International Conference on Renewable Energies and Power Quality (ICREPQ'16)
Madrid (Spain), 4th to 6th May, 2016
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.14 May 2016

# A comparative analysis of loss current obtained by measuring circuits used in studies of degradation power cables

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**Abstract**—It is widely recognized that water tree degradation would cause serious problems and it is generally agreed that is one of the most hazardous factor in the life of XLPE power cables and hence a major cause of MV power insulation premature failure. Such accidents affect the power supply system operation and reliability. Therefore, many techniques have been developed and employed in order to detect water tree at the early stages. In this context, the loss current technique is a suitable method for investigating slight degradation, since the cable degradation by water tree gives rise to harmonics components in the loss current. A comparative analysis of the values of various performance parameters that has been used in studies to evaluate the water tree degradation in power cables, obtained from the different loss current measuring circuits, is presented. This comparative analysis is made through a mathematical procedure and confirms the possibility to identify, with a very good accuracy, the loss current only from the measured leakage current without the need for specific measurement circuit used to distinguish the loss current that flows in the insulation layer. Furthermore opens the possibility to use the Fryze's equivalent conductance to eliminate in real cases the fundamental capacitive current of the total leakage current and perform online diagnosis only from the applied voltage and total leakage current measurements.

## Key words

XLPE insulated cable, water tree, loss current, cable diagnosis, power system.

## 1. Introduction

Questions related to power quality definitely challenge engineers all over the world. Amongst these, the matter of energy supply reliability emerges as an important point towards the improvement of continuity indexes such as the duration and frequency of interruptions. In this way, the information associated to the operational condition of equipment such as transformers, power cables, have a relevant role in the behavior of the electrical system. The reference [1] reported that many factors can result in the formation of faults in power cables and accessories. These could form in the process of manufacturing, handling, storage, transportation and installation.

Among the most prominent phenomena responsible for the degradation of power cables, the water tree [2-4] consists in a relatively common problem that is developed in the insulation layer of these components, as at Fig.1. Usually, it occurs when power cable is immersed in humid environment and presents voids and impurities inside the insulation or protrusions in the semiconductor layer of XLPE cables.

Fig. 1. Water tree growing from the inner (bottom) and outer (top) semi conductive screens [2]

Figure 2 shows the physical conception and allows noting two different and complementary circuits. The first one is destined to represent the healthy portion of the cable (multiple RC sets combined in a parallel association). The second one is composed by a series combination of a nonlinear arrangement, which includes a nonlinear resistance and is intended to represent the insulation damage, and a linear circuit, aiming to indicate the healthy regions around water tree deterioration. Naturally, the values assigned to these parameters will dictate the level of degradation involved in each situation under analysis.

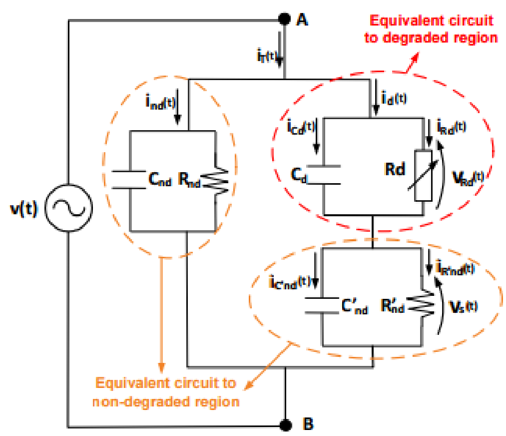



Fig. 2. Equivalent circuit which comprises healthy and degraded parts, for a given length of cable.

In Figure 2:

• $C_{nd}$ – Equivalent capacitance to the non-degraded cable extension;
• $R_{nd}$ – Equivalent resistance to the non-degraded cable extension;
• $C_d$ – Equivalent capacitance to the degraded region along the deteriorated cable insulation extension;
• $R_d$ – Equivalent resistance to the degraded region along the deteriorated cable insulation extension;
• $C'_{nd}$ – Equivalent capacitance to the non-degraded region along the deteriorated cable insulation extension;
• $R'_{nd}$ – Equivalent resistance to the non-degraded region along the deteriorated cable insulation extension.

Aiming at the diagnosis of the operational conditions of an insulated cable, in terms of life expectance, several methods have been developed and employed to evaluate, predict, and indicate the operational status of operating cables. In particular, when seeking practical ways for determining the final effects of water tree phenomenon on cable degradation, several researches are intended to propose procedures to detect this kind of failure through the extraction of information from performance parameters that indicate the degradation level of the insulation layer of a power cable and help the decisions about the replacement of the cables. Some methods examine the component in a de-energized condition while others are based on measurements carried out with an energized cable but without load. The reference [5] describes a synthesis of these strategies.

The present article is inserted in the context of the diagnostic method utilizing the harmonics in the loss current as a technique to diagnose water tree deterioration in XLPE cables. The latter current is called loss current as it relates to power losses in the insulation. As water tree degradation advances, the loss current waveform becomes distorted and harmonic components are included as result of nonlinear voltage-current characteristic of the water tree. The evaluation of these current harmonics provide a suitable diagnostic method for evaluating, predict, and indicate the operational status of operating cables. The reference [6] presents a brief review on methods introduced in literature to utilize the loss current as a diagnostic tool to identify and quantify the power cable degradation.

## 2. Diagnostic method using harