INVESTIGATION THE EFFECT OF SOLUTION CONDUCTIVITY ON THE GROWTH RATE AND SHAPE OF WATER TREES OBSERVED IN DISTRIBUTION CABLES

Mustafa Karhan [1,2], Aysel Ersoy Yılmaz[1], Mukden Uğur[1]

[1]Department of Electrical and Electronics Engineering, Istanbul University, Türkiye
[2]Electronics & Communication Department, Cankiri Karatekin University, Türkiye
mustafakarhan@gmail.com, aersoy@istanbul.edu.tr, mugur@istanbul.edu.tr

Abstract: *In this study, samples were taken from the polymeric insulator parts of XLPE insulated medium voltage cables already used for energy transmission and distribution.These samples have been aged in a controlled manner in the laboratory environment. The applied voltage and frequency was adjusted 24 kV_{pp} and 3 kHz respectively to initiate and grow water treeing in a short time period. The thickness of the samples taken from the polymeric insulator part of the cable was determined as 800 µm - 950 µm. The lengths, widths and geometry of water trees formed in saline solutions with different conductivities were analyzed. The study is mainly based on investigation the effect of external factors on the growth of water trees observed in XLPE type transmission and distribution cables.*

Keywords: *Water treeing, vented tree, cross linked polyethylene insulation (XLPE), molarity, conductivity*.

1. Introduction

Due to the high demand to electrical energy, underground cables used in energy transmission and distribution lines become quite popular and interesting for a vast mojority of researchers. The developments in insulation technology enable to transfer electrical energy at higher levels to further areas; however several factors such as line losses, insulation degradation, etc. need to be consired in detail during installation and operation phase.

For underground cables, Polyethylene (PE), Cross-linked polyethylene (XLPE) and Ethyle propylene rubber (EPR) can be considered as the most well known and widely used insulating materials.

Polyethylene cables has been first introduced in 1945, whereas for XLPE cables it took another 15 years to be available on the market [1]. Nowadays XLPE cables are widely used in medium and high voltage cables due to their superiour physical and electrical properties.

Although XLPE cables, used in medium and high voltage applications have good dielectric properties, aeging phenomenon after a curtain service period is unevitable. Among several factors, which effect the ageing phenomenon, water treeing is very crucial in defining the insulation capability and service life of a cable [2], [3].

Received on: 05.05.2017
Accepted on: 20.06.2017

Water treeing can be regarded as a prebreakdown mechanism before the electrical treeing, which eventually leads to the total failure.

Water trees have a dispersed and diffused structure in appearance. These are typically between 0.1 and 1 mm in size [4], [5]. Water treeing was first detected by Miyashita in 1969 [6].

Within the scope of this study, as a polymeric insulator XLPE is used, which is quite popular among in power cords. Strong resistance against the environmental conditions and humidity, flexibility, weak mechanical power and superiority in chemical resistance can be shown as general feautures in cable industry, of the XLPE material. It has a pretty wide range of usage while it is low-cost.

In this study, the water treeing phenomenon, which has a crucial role in the service life of medium and high voltage cables, is examined with its formation and growth stages for solutions with different conductivities. Water treeing is analysed based on the parametres of molarity, conductivity and electiric field.

2. Water Treeing

Water treeing phenomenon is a dominant phenomenon among the early emerging breakdowns in the underground XLPE distribution cables. Water trees are permanently localised damages and breakdowns. Their size may vary from a few microns to 1 mm. Generally water trees have hydrophilic diffused branched structure. In order to form water trees, a high electric field is needed [7]. In time, water trees may evolve into electric trees and hence lead to insulator breakdowns. In time water trees may weaken the insulation and hence large water trees may be considered dangerous. Because these trees might initialise insulation breakdowns [8].

There are two types of water treeing, namely the bow-tie water tree that is formed within the insulator and the vented water tree that emerges in the interior and/or exterior conductor screens of the cable and expands through the conductor [2]. In this study, the vented water tree has been formed and analysed in laboratory environment. The images of the bow-tie and vented water treeings are shown in Figure 1 and Figure 2 respectively. The factors that have an impact on the formation and growth of water treeing can be listed as the duration of the application of voltage, electric field, frequency, voltage applied, temperature, relative humidity, ionic content, solution concentration, polymer morphology, mechanical pressure, additives, pollutants and retarding agents for treeing, type of the electrode material, etc. [7]-[10]. Filippini and Meyer, has examined the growth of water tree under the same voltage for different curvature radii. As a result of the conducted study, it has been observed that as the curvature radius decreased the diffusion of the water treeing increased [11]. The parametres that change the electric field value are the distance between the end of the water needle and the counter plane electrode (d), the curvature radius (r) and the applied voltage (U).

