Investigation into Oversheath Failure of a 275 kV Cable

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***Abstract*—A lightning event caused a 275 kV cable, which was part of a composite overhead line-cable circuit, to fail. ATP-EMTP package was used to model the network around the cable. It was found that a lightning event with current magnitude of 24 kA, striking the tip of the transmission line tower adjacent to the Cable Sealing End (CSE), can result in an increase to the sheath voltage with respect to the substation earth mat that exceeds the recommended limit. The study confirms that the Sheath Voltage Limiter (SVL) rating should not be exceeded and that the SVLs should remain intact. The finding of the study is in line with the site inspection report.**

Recommendations are made to reduce the sheath voltages during lightning and switching transient events. The recommendations include changing the sheath earthing arrangement by moving the SVLs to the cable entry points and earthing the sheath at the existing junction box. It is shown that the earth mat inductance around the CSE and earthing points can be reduced by using appropriate earthing rods. It is also suggested that high quality earthing straps are used to ensure a good connection to earth.

***Keywords*: ATP-EMTP, cable sheath, transients, cable oversheath, insulation failure.**

I. BACKGROUND

NATIONAL GRID (NG), are the Transmission System Owner for England and Wales and operator for Great Britain, and own and operate a number of composite Overhead Line (OHL) and cable transmission circuits at 275 kV and 400 kV voltage levels. The cable sections are of varying length and there can be at OHL at ends, or at points along the line route.

This paper presents the results of study on a 275 kV oil-filled cable oversheath insulation failure which caused the outage of the circuit. The cable sheaths are sectionalised and isolated from each other, approximately in their centre. More detail are provided in Section II.

On the early evening of Monday 29th July 2013, multiple lightning events occurred in the north of the Greater London region. One of the lines of a double circuit composite OHL to cable circuit connecting substations A and B tripped at 17:38 GMT, and successfully reclosed 35 seconds later by the line's Delayed Auto-Reclose (DAR) relay. The protection event records showed that there was one single event, earth fault to red phase, which led to the operation of main protection on both ends of the circuit. The circuit was in service until an oil pressure low alarm was received at Electricity National Control Centre (ENCC), around 1:30 am on Tuesday 30th July 2013. An Electricity Transmission Asset Management (ETAM) site team attempted to increase the pressure but were subsequently forced to take the circuit/cable out of service because of loss of oil pressure.

Site excavation was carried out and a hole (measuring approximately 25 mm × 15 mm) was found, on the bottom side, through the copper joint sleeve showing signs of flashover. Further strip-down examination showed that the insulation paper was burnt for a number of layers up to the stress wires. However, the main electric insulation (from phase conductor to sheath) was not damaged. The conclusion was that a possible cause of failure was the overvoltage on the cable sheath causing oversheath insulation failure.

On initiating the site repair work, it was observed that within the sealing end compound at the substation B side of the cable, the connection to the substation earth mat had been compromised as some of the earth tapes were missing.

It was postulated that an overvoltage (probably transient due to a lightning surge in the phase conductor) appeared at the sheath separation and managed to break the separation via a path bridging the copper sleeve (bonded to the sheath on the substation A side) and the stress wires (bonded to the sheath on the substation B side).

Fig. 1 illustrates the damaged cable joint cover, showing the hole. Note that to take the photo the joint has been turned by 180°, i.e. at the time of incidence the hole was facing downwards..

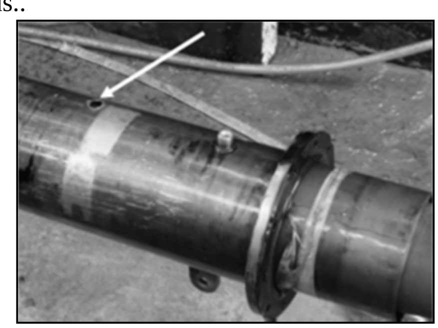

Fig. 1. Damaged cable joint.

A number of possible causes were identified and are listed below; they follow the general theory that either insulation was compromised or that the voltage that occurred exceeded the design ratings.

Insulation problem:

- Design: it was confirmed that this join is an unscreened design.

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- Manufacture quality: unverifiable due to damage.
- Material (paper and wires) quality: unverifiable due to damage.
- Insulation degradation over the years of operation: electric stress and possible mechanical abrasions between the made joint and the copper sleeve.

Overvoltage problem:

- Lightning protection to the cable section: no Surge Arrester (SA) had been installed for the CSE; co-ordination gaps had been installed instead.
- Bonding arrangement: mid-point; one of the standard approaches to ENA C55 [1].
- Bonding lead design: concentric cables used as single ones.
- SVL performance: intact.
- What is the effect of partially missing earth tapes?

A study was planned, focussed on the high voltage surges on the cable sheath and at the mid-point where the sheath is sectionalised.

II. NETWORK DESCRIPTION

Substations A and B (SUBA, SUBB) are connected by a double 275 kV transmission circuit which comprises of two sections of OHL, of 26 km and 33 km, and a cable section. The cables are situated along the route at Substation X (SUBX) buried underground above the substation earth mat. Fig. 2 shows the layout of the circuits. The earth wires of the two OHL sections are brought down and connected to the earth mat of SUBX, along with the cable sheaths at the CSE and earthing at the junction box. The last section of the OHL of Circuit 1 (CCT1) does not have an earth wire, as shown in Fig. 2. This is because of the location of the two cables in the substation and the need to avoid circulating current flow in the earth wire. The towers are of double circuit vertical construction, for which details are provided in Appendix A. In Fig. 2, the OHL on the SUBA side of the cable is of L2 type and the OHL on SUBB side is of type L2/2. The phasing of CCT1 is ABC with A phase being the top conductor, whilst CCT2 phasing is CBA with C phase at the top.

