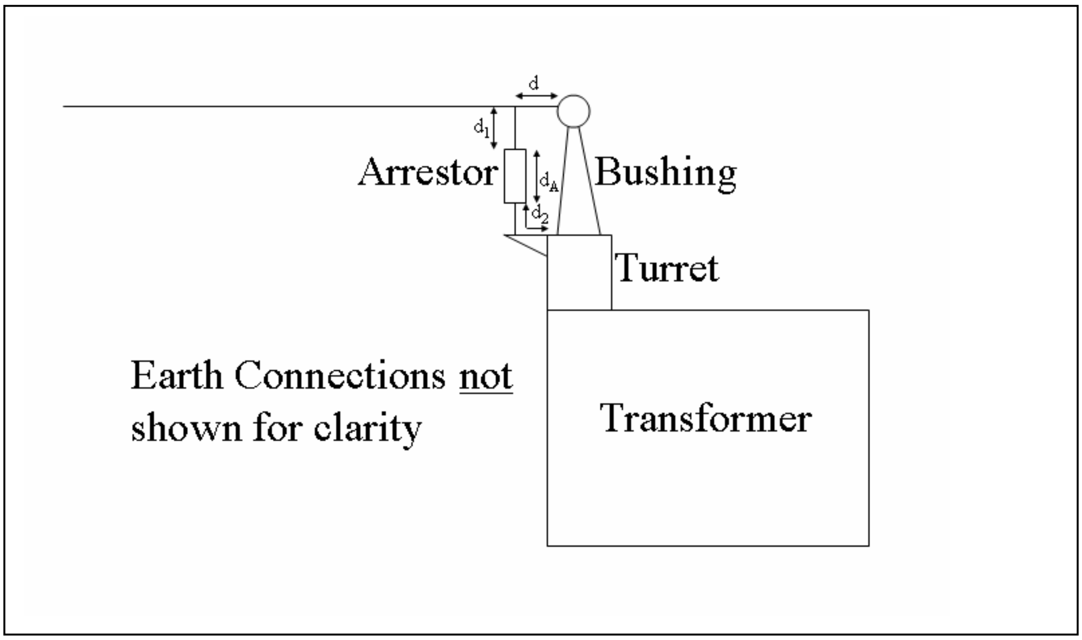

Figure 1 – Turret-mounted surge arrester (with 'inductive' loop length = d + d_1 + d_A + d_2 shown – see below for relevance)

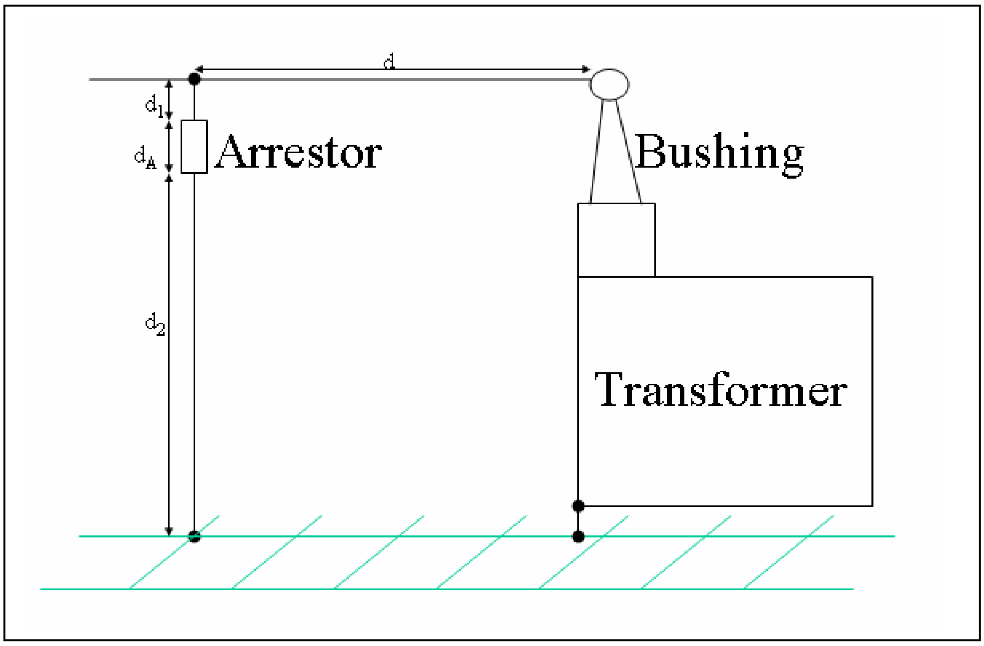

Figure 2 – Post-mounted surge arrester (with 'inductive' loop length = d + d_1 + d_A + d_2 shown – see below for relevance)

3.1.2 To maximise the benefit from the surge arresters:

a) Position surge arresters as close as practicable to the protected transformer bushing, ideally mounted on the transformer turrets, but ensuring compliance with manufacturer's guidance on the minimum clearance[1].

b) Minimise connection lead length to minimise the 'inductive' loop length (i.e. loop length = d + d_1 + d_A + d_2). NB In Figure 1 this is optimised by taking the top surge arrester connection straight to the bushing termination – see Figure 3.

Note: if the loop length is too long, as can be the case for post-mounted arresters, the arresters may not prevent the lightning withstand voltage of the transformer from being exceeded. See 4.0 below for further detail.

3.1.3 Where post-mounted arresters are to be used, the maximum loop length shall be assessed using the spreadsheet "Arrester Calculation.xls". This shall be used to decide the position of the posts to ensure the arresters protect the transformer by design and achieve the required maximum failure rate.

Note: in practice, for overhead fed sites when the number of 132kV lines is 'small' the arrester must be, in general, turret-mounted. In some circumstances, due to line configuration or turret type, this may not be practicable.

[1] NB For the ABB PEXLIM arrester it is recommended that i) the minimum clearance between bottom of the surge arrester and any HV insulator in the same phase is taken as D where D is the selected phase-to-earth clearance and ii) the minimum clearance between top of the surge arrester and any HV insulator in the same phase is taken as D/2.

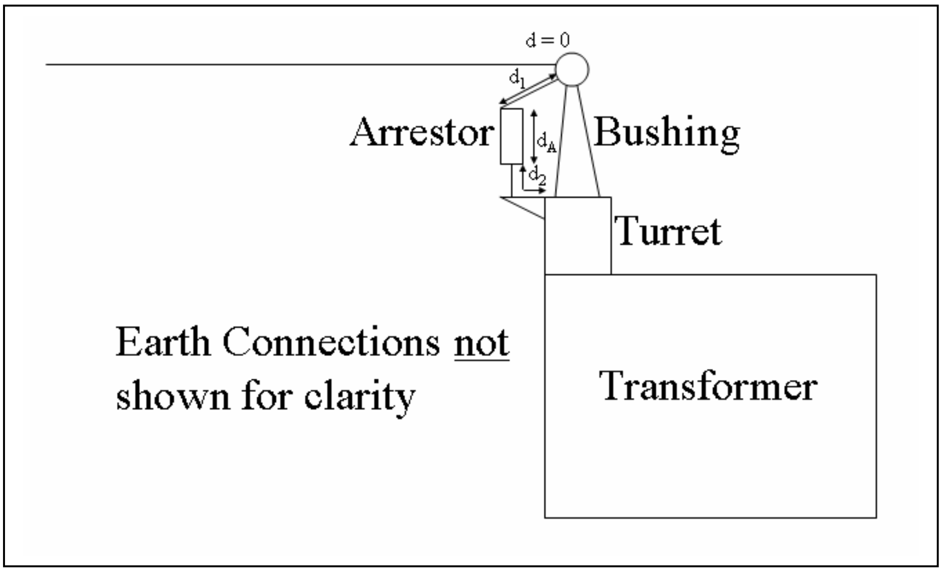

Figure 3 – Turret-mounted surge arrester – optimum arrangement

3.2 Arrester Earthing

3.2.1 The bottom terminal of each surge arrester shall be connected to earth. This connection shall comprise:

a) Above ground earthing conductor (and transformer tank as a parallel path in the case of turret-mounted arresters)

b) Below ground earth electrode.

3.2.2 To protect plant on the lower voltage side of the transformer and also multicores from damage due to transient potential rise the requirements below in sections 3.2.3 and 3.2.4 shall be met.

3.2.3 Above Ground Earthing Conductor

3.2.3.1 Figure 4 - 7 refers.

3.2.3.2 Where reasonably practicable, minimise impedance and, in particular, inductance of the above ground earthing conductor:

a) Minimise changes in conductor direction. Ensure there are no ‘sharp bends’. Where practicable use a minimum bend radius of 20cm.

b) Avoid ‘loops’ where possible. If loops cannot be avoided (e.g. bund walls), avoid loop length more than eight times the width of the loop open end (as flashover is possible. Minimise loop length relative to the width of the open end.

c) Avoid unnecessary length. Route conductor to earth electrode directly. Ensure buried earth electrode established at closest practicable point (e.g. just outside bund).

d) Use multiple paths to the buried earth electrode system, where practicable.

3.2.3.3 In addition to the above, for transformer turret-mounted arresters:

a) Do not rely on the steel transformer tank as the sole path to the earth electrode.
b) Connect each surge arrester bottom terminal directly to the main transformer tank and lid with earthing conductor. NB Care is required in making the connections to the transformer tank so as not to impair its integrity; for new transformers suitable connection points can be specified.
c) Join the three surge arrester earthing conductors in (b) together with earthing conductor as close as practical to the point where the earth conductors connect to the main transformer tank/lid.
d) Provide at least one vertical earthing conductor connection from the horizontal earthing conductor in (c). The optimum is three separate conductors, providing direct paths to the earth electrode but this may not be practical. See Figure 4.

3.2.3.4 Copper strip shall be used for the above from the bottom of the surge arrester and below. Where no separate power frequency earth is present, the cross-sectional area shall match that used for earthing other plant as per EE SPEC: 89, Table 1. If a separate surge arrester power frequency earth is provided (e.g. aluminium support structure of sufficient cross-sectional area where the structure is earthed at its base) then the surge arrester lightning earth shall be a minimum of $150mm^2$ for 132kV and 66kV and $100mm^2$ for 33kV and below. EE SPEC 89, section 8.5.2, gives requirements for anti-theft measures; if security fixings are not used then fix earthing conductor at a minimum of 1m intervals.

3.2.4 Below Ground Earth Electrode System

3.2.4.1 Where reasonably practicable, minimise the high-frequency impedance (i.e. to lightning) of buried earth electrode at the point(s) where surge current would enter:

a) Create an electrode arrangement that fills the volume of soil, a hemisphere, around the surge current injection point(s) by installing vertical rod (ideally 6m) and horizontal electrode to approach a ‘star’ arrangement. See Figure 8 for idealised arrangement. As a minimum, install the rod (star) arrangement at the surge current injection point nearest to the surge arresters.

b) Integrate the above into the substation power frequency earthing system

c) If practical, increase mesh ‘density’ in the horizontal plane to further fill the effective volume, up to a radius of 20-50m. The theoretical optimum is with spacing between parallel mesh electrode on an exponential basis with the highest mesh density closest to the rod (e.g spacings between parallel electrodes of 0.6m, 1.6m, 4.4m within a 12m mesh square. See Figure 9.

Note: electrode further than about 20-50m, measured from the surge injection point along the electrode, has little effect on reducing the high-frequency impedance. Horizontal electrode is generally cheaper to install than deep-driven vertical rods.

.

3.2.4.2 See Figure 5-Figure 7 . The requirements apply equally to post-mounted surge arresters where the above 'star' plus horizontal mesh apply at the surge arrester position. See example in Figure 10.

3.3 33kV Surge Arresters on Grid Transformers

3.3.1 As with 132kV, in the case of 33kV surge arresters the maximum protected loop length (i.e. $d + d_1 + d_A + d_2$ in Figures 1 and 2) is again an issue. If an arrester is situated 'remotely' (i.e. at the cable-line interface outside a substation or line-substation termination inside a substation) then the distance to the 132/33kV transformer may be considerable and too long to get adequate protection from the 'remote' arrester(s). In such cases, where possible and judged both economic and practical, 33kV arresters shall be applied directly across the grid transformer 33kV bushings where present via turret-mounted brackets; for the alternative case of a 33kV cable box they shall be applied at the earthing transformer.

Note: Past practice regarding the application of surge arresters at 33kV has been varied. Some 132/33kV substations with overhead lines terminating in them have 33kV surge arresters fitted close to the termination, others do not. Consistently, however, surge arresters have been fitted at most cable-overhead line terminations and not at the cable-substation interface.

4.0 BACKGROUND

4.1 Surge arresters can be used to prevent insulation damage when the lightning withstand voltage (previously known as BIL) of a transformer is exceeded (as can occur across a bushing or more importantly the transformer winding). Arresters work by limiting the voltage developed across them. However, the inductance of the loop from the transformer bushing phase terminal through the arrester and back to the protected object tank means that the voltage developed across the protected object is not simply the arrester let-through voltage (lightning impulse protection level) but instead has an additional L_{loop}.di/dt component (where L = inductance and di/dt = rate of change of the surge current). This additional component depends on the length of the loop, any bends in the conductor (which add inductance, increasing the effective length) and the rate of change of the surge current. By design/construction we can influence the loop length.

4.2 For maximum effectiveness, surge arresters should be turret mounted. If they are not then the length of the connections determines the degree to which the surge arrester is actually protecting the plant. A spreadsheet has been prepared that allows the maximum loop length to be calculated. See "Arrester Calculation.xls". This is based on the standards EN 60099-5, IEC 99-5 and IEC 60071-2. This shows that for a typical case the maximum loop length calculated can be as low as 4.8m and as high as 26m, depending on circumstances, if a 132kV arrester is to protect the transformer insulation against an assumed surge magnitude and wavefront rise-time. The maximum loop length will vary from case to case being influenced by site-specific detail (e.g. minimum number of lines connected – this influences surge impedance and hence overvoltage).

4.3 The surge arrester diverts surge current to earth. Voltage is developed both across the above ground earthing conductor (L.di/dt + i.R where L and R are the inductance and resistance of the above ground earthing conductor and i = surge current) and the bare earth electrode in the soil ($Z_{\text{earth electrode}}$.i where Z = earth impedance).

4.4 The voltage developed across the transformer tank to earth connection increases the voltage stress on the 66/33/11kV system insulation (e.g. earthing transformer) and therefore to minimise this the 'self-inductance' of the connection must be minimised. This objective is achieved by minimising route length, keeping the conductor as straight and as free from changes in direction as possible - in particular from loops and sharp bends - and using multiple connections.

4.5 Although it would be ideal to connect to a buried earth electrode under the transformer plinth, this is not practical. Care is however required to ensure that the length of the connection is not excessive. Assuming a lightning surge current with an 8µs rise time we find that each metre of connection length gives a voltage rise of approximately 2kV (assuming L=1.5µH/m and surge current of 10kA - the nominal for an ABB 132kV arrester, type PEXLIMQ132-WV145). The introduction of a loop over the bund increases the self inductance of a conductor (by increasing the effective length compared to a direct route) and introduces a mutual inductance between the parallel sides of the loop. Typically, a three sided square loop of 0.3m sides can increase the self inductance from 1.5 to 2.5 µH/m and additionally add around 1.7 µH/m to the overall lead inductance. This compares with the 33kV plant lightning withstand voltage in the range of 145-175kV (new) and so clearly lengths above a few tens of metres are undesirable. On this basis, it should be satisfactory to take earthing conductors over the transformer plinth and bund wall given expected lightning surges (although worse case conditions can be conceived they have a low probability). Multiple connections to buried earth electrode will reduce the voltage developed.

4.6 Limiting the transient voltage rise on the buried earth electrode system is beneficial as this reduces transient voltage differences throughout the substation. This is achieved by minimising the high-frequency impedance of the earth electrode system as seen at the points of surge current injection. The use of flat tape rather than circular conductors also reduces high frequency impedance as this increases the surface area for good contact with the ground as well as reducing the skin effect problem at high frequencies. Furthermore, transient voltage differences are also minimised by ensuring the earth electrode forms a single integrated system (i.e. ensuring the high-frequency surge arrester earth is integrated into the substation 50Hz earthing system).

4.7 The above requirements are met by connecting to the general substation power frequency earthing system (which in most 132kV substations will be a meshed electrode system) at multiple points. The high-frequency impedance requirement is met by utilising the 'effective volume' of soil, a hemisphere, at the points of surge current injection. That is, installing vertical (rod) and horizontal electrode at these points to maximise use of the volume using a radial 'star' type of configuration but integrated into the power frequency meshed grid (and accepting that electrode cannot be installed under an existing concrete transformer bund/plinth or skid-way). Note that although a 6m rod is recommended the optimum choice can be derived from knowledge of the resistivity of the different soil layers – ST:TP21O provides a measurement technique from which a model can be developed – for further advice contact Primary System Design.