The electric field in the axis between the end of the water needle and the counter plane electrode is given in Equation 1. [11].

$$E = \frac{2U}{r\ln(1+\frac{4d}{r})} \quad (1)$$

For the formation and growth of the water tree, which is a local phenomenon, the presence of electric field is required. The growth rate of the water tree can be explained by Equation 2.

$$\frac{dL}{dt} = f[E(L,t)] \quad (2)$$

Here, L stands for the length of the tree, and f[E(L,t)] stands for the function of E(L,t) which is the local field [12].

$$f[E(L,t)] = CE^2(L,t) \quad (3)$$

The parameter 'C' that is given in Equation 3, is a factor named 'growth rate' by Ashcraft. C depends to other variants such as temprerature, frequency, electrolyte concetration and others that may effect water treeing [12], [13].

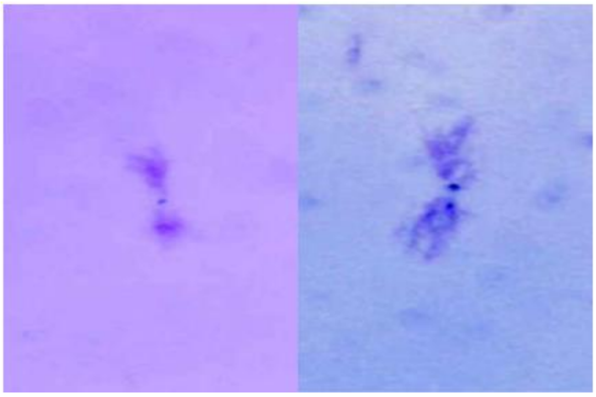

Figure 1. Images of bow-tie water treeing [14]

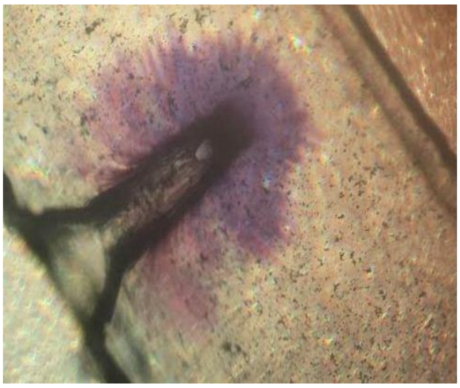

Figure 2. Image of vented water treeing

It is known that water trees perish when the insulating material dries up and reappear when it is damped. Water trees are rendered permanently visible with the help of water soluble dyes. Mostly, methylen blue is used [4]. Stancu and his fellows used the rhodamine solution as dyeing technique in the study they conducted [15]. Within the scope of this study, the samples have been dyed with methylen blue before the microscope images are taken.

2.1. The Effect of Solution on Water Treeing

If the water is perfectly deionized, water treeing is not observed on the samples. For that reason, in order to form the water tree the presence of ion in the solution is required. Different results and values shall be observed in different solutions. Under this title, emphasis must be put on factors such as the type of salts in the solution, the density of salts, acidity (pH), solubility, type of the electrode material [9], [10]. Increase in the ionic concentration causes the growth rate of water treeing to increase as well.

The type of the electrode material may be also considered under this title. In the studies conducted on the electrode material, most probably more treeing will be observed since Pt and Cu electrodes are exposed to less oxidation in the solution when compared to Al, Fe and Pb electrodes. When the pH value increases, the growth rate of the vented treeing increases as well [7]. In this study, Al is chosen as the electrode material.

Bamji and his fellows contucted a study to examine the effect of the various salts dissolved in water on the length of vented water tree. The growth rate of water treeing noted to be well in the $CuSO_4$, NaCl and $CaCl_2$ solutions respectively. No treeing was observed in distilled water. The duration of the experiment designated 90 hours and the frequency was selected as 1kHz [16].

Koo and Filipini conducted a study in 1984 to examine the spreading of water tree as a function of time in salty water solutions with different concentrations, in different ionic solutions (NaCl, KBr, $CuSO_4$, $Cu(NO_3)_2$, $CuCl_2$) and with different electrode materials (Pt, Fe) [17].

