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B1 - Insulated Cables
PS1: Learning from Experience

Analysis of Failed Cable Termination: Role of Workmanship and Electrical Stresses

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SUMMARY

Cables are crucial part of electrical transmission network. Failure of cable or its accessories before their service life results in service disruption and requires expensive repair. Cable accessories are designed to deal with high concentration of electrical stresses, however, despite routine tests on prefabricated accessories there is still a remaining risk connected to quality of assembly and skill of workmanship that may impact the failure rate. In this paper, we report analysis of failed cable terminations installed on 33 kV XLPE insulated, single core cables. Since the failures took place within a year of installation, ageing related issues can be neglected. All the cable terminations used capacitive stress control to minimise electric stress at the triple point. The failure investigation was carried out using visual observations, material analysis of failed and healthy termination pieces and analysis using FEM based software simulation. Visual observations of the cable terminations showed non-uniformity, indicating deviation from standard practices of preparation and installation process. Some of the specific issues observed were – use of non-standard tools for termination preparation; insufficient heating treatment on outer heat shrinkable tube and improper sealing at cable junctions. Among four failed samples, three of them were found damaged near the cable junction beneath the electric stress control tube. Usually, area near the cable junction and triple point is subjected to maximum electrical stress in a cable termination. FEM analysis was carried out to understand the electrical stress profile and to correlate with failure and visual observations. FEM results confirmed that the maximum electrical stresses at the triple point can overshoot in certain circumstances which may lead to failure. This paper provides an overview of effects of improper workmanship of cable termination preparation and installation on the performance of cable terminations.

KEYWORDS
Cable, Cable-Termination, Failure, FEM analysis, Heat Shrink, Electrical Stresses

1.0 Introduction

Cable termination and joints are important accessories of cable network. They are also prone to failure because of their functionality which involves minimizing and balancing of localised electrical stresses. This delicate balance in electrical stresses is achieved through careful design, right selection of materials and highly skilled manpower for installation. Any deviation or mistake can lead to imbalance of electrical stresses leading to failures. Recent statistics of in-service failures of accessories indicate that the main factor (more than 50%) is related to installation, followed by design and production issues, which also resembles the main factor in the testing failures [1]. Our investigation of cable termination failures presented in this paper confirm the finding that the installation errors are the major cause of accessories failures.

In this paper, we report findings of failure investigation of cable terminations in an electrical distribution network. Frequent failures of cable terminations were noticed by a transmission and distribution utility. The problem started immediately after installation and charging of 33 kV cable transmission line. All the cable terminations were either installed on transmission poles or at a 33 kV substation. In two years of service life, about 20 cable terminations failed out of the total 48 installed at the site. The failures led to frequent disruption of service leading to increased downtime and maintenance activity. To understand the root cause of failures, the failed terminations as well as working cable terminations were received at laboratory for analysis. The length of terminations with attached cables were not long enough, to carry out routine electrical test on the sample as per the relevant test standards. Therefore, analysis of the cable terminations was carried out to check the internal components, surface preparation and general workmanship. The analysis showed significant deviations from standard operating procedures (SOP) in preparation and installation of the cable terminations which led to failures of the cable terminations.

The electrical stresses are maximum at the edge of semi-conductive layer, to control these stresses either geometric or capacitive stress control is used [2]. All the cable terminations analysed were having capacitive electrical stress control (ESC) tube to reduce the electrical stresses. It appeared that there was no uniformity of installation of ESC tube on the semiconducting layer i.e. the length and placement of ESC was random. Most of the damage in failed cable terminations were observed under the ESC tube, near the cable junction. This indicated a problem area of high electrical stress concentration. To understand the nature of electrical stress under the ESC tube, FEM analysis was carried out. Actual cases of as-prepared terminations were simulated to understand how the electrical stress concentration changes with ESC tube placement. This analysis indicated high electrical stress points near the cable junction and ways to reduce the electrical stresses so that the failure rate can be minimised.

2.0 Sample Details

To analyse the frequent failures of cable terminations, in this study total 8 cable termination were received at our laboratory for analysis. Out of 8 samples, 4 were failed cable terminations, 2 unused healthy cable terminations and 2 healthy cable terminations removed from service. All cable terminations were for 33 kV single core XLPE insulated cables. The details of as-received samples and preliminary observations on the same are given in Table I. The service life of all the cable terminations were not more than 2 years.

To understand the terminology used in the paper, various components of cable termination are shown in Figure 1. The cable terminations analysed were having capacitive stress control tubes near the cable junction to minimize the electrical stresses at the edge of semiconducting layer.

Table I: Cable termination samples received for analysis

Sample Received	Description	Observation
Sample 1	Failed	Silicone sheath damaged with black marks
Sample 2	Failed	Punctures near cable junction
Sample 3	Failed	Sheath puncture near (lug) termination end
Sample 4	Failed	Puncture near cable junction
Sample 5	Healthy, removed from service	No abnormality
Sample 6	Healthy, removed from service	Bulging of sheath near cable junction
Sample 7	Unused, Healthy	No abnormality
Sample 8	Unused, Healthy	No abnormality

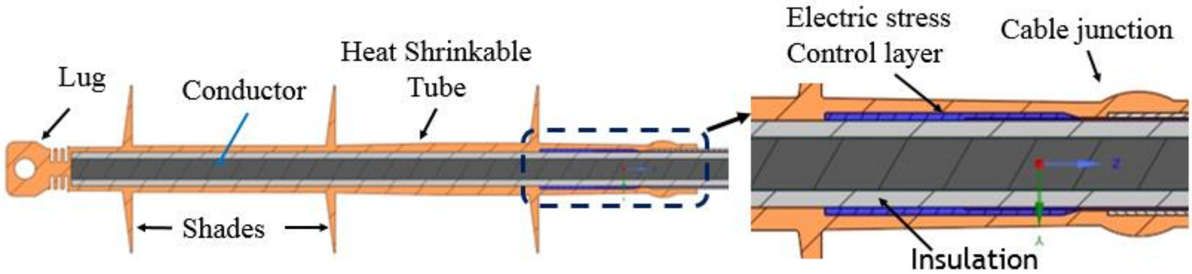


Figure 1. Cable termination components

3.0 Visual Examination

Both failed and working cable terminations were subjected to visual examination to understand the construction details and decide prima-facie causes of damages.

3.1 Analysis of Failed Cable Terminations

One of the failed sample showed gap at the cable junction, and indicated that the inner components were exposed to outer environment, as shown in Figure 2. This also indicated that the outer heat shrink tube was not properly heat treated or not treated at all. The termination had failed with visible damage between the first and second shades, as shown in Figure 3a. Back side of the damaged surface showed a fold in the heat shrink tube as shown in Figure 3b. After cutting the heat shrink tube from the folded region, electrical stress control (ESC) tube is visible which was also folded near the damaged area, refer Figure 3c. It appears that both the heat shrink tube and ESC tube moved upward because of improper installation. Since both the ESC tube and heat shrink were not heat treated and only loosely placed on the termination, it may have folded during installation on an electric pole. The cable termination was installed on an electric tower and connected to an overhead conductor.

Removal of the outer heat shrink tube and ESC tube revealed puncture in the XLPE insulation, as shown in figure 4a. After cleaning the surface of the XLPE insulation under the ESC tube, showed surface morphology indicating localised heat over a long period of time, refer Figure 4b. The localised heating may have taken place because of electrical discharges due to improper placement of ESC tube and lack of heat treatment resulting in air cavities in the cable termination.

Most of the XLPE insulation in the cable termination had blackened because of degradation of insulation due to the electrical discharges. Only one area where heat shrink tube was properly attached to XLPE insulation remained unaffected. This was the results of poor adhesion of heat shrink tube with XLPE insulation resulting from improper heat treatment.