4.8 With turret-mounted surge arresters the path to earth must be adequate to carry the prospective surge current. Further, the metal bases upon which the HV bushings are mounted are relatively small compared with the bulk of the transformer tank and therefore would present a more significant impedance to high frequency surge arrester current. Given this, direct connections from the base of the surge arrester to the combined high-frequency and power-frequency earth electrode are required. Tee-offs from these connections are made to the transformer tank to limit the loop length and to benefit from the parallel path of the transformer tank. Furthermore, the arrester-earth electrode connections are also connected to the horizontal earth tape loop inside the bund to benefit further from parallel paths and ensure a rated rather than fortuitous connection. Care is required to ensure the parallel path is not made ineffective by gaskets/seals (e.g. transformer lid).

4.9 Example costs are given in Appendix B (excluding labour and additional earthing costs).

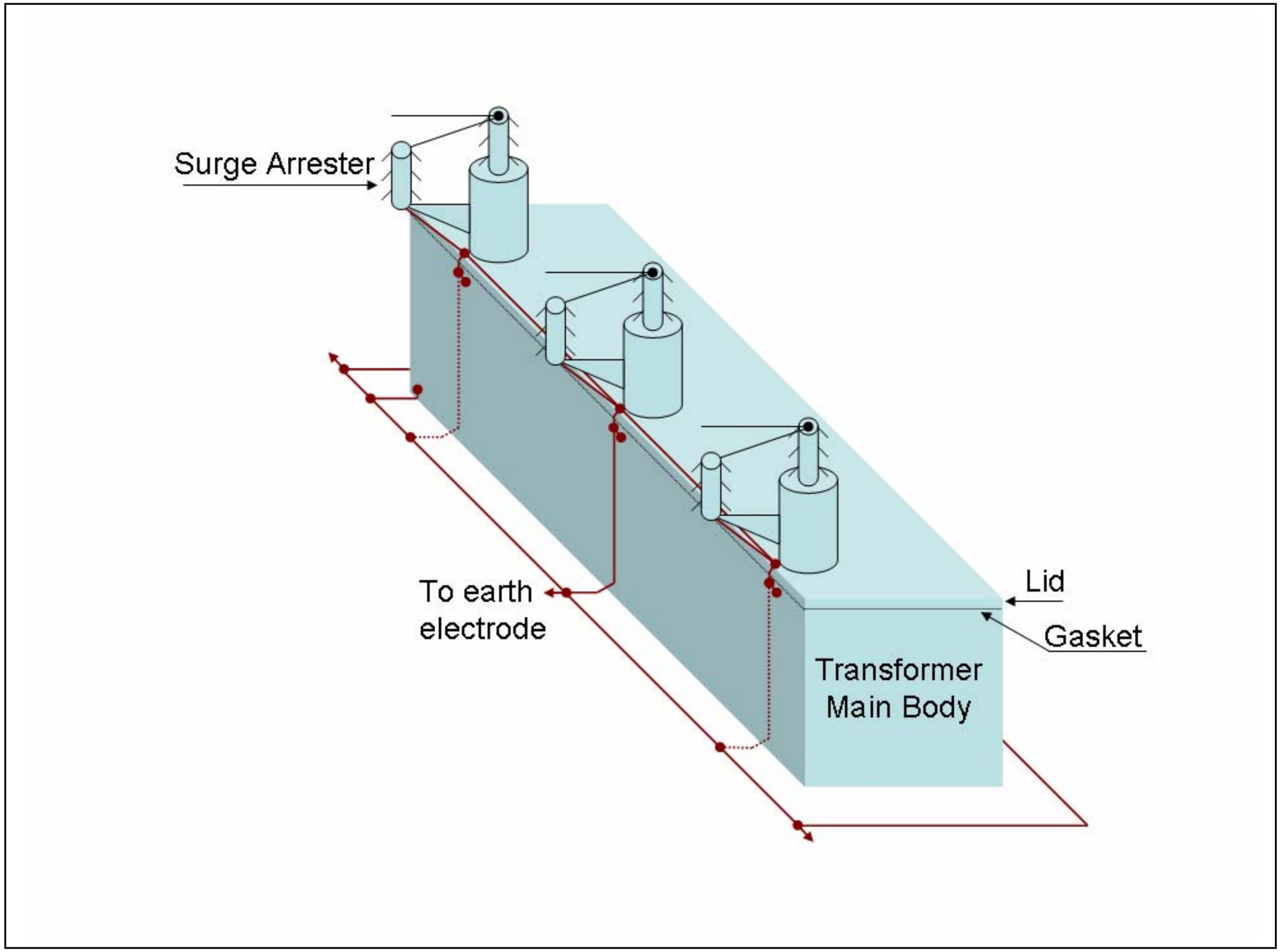

Figure 4 – Turret-mounted Surge Arresters – 3D view NB Provide at least one vertical earthing conductor; the optimum is three.

