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Classifying Faults Locations in Cable Terminations and Investigation of the Faults Reasons

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Abstract: Cable termination faults are problematic in electrical networks almost always. Technology has solved problems somewhat, but there are many annual reports about damaged cable terminations. For analyzing the problems, faults in two regional electricity companies are studied. At first step, damaged cable terminations are analyzed statistically and grouped according to their problems. Then, some of the damaged cable terminations are checked to classify vulnerable areas. The investigation is completed by simulation, analysis and study of equivalent circuit. Conclusions underline important points which can be helpful for reducing the damages.

Keywords: Cable Termination, Stress Grading, Assembly Error, Triple Point, Insulation Layers, Partial Discharge.

1 Introduction

Cable terminations connect points in medium voltage (MV) and high-voltage (HV) networks and using them is irrefutable. Most of the previous studies focused on stress grading mass and tube as essential parts [1,2]. Materials properties impact electrical field stress in triple points which is connection between semiconductor layer, stress control layer and XLPE [1,3]. Stress in critical points and equivalent circuits depend on dielectric coefficient and electrical conductivity. Stress grading tubes with high resistivity are success in confronting with the stress, but, they have thermal limits [3,4]. Nonlinear materials show flexible reactions under different electrical fields and they control stress related to electric filed values [6-8]. The nonlinear materials cost is a problem and they need high technology which make resistive stress control universal (Medium-voltage cable terminations (20 kV) are usually heat shrink with resistive stress control tube).

There are many reasons that cause breakdown in cable termination layers. Thermal breakdown happens when produced heat doesn't transfer suitably [3,4]. It depends on material properties or some problems take place during installation. With carelessness in critical points a disaster happens and the only way is cable termination replacement.

Harmonic, weather condition for outdoor terminations, partial discharge, cavity and pollution under layers are the other reasons for fast breakdown in cable terminations. Material properties and breakdown reasons have been discussed in most of the published titles [1-10]. For classifying the occurred problems, breakdown statistics for two regional electricity companies in Iran are studied in the paper. Fifty damaged cable terminations are analyzed to identify percentage of fault locations. According to the review about damaged cases, fault reasons are investigated by finite element method (FEM) and analytical methods. Conclusions underline important points which can be helpful for reducing the damages.

2 Damaged Cable Terminations

In this part fifty damaged terminations were chosen and analyzed to identify faults common regions. In most of the damaged terminations, faults occurred in connection edges of different layers. The first rank of damaged region was main triple point connection in which stress control layer (SG), XLPE and semiconductor (the most sensitive edge) connect to each other. Breakdown in main triple point punctures layers

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as SG and causes flowing current between the point and ground which burns termination in the region (see Fig. 1).

About 35 terminations had damages in main triple points region (70% of faults) that introduces the region as the most sensitive part. It is anticipated 30% of the remind breakdown belong to other connection edges between layers. The connection edges between layers in cable termination are:

1. **Case 1**- Triple point between: XLPE, SG and silicone rubber (near cable junction);
2. **Case 2**- Connection between: silicone rubber and XLPE near cable junction;
3. **Case 3**- Triple points between: SG, XLPE and semiconductor (near the sensitive triple point).

In all of the edges, electrical field increases strongly. High value of electric field produces a high drop voltage between the edges and ground which causes partial discharge and breakdown. A short distance between the critical triple point (explained in Fig. 1) and ground impacts possibility of problems in the region. Similar problems occur in the other edges connections with less intense. However, about 30 percent of the failures assigned to the edges near case 1 and case 2 (Figs. 2 and 3).

According to the review, breakdown occurs in edges connection especially in triple points almost always (Figs. 1-3). Assembly errors during instruction intensifies the failures. Electric field has maximum values in the edges connections that can be affected by assembly errors.

3 Simulation and Test Methods

Electric field in cable terminations for assembly errors should be calculated and analyzed. Electric field simulation in cable terminations is possible by FEM method. Geometry of termination and material properties have to be imported in a software which analysis electromagnetic equations based on FEM method. According to information about system and cable termination situation, boundary conditions were defined in the software. In Fig. 4 and Table 1 geometry of simulated cable termination and layers properties are illustrated (simulations are 3D). To study assembly errors some of the geometry and boundary conditions were changed based on the case studies.