Figure 2: Images near the cable junction: a) the heat shrink tube slipped away from junction highlighted by yellow arrow and b) gap visible between heat shrink tube and internal layer of termination

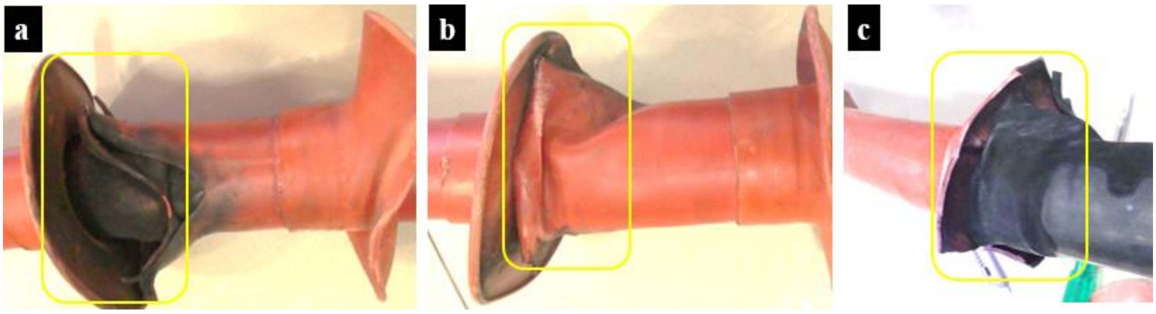


Figure 3: Damaged cable termination: a) blackened part near a shade and b) fold in head shrink tube and c) after removal of heat shrink tube, folded stress control tube is visible. Damaged part highlighted in box

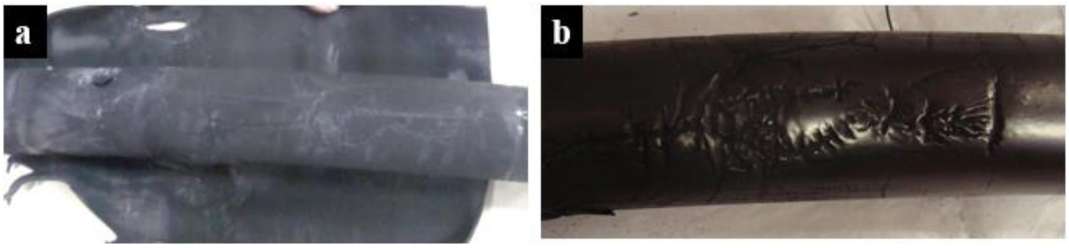


Figure 4: a) Stress control tube under heat shrink tube removed from XLPE insulation and b) damaged XLPE insulation indicating localised heating

Two more cable terminations were found damaged in the same region below the ESC tube. The damaged area with ESC tube was visible, the XLPE insulation found punctured beneath the ESC tube. In this cable termination the components of cable junction were corroded indicating water ingress, visible in Figure 5a. Improper sealing of the cable junction may have resulted in the water ingress. The ground connection, near the cable junction, was connected through steel wires wrapped around the copper shield. Due to the tight fitting, the wires partially penetrated the insulation thereby changing the localised electric field, refer Figure 5b. The XLPE insulation also showed indications of tracking which might have resulted from high electrical stresses.

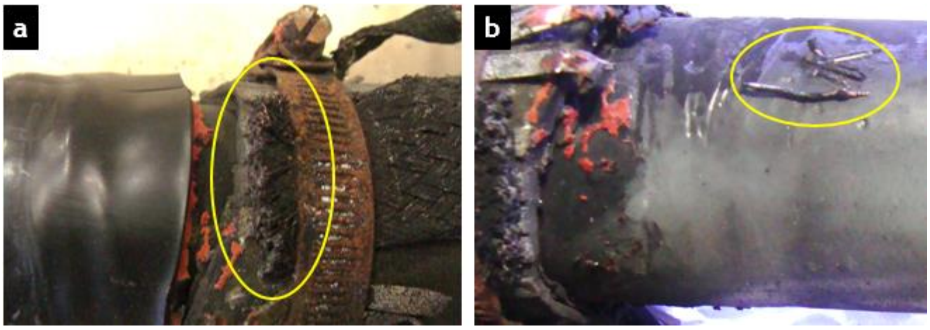


Figure 5: a) Ground connection at the hose clamp and b) Wires used for grounding on copper screen penetrated the insulation

Among the four failed samples, only one of the cable termination failed near the termination end. This sample showed number of cuts in XLPE insulation near lug as shown in Figure 6. These cut showed clear tracking marks indicating high electrical stresses. The sharp edges in the insulation resulted in localised concentration of electric stresses leading to tracking and failure of the cable termination.