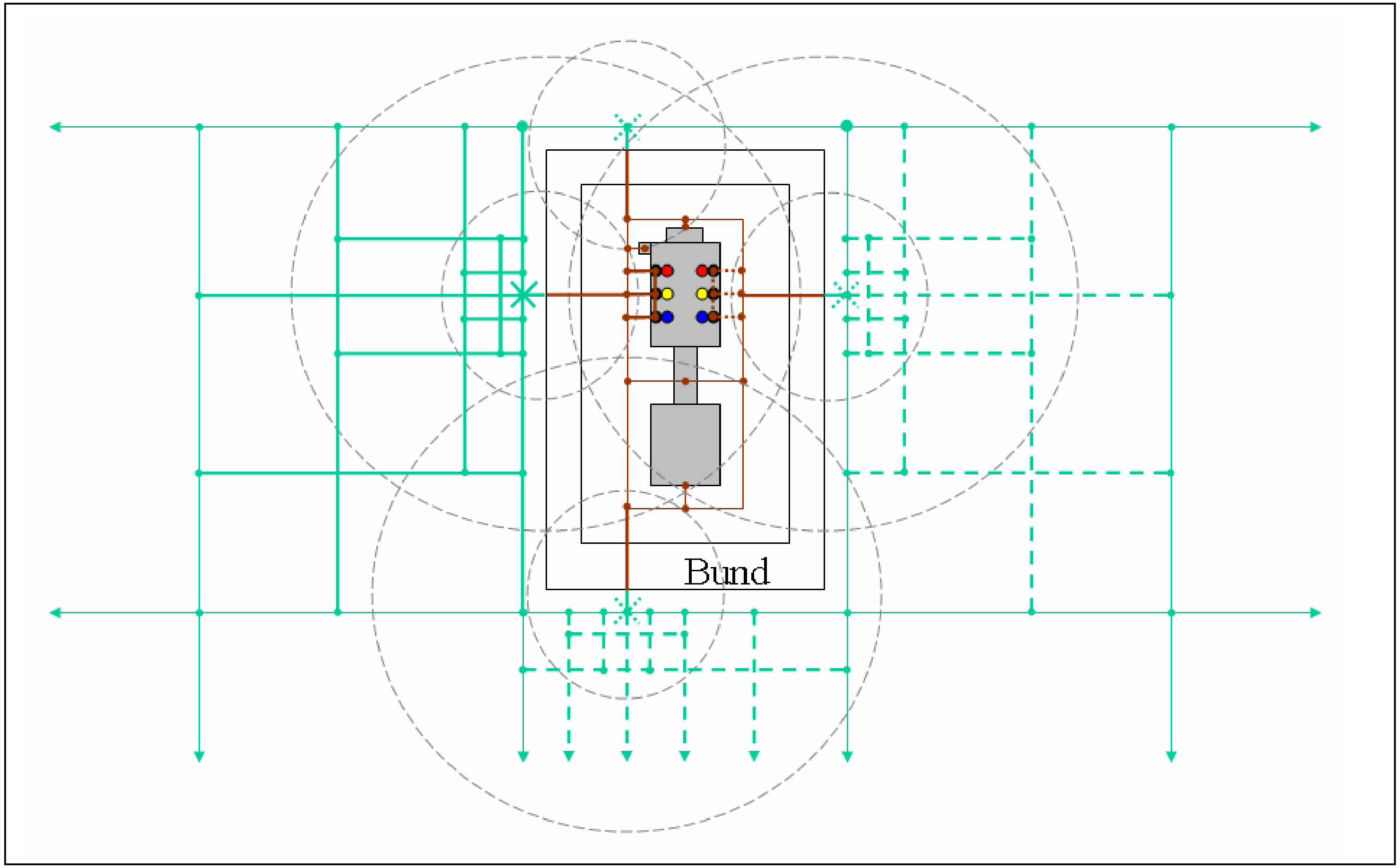

Figure 5 – Turret-mounted Surge Arresters - Plan View - Earthing Arrangement (thick lines = additions to improve surge arrester performance, cross = earth rod, circles explained in Figure 8 and Figure 9)