PD occurs in cable termination insulations as the results of high value of electric field. Thus, PD analysis has to be done in the study. PD severity and possibility can be studied by an acoustic PD analyzer [12] or other kinds of PD analyzers. To show impacts of the problems in edges connections, a cable termination with assembly problems was prepared. The setup consisted of a high-voltage circuit, a 20kV heat shrink cable termination, a small oil tank for the second side of termination and PD analyzer (Fig. 5). The oil tank prevents happening breakdown and arcs in the second side of cable

Fig. 1 Damaged and burned cable terminations in main triple point region.

Fig. 2 Damaged cable terminations in case 1.

Fig. 3 Damaged cable terminations in case 2.

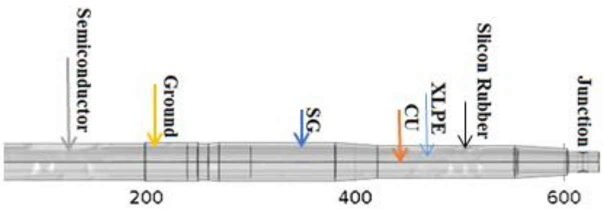

Fig. 4 Geometry of 20kV heat shrinks cable termination (diameter are in mm).

Table 1 Properties of cable termination layers used in simulations.

Layers	Electrical conductivity (S/m)	Dielectric coefficient	Thickness (mm)	Length (cm)
Inner insulation (XLPE)	10^{-14}	2.3	5	55 (from earth till junction)
Stress grading mass	10^{-10}	10	2	5
Stress grading tube	10^{-6}	8	2	20
Semiconductor	10^{-3}	1	1	5 (from earth till triple point)
Cover insulation	10^{-11}	3.5	2	60

Fig. 5 Test setup consist of PD analyzer, HV circuit (1), PD sensor (2), cable termination (3) and oil tank (4).

Fig. 6 HV test arrangement.

termination. Based on cable termination standard tests (IEEE Standard 48™-2009), additional AC, DC and impulse were done. The HV tests need usual test setup as shown in Fig. 6.

Introduced simulation and test methods were used for the case studies and results are visible in figures and tables as the main parts of analysis.

4 Analysis of Effective Assembly Errors

Different assembly errors occur during installation that have been noticed in reports. Some of the errors are more effective as: remaining void because of not appropriate heating, forming scrapes on XLPE during removing semiconductor, remaining semiconductor under cable termination insulations and remaining wet and pollution under insulation layers. For distinguishing cable termination sensitivity to the problems, they are discussed and analyzed in the following parts.

How to heat termination layers is important. Heating paste the layers (SG and silicon rubber) in to the others (XLPE, semiconductor and etc.). If during heating a void or voids remain between the layers, partial discharges (PD) would occur in their locations. The voids may contain air, wet or contaminations which change equivalent circuit and electric field distribution formations. Changes in dielectric coefficient and electrical conductivity in voids area disturb potential distribution in other regions which causes occurring PD.

Maximum electric field in the triple point is about 2×105 V/m in common condition. When a void adds to the region by not enough heating in the area, electric field increases 10 times (Fig. 7). The electric field value in air void is more than air breakdown that creates PD. PD occurs continuously in each cycle and develops the void till punctures termination. In Fig. 7 void is simulated by a layer of air in which electric field would be similar to void.

As mentioned before, electric field increases in the void or the layer of air and makes a high potential difference between both sides of the void. Insulation endurance weakness in the layer of air causes PD and breakdown. For more clarification, electric field and electric potential curves on boundary conditions are shown in Figs. 8 and 9.

At end edges, internal and external boundaries connect to each other (Z = 310 mm and Z = 340 mm) in which there is no electric potential difference (Fig. 9). There is a constant electric potential difference between other parts of the boundaries (about 3kV/mm) and PD will occur (Fig. 9). Study of the air layer effect was done by changing its location and average electric field value (by equation (1)) in the air layer was calculated. Simulations consisted of ten cases for the layer location. Average electric field in three of them had maximum

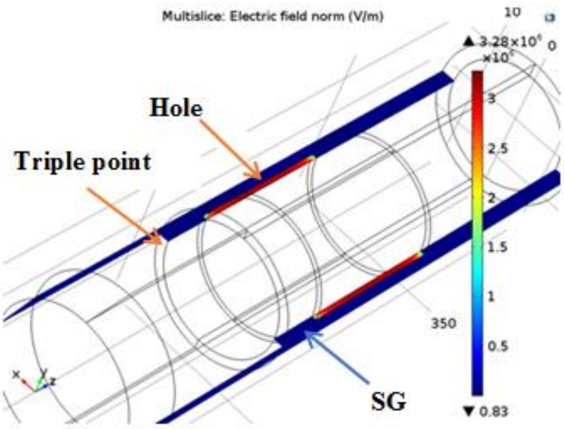

Fig. 7 Electric field in a layer of air between XLPE and SG near main triple point.

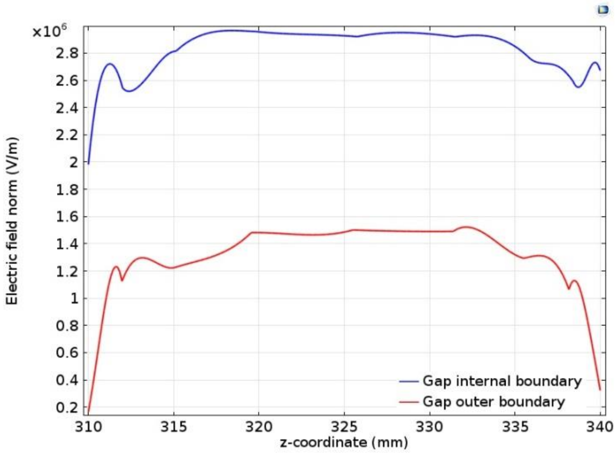

Fig. 8 Electric field on internal boundary condition of the layer of air (subscribe to XLPE) and external boundary condition (subscribe to SG).

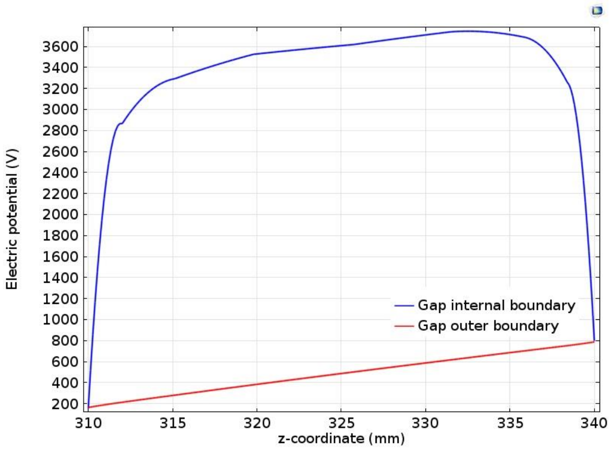

Fig. 9 Electric potential on internal boundary condition of the layer of air (subscribe to XLPE) and external boundary condition (subscribe to SG).

values which are compared in Table 2. Based on the results, electric field is critical for the air layers located under SG and near layer connection, especially near to main triple point.

$$E_{av} = \frac{\iiint E.dV}{V} \tag{1}$$

By a simple high-voltage test, impacts of remaining void are searchable (a void under SG layer and near the main triple point should be created). AC overvoltage made problems for the case study and treeing effect occurred in SG tube as shown in Fig. 10.

The first step of termination assembly is removing insulation cover (silicone rubber) and semiconductor. The step needs enough accuracy and carelessness makes scrapes on XLPE. Permittivity of the scrapes is equal to air that causes increasing electric field and possibility of PD in the scrapes. Studying impacts of scrapes on PD and insulation lifetime is possible with simulation and test results. Thus, scrapes were made at different parts of XLPE in the simulations and their effects on electric field were obtained as shown in Table 2. As the previous case, scrap near main triple point has maximum electric field value in which happening PD seems possible.

In cable termination assembly, after removing cover insulation, semiconductor should be removed till 4cm left to the cut point. Imperfect removing of semiconductor causes non-uniform electric potential distribution and increasing current density in the remaining semiconductor area. The situation has a secondary effect on other regions and increases electric potential in them. Thus, PD possibility seems high which is obvious in simulation and test results.

Simulation of reminding semiconductor in different positions shows reminded parts near the triple points making high sensitivity. Current density near semiconductor, SG and cover insulation connection has the highest values as shown in Table 3.

Reminding wet and pollution under layers is the last case studied in this part. Insulation layers should be cleaned during installation, because reminding wet or pollution may cause a fault in cable terminations. In the simulations, wet and pollution were assumed with different electrical conductivities in sensitive parts. According to the results in Table 4, wet and pollution have the most effect on current density when they remain under SG tube.

Impacts of remaining wet and pollution were studied by moistening surface under SG layer. By connecting cable termination to HV test circuit, current density increased intensively in rated voltage that damaged XLPE and SG tube as shown in Fig. 11.

At the end of this part, the events are explained by equivalent circuit. Regions with high electric field can be assumed as an electrode and the grounded shield wire is second electrode (Fig. 12). When electric field increases in the voids area, it produces an electric potential between the electrodes. Areas as the voids with weakness in insulation endurance can't stand under stress and PD occurs in them. PDs extent the void and

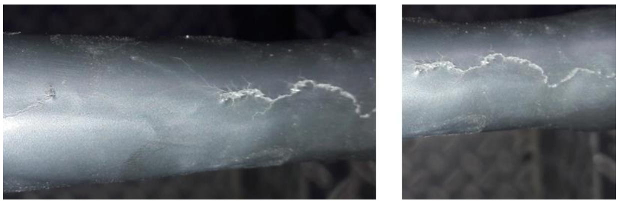

Fig. 10 Treeing effect in the area with void under SG.

Table 2 Average electric field for air layers and scraped XLPE in different locations.

Void location	Average Electric Field (V/m)	Scraped XLPE Location	Average Electric Field (V/m)
Between SG and XLPE- near main triple point	2.92e6	Near main triple point	3.65e6
Between SG and XLPE- far from main triple point	2.41e6	Between earth and triple point	3.00e6
Between XLPE and silicone rubber connection- near junction	2.3e6	Near junction	1.62e6

Table 3 Average current density in reminded semiconductor area.

Reminded Semiconductor Location	Average Current Density (A/m^2)
Under SG near semiconductor-SG- cover insulation connection	5.1e-6
Under SG- middle of the tube	2.84e-6
Under control stress- near XLPE-SG connection	1.84e-6

Table 4 Average current density due to different levels of wet and pollution in different areas.

Electrical Conductivity of Wet and Pollution (S/m)	Location of Wet and Pollution	Average Current Density (A/m^2)	Location of Wet and Pollution	Average Current Density (A/m^2)
5.00e-15	Under cover insulation and near earth-semiconductor connection	1.8e-13	Under SG - middle of the tube	2.1e-8
5.00e-12		5.1e-11		1.09e-7
5.00e-09		8.67e-11		4.9e-6
5.00e-06		1.85e-8		5.2e-6
5.00e-03		3.4e-6		5.22e-6
5.00e+00		4.18e-6		2.5e-6
1.00e+02		4.18e-6		2.51e-6

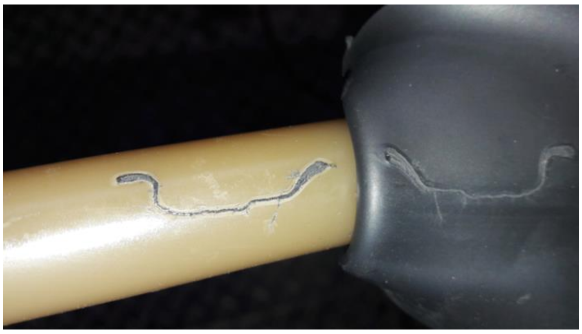

Fig. 11 Fault under SG because of wet and pollution.

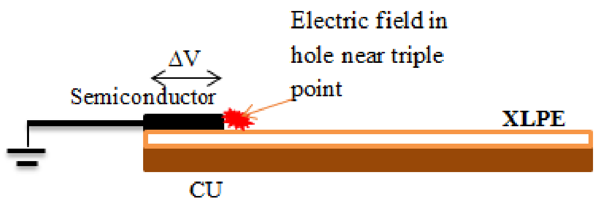

Fig. 12 Drop voltage and created electrodes between void and ground.

increase drop voltage that is the reason of treeing and puncture. Possibility of the introduced fault is high when there is nonconformity near triple point connections.

5 Analysis of Possible Events by HV Test

According to the previous discussions, problems in the critical area can happen because of some reasons as; scarping XLPE, remaining semiconductor under SG or silicone rubber, and etc. The noticed cases cause changing in equivalent impedance and voltage distribution. In edges two or three layers connect with heating in which electric field has maximum value. The problems intensify electric field by changing voltage distribution which causes PD.

In the case with problem under SG, PD starts from 9 kV and the analyzer registers 1000 PDs point during 22-second near the triple point area (Fig. 13 contains details of the test). PD starting voltage is less than rated voltage which reduces the termination insulation lifetime quickly.

According to the simulation results, three cable terminations with problems were prepared and tested (based on IEEE Standard 48™-2009). Results of AC, DC, impulse, and PD tests were registered for the three case studies. Scraps and reminded semiconductor were made in different parts of case studies. But, PD happened near layer connections (especially around main triple point) that confirms the paper discussion. Problems under SG tube (wet and pollution or void) and reminded semiconductor caused too many numbers PD under rated voltage in a short period of time (Table 5 last row). Thus, they can be considered as the two main mistakes in cable termination assembly.

PD test helps to find cable termination with problems. In the project related to the paper topic, PD test was done for real cases in substations. PD reports for 20 cable terminations were registered and in one of them occurring PD was observed as shown in Fig. 14. In the real case, 1000 PDs occurred during several minutes which means the cable termination needs to be replaced. Most of the PDs happened in maximum voltage (Fig. 14- around 90° and 270°) and its distribution is less than PDs in Fig. 13. All the mentioned points illustrate critical situation and fault in near future (PDs cause growing its happening reasons).

6 Exhaustion

The other effect of increasing electric field in edges connections with voids or other problem is exhaustion. Exhaustion occurs because of PD and electro-mechanical pressures. PD is a familiar topic in insulation studies, but less attention has been paid to electro-mechanical forces. This force has relation with electric filed to power 2 and dielectric coefficient difference between the two materials. In layers edges connections, electric field increases and dielectric differences have attention values in the case with voids and other problems.

Layers connections edges have geometric angles and for the pressure calculation, there is an equation as bellow.

$$P_{12} = \frac{\varepsilon_2 - \varepsilon_1}{2}.E_1^2\left(1 - \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2}.\cos^2\alpha_1\right) \tag{2}$$

where α_1 is angle between electric field and vertical vector to the surface. If we assume $\varepsilon_2 > \varepsilon_1$ thus for different parts of (2) can write:

$$0 < \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2}.\cos^2\alpha_1 < 1 \tag{3}$$

$$0 < \left(1 - \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2}.\cos^2\alpha_1\right) < 1 \tag{4}$$

$$\frac{\varepsilon_2 - \varepsilon_1}{2} > 0 \tag{5}$$

So, the pressure pushes out insulation layer and expands it. Further, the second layer puts pressure to the first layer and its relation can be as (6).

$$P_{21} = \frac{\varepsilon_1 - \varepsilon_2}{2}.E_2^2\left(1 - \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1}.\cos^2\alpha_2\right) \tag{6}$$

Similar to the previous step:

$$0 < \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1}.\cos^2\alpha_2 < 1 \tag{7}$$

$$0 < \left(1 - \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1}.\cos^2\alpha_2\right) < 1 \tag{8}$$

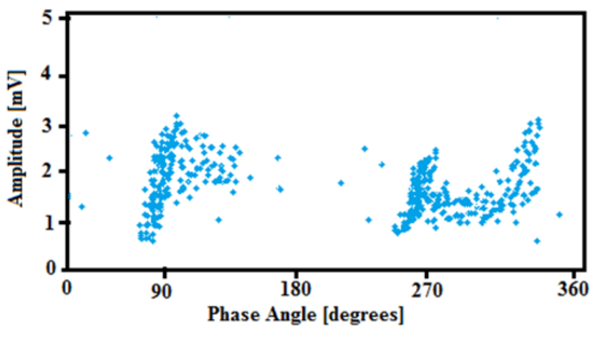

Fig. 13 Amplitude in mV during periods according to phase angles for problems under stress control tube.