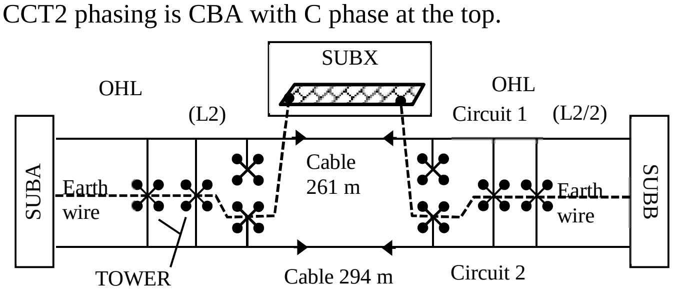

Fig. 2. Circuit diagram.

The cable has a 3.0 square inch (1935 mm^2) hollow-core copper Milliken Conductor, paper insulation, lead alloy sheath, tin bronze tape re-enforcement and an extruded PVC oversheath. The cable design data and calculated electrical parameters are given in Appendix A.

The sheaths of the cables are earthed at the outdoor sealing ends and unearthed at the joint positions. The sheath systems are separated by the resin sheath sectionalising ring at location. Both sides of the joints are connected through SVLs to earth. Each cable length is thus an individual single end-point bonded system so that the sheath current is zero for normal load conditions. A length of copper strip connected the link box earth to two insulated earth leads which were believed to be the connection to the earth continuity conductor. An earth continuity wire runs in parallel with each cable. Fig. 3 illustrates CCT1's cable configuration; CCT2 is similar. The length of each section is given in Table I.

The damaged cable was the A phase of CCT1 and was adjacent to one side of the joint bay. The 50 Hz Positive Phase Sequence (PPS) and Zero Phase Sequence (ZPS) series impedances are calculated by applying PPS and ZPS current of 1.0 pu in short and open circuit tests, giving:

$Z^{+} = 0.01176 + j0.1273\ \Omega$/km,

$Z^{o} = 0.1203 + j0.4365\ \Omega$/km,.

Capacitance at 50 Hz = 0.379 μF/km and

Characteristic impedance $\approx$ 31 Ω.

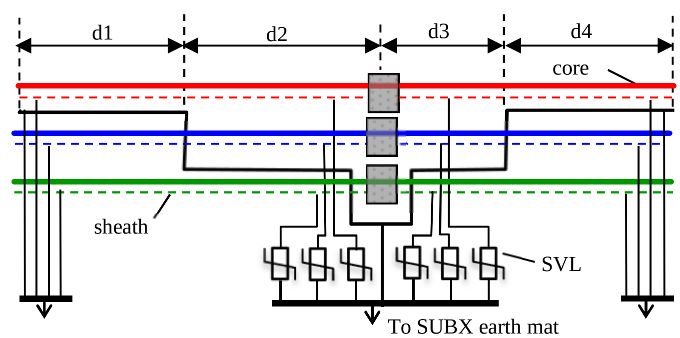

Fig. 3. Cable junction box arrangement.

TABLE I.
LENGTH OF CABLE SECTIONS

	d1 (m)	d2 (m)	d3 (m)	d4 (m)	Total (m)
CCT1	65.3	81.1	49.4	65.3	261.1
CCT2	73.3	86.0	60.7	73.3	293.3

III. NETWORK AND CABLE MODEL

ATP-EMTP simulation package was used to model the network. In compliance with IEC 60071-4 [2], the network around the point of evaluation, i.e. the point of cable failure, was reduced to at least two substations away. These boundary points are designated sub C and sub D respectively. The data for each element of the network is given in Appendix B. Six towers each side of SUBX are modelled explicitly. The length of each section is shown in Fig. 4. A J. Marti model is used for all OHLs. As the model is used to study the effect of lightning, the towers around the cable entry points are modelled as described in [2]. The model for the tower and its parameters are given in Appendix C. The earth wires of the lines between SUBA and SUBX (LN1) and between SUBB and SUBX (LN2) are connected to the top of the tower. The earth wire of the longer sections of LN1 and LN2 adjacent to SUBA and SUBB are considered to be continuously earthed. A simple switch is used to model possible flashover in the case where the insulation level is exceeded. It is assumed that the system insulation level is 1050 kV phase to ground. An inductance of 2.5 μH (equivalent to 2.5 m of insulation string [2]) in parallel with 2500 Ω resistor are used to reduce the steepness of the voltage change during breakdown to avoid unrealistically high voltages.

The sheaths at both cable sealing ends are connected to the SUBX earth mat and so is the common connection of all SVLs as shown in Fig. 3.

The earth mat impedance at SUBA is modelled as a lumped impedance of 0.0592 + j0.0411 Ω at 50 Hz, which is obtained from the earthing archive. The same for SUBX is 0.0737 + j0.06 Ω. Note that all earth mat impedances in the archive are at 50 Hz. No data for SUBB, sub C and sub D earth mat impedance is available and are therefore assumed to be equal to that of SUBX. As these substations are relatively far from SUBX, the influence of their earth mat impedance on the results is minimal.

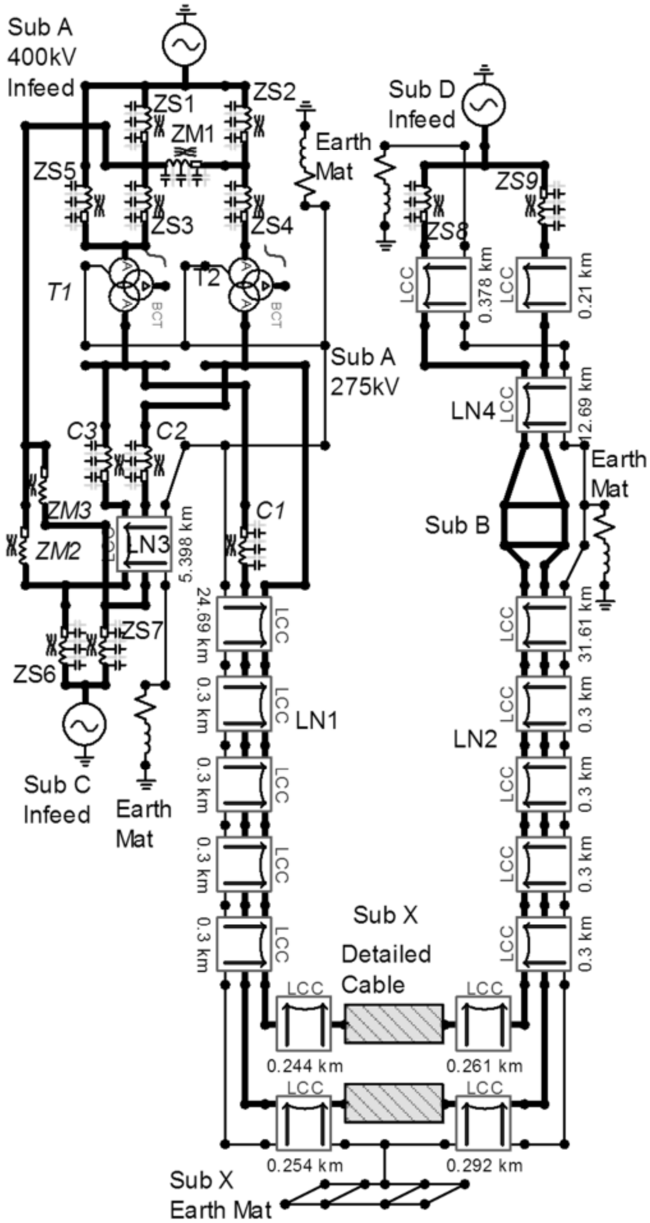

Fig. 4. Network considered in the study.

The cable is modelled in four sections as shown in Fig. 5. A Bergeron model is used with the frequency of 10 kHz for lightning and 5 kHz for the switching studies. Sections are identical apart from the position of the earth continuity wire and section length. The bases of the towers are connected to the SUBX earth mat by the earthing straps. Therefore, each section of the cable, on either side of the junction box, is single point earthed. During normal operating conditions the sheaths currents are nil as they are open circuit. If the voltage on each sheath section rises above the SVL knee-point voltage then the SVLs conduct and current flows in the sheath, thus limiting the voltage.

The SVLs are of SVL45 type with knee-point voltage of 10 kV with 16 kJ energy rating. The characteristic is given in Table II. An MOV element in ATPDraw is used to model the SVL. Several benchmarking exercises of the V-I characteristic were carried out for an 8/20 μs impulse wave for different impulse current magnitude and the results were compared with the type test data provided by the manufacturer. More detail about the SVL characteristic and modelling is given in [3]. The ATP MOV parameters are, V_{ref} = 20 kV, V_{flash} = -1, V_{zero} = 0 kV, #COL = 1, #SER = 1, ErrLim = 0.1 pu. The simulation sampling frequency is 20 ns.

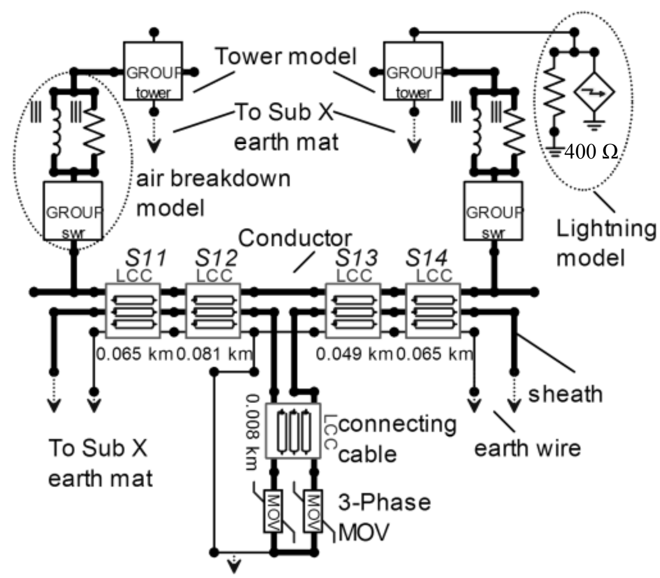

Fig. 5. Cable model

TABLE II
SVL45 V-I CHARACTERISTIC

V (kV)	10.5	11	11.5	12.2	13.2	14.5
I (kA)	1.5	3	5	10	20	40

IV. PRELIMINARY STUDY

Several analysis and tests were carried out to examine the voltage profile of the sheath at the junction box location with respect to true (remote) earth as well as the substation earth mat and across the sheath isolation barrier. True, or remote earth, refers to earth with zero potential. The substation earth mat is not a true earth.

In order to examine the sheath voltage and voltage across the barrier at the junction box, an 8/20 μs impulse of 100 kV was applied to the core of phase A of the cable model at its SUBB end while the other end of the cable was open. In this test only the cable was considered, isolated from the rest of the network. The impulse is shown in Fig. 6. In this test an 8/20 μs impulse was considered because it was assumed that when lightning strikes the tower tip, by the time the impulse arrives at the cable entry point, high frequency content would have reduced. Note that this test was done with the sheath and the common point of the SVLs connected to true earth. Fig. 7 illustrates the voltage of the sheath with respect to true earth at the junction box along with the voltage across the barrier. It can be seen that the sheath voltages either side of the barrier were limited to around 11 kV and that the voltages at the initial instance of the impulse arriving at the junction were in opposite direction. This is expected, as the current impulse in the core produced by the initial voltage impulse sets up travelling wave voltages on the sheath ‘arriving’ at the junction SVLs on the SUBB side and ‘initiating’ for the SVLs on the SUBA side. The voltage across the barrier was approximately twice the sheath voltages on either side of the barrier. The voltage across the barrier reached around 24 kV. These traces are for the condition when it was assumed that SVL circuits on either side of the barrier were exactly the same and thus SVLs started conducting at nearly the same time. Inspection of the SVL currents confirmed that the conduction in the two sets of SVLs were very similar but had opposite polarity. In order to check the effect of imperfect manufacturing and connections between the two sets of SVLs, a series 1 μH inductance was added to the SVL connection on the SUBA side of the barrier, causing a delay in the rise of voltage across the SVL set, thus causing different voltages to appear across the SVLs and hence current flow in the SVLs. It can be seen from Fig. 8 that the voltage across the barrier increased to about 33 kV. For both tests, the energy absorbed by the SVL was minimal as the conduction duration and magnitude of the currents were minimal. The frequency content of the incident wave affects the sheath voltage at the junction box, i.e. a 1.2/50 μs wave would produce higher voltages.

With all earth wires and cable sheath connected to the SUBX earth mat, a frequency scan of the earth mat impedance was carried out. Initially, a lumped earth mat impedance to remote earth is considered (0.0737 + j0.06 Ω). The frequency scan is shown in Fig. 9, which gives the impedance that the earth mat presents to a current or voltage source at different frequencies if the earth mat were to be assumed as a lumped impedance. The scan shows a major resonance at about 4.8 kHz with magnitude of about 70 Ω and a few minor resonances, which were found to be due to interaction between the mainly lumped inductance of the earth mat and the capacitance between the sheath and remote earth formed by the oversheath insulation. This was confirmed by varying the oversheath thickness (hence, capacitance) and earth mat inductance. As all main conductors of the cable in this test were open at both ends, the capacitance between the sheath and remote earth was found to be the major parameter contributing to the resonances.

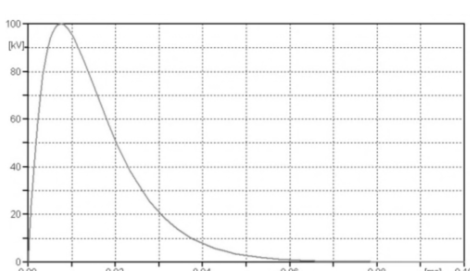

Fig. 6. An 8/20 μs impulse applied to an isolated cable.

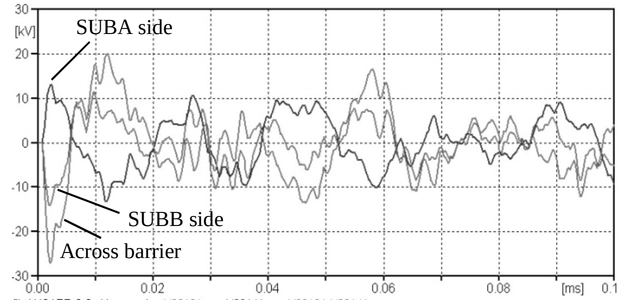

Fig. 7. Sheath voltage to true earth and across insulation barrier for symmetric connection.

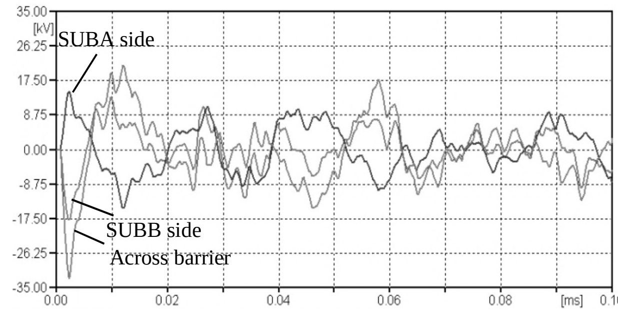

Fig. 8. Sheath voltage to true earth and across insulation barrier for asymmetric connection.

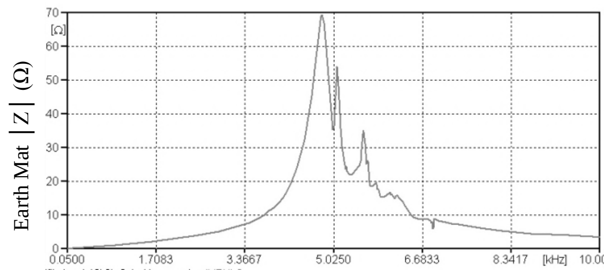

Fig. 9. Frequency scan looking into SUBX earth mat with cables and all earth wires connected.

It was assumed that a lightning event with 1.2/50 μs wave-shape struck the top of the tower, adjacent to the CSE on CCT1, causing flashover between the tower apex and phase A, which was the closest phase. Note that this tower does not have an earth wire. Fig. 10 shows the phase A core voltage at the cable entry point. Fig. 11 shows the earth mat voltage which was also imposed upon the cable sheath, measured with respect to the remote earth. The earth mat voltage oscillates at nearly 4.8 kHz and increased to about 38 kV, producing high voltages on the sheath across the barrier.

The lumped model for the earth mat at the point of study, where it directly affects the overvoltage profile, is considered to be unrealistic. A better approximation to the earth mat model was devised. Several models for earth mat exist with different degrees of complexity [4-6].