Malik and his fellows investigated the length values of the water treeing formed in XLPE insulated cables in the NaCl, $CuSO_4$ ve $Cu(NO_3)_2$ aqueous ionic solutions under different temperatures in the study they conducted in 2006 [18].

Al-Arainy and his fellows also investigated the length values of the water treeing in deionized water and NaCl, $AgNO_3$ solutions with different samples, under different temperatures in the study they conducted in 2004 [19].

In 2014, Boonraksa and Marungsri examined the role of ionic solutions in the growth of water treeing in their study. In this study, they demonstrated that Na_2SO_4 and $CuSO_4$ solutions showed a stronger tendency in the growth of water treeing [2].

3. Experimental

3.1. NaCl Solution Preparation

In order to analyse the effect of molarity and conductivity on the growth and the geometry of water treeing, initially NaCl solutions of 1M and 1.4M were prepared. The solutions were prepared with ultra pure water (milli Q) instead of tap water to conduct a controlled experiment. The conductivity and pH values of the prepared solutions were measured with the aid of SG78 – (SevenGo Duo pro pH/Ion/Conductivity Meter, Mettler Toledo, Spain). The conductivity and pH values of the salty water solutions of 1M and 1.4M are given in the table below.

Table 1. Conductivity and pH values of NaCl solutions of 1M and 1.4M

Molarity	Conductivity	pH
1 M	84.2 mS/cm	6.21
1.4 M	109.9 mS/cm	6.54

3.2. High Voltage Generator Part

One of the most important steps to form water treeing in laboratory environment is to create high voltage in high frequency. (For a large electric field either a high voltage supply or minimum distance to the counter electrode is needed. AC signals can be generated in square or sinusoidal form. For the generation of the high voltage, signal generator, amplifier and transformer were used in this part of the experimental system. With the help of signal generator, signals in the desired frequency and low amplitude can be generated. The amplitude values of these signals can be amplified up until a certain level with the help of the amplifier. In Figure 3. block diagram of high voltage generator section is demonstrated and in the block diagram the amplitude and frequency values that signal may take as a result of each block are included.

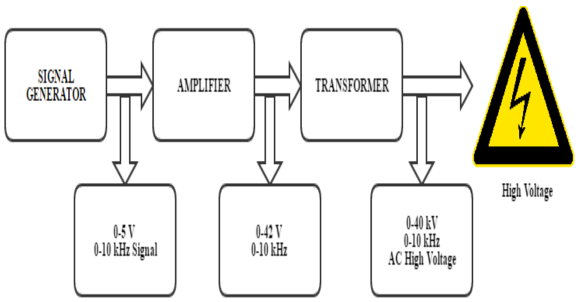

Figure 3. Block diagram of high voltage generator section

3.3. Sample Preparation

The samples, in which water trees are formed were prepared by taking slim profiles of 800 µm - 950 µm from ready-to-use single core medium tension XLPE insulated cables. Holes in different lenghts were made to form water needles in the samples. These samples were glued to the base of a cylindiric container made of polyamid material within which they were put into the NaCl solution.

Aluminium plate was placed under the polyamid container to which XLPE samples had been glued. Conductive gel was applied between aluminium electorde and the sample lest space occurs between the entire surface of the sample and the aluminium plate. The conductivity of this gel was measured as 1169 μS/cm. In Figure 4. the test setup prepared to form water treeing is given.

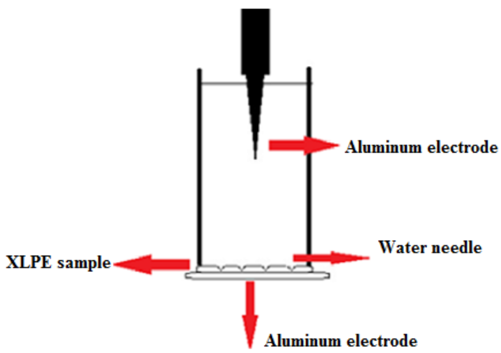

Figure 4. Test setup prepared to form water treeing

The type of material electrodes is among the factors that affect water treeing. In literature there are many studies related to effect of electrode's material type affects water treeing. In this study Aluminium (Al) is chosen as the electrode material. In Figure 5. aluminium bar electrode, polyamid reservoir, conductive gel and aluminium plate electrode are demonstrated.