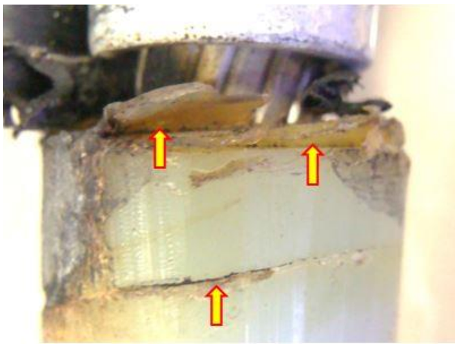


Figure 6: Cut marks on XLPE insulation shown by arrows

3.2 Analysis of Sample Removed from Service

One of the apparently healthy sample removed for analysis had a cut mark on outer heat shrink tube. The cut mark was located approximately mid distance from cable junction and inner XLPE insulation was visible. This indicated poor handling and installation of the cable termination. The cable termination was cut open for visual analysis. Opening of the cable junction led to powder falling out from the cable junction. When insulation tape from the cable junction was removed, accumulated white-green colour powder was visible on the cable junction. The copper screen and aluminium armour was found completely corroded, as shown in Figure 7.

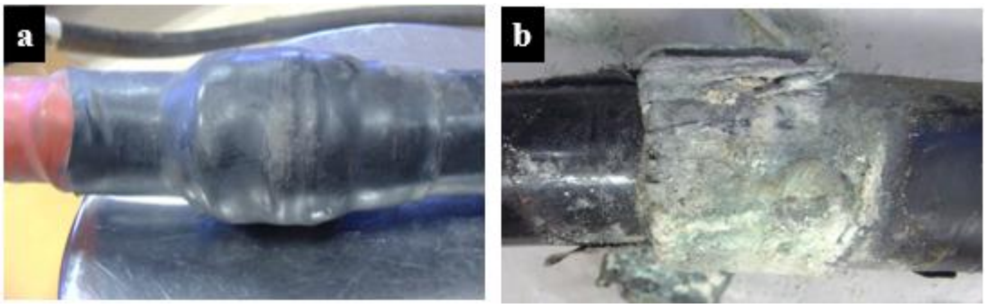
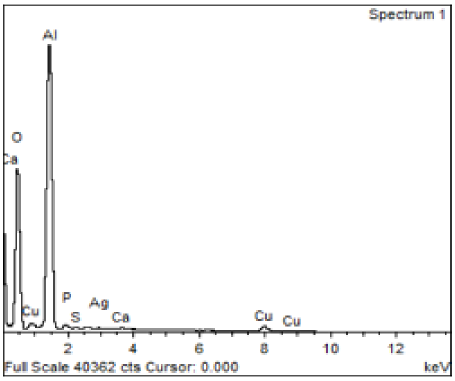


Figure 7: a) Cable junction before opening, b) after removal of outer layer – white green powder observed and copper screen and aluminium armour found corroded

The white-green residue at the cable junction was analysed using Energy Dispersive X-ray Spectroscopy (EDS). EDS gives the elemental composition of material under investigation. EDS spectra of the powder collected from the cable junction is shown in Figure 8 along with the result table. The EDS result of powdered residue, from cable junction, showed prominent presence of aluminium oxide and copper oxide, both are by-products of corrosion reaction. Rest of the elements found in EDS investigation were in low quantity and may come from fillers used in polymeric insulation.

It appears that water along with dust particles may have entered the cable junction which was indicated by dust collected along the grounding wire path as shown in Figure 9. At the cable junction, two dissimilar materials, copper and aluminium, are bound together this can result in galvanic corrosion. The water acts as an electrolyte in presence of two dissimilar metals resulting in accelerated corrosion of copper and aluminium. This results in formation in corrosion by-products copper oxide and aluminium oxide in the form of white-green powder. This may cause failure of cable termination because ground connection was almost lost.



Element	Weight%	Atomic%	Compd%	Formula
Al K	47.13	37.07	89.06	Al_2O_3
P K	0.97	0.66	2.22	P_2O_5
S K	0.33	0.22	0.83	SO_3
Ca K	0.35	0.19	0.50	CaO
Cu K	5.29	1.77	6.62	CuO
Ag L	0.73	0.14	0.78	Ag_2O
O	45.20	59.95		
Total	100.00			

Figure 8: EDS spectrum (left) and elemental analysis results in table (right)

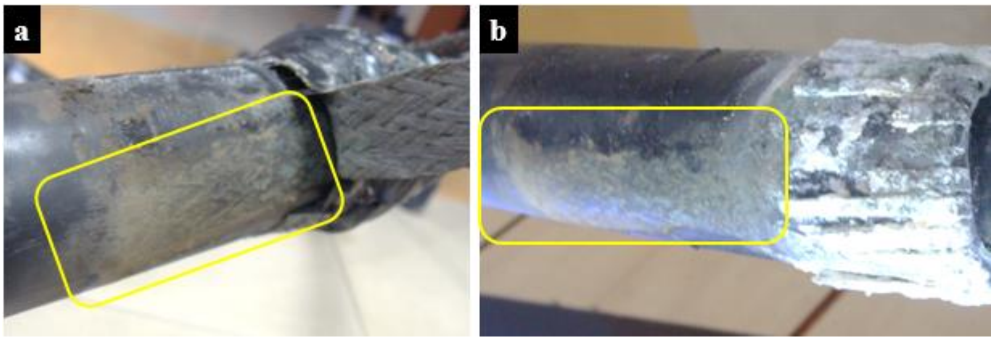


Figure 9. Indication of dust collected along the grounding wire path (yellow box): a) before opening the junction, b) after opening the cable junction showing corroded aluminium armour and copper sheath.

3.3 Analysis of Healthy Samples

To check the quality of cable termination, as prepared not in use cable termination was opened up for analysis. It was observed that most of the heat shrink tubes on cable terminations were not properly heat treated, resulting in loose contact between heat shrink and XLPE insulation which can cause internal discharges. To check the quality of heat treatment of heat shrink tube, one circular piece was taken from heat shrink tube. Thickness of tube was measured at three locations and then the sample was put in oven at 200°C for 30 minutes. The change in dimension of heat shrink tube, before and after heat treatment, is visible in Figure 10. The wall thickness values of as-received sample and after heat treatment, is given in Table II. Wall thickness of heat shrink tube from as received cable termination shows large variations in wall thickness indicating non-uniform heat treatment during preparation. After heat treatment, the wall thickness has increased and became uniform. This indicates that the quality of heat shrink tube was good but the heat treatment was deficient at the time of termination preparation. This issue was observed for most of the cable terminations.

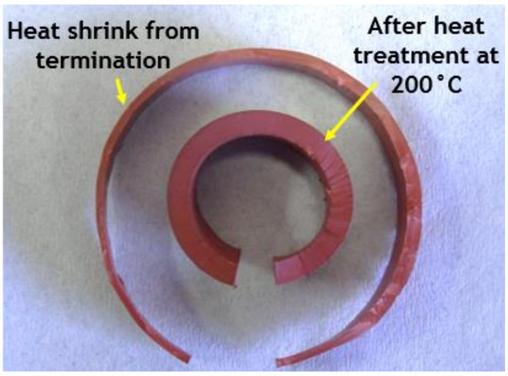


Figure 10: Outer tube is a piece of heat shrink tube removed from termination sample-10 where the thickness is uneven and inner tube is after heat treatment at 200°C

Table II: Wall thickness of heat shrink tube

Sample Detail	Wall Thickness [mm]		
	Location-1	Location-2	Location-3
As received heat shrink	1.34	1.74	3.07
After heat treatment in oven	3.57	3.72	3.77

Many of the healthy cable terminations showed rough surface of XLPE, which indicated that insulation was not polished or cleaned, as shown in Figure 11a. At several places the semi-conducting layer was not properly removed from the insulation, Figure 11b. The partially remaining semiconducting layer can increase the localised electric stress which can lead to failure. Edge of the semiconducting layer near the cable junction was not properly smoothened, living behind edges of semiconducting layer as shown in Figure 11c. Sharp edges result in localised concentration of electric field.