The complete substation earthing system was designed and modelled in a dedicated earthing scheme where details such as complete mesh and rod electrical data, accurate soil resistivity etc. were considered. The suite has the capability to perform frequency scan for impedance from any point of interest. The contractor that performed the earthing design, assessment and measurement works was requested to perform a frequency scan to determine the magnitude and phase angle of the earth mat impedance seen at the point of connection of the first tower on the SUBB side of the cable. Note that the first towers either side of the cable were connected to the earth mat. The current injected into the earth mat at this point caused the earth mat potential at the point of injection, and its vicinity, to change with respect to the remote earth. It was assumed that the earth mat voltage at the junction box was the same as this voltage. For an isolated earth mat, i.e. all line earth wires and cable sheath disconnected, Fig. 12 shows the earth mat impedance magnitude and angle for the detailed and simplified models, which consist of several series-parallel connections of resistances and inductances. The simplified model was set up to obtain the same response as the detailed model. The model does not have any propagation time associated with it. The earth mat impedance magnitude is around 0.8 Ω at about 5 kHz and around 1 Ω at 10 kHz. The 50 Hz impedances from frequency scan of the detailed and simplified models are $0.1183 + j0.06826\ \Omega$ and $0.12503 + j0.056\ \Omega$ respectively. Fig. 13 illustrates the frequency scan seen from the same point as Fig. 9 but with the simplified earth mat model. The impedance, and hence voltage profile, of the earth mat is very different from that obtained from a lumped model. This improved model was used in the study. The frequency scan is performed up to 10 kHz due to limitation of the earthing software and the fact that the lightning impulse arriving at the earth mat entry point losses most of its high frequency contents by the time it goes through the tower model.

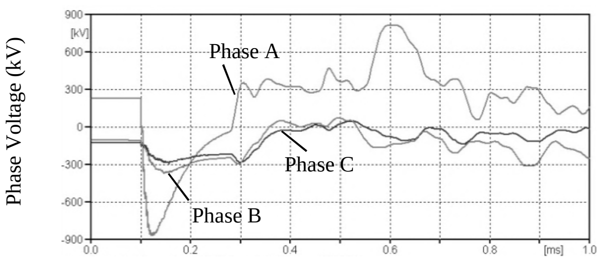

Fig. 10. Conductor voltages at CSE.

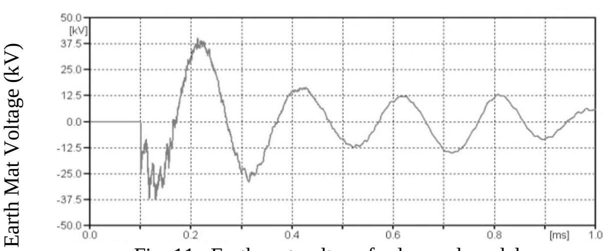

Fig. 11. Earth mat voltage for lumped model.

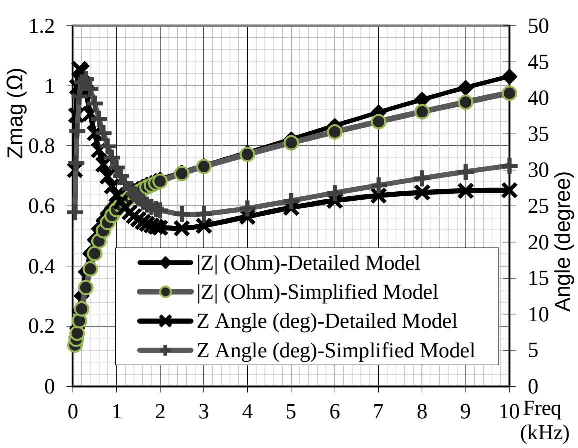

Fig. 12. Earth mat impedance for detailed and approximate models.

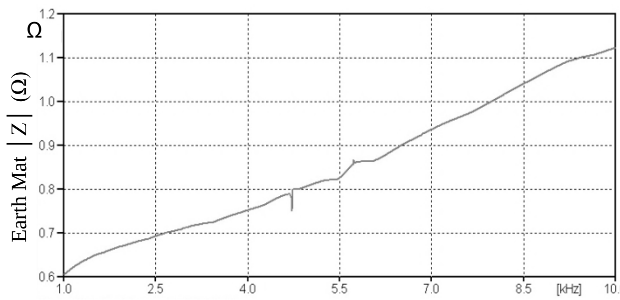

Fig. 13. Frequency scan of the SUBX earth mat approximate model with cables and all earth wires connected.

V. Sheath Voltage Limits

Requirements for the maximum permissible sheath voltage are given in ENA C55 [1] and IEEE 575 [7], which are summarised in Table III and Table IV respectively. According to ENA C55, for a 275 kV cable, each sheath section should withstand 37.5 kV and the voltage across the barrier should not exceed 75 kV. IEEE does not give a limit for 275 kV but the figures for 245 kV can be assumed to be appropriate for 275 kV. These are 40 kV and 80 kV respectively. As can be seen due to opposite signal polarity across the barrier, illustrated before, the barrier should be designed to withstand at least twice the permissible voltage on the sheath.

None of the standards provide any method to calculate the adjustments that need be considered to the above limits to account for cable insulation ageing. The limits in ENA C55 were considered for this study, i.e. the sheath and barrier should withstand the voltages given in Table III.

TABLE III
ENA C55 (Table 2A) Permissible Sheath Voltages

System Voltage	Joint Sleeve	
	Between Halves	Each Half to Earth
kV	kVp	kVp
33	35	17.5
66	35	17.5
132	45	22.5
275	75	37.5
400	110	55.0

TABLE IV
IEEE Permissible Sheath Voltages

Typical BIL withstand of Sheath Interrupt and Jacket kV peak (1.2x50 us wave)			
System kV	Across Halves	Each Half to Ground	Jacket
69-138	60	30	30
161-240	80	40	40
345-500	120	60	60

VI. Study Results

Information from the field was used to set up the study scenarios. It is not known which tower was struck by the lightning. It is however known that only one breakdown was recorded. Based on this information, it was assumed that the tower adjacent to the CSE on the SUBB side of the cable was struck. This tower does not have an earth wire. The lightning 1.2/50 µs impulse current magnitude to produce a single breakdown between the tip of the tower and the nearest conductor (phase A) was −24 kA, when the voltage is passing through its positive peak in phase A. At this current level no other breakdown at any other location on the line occurred.

Fig. 14 shows the sheath and earth mat voltages at different locations along the cable with respect to (w.r.t.) remote earth and the earth mat. The key for the locations are given in Table V. For example, ASVL-E means the sheath voltage to remote earth at the SVL location on the SUBA side of the barrier and BCSE-MAT means the sheath voltage to earth mat at the cable sealing end on the SUBB side of the barrier at the cable entry point. For the existing configuration, the sheath at the CSE locations were connected to the earth mat by earthing straps.

As can be seen from Fig. 14 that the sheath voltages with respect to the remote earth and also the voltage across the barrier were within the ENA C55 limits. The calculated voltage for the latter being about 60 kV whereas ENA C55 allows 75 kV. However, the voltage of the sheath w.r.t. the earth mat at the SUBB side of the barrier exceeded the permissible voltage of 37.5 kV by about 11 kV, resulting in a voltage of nearly 48 kV. Several different studies were performed to confirm the finding, which included considering direct stroke to CCT1 phase A conductor and imperfect joints and connections. The latter were simulated by adding 1 µH in the SVL connections on one side and in the CSE connections to the earth mat. Throughout the study, a perfect connection was modelled as having 0.1 Ω pure resistance and 0.1 µH inductance. Higher sheath voltages to the earth mat and also to remote earth were calculated for these conditions, exceeding the permissible voltages given not only by ENA C55 but also IEEE 575, as illustrated in Fig. 15 where 1 µH was added to the SVL connections on the SUBA side. Sheath voltages to remote earth, to earth mat and across the barrier exceeded the permissible voltages.

TABLE V
LOCATION ABBREVIATION AND DEFINITION FOR FIG. 14.

Location	Definition
ACSE-E	SUBA side-CSE w.r.t. remote earth
ASVL-E	SUBA side SVL w.r.t. remote earth
BSVL-E	SUBB side SVL w.r.t. remote earth
BCSE-E	SUBB side CSE w.r.t. remote earth
ASVL-EMAT	SUBA side SVL w.r.t. earth mat
BSVL-EMAT	SUBB side SVL w.r.t. earth mat
ASVL-BSVL	Voltage across barrier, sheath Phase A-Phase A
BCSE-EMAT	SUBB side CSE w.r.t. earth mat
BMAT-E	Earth mat voltage w.r.t. remote earth

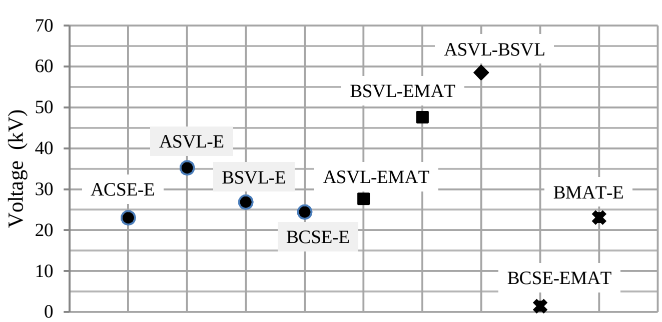

Fig. 14. Voltage of sheath and earth mat.

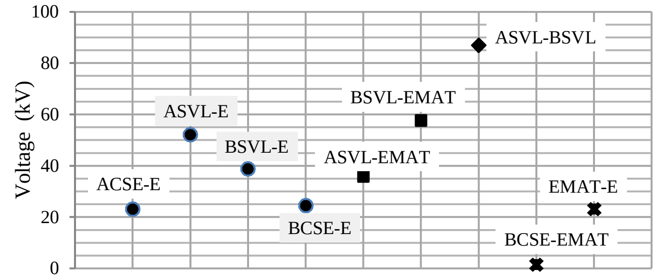

Fig. 15. Voltage of sheath and earth mat with 1 µH in SUBA side SVL connection.

The study results are in line with the damage to the oversheath and the joint copper jacket, presented in an NG internal site report. Therefore it was concluded that the possible cause(s) of the failure was/were configuration of sheath earthing including SVL locations and earth mat apparent impedance to remote earth. Studies were performed to examine possible solutions to reduce the sheath and/or earth mat voltages.

Two more earthing/SVL-location configurations were considered. One was to move the SVL set on the SUBA side of the barrier to the CSE location and earth the sheath through the SVL at that location whilst solidly earthing the sheath at the barrier location. The other option was to earth the sheath at the existing junction box and move both SVL sets to the CSE locations. Both configurations are referenced in ENA C55. Fig. 16 shows the sheath voltages at different locations with respect to the remote earth and earth mat for the existing and two aforementioned configurations. The study considered the case of assumed imperfect connection for the SVL set on the SUBA side as discussed earlier. Fig. 16 shows that the sheath voltages at different locations with respect to remote earth reduced to well below the limit. However, for the case when SVLs were positioned at the cable entry point, i.e. CSE, the sheath voltage at the SUBB side approached the limit.