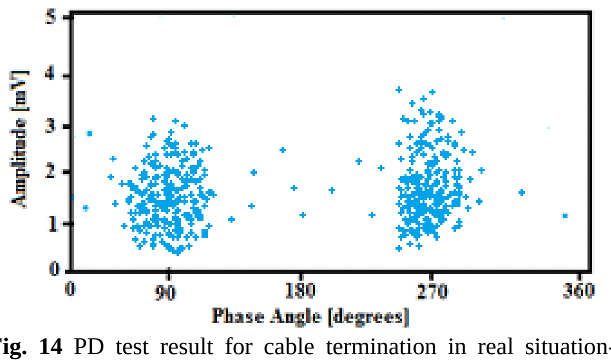

Fig. 14 PD test result for cable termination in real situation- 1000 PDs registered during minutes.

Table 5 HV and PD test for cable termination with assembly errors.

Test title	Scraped XLPE	Reminded semiconductor	Problem under SG near main triple point
AC (1 min-52 kV)	Corona noise- intense sound of PD in 45 kV	Without corona noise	High corona noise
AC (5 min-52 kV)	Intense PD after 2min	Intense PD after 3min	Intense PD
AC-Wet (10 s-47 kV)	Weak PD sound	Without corona sound	High PD sound
DC (15 min-85 kV)	Continues PD sound	Continues PD sound	Intense and continues PD
Impulse (100 kV)	Without breakdown	Without breakdown	breakdown
PD	520 PDs in 80s- 14.5kV	1000 PDs in 44.7 s-4.5 kV	1000 PDs in 22 s-9 kV

$$\frac{\varepsilon_1 - \varepsilon_2}{2} > 0 \tag{9}$$

So, the force is negative that pulls inward insulation layer and constrict it. The pressures deform insulation layers on boundary conditions. More stress and insulation exhaustion are results of the deformation.

Electric field values in edges make the issue important. The condition becomes more destructive when PD occurs. During PD, electric field in one side is equal to zero which makes the pressures unbalanced. Due to the number of PDs in critical situations (as the test result), high frequency stress and shakes intensify exhaustion. Fig. 15 shows different forms of boundaries between a void and insulation layer during PD. In the steps of Fig. 15, shaking the boundary is obvious which can exhaust insulation and decrease insulation lifetime. Exhausting can cause mechanical breakdown in termination or lead to reduce mechanical durability as shown in Fig. 16.

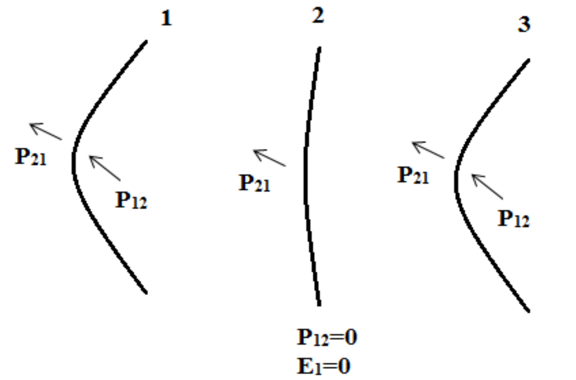

Fig. 15 Deformations during PD in void-insulation boundary- 1) balanced pressures from 2 sides- 2) unbalanced pressures during PD- pressure from one side- 3) balanced pressures from 2 sides.

Fig. 16 Damaged cable termination because of breakdown and electro-mechanical forces.

7 Conclusion

Cable termination faults happen because of different reasons and most of the investigations discuss importance of SG. Study of this paper is divided to multistage for taking trustable conclusions. According to the reports, after quality, observation of install instructions is important. However weather impact external terminations and cause flashover on them, assembly errors during installation increase puncture possibility. Based on the damaged termination study, there are three sensitive areas which can't stand under extra stress. The problem becomes critical when voids, wet, pollution or semiconductor between cable termination layers remain. Further, scraping XLPE has similar effect and cause fault. Low endurance in the voids causes high electric field and high drop voltage on them. Because of high electric field in triple point regions and connections with edges, heating layers should be done by extra care in these areas. Further, layers surface has to be cleaned for preventing contamination and wet effects which make weakness in the areas. Highlighted point in the paper is classifying critical areas based on the reports and study of damaged cable termination. PD test, simulation results and analysis equations confirm the paper discussions. PD test shows importance of the issue, because in the case studies 1000 PDs occurred during a short time which destroy cable termination. Further, insulation exhaustion is discussed as a hidden effect that decreases insulation lifetime.

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