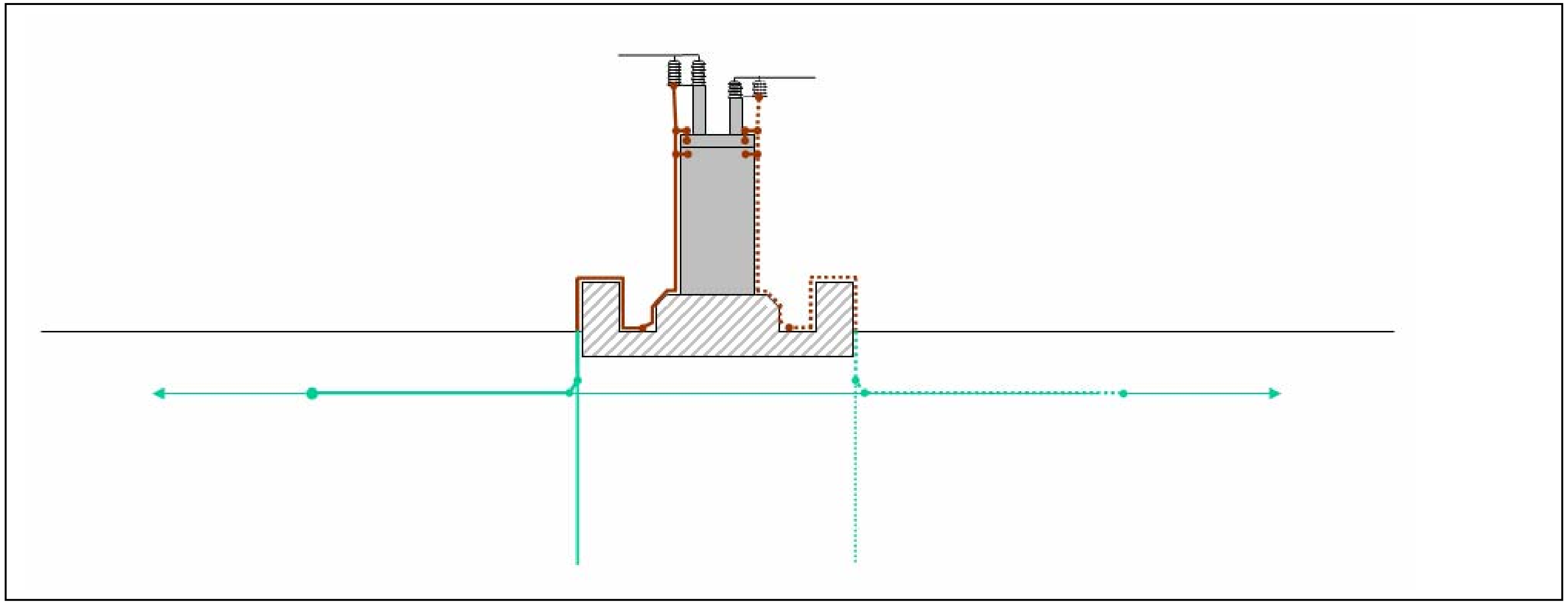

Figure 6 – Turret-mounted Surge Arresters - Side View - Earthing Arrangement (thick lines = additions to improve surge arrester performance)

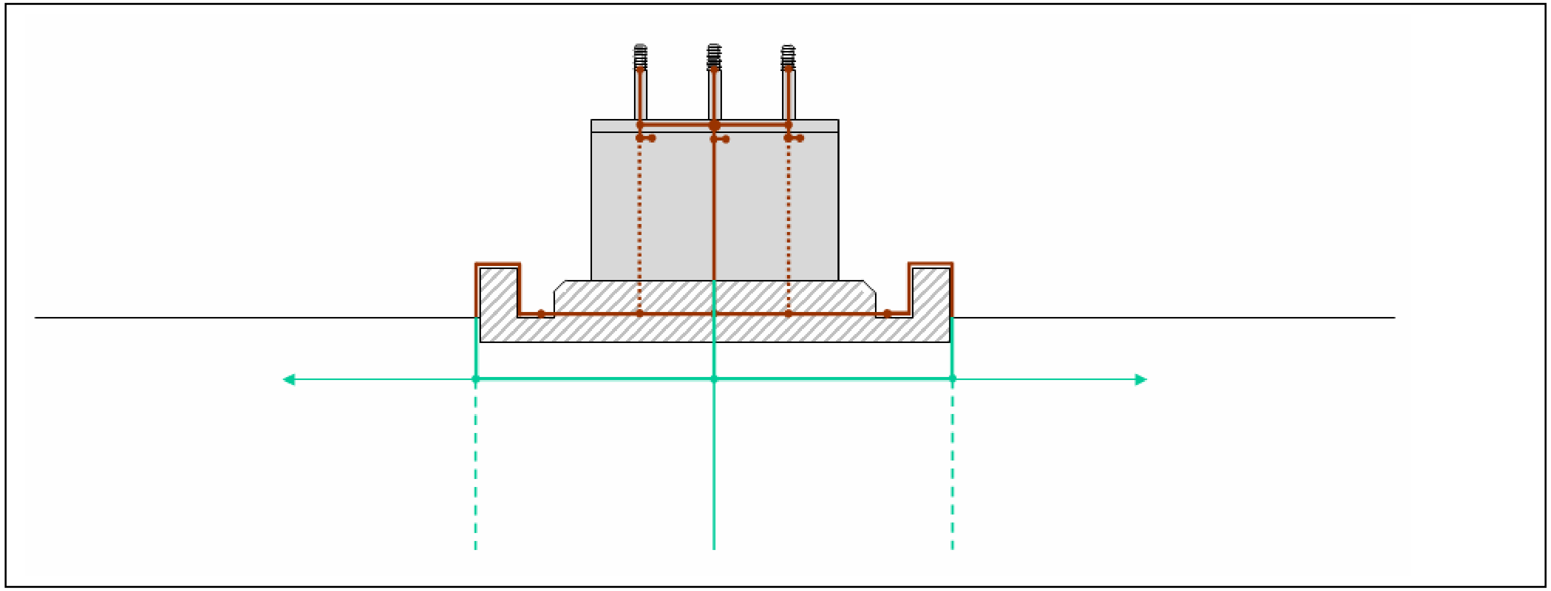

Figure 7 – Turret-mounted Surge Arresters - Front View - Earthing Arrangement (thick lines = additions to improve surge arrester performance). NB Provide at least one vertical earthing conductor from the top of the tank to the loop around the transformer inside the bund; the optimum is three.