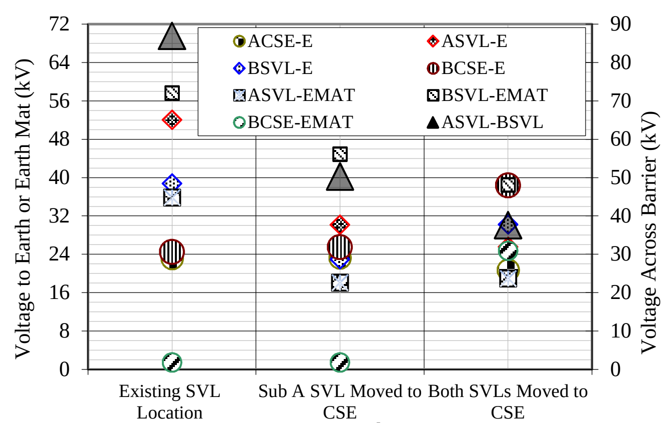

Fig. 16. Sheath voltages for different SVL and earthing arrangements.

Fig. 17 illustrates the sheath voltages for the same conditions as shown in Fig. 16, when the earth mat impedance was changed to a pure resistance of 0.1 Ω. All voltages were below the limit, with the highest voltage being for the CSE of the SUBA side, where the imperfect connection of 1 μH was considered.

Fig. 18 shows the sheath voltages at different locations with the earth mat modelled as a pure resistance of 0.1 Ω and with perfect connections throughout. When SVLs were placed at the CSE and the sheath was earthed in the middle the sheath, the resulting voltages were lowest, and were well below the limits if the earth mat impedance was pure resistance, i.e. minimal inductance, and the connections were of good quality.

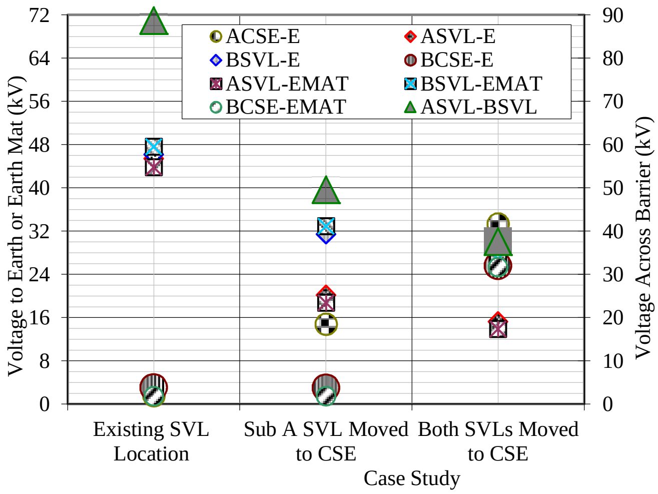

Fig. 17. Sheath voltages for different SVL and earthing arrangements with earth mat as pure resistance.

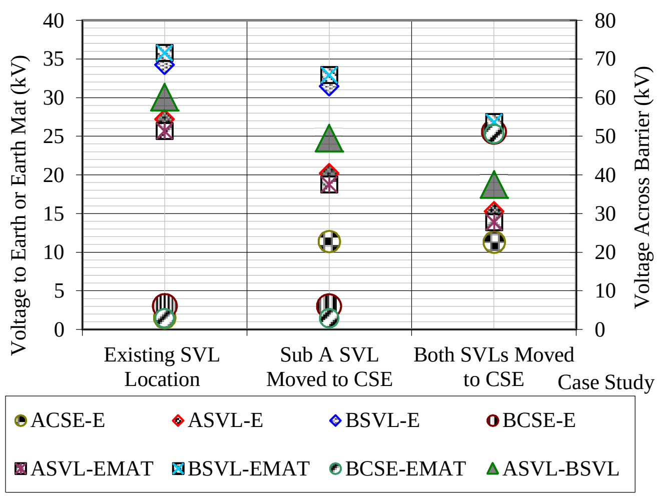

Fig. 18. Sheath voltages for different SVL and earthing arrangements with earth mat as pure resistance and perfect connections.

VII. Recommendations

It is recommended that the earthing and SVL arrangements are changed. It is suggested that the SVLs are moved to the CSE and the cable sheath is connected to the earth mat at the existing junction box location. It is also suggested that the earth mat is re-enforced at the points where the cable sheath is connected. This re-enforcement should include installing appropriate rods at the cable CSE and mid-point. It is further recommended that the earth strap connections are regularly inspected to ensure good quality contacts. All earth wire straps connected to the CSE and mid-point should be of high-frequency grade.

VIII. Conclusions

ATP-EMTP package was used to model a double circuit composite overhead line-cable feeder to investigate a cable failure after stormy weather. Following site inspection, the fault was found to be between the oversheath sleeve and earth causing oil loss from the cable. The study showed that the possible causes of the failure were excessive sheath voltages with respect to the substation earth mat, poor connection and joints and the position of the SVLs. The substation earth mat was modelled as a series-parallel combination of linear resistances and inductances to match the frequency response of a detailed earth mat model. It is recommended that the SVLs are moved to the ends of the cables and the sheath is earthed at the existing junction box.

IX. Appendices

A. Appendix A

Details of overhead lines used in the simulation are given in Table A. 1 and Table A.2 and tower structure in Fig. A. 1.

TABLE A. 1
Conductor Details for Transmission Line L2 and L2/2

	Conductor		Earth Wire			
	R_{Outer} (cm)	R (Ω/km)	R_{Outer} (cm)	R Ω/km	No Bundle	Bundled(cm)
L2	1.575	0.0545	0.9765	0.1654	2	40
L2/2	1.431	0.0673	0.9765	0.1489	2	30

TABLE A. 2
Tower Dimension Detail for Tower L2 and L2/2

	X_{11} (m)	X_{12} (m)	X_{13} (m)	X_{21} (m)	X_{22} (m)	X_{23} (m)	X_0 (m)
L2	-5.48	-5.71	-6.09	5.48	5.71	6.09	0
L2/2	-5.94	-8.53	-6.7	5.94	8.53	6.7	0

	Y_1 (m)	Y_2 (m)	Y_3 (m)	Y_0 (m)
L2	29.86	22.09	14.25	35.6
L2/2	30.01	20.57	12.57	39.77

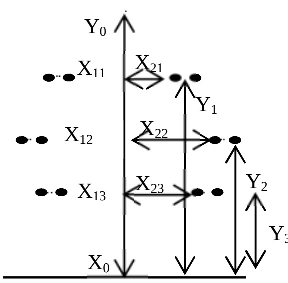

Fig. A. 1. Tower structure.

The cable is copper conductor, oil-filled and paper insulated and its layout and spacing is shown in Fig. A.2. The cable data is given in Table A.3. The relative permittivity of the main insulation is considered to be 3 and of the sheath it is 5 at 5 kHz and higher. The overall cable radius is 5.4 cm. The earth resistivity is considered to be 20 Ω.m throughout.

TABLE A. 3
Cable Data

	Core	Sheath	Earth wire
Inner R (mm)	8.3	45	0
Outer R (mm)	29	49	10

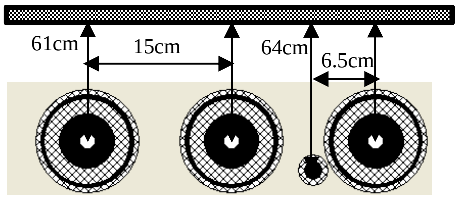

Fig. A.2. Cable layout, spacing and trench depth.

B. *Appendix B*

Table B. 1 gives the type and length of the lines in the model. The lengths for LN1, LN2 and LN4 have been shown as an approximation because there are single circuit sections with different length in these lines. The exact lengths are shown in Fig. 4. The cables, except the cables in the area of evaluation, are modelled as Clarke models. The parameters are given in Table B. 2. The self and mutual impedances between sources are given in Table B. 3. With transformer impedances given in Table. B. 4.

TABLE B. 1
LINE LENGTH

ID	Type	Length (km)
LN1	L2	≈26
LN2	L2/2	≈33
LN3	L2	5.4
LN4	L2	≈3

TABLE B. 2
NETWORK CABLES PARAMETERS

ID	R+ mΩ/km	X+ mΩ/km	RO mΩ/km	XO mΩ/km	B+ nF/km	BO nF/km	L km
C1	12.9	211	216	74.8	457	457	0.322
C2	12.9	211	216	74.8	457	457	0.399
C3	12.9	211	216	74.8	457	457	0.222

TABLE B. 3
PARAMETERS OF SOURCES

ID	Z^+ (Ω)	Z^O (Ω)	C^+ (μF)	C^O (μF)
ZS1	1.2+j5.969	1.85+j9.111	0.1	0.1
ZS2	1.44+j7.383	2.13+j11.153	0.1	0.1
ZS3	4.0+j21.991	5.2+j12.566	0.1	0.1
ZS4	2.02+j10.1	4.66+j15.708	0.1	0.1
ZS5	1.9+j10.367	1.0+j12.0	0.1	0.1
ZS6	2.05+j20.518	1.88+j18.809	0.1	0.1
ZS7	2.25+j22.469	2.0+j19.792	0.1	0.1
ZS8	3.0+j15.708	2.2+j11.184	0.1	0.1
ZS9	3.0+j17.279	2.0+j10.367	0.1	0.1
ZM1	50+j219	50+j201	0.1	0.1
ZM2	7+j74	5+j16	0.1	0.1
ZM3	6+j31	6+13	0.1	0.1

TABLE. B. 4
NETWORK TRANSFORMER DATA

ID	kV	MVA	HV-LV		HV-TV		LV-TV	
			X (%)	P_C (W)	X (%)	P_C (W)	X (%)	P_C (W)
T1	400/275/13	1100/1100/60	17.42	2191	6.9	90	5.4	90
T2	400/275/13	1000/1000/60	15.8	1763	7.0	105	5.47	109

C. *Appendix C*

Fig. C. 1 shows the tower model that was used in the study [2]. Its parameters are given in Table C. 1. Zt1 represents the surge impedance of each section of the tower between the cross arms. The surge impedance is considered to be 200 Ω.

The tower grounding impedance is considered to be 15 Ω and is represented by a lumped resistor in parallel with a 1 nF capacitance.

TABLE C. 1
TOWER MODEL PARAMETERS

R_1 (Ω)	R_2 (Ω)	R_3 (Ω)	R_4 (Ω)
10.537	16.941	16.941	16.941
L_1 (μH)	L_2 (μH)	L_3 (μH)	L_4 (μH)
2.5	4.02	4.02	4.02

Lca1 (μH)	Lca2 (μH)	Lca3 (μH)
5.48	5.71	6.09

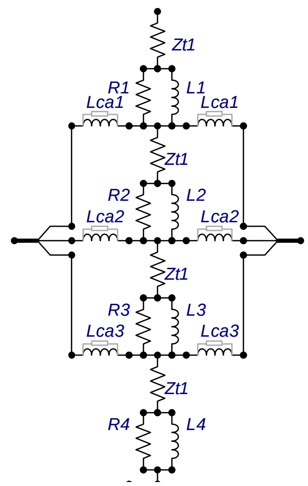

Fig. C. 1. Tower model.

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