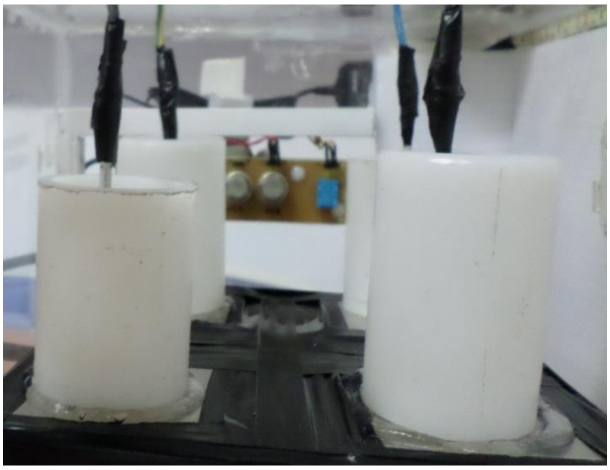

Figure 5. Aluminium bar electrode, polyamid reservoir, conductive gel and aluminium plate electrode.

3.4. Observation of Water Treeing

In order to observe the water treeing formed in the XLPE samples that were aged in laboratory conditions, profiles of 100 μm were taken from the samples with the help of microtome knife. Profiles were cut vertically with respect to the place where water needles had been formed. Samples were kept for 4 hours in the methylen blue solution at 70˚C. The samples kept in methylen blue were rinsed with tepid water in a separate container. Finally, they were smoothly wiped with ethanol to get rid off the leftover dye scraps on them. In order to observe the treeing with the methylen blue permanently, the dyeing technique developed by Siemens was used.

The images were taken from the samples dyed with methylen blue with the aid of Olympus CX41 light microscope and Olympus SC-100 CMOS digital camera. In Figure 6. and 7. the images taken with the Olympus CX41 light microscope and Olympus SC-100 CMOS digital camera are demonstrated.

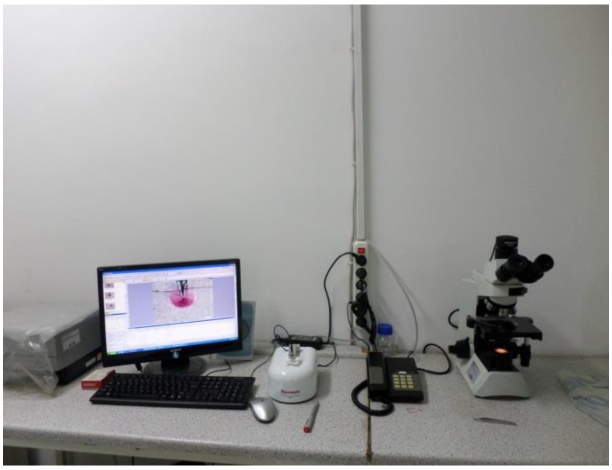

Figure 6. Images taken with the Olympus CX41light microscope and Olympus SC-100 CMOS digital camera

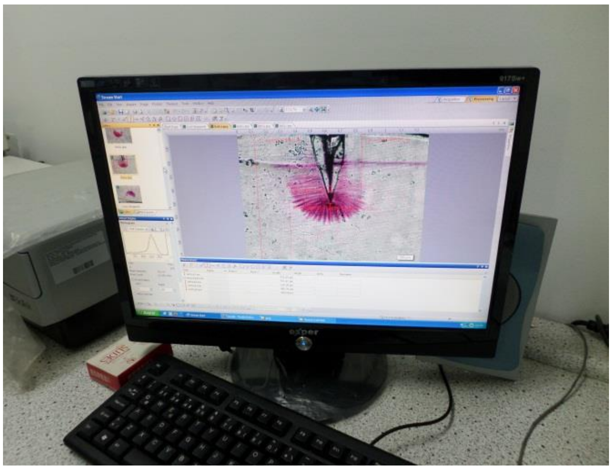

Figure 7. Images taken with the Olympus CX41 light microscope and Olympus SC-100 CMOS digital camera

4. Results and Analysis

The length and width of the water trees and distance between water needle and aliminium electrode were analysed Table 2 by using microscobic images taken under the same external conditions. ($24kV_{pp}$ applied voltage, 3kHz frequency and 24hours test period)

While forming the vented type water trees, the length of the water tree, the width of the water tree, the distance between the water needle and the aluminum electrode, the distance between the water needle and the aluminum electrode and finally the scatter plot of the water tree width in terms of μm are given respectively in Figure 8,9 and 10 for NaCl solutions with 84,2 mS/cm and 109,9 mS/cm conductivity. The length and the width of the water trees are based on the measurement diagram given in Figure 11. The test environment values are given in Table 3.

Table 2. Values of the length, the width of the water treeing and also the distance between the water needle and the aluminium electrode for the microscope images ($24kV_{pp}$, 3kHz, 24 hours)

Conductivity	Distance between the water needle and the aluminium electrode (μm)	The length of Water treeing (μm)	The width of Water treeing (μm)
84,2 mS/cm	422,00	163,00	603,00
84,2 mS/cm	429,00	162,00	591,00
84,2 mS/cm	281,00	216,00	540,00
84,2 mS/cm	296,00	256,00	519,00
84,2 mS/cm	408,00	141,00	569,00
84,2 mS/cm	385,00	97,00	575,00
84,2 mS/cm	474,00	140,00	537,00
84,2 mS/cm	418,00	143,00	558,00
84,2 mS/cm	487,00	165,00	535,00
109,9 mS/cm	503,00	254,00	633,00
109,9 mS/cm	378,00	213,00	597,00
109,9 mS/cm	362,00	289,00	632,00
109,9 mS/cm	422,00	285,00	624,00
109,9 mS/cm	357,00	275,00	622,00
109,9 mS/cm	560,00	318,00	613,00
109,9 mS/cm	591,00	300,00	581,00
109,9 mS/cm	465,00	357,00	803,00
109,9 mS/cm	451,00	345,00	802,00

Table 3. Test environment values

Application time	24 hours
Applied voltage and its frequency	24 kV_{pp} – 3kHz
Relative Humidity	% 43 RH
Temperature	22.5˚C
Pressure	929,93 hPa (0,917769 atm)
Solution type, molarity and conductivity	NaCl, 1M-1.4M, 84,2 mS/cm ve 109,9 mS/cm

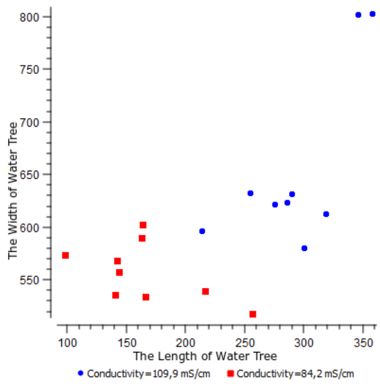

Figure 8. Length of water tree (μm) – width of water tree (μm)

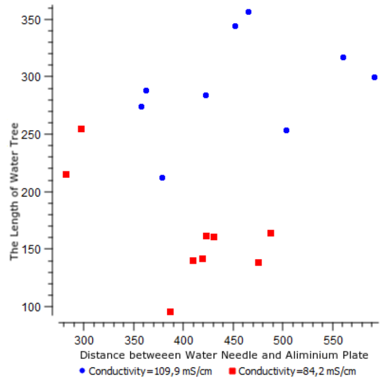

Figure 9. Distance between the water needle and the aluminum electrode (μm) - the length of the water tree (μm)

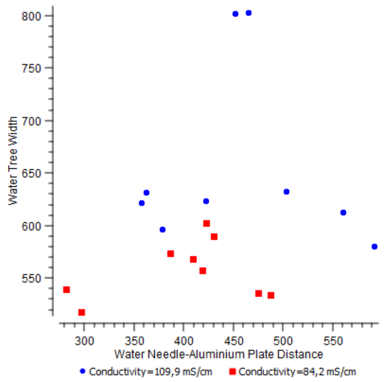

Figure 10. Distance between the water needle and the aluminum electrode (μm) - width of water tree (μm)

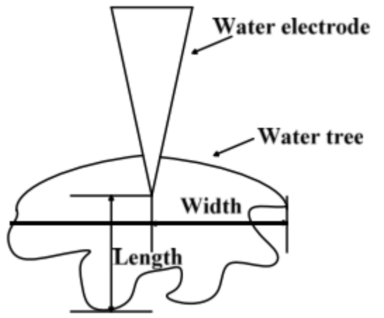

Figure 11. Water tree measurement diagram

The water tree microscope images were obtained after the profiles taken from samples aged in laboratory environment and have been dyed with methylen blue. In Figure 12. and 13., the microscope images of vented water trees for solutions with different conductivity levels are given.

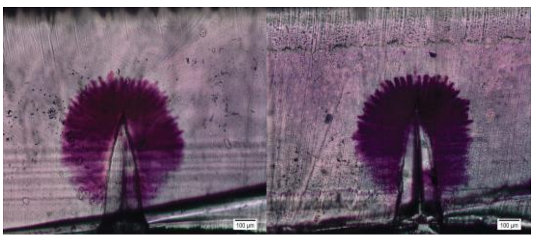

Figure 12. Vented water tree microscope images (24 kV_{pp}, 3kHz, 24 Hours, 1M, 84.2 mS/cm)

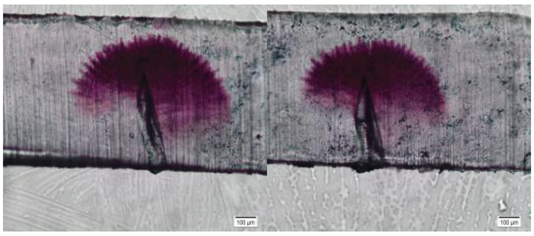

Figure 13. Vented water tree microscope images (24 kV_{pp}, 3kHz, 24 Hours, 1.4M, 109.9 mS/cm)

5. Conclusions

In this study, the molarities and hence the conductivities of the solutions were altered. The width and the lenght of water trees that had been formed in response to different solution conductivities were measured. Both parameters formed in the experiments done with the NaCl solution of 1.4 M, measured to be bigger. In some experiments conducted with the NaCl solution of 1 M, the electric field was kept high, however the length and the width of the water tree measured quite small when compared to the experiments done with the NaCl solution of 1.4 M. Ionic solution has a significant impact on the water treeing phenomenon that dramatically affects the service life of the cable. With this experiment conducted, it has been demonstrated that even if the ionic solution is the same, increasing the molarity has an active role in the growth of the water treeing. In the light of this study, the test environment data are periodically collected for the currently on-going aging tests done on the polymeric insulators, and microscope images are taken from the aged samples that have been dyed with methylen blue. With these results, the analysis of the polymeric insulators in the distribution cables will be carried out by using different image processing techniques. It is thought that the analysis of the parameters that might affect the phenomena of the electric tree and the water tree, which has an important role in the service life and breakdown of the high voltage cables, would be possible with the help of the advanced image processing techniques.

6. References

[1] Werelius, P. (2001). *Development and application of high voltage dielectric spectroscopy for diagnosis of medium voltage XLPE cables* (Doctoral dissertation, Elektrotekniska system).

[2] Boonraksa, T., & Marungsri, B. (2014). Role of ionic solutions affect water treeing propagation in XLPE insulation for high voltage cable. *World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, *8*(5), 788-791.

[3] Wang, J., Zheng, X., Li, Y., & Wu, J. (2013). The influence of temperature on water treeing in polyethylene. *IEEE Transactions on Dielectrics and Electrical Insulation*, *20*(2), 544-551.

[4] Shaw, M. T., & Shaw, S. H. (1984). Water treeing in solid dielectrics. *IEEE Transactions on Electrical Insulation*, (5), 419-452.

[5] Nunes, S. L., & Shaw, M. T. (1980). Water treeing in polyethylene-a review of mechanisms. *IEEE Transactions on Electrical Insulation*, (6), 437-450.

[6] Miyashita, T. (1971). Deterioration of water-immersed polyethylene-coated wire by treeing. *IEEE Transactions on Electrical Insulation*, (3), 129-135.

[7] Lanca, M. C. (2002). Electrical ageing studies of polymeric insulation for power cables (estudo do envelhecimento eléctrico do isolante polimérico de cabos eléctricos.

[8] Steennis, E. F., & Kreuger, F. H. (1990). Water treeing in polyethylene cables. *IEEE Transactions on Electrical Insulation*, *25*(5), 989-1028.

[9] Sanniyati, C. N., Arief, Y. Z., Adzis, Z., Muhamad, N. A., Ahmad, M. H., Sidik, M. A. B., & Lau, K. Y. (2016). Water tree in polymeric cables: a review. *Malaysian Journal of Fundamental and Applied Sciences*, *12*(1).

[10] Steennis, E. F. (1989). Water treeing. *The behavior of water tress in extruded cable insulation. Delft: Delft University of Technology*.

[11] Filippini, J. C., & Meyer, C. T. (1988). Water treeing using the water needle method: the influence of the magnitude of the electric field at the needle tip. *IEEE transactions on electrical insulation*, *23*(2), 275-278.

[12] Dissado, L. A., Wolfe, S. V., Filippini, J. C., Meyer, C. T., & Fothergill, J. C. (1988). An analysis of field-dependent water tree growth models. *IEEE transactions on electrical insulation*, *23*(3), 345-356.

[13] Ashcraft, A. C. (1977) Treeing Update Part III: water trees. Kabelitems 152, Union Carbide Corporation. Based on Water treeing in polymer dielectrics , in *World Electrotechnical Congress in Moscow*, No. 152, pp.5- 11.

[14] Hellesø, S., Benjaminsen, J. T., Selsjord, M., & Hvidsten, S. (2012). Water tree initiation and growth in XLPE cables under static and dynamic mechanical stress. In *Electrical Insulation (ISEI), Conference Record of the 2012 IEEE International Symposium on* (pp. 623-627). IEEE.

[15] Stancu, C., Notingher, P. V., Ciuprina, F., NotingherJr, P., Castellon, J., Agnel, S., & Toureille, A. (2009). Computation of the electric field in cable insulation in the presence of water trees and space charge. *IEEE transactions on industry applications*, *45*(1), 30-43.

[16] Bamji, S., Bulinski, A., Densley, J., Garton, A., & Shimizu, N. (1984). in *Conférence Internationale des Grandcs Rcseaux Elcctriques a Haute Tcnsion (CIGRE*), pp. 15–07: 7 pp.

[17] Koo, J. Y., & Filippini, J. C. (1983, July). Effect of physico-chemical factors on the propagation of water trees in polyethylene. In *Conduction and Breakdown in Solid Dielectrics, Proceedings of First International Conference on* (pp. 255-260). IEEE.

[18] Malik, N. H., Qureshi, M. I., & Al-Arainy, A. (2006, June). The role of cations in water tree growth in technical grade XLPE insulated cables. In *Properties and applications of Dielectric Materials, 2006. 8th International Conference on* (pp. 127-130). IEEE.

[19] Al-Arainy, A. A., Ahaideb, A. A., Qureshi, M. I., & Malik, N. H. (2004). Statistical evaluation of water tree lengths in XLPE cables at different temperatures. *IEEE Transactions on Dielectrics and Electrical Insulation*, *11*(6), 995-1006.

ACKNOWLEDGEMENTS

M. Karhan acknowledges TUBITAK BIDEB (2211-C) for National Ph.D. Scholarship.

Mukden UĞUR was born in Istanbul in 1968. He studied Electrical Engineering at the University of Yıldız, Istanbul from 1987 to 1991. He received an MSc degree from UMIST in 1993 and obtained his PhD in Electrical Engineering in 1997 from University of Manchester, UK. From 1995 to 1996 he worked for the National Grid Company as a research assistant at the University of Manchester in the subject of analyzing the breakdown process in transformer boards. Currently he is working as a Prof. in the Electrical & Electronics Engineering Department of Istanbul University. His main research interests are tracking in polymeric dielectric materials, power systems protection, fractal modeling and statistical evaluation of breakdown.

Mustafa KARHAN was born in Malatya in 1985. He received his BSc. degree in Electronics and Communication Engineering from Suleyman Demirel University in 2008. He received his MSc. degree in Electronics and Communication Engineering from Namik Kemal University 2012. He is a Ph.D. student at Istanbul University at Electrical-Electronics Engineering Department. from 2008 to 2012 he worked as a research assistant at the Namik Kemal University. From 2012 to 2013 he worked as a lecturer at the Bingöl University. Currently he is working as a lecturer in the Electronics & Communication Department of Cankiri Karatekin University. His main research interests are polymeric dielectric materials, water treeing phenomenon, digital image processing, signal processing, data mining, development boards.

Aysel ERSOY YILMAZ was born in Eskişehir. She received the M.Sc and Ph.D. degrees in Electrical& Electronics Engineering from Istanbul University, in 2003 and 2007 respectively. She studied as a post doctorate researcher at Kettering University in USA between 2008 and 2009. Currently she is working as an Assist. Professor in the Electrical & Electronics Engineering Department of Istanbul University. Her main research interests are tracking in polymeric dielectric materials, power systems protection, lighting and indoor installation.