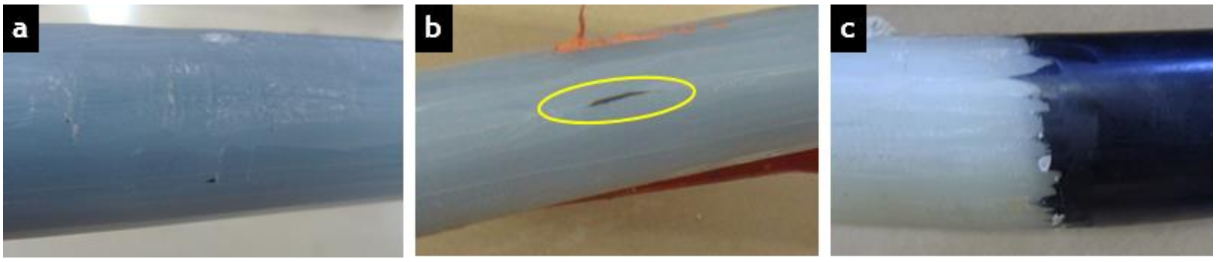


Figure 11: a) Cut marks and rough surface of XLPE insulation, b) Partial semiconducting layer remained on XLPE insulation and c) Un-evenly cut edge of semi-conducting layer

In all the failed and working cable termination it was found that the placement of ESC tube was not consistent. The length of ESC tube was different; the copper screen and semiconducting layers had different lengths, as shown in Figure 12 for two samples. Gap between semiconducting layer and ESC tube was also observed in some cases. This non-uniformity in sample preparation may have resulted in different electric field profile and stress concentration near the cable junction. To understand the electric field distribution near the cable junction FEM analysis was performed.

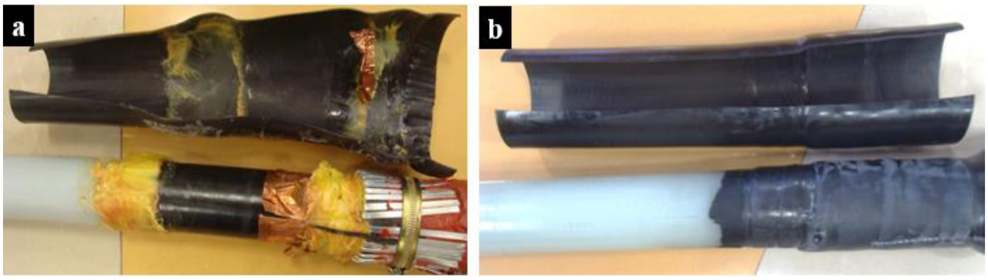


Figure 12: Near cable junction, semi conducting layer and detached electrical stress control tube from two different cable terminations

4.0 FEM Analysis

Various components of cable termination play an important role to reduce the localised electrical stresses, otherwise uncontrolled electrical stress may lead to failure. In a continuous shielded cable the electric field stress varies radially, with maximum stress on insulation near the conductor. For preparation of termination the continuity is lost because the shield is removed as certain insulation distance has to be maintained from the exposed conductor. This discontinuity in the cable results in high electrical stress at the edges of semi-conducting layer. The electrical stress at the edge of semi-conducting layer can be higher than at the insulation near the live conductor. Therefore to reduce this excess electrical stress an electric stress control (ESC) tube is wrapped around the semi-conducting layer [2]. The ESC tube distributes the electrical stress so that electrical field lines are not concentrated at the edge of semiconducting layer.

The ESC tube overlaps the XLPE insulation with semiconducting layer as shown in Figure 13. At the edge of semiconducting tube, when covered with ESC tube, three interfaces are overlapping which are: XLPE insulation, semiconducting layer edge and ESC tube, this junction is called 'triple point'. In this simulation work, electrical stress at the triple point is evaluated as the actual length observed in the cable termination prepared on site and compared with an optimised case where the electrical stresses are minimised.

Case-1 (as received termination): dimensions measured from one of the as-received cable termination:

- length of semi-conducting (SC) layer (L) measured from edge of copper screen (Figure 13) = 65 mm,
- Length of electrical stress control (ESC) tube
    1. Actual length = 30 mm from triple point
    2. Proposed optimised length used for simulation = 10 mm

Case-II (Proposed changes): All the above dimensions of cable termination remains same but dimensions of semi-conducting layer and ECS tube are modified as -

- Length of semi-conducting layer (L) = 30 mm
- Length of electrical stress control (ESC) tube
    1. Actual length = 30 mm from triple point
    2. Proposed optimised length used for simulation = 10 mm

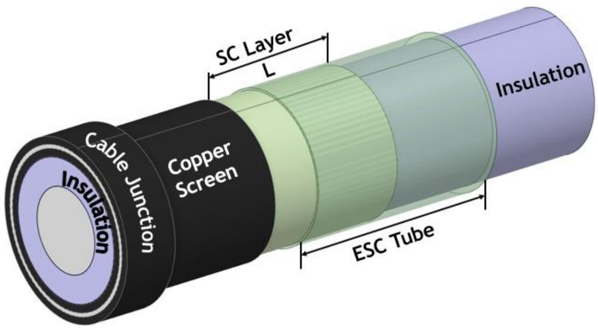


Figure 13: Sketch of cable termination components near cable junction

In order to understand the behaviour of cable under stressed condition, simulations were performed using commercially available FEM simulation software. The FEM simulations were performed to check the impact of geometrical changes on the peak value of electric stresses. The material properties used for FEM simulations are tabulated in Table III. For each of the above two cases the length of ESC tube was changed 30 mm and 10 mm.

Table III: Permittivity and conductivity values for the materials are as following,

Material	Relative Permittivity#	Conductivity (S/m)*
Aluminium Conductor	1	38000000*
Copper Sheet	1	58000000*
Outer Sheath	4	0
Inner Sheath	4	0
Semiconducting Layer	4	0.001
XLPE Insulation	2.3	0
Electric stress control tube	30	0

Note:

For FEM simulations, relative permittivity of aluminium and copper is set as 1. Electrical conductors have no bound electrons therefore they are modelled as free space for simulation purpose.

* Electrical conductivity values of aluminium and copper are taken from databank included with FEM simulation software.

Figure 14 shows FEM simulation results. The ESC length is set to several groups to better indicate its influence on electrical stress. A case where ESC tube is not installed also considered to show the large value (10.2 kV/mm) of electrical stress as triple point (this case was not observed in actual cable termination). When ESC covers the triple point the electrical stress reduces to around 4.4 kV/mm. FEM simulations were carried out to find the optimum value of length of ESC that covers the triple point towards the end of termination. Simulations were performed by increasing the length of ESC in step of 5 mm from the triple point. The optimum length was found to be 10 mm from triple point, a length more or less than 10 mm increases the electrical stress at triple point. Optimization of ESC tube length can reduce the electrical stress by 1 kV. This optimised length ESC tube corresponds to a particular case with material properties in Table III. Therefore, optimum design and length of each component near cable junction will vary for different manufacturer due to variations in material properties of the termination kit. Optimization of different parameter based on material properties is important for cable termination to reduce the electrical stress. Optimization of localised electrical stresses at the cable junction can result in better performance of cable terminations with reduced failures.

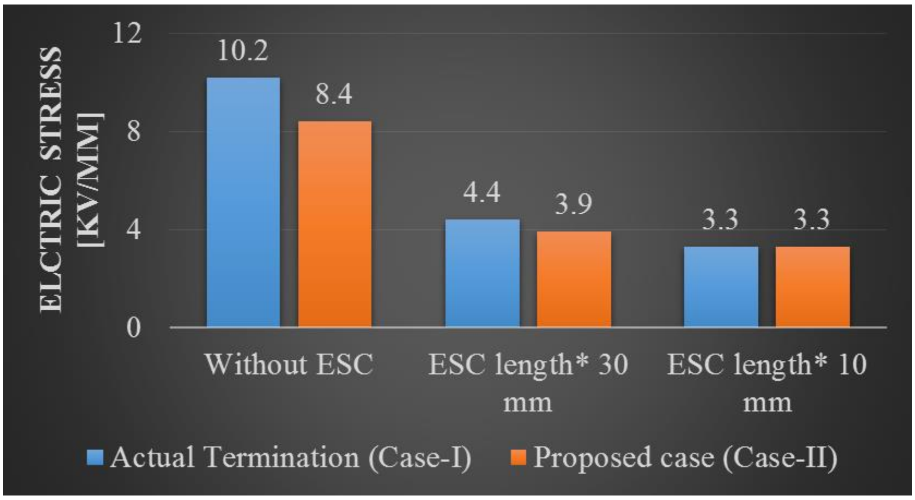


Figure 14: Electrical stress in the actual and proposed geometry of cable termination with or without electrical stress control (ESC) tube. (*ESC length – overlap of ESC tube measured from triple point towards end of cable termination)

Some of the cable terminations were not properly heat treated, increasing the possibility of air gap over the XLPE insulation and the semiconducting layer. FEM simulation results of a case where air gap is present between insulation or semiconducting layer and ESC tube is shown in Figure 15. In both cases ionization of air can lead to electrical discharges and failure of cable termination. Therefore, uniform and proper heat treatment of the ESC tube and heat shrink tube is essential.

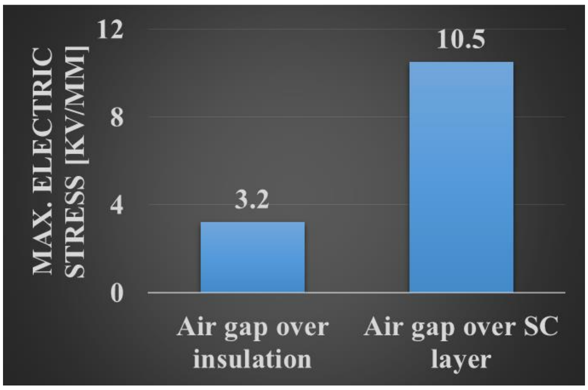


Figure 15: FEM simulation results in case of air pockets under ESC tube for air gap over insulation and air gap over semiconducting layer (SC layer)

5.0 Conclusion

Analysis of failed and healthy cable terminations indicated following factors which resulted in frequent failures:

- Improper heat treatment of heat shrink tube and electrical stress control tube which results in gap between the insulation and respective component
- Use of non-standard tools resulted in deep cut marks and rough surface of XLPE insulation
- Semiconducting layer improperly removed leaving behind visible traces on insulation. At the triple point, the semi-conducting layer had sharp edges.
- Cable junction was improperly sealed which allowed water in the cable termination
- Cable terminations were not prepared in clean environment, dust particles visible on some inner components
- Outer heat shrink tube showed deep cut marks indicating improper handling during installation

Above factors indicated that the preparation of cable terminations was lack of skill and not following standard operating procedures (SOPs). Such SOPs include either the manufacturer's recommendations or standard guidelines, such as CIGRE brochure 476 [3]. It is important to follow detailed guideline for cable termination preparation to avoid such failures. It is better if the manufacturer to carry out termination preparation and installation work to minimize the common mistakes. It is also recommended to do electrical testing of the cable terminations as recommended in relevant standard.

FEM analysis showed high electric stresses at the triple point which can further enhance in case of improper placement of ESC tube or presence of air gap between the stress control tube and inner insulation. Length of semiconducting layer and ESC tube can be optimised based on material properties to minimize the electrical stresses at triple point.

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