Analysis of the insulation deterioration of high voltage cross-linked polyethylene power cables (XLPE) under switching impulses stress

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Electric power systems include a large number of expensive and crucial power cable systems over many decades. Every power cable is composed of at least two components; an electrical conductor, and the conductor insulation which prevents direct contact or unsafe proximity between conductor and other objects. The need to provide adequate electrical insulation which will also permit heat to be conducted and dissipated poses technical challenges at higher voltages. The insulation systems of high-voltage power cables and their accessories are subject to different kinds of stresses during their service life and thus suffer degradation and deterioration. The insulation materials of the high voltage cross-linked polyethylene power cables (XLPE) will be placed under high electrical stress caused by switching impulse. These high voltage switching impulse have an important effect on the aging of the insulation materials. These can lead to a reduction of life which in turn can lower the reliability of electrical power systems. This paper presents deterioration of XLPE-insulation will change insulation material properties and it should be possible to detect these changes with electrical analysis. These changes can lower the voltage withstand level of XLPE cables. Methods such as measurement of partial discharge parameters, and alternative current breakdown voltages analysis were used to determine the degree of deterioration.

1. Introduction

Overhead lines and power cables are significant components of electrical networks [1]. Their technical target, the reliable and economic transmission and distribution of electrical energy, can be carried out equally well by both overhead lines and power cables. High voltage power cables are far more expensive to install and maintain than overhead transmission lines [2-3]. The greater cost of underground installations reflects the high cost of the equipment, labor, and time necessary to manufacture the cable, to excavate and backfill the trench, and to install the power cable. The demand for power cables in all voltage ranges will increase further in the future, the environmental compatibility of this product being of decisive importance. It is known that temperature and radiation are the most crucial environmental factors affecting the aging of the polymers [4].

High and extra high-voltage power cables and their accessories have common design features independent of the type of dielectric, the rated voltage and operating frequency [5]. The components that essentially determine the electrical and thermal behavior of the power cable are the conductor, the insulation with inner and outer field limitation and the metallic sheath. These can lead to a reduction of life which in turn can lower the reliability of electrical power systems. So, a lot of research effort, activities and publications are directed towards a better understanding of deterioration phenomena, the finding of tools for insulation diagnosis and the establishment of remaining life estimation techniques.

Previous research has chiefly focused on the synthesis and its electrical properties [6], on the influences of switching impulse stress, ultrasonic irradiation, and ionizing radiation [7-9], on the thermo oxidation [8-10], and on the effect of oxygen uptake under isothermal and isobaric conditions [11]. So as to check the quality and dependability of a power cable system, it is significant to conduct diagnostic tests before putting the power cable system into operation and after a defined period of operation. On site insulation detection to determine the deterioration state of high voltage equipment is of great interest within the power and grid companies and utilities.

Since the 1970s, cross linked polyethylene (XLPE) insulated power cables have increasingly come into practice. XLPE is usually produced by the activation chemical agent, dicumyl peroxide. The deterioration processes of XLPE insulation can be classified into two primary groups as either extrinsic, i.e., those owing to voids, contaminants, physical defects or poorly dispersed elements, or intrinsic, i.e., those owing to physical or chemical changes or trapped accusations [12]. Physical,

chemical and electrical deterioration are the main deterioration mechanisms affecting polymeric insulation. Polymeric insulation is sympathetic even to slight partial discharges [13]. The molecular structure of polyethylene is adjusted by electrical deterioration. Electrical stress is known for generating bonds deformation, free radicals and rupture, and also carbonyl croups in polyethylene [14].

2. Dielectric materials in power cables

Dielectric materials are utilized to provide electrical isolation over the metallic conductors of underground power cables. The insulating materials physically protect the conductor and provide a margin of safety. These materials are comprised of either synthetic or natural polymers. The polymeric insulation material selected for use may vary with the voltage class of the power cable. Compatible polymeric shields are employed between the insulation and the conductor, and over the insulation to grade the voltage stress; these are comprised of flexible polymers blended with conducting carbon black that imparts the semiconducting characteristics.