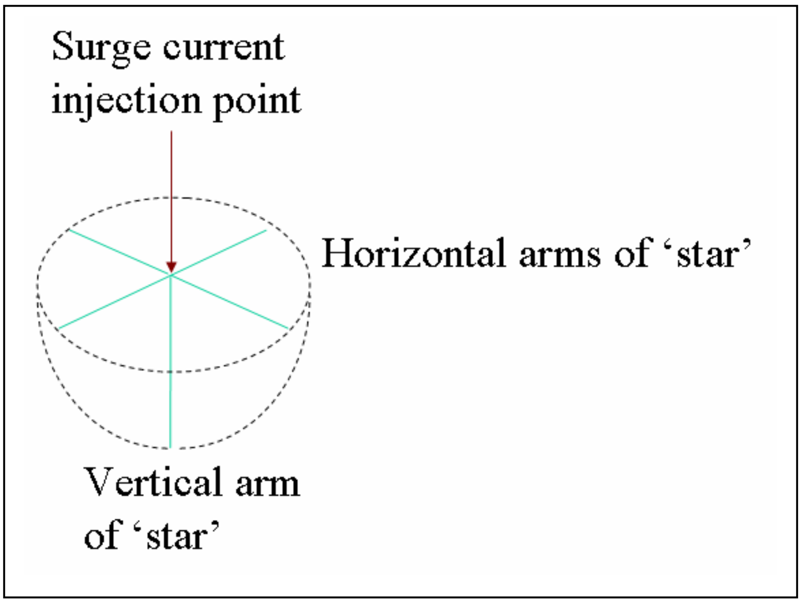

Figure 8 – Idealised Arrangement – High-frequency Earth

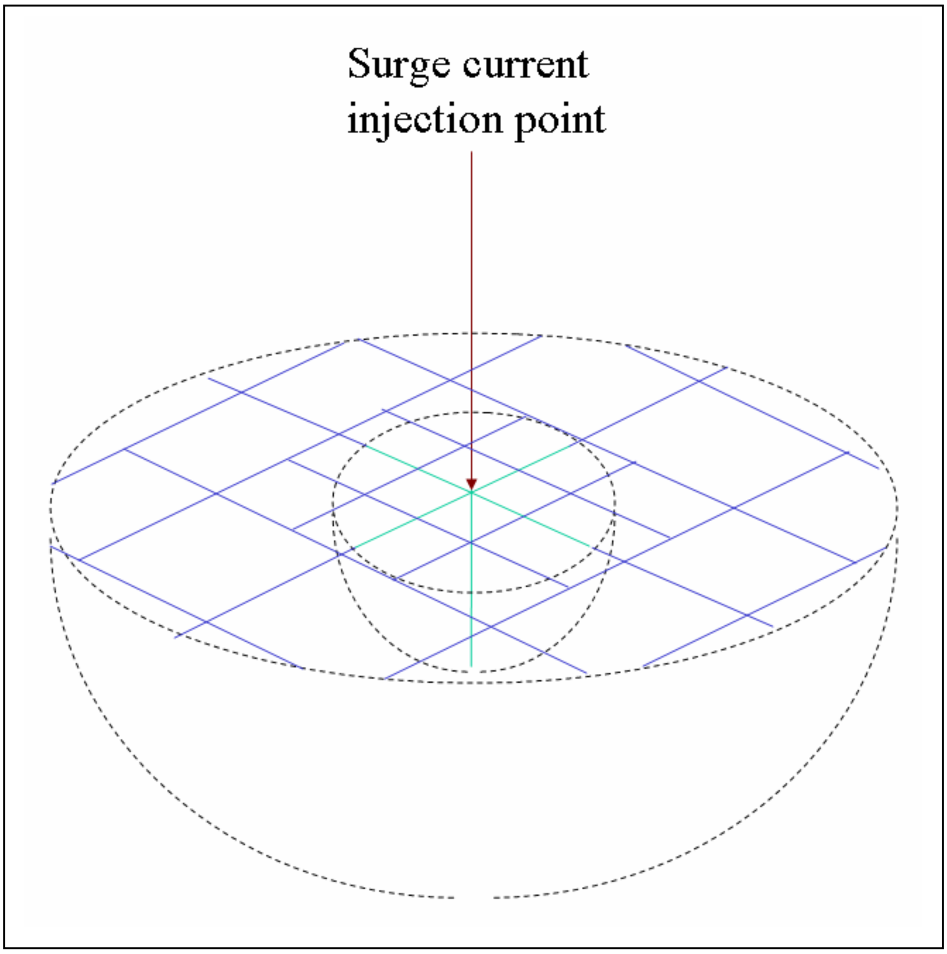

Figure 9 – Further Meshed Electrode In 'Effective Volume' (radius 20-50m) Improves High-frequency Earth

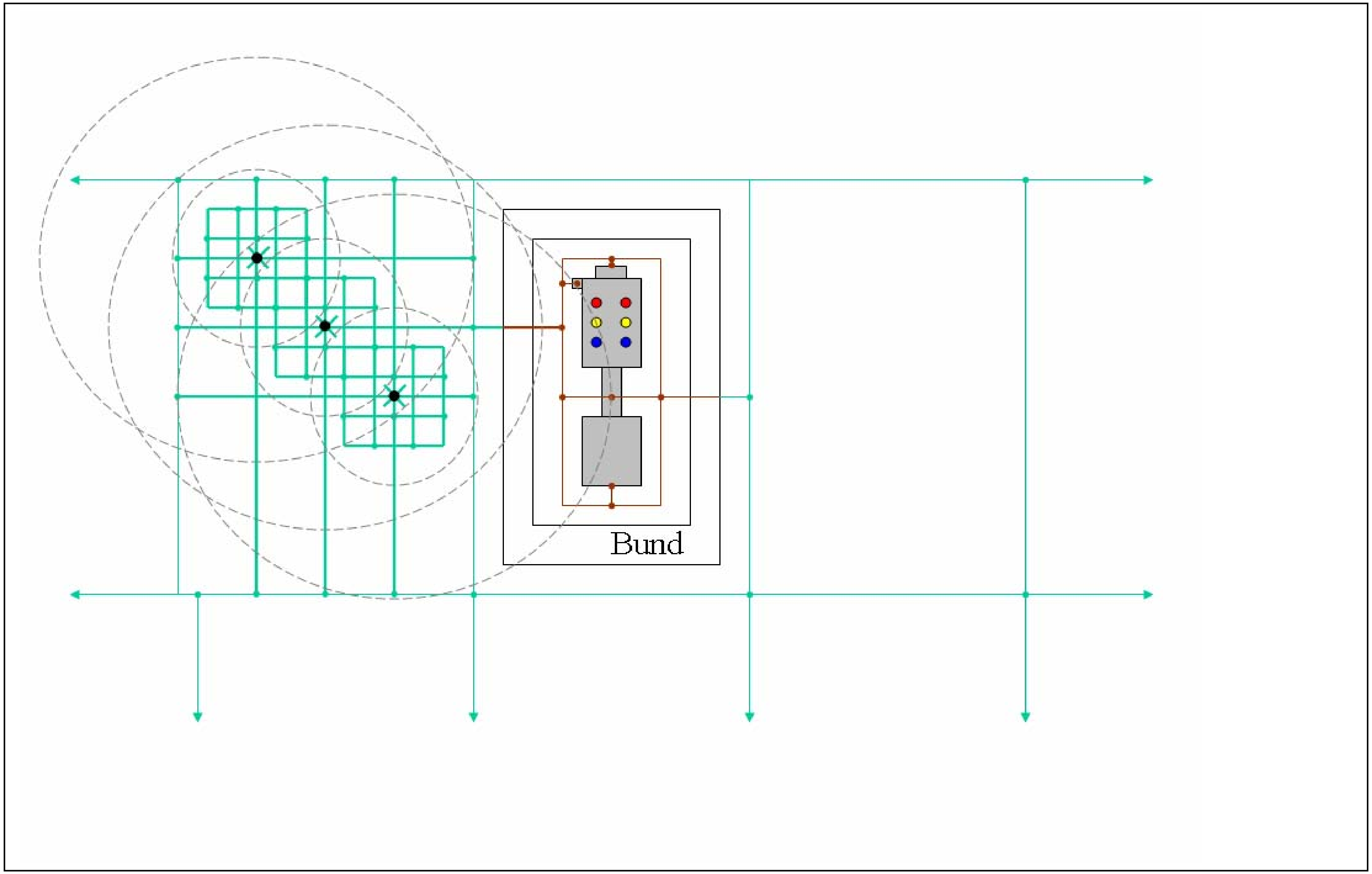

Figure 10 – Post-mounted Surge Arresters - Plan View – Optimum Earthing Arrangement (thick lines = additions to improve surge arrester performance, cross = earth rod, dotted circles explained in Figure 8 and Figure 9)

APPENDIX A

DESIGN OBJECTIVES

Minimise Transient Potential Rise

- Minimise impedance and, in particular, inductance of above ground connection to buried earth electrode
    - No 'sharp bends' – minimum bend radius of 20cm.
    - Avoid loops where possible. If loops cannot be avoided (e.g. bund walls), avoid loop length > 8 d (flashover possible) and minimise loop length relative to the width of the open end.
    - Avoid changes in direction.
    - Avoid unnecessary length. Route conductor to earth electrode via direct route. Ensure buried earth electrode established at closest practicable point (e.g. just outside bund).
    - Use multiple paths where practicable.
- Minimise the high-frequency impedance of buried earth electrode system at the point where surge current would enter
    - Utilise effective volume of soil for earth electrode by installing vertical rods and horizontal electrode to form a star arrangement and increase mesh density around surge current injection points. Electrode further than about 20-50m, measured from the surge injection point along the electrode, has little effect on reducing the impedance
    - Integrate surge arrester lightning earthing system into substation power frequency earthing system.

Allow discharge in controlled fashion

- Provide paths to earth of suitable rating from the surge arrester base terminal.
- Ensure cross-sectional area suitable for power frequency current and lightning current.
- Utilise transformer tank as a parallel path (from below transformer lid gasket).

Avoid transient potential difference that could damage insulation

- Avoid exceeding BIL of transformer insulation
    - Use surge arresters
    - Short connections
    - Ideally, mount arrester across transformer bushings
    - Judge connection length with Arrester Calculation spreadsheet.
    - Integrate surge arrester lightning earthing system into substation power frequency earthing system.

Control movement of earthing conductor due to magnetic effects

- Fix earthing conductors using secure mechanical fittings

APPENDIX B

EXAMPLE COSTS

Item	Basic Cost	Date
132kV Surge Arrester	£3630 per set of three	2009
33kV Surge Arrester	£300 per set of three	2003
132kV Surge arrester Transformer Turret-mounting Bracket	£600 per set of three	2003
33kV Surge arrester Transformer Turret-mounting Bracket	£150 per set of three	2003

Table B1 – Example Surge Arrester Costs

APPENDIX C

SUPERSEDED DOCUMENTATION

ST:TP21S	Application Of Surge Arresters to Grid Transformers

APPENDIX D

ASSOCIATED DOCUMENTATION

EE SPEC: 84	Surge Arresters
EE SPEC: 89/1	Fixed Earthing Systems For Major Substations
ST:TP21B/2	Fixed Earthing Systems – Major Substations
POL TP16	Over-voltage Protection (to be issued)
ST:TP16A	Lightning Protection Design for Major Substations (to be issued)

APPENDIX E

IMPACT ON COMPANY POLICY

This Standard Technique is relevant to personnel involved in the design and installation of surge arrester protection for grid transformers.

APPENDIX F

IMPLEMENTATION OF POLICY

To be implemented with immediate effect for new installations and those done as part of the planned programme of surge arrester installations at grid transformers.

Where existing 132kV surge arrester installations at grid transformers are post mounted, rather than turret mounted, the adequacy of the arresters to protect the grid transformer shall be assessed by the asset owners and changed to turret mounting if economically justified.

The earthing conductor arrangements at turret-mounted 132kV surge arresters shall be checked to verify the presence of a connection from the surge arrester base terminal to the transformer tank and lid at around gasket level; where this is possible by visual inspection from ground level this shall be completed within 4 months of issue of this document. If the connection is missing then the connection shall be modified to meet the requirements of this ST within 3 years of identification.

APPENDIX G

KEY WORDS

Surge arrester, earthing, earth electrode, earthing conductor, transformer.