The insulation layer of the power cable has the form of a hollow cylinder and consists of a dielectric material or material combination. Two different groups of dielectrics are available as insulation for the high and extra high voltage cables being considered; impregnated paper and extruded synthetic materials [15]. From the high voltage technology point of view, the insulation layer is the most important component of the power cable and the most difficult one to calculate in terms of its long term behavior.

2.1 Impregnated paper dielectrics materials

The most important common feature of all paper insulated high and extra high voltage cables is the multi layer construction of the dielectric. Differences result mainly from the type of impregnated medium used to prevent pre-discharges. This type of insulation thus has a multi-layer multi-material dielectric. An exception among impregnated paper dielectrics is a development for the highest transmission voltages; the so-called plastic foil paper laminate. The paper is coated with a foil-polypropylene (PP) among others and can be processed to form multi-layer power cable insulation (Polypropylene Paper Laminate - PPL) in the same way as the usual cellulose paper. Simple molecular structure of cellulose is shown in figure 1. Only low viscosity synthetic insulating liquids are used as impregnating media, as mineral oil can cause swelling of the polypropylene part of the laminate. The main advantage of the more costly PPL insulation compared with the usual paper dielectrics is its considerably lower dielectric loss and greater electrical strength, thus allowing higher electrical operating field strengths.
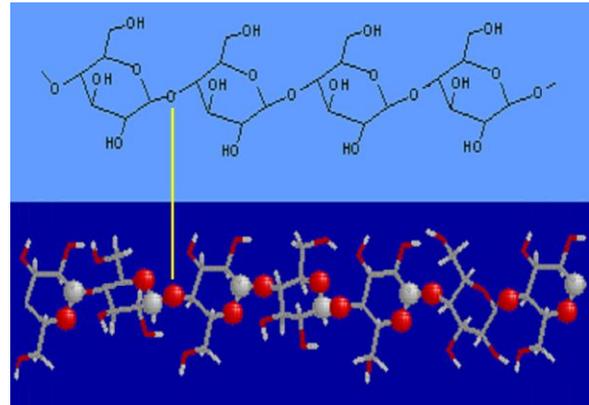
Fig. 1. Molecular structure of cellulose.

2.2 Extruded synthetic dielectrics materials

The costly processing of paper and impregnating medium to form a voltage resistant impregnated multi layer dielectric, consisting of several individual steps, some of these time-intensive, favored the development of a solid dielectric that could be extruded over the conductor in a continuous, fully automatic operation that, in addition, required no impregnating medium. The prerequisite for the use of such a single layer dielectric in high voltage cable technology was the availability of low loss and permanently voltage resistant materials that could be extruded without voids. These conditions are fulfilled by the naturally non-polar thermoplastic polyethylene (PE) and its chemically cross-link-able variant XLPE which, because of its thermo elastic properties, permits higher operating temperatures and has large thermal reserves in the case of short circuits. The insulation of an extruded power cable is therefore based on a single-layer, single-material dielectric.

3. Designing the insulation thickness

Lapped insulation consisting of impregnated paper has excellent long term electrical stability. With correct thermal design, there is no significant occurrence of aging or measurable deterioration of the breakdown properties. In addition, defects that cause field increases play a much less important role than is the case with polymer-insulated cables. As a result, paper insulated cables are designed in the first place on the basis of short term electrical stress at the location of the geometrically determined highest field strength E_{max}, which occurs at the conductor screen. The determining factors are the stresses under test conditions, which may be many times the operational field strengths. The insulation thickness must be calculated individually to withstand safely the impulse and alternative current stresses that occur during type testing, taking in to account the type of cable, the method of construction of the insulation and the electrical properties of the materials used [16].

One possibility is the use of a calculation method originally investigated by Japanese manufacturers [17], which was later modified and extended by Siemens Company [11-13-18]. With this method, the insulation thickness is;

$$w = (\frac{U_d}{E_d}) \qquad (1)$$

where w is the insulation thickness, U_d is design voltages, E_d is design field strengths.

Method 1: The following applies for alternative current voltage;

$$w = (\frac{U_{dac}}{E_{dac}}) = U_o . k_T . k_{ii} . (\frac{k_T}{E_{dac}}) \qquad (2)$$

where E_{dac} is the design alternative current field strength, U_o is conductor to screen operating voltage, k_T is temperature factor, (depending on insulation material for XLPE: $k_T = 1,25$) k_{ii} is voltage magnification factor, ($k_{ii} = 1,15$) k_t is aging factor. (Takes account of the loss of dielectric strength during the course of the nominal service life of the power cable compared to one hour stressing time.) Factor k_t is determined from two quantities, the calculated nominal service life t_N and the life exponent N is calculated to equation 3.

$$k_t = (\frac{t_N}{1_{hour}})^{\frac{1}{N}} \qquad (3)$$

The value of t_N is usually 30 to 40 years; on the other hand, the life exponent depends on the power cable dielectric and must be determined from long term tests that are carried out as realistically as possible.

Method 2: The relationship for impulse voltage is; (corresponding to equation 2)

$$w = (\frac{U_{ds}}{E_{ds}}) = U_{rB} . k_T . k_f . (\frac{k_s}{E_{ds}}) \qquad (4)$$

where E_{ds} is the design impulse field strength, U_{rB} is rated withstand lightning impulse voltage, k_T is temperature factor, (as in equation 2) k_f is repetition factor, ($k_f = 1,1$) k_s is safety factor, ($k_s = 1,1$). The modified method derived from the classic method [17] takes account of the knowledge that impulse voltage breakdowns in technically fault-free polymer power cable insulation occur first at the inner semi conductive layer where the electrical stress is at its highest [19].

Method 3: The provisional insulation thickness calculated using methods 1 and 2 must therefore be checked, especially for small conductor cross-sections (greater field in homogeneity), under impulse stress using method 3.

$$U_{ds} = w . E_{ds \, max} . \eta \qquad (5)$$

$$\eta = r . In \frac{(\frac{r+w}{r})}{w} \qquad (6)$$

where E_{dsmax} is the design impulse field strength at the inner semi conductive layer, U_{ds} is the design impulse voltage from equation 4, r is the radius of the inner semi conductive layer. The combination of equations 5 and 6 then result in;

$$w = r . [\exp(\frac{U_{ds}}{r . E_{ds \, max}}) - 1] \qquad (7)$$

As a rule, the field concentration at the inner semi conductive layer according to method 3 results in the insulation having to be made thicker for very small conductor cross-sections compared to the thickness calculated for homogeneous field distribution (method 1 and method 2).

4. Types of stress in the cable dielectric

4.1 Switching impulse stress

The switching impulse stress in the insulation results from the instantaneous phase to ground voltage and the geometry of the insulation layer. However, the macroscopic cylindrical symmetry of the radial field cable specified according to definition does not completely define the switching impulse stress condition that actually occurs locally. In terms of switching impulse stress, conductive impurities including semi conductive layer protrusions are of the greatest importance as; with unfavorable contour and position (pointed, radial direction) they can lead to theoretically infinite field magnification.

Metallic inclusions present an additional risk factor in that, because they have a many times smaller coefficient of thermal expansion compared to the surrounding polymer dielectric, they may loosen and form microscopic voids in an already overstressed area. The prevention of even the smallest metallic inclusion therefore has the highest priority in the handling of material and the manufacture of solid-insulated high voltage cables [20]. A similar situation applies to protrusions, which are mainly avoided by the use of selected especially homogeneous conductive compounds.

4.2 Thermo-mechanical stress

Thermo-mechanical stress must be limited to a tolerable level for each type of power cable to prevent any resultant damage. This stress includes;

• In the case of paper insulated cables, the drying processes of the insulating paper and the impregnating medium which, for physical reasons, become quicker and more effective the higher the temperature used. Too high a temperature can lead to the beginning of decomposition of the paper or the vaporization of the more volatile fractions of the impregnating medium and can thus undesirably influence the chemical composition of the components.

• In the case of polymer-insulated power cables, the extrusion and, if applicable, the subsequent cross-linking processes are also usefully accelerated at increased temperatures. The viscosity of the melt is reduced, simplifying extrusion, and the subsequent cross-linking process takes place more quickly. Nevertheless, too high extrusion temperatures can cause scorching of the material and too high a thermal stress during cross-linking leads to the start of aging of the material.

• In the case of all types of power cable, the transport on drums and the cable laying, both of which are associated with substantial bending stresses. To prevent early mechanical damage in these cases, a lower limit is specified for the permissible bending radius of the cable depending on the type of power cable, the conductor diameter and overall diameter, and the bending ability must be proven during type testing by repeated unrolling and re-rolling of suitable test drums.

4.3 Internal partial discharges

The occurrence of partial discharges (PD) within a dielectric means that either the electrical field or the dielectric stress or both are distributed in a highly inhomogeneous manner. Fig. 2 shows two classical examples: a pointed protrusion in a semi conductive layer that influences the field distribution on its own and a gas-filled cavity in the dielectric that disturbs both the field pattern and the distribution of the dielectric stress.
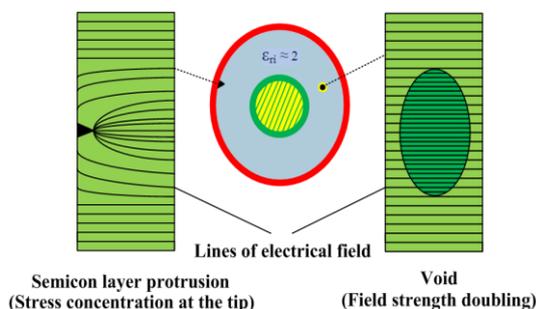
Fig. 2. Defects in solid dielectrics as origins of partial discharges.

The inhomogeneous caused by the cylindrical geometry of the power cable is not sufficient in its own to cause partial discharges. In the case of the pointed protrusion in the semi conductive layer, the danger exists of electrically overloading the dielectric in the area of the greatest concentration of field lines in the direct vicinity of the defect. On the other hand, the existence of a gas-filled cavity permits the onset of partial discharges without previous damage to the material having occurred. This is because the field strength inside the void ($\varepsilon_r = 1$) exceeds the stress in the surrounding dielectric by a factor of nearly ε_{ri}, the permittivity of the insulation material. At the same time, gases usually have a considerably lower dielectric strength than solid, liquid or impregnated dielectrics. As a result, discharges occur in the void above a definite voltage that can be measured externally and can lead to a gradual erosion of the surrounding material.

5. Experimental details and results

The measurement of partial discharge limit was implemented after imposing characteristic numbers of switching impulses. With respect to IEEE Standard 4-1995, switching impulses of 100/1000 μs with 50 kV in degree were imposed at a proportion of 4 impulses per minute. Ambient temperature through the experiment was maintained at 23 °C. Partial discharge imposition limits were quantified at a power frequency of 50 Hz using the Hipotronics DDX 7000 & 8003 test detector.

The initiation and elimination voltages of partial discharge were registered. The pulse counts and partial discharge degrees were predicted in the 25 second time frame. At the turn of the analysis, alternative current breakdown voltages of all assessment patterns were quantified to evaluate the remaining dielectric strength. The alternative current breakdown voltages were decided after imposing 0, 50, 100, 500, 1000, and 5000 impulses to the patterns. Five patterns of XLPE cable were evaluated at each rank of imposed impulses. The offered data are the mean value of five patterns. The 3-D plots are offering the partial discharge limits for characteristic patterns and conditions.

For patterns to which 5000 impulses were imposed, measurement of partial discharge limits were taken every 500 impulses. For experiment patterns to which 1000 impulses were imposed, partial discharge measurements were saved every 100 impulses. For the patterns which were energized for 500 impulses, partial discharge events were evaluated every 500 impulses. For the power cable patterns to which 100 impulses were imposed, the partial discharge limits were saved every 50 impulses. The partial discharge limits for novel patterns were also measured. Figs. 3, 4, 5 and 6 shows the change of initiation and elimination voltages of the XLPE cable patterns during aging process.
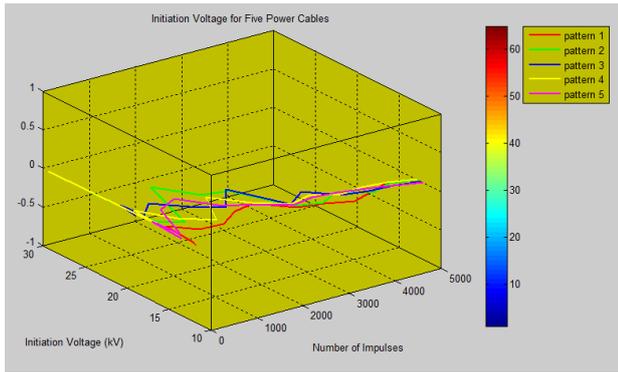
Fig. 3. Initiation voltage for five XLPE cable patterns.
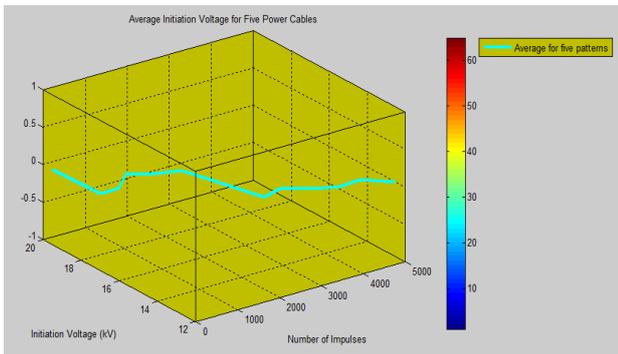
Fig. 4. Average initiation voltage for five XLPE cable patterns.
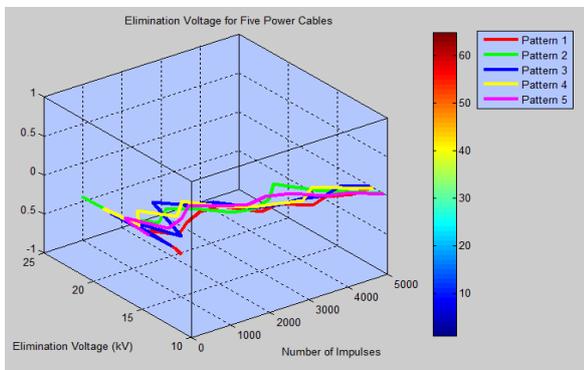
Fig. 5. Elimination voltage for five XLPE cable patterns.
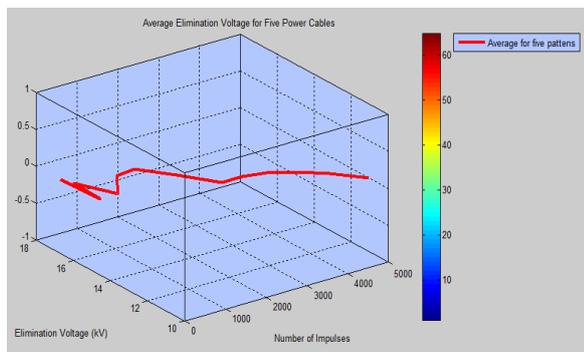
Fig. 6. Average elimination voltage for five XLPE cable patterns.

From the figures, it apparently indicates that both the initiation and elimination voltages of the XLPE power cable patterns diminished as more switching impulses stress were imposed. The values of novel patterns and aged patterns indicates that the pattern 2 power cable have higher initiation and elimination voltages than average patterns values, which shows that the pattern 4 power cable has better partial discharge performance than other pattern power cables. Figs. 7 and 8 indicate the variation of initiation and elimination voltages of power cable patterns during the 1000 imposed switching impulses.
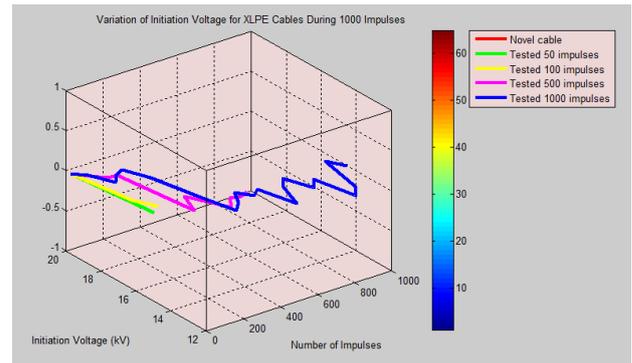
Fig. 7. Variation of initiation voltage for XLPE power cable patterns during the 1000 imposed switching impulses.
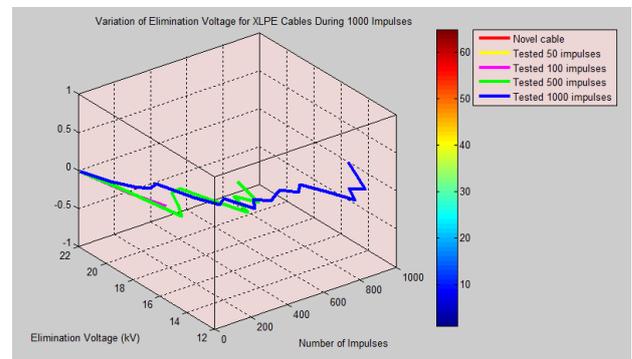
Fig. 8. Variation of elimination voltage for XLPE power cable patterns during the 1000 imposed switching impulses.

During the first 500 imposed switching impulses, the initiation and elimination voltages diminished and then rise. It has been proposed that diminish was owing to novel bruises constituted by electrical and thermo mechanical stress. After that, some of the bruises were stuffed by the decomposing insulation provisions, which clarified the rise of initiation and elimination voltages. The latter diminish of initiation and elimination voltages were owing to the permanent aging of insulation provisions. Partial discharge evident variation amplitudes were also saved. Figs. 9 and 10 indicates the measurement results. The evident variation amplitude of partial discharge rise as more switching impulses were imposed.
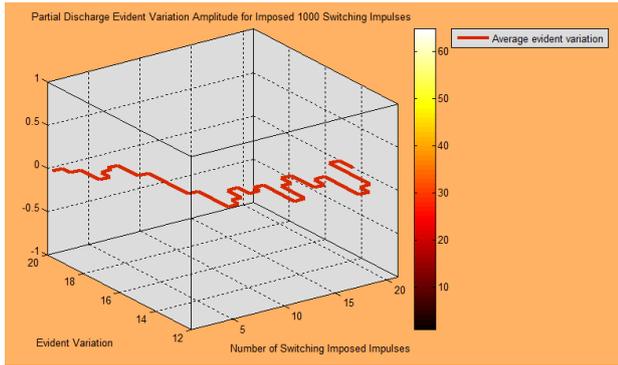
Fig. 9. Partial discharge evident variation amplitude for imposed 1000 switching impulses cable patterns.
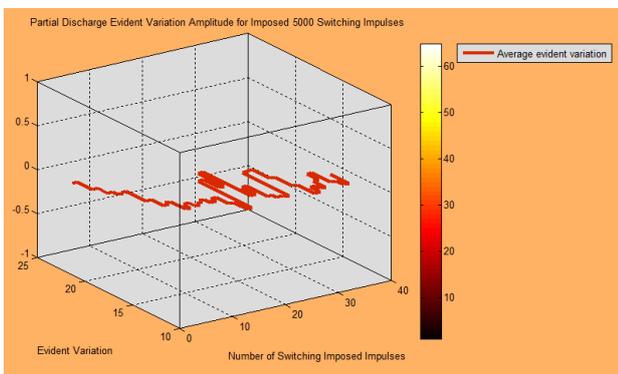
Fig. 10. Partial discharge evident variation amplitude for imposed 5000 switching impulses cable patterns.

Fig. 12. Partial discharge of XLPE cable after 1000 imposed impulses.
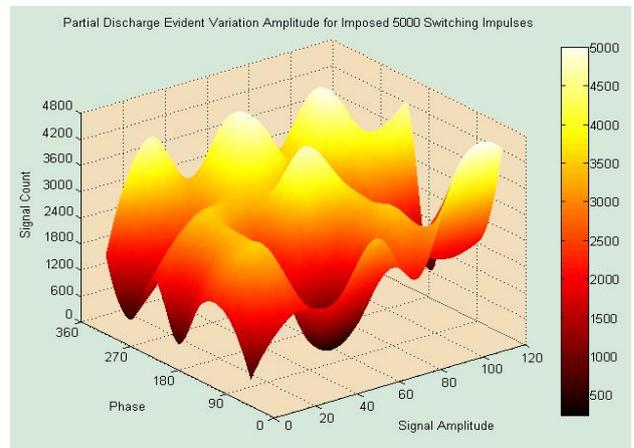
Fig. 13. Partial discharge of XLPE cable after 5000 imposed impulses.

Hipotronics DDX 7000 & 8003 test detector was operated to do the three-dimension analysis of partial discharge limit during aging process. Three dimension plots below indicate the phase, signal count and signal amplitude of partial discharges in a 5 second time frame. Figs. 11, 12 and 13 indicates the measurements of partial discharge events for XLPE power cable patterns 100 impulses than 1000 impulses and after 5000 impulses. The signal count and amplitude rise importantly after 5000 impulses, which show that the degradation of insulation has occurred.

Alternative current breakdown event in this study was chiefly initiated from the bruises inside the insulation materials. The bruises were created during the manufacturing operation. Novel bruises would be comprised or expanded during the aging because of the electrical switching impulses stress. After a number of switching impulses were imposed, alternative current breakdown voltages of all test power cable patterns were designated. The remaining dielectric strength of power cable patterns after aging can be considered by alternative current breakdown voltages measurement. Obviously in Figs. 11, 12 and 13, distinctness in samples of partial discharge measurement results was acquired. Each partial discharge production source produced individual partial discharge sample. These measurement data are used to test the target technique. Feature of partial discharge data were calculated by using fractal features. The individual 3-D partial discharge samples are plotted. The x and y axes correspond to the phase and signal amplitude respectively. The matrix elements correspond to the signal count data. Fractal characteristics are computed for all the available samples saved.

Fig. 11. Partial discharge of XLPE cable after 100 imposed impulses.

According to Fig. 11, the alternative current breakdown voltages and dielectric strength of XLPE power cable patterns diminished sharply after the first 100 imposed switching impulses. The dielectric strength initiated to rise as more impulses were imposed till 1000 switching impulses were imposed. In the interval partial discharges between 50 and 100 imposed switching impulses, the dielectric strength slightly rise or it was constant. The breakdown voltages diminished step by step as more impulses were imposed after 100 switching impulses were imposed. Alternative current breakdown voltages of XLPE power cable patterns diminished at first 100 imposed impulses and then rise as more switching impulses were imposed. Similar to the event monitored in partial discharge limits measurement, this was owing to the decomposition of bruises inside insulation materials. From the figure 13, it can be deduced that after 5000 imposed switching impulses, the remaining dielectric strength was merely 83.9% percent of the aged power cable patterns.

6. Conclusions

Partial discharge measurement is helpful for power cable detection because it is the merely technique that is able to give a localized estimate of the insulation circumstance. In this work, if partial discharges and breakdown is exhibit, then there are defects producing the partial discharges. However, when interpreting the partial discharge measurements maintenance must be taken. The detection of insulation deterioration using partial discharge measurements is not an easy process due to the spacious range of imperfections that can generate partial discharges, switching impulse stress and the other many different related deterioration processes.

In these experimental details, XLPE power cable patterns were energized by switching impulses stress. Based on measurement results derived from power cables and the following points have been performed:

1-) After switching impulses stress were imposed, XLPE power cable patterns indicated signs of deterioration degree. XLPE power cable patterns indicated rise in magnitude of clear charge for partial discharge.

2-) Measurement of initiation and elimination voltages obtains the most apparent proof that degradations of insulation have occurred. The alternative current breakdown voltages of XLPE power cables diminished importantly after 5000 imposed switching impulses stress.

In addition, partial discharge measurement and switching impulse stress characteristics also depend upon the situation of the imperfections, operating and testing voltage magnitudes, circuit operating situations, system design and length. A short review of the early history of partial discharge investigation shows that influential partial discharge measurement and situation technology was improved rapidly. Later progress tended over excess developments by means of implementation of novel technology, as well as expanding of the area of event covered by the technique.

References

[1] C. Katz, M. Walder, IEEE Transactions Power Delivery, **13**, 1 (1998).

[2] C. P. Martin, A. S. Vaughan, S. J. Sutton, 2003 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2003, Albuquerque, USA, pp. 309.

[3] E. F. Peschke, R. V. Olshausen, Cable Systems for High and Extra-High Voltage, Pirelli Cable and System, Publicis MCD Verlag, Berlin, Germany, (1999).

[4] M. L. Ciurea, V. Lancu, I. Stavarache, J. Optoelectron. Adv. Mater., **8**(6), 2145 (2006).

[5] W. A. Thue, Electrical Power Cable Engineering: Second Edition Revised and Expanded, Marcel Dekker Inc., New York, USA, 2003.

[6] Aman Mahajan, Anshul Kumar, Mandeep Sıngh, Dınesh Pathak, R. K. Bedi, Optoelectron. Adv. Mater. - Rapid Commun., **6**(7-8), 755 (2012).

[7] G. J. Anders, Rating of Electric Power Cables: Ampacity Computations for Transmission Distribution and Industrial Applications, McGraw-Hill, IEEE Press Power Engineering Series, New York, USA, (1997).

[8] SK. Khadeer Pasha, K. Chıdambaram, N. Vıjayan, W. Madhuri, Optoelectron. Adv. Mater. - Rapid Commun., 2012, **6**(1-2), 110 (2012).

[9] S. Grzybowski, L. Cao, P. Shrestha, Proceedings of the 16th International Symposium on High Voltage Engineering, 2009, (SAIEE), Innes House, Johannesburg, South Africa, Paper A-18.

[10] N. Yoshimura, S. Kumugai, S. Nishimura, IEEE Transactions on Dielectrics and Electrical Insulation, **6**(5), 632 (1999).

[11] P. Fischer, P. Röhl, Siemens R&D Report, **3**, 125 (1974).

[12] T. Sato, K. Muraki, N. Sato, Y. Sekii, IEEE International Conference on Power Cables &

Accessories 10 kV ~ 500 kV, November 1993, London, England, pp. 5.

[13] N. Pamuk, J. Optoelectron. Adv. Mater., **16**(3-4), 422 (2014).

[14] J. Perkel, N. Hampton, M. Begovic, R. Hartlein, International Conference on Insulated Power Cables, (JICABLE-2007), 2007, pp. 449.

[15] B. M. Weedy, D. Chu, IEEE Transactions on Power Apparatus & Systems, PAS-103, 1984, pp. 662.

[16] M. Kuschel, W. Kalner, IEEE High Voltage Engineering Symposium (IEE Conf. Publ. No. 467), 23-27 August 1999, London, England, pp. 3443.

[17] S. Sriram, S. Nitin, K. Prabhu, M. Bastiaans, IEEE Transactions on Dielectrics and Electrical Insulation, **12**(6), 1182 (2005).

[18] P. Metra, L. Rühe, Siemens R&D Report, **12**(4), 34 (1983).

[19] S. Hvidsten, B. Holmgren, L. Adeen, J. Wetterstrom, IEEE Electrical Insulation Magazine, **21**(6), 17 (2007).

[20] S. Grzybowski, P. Shrestha, L. Cao, International Conference on High Voltage Engineering and Application, 2008, (ICHVE'08), Chongqing, China, pp. 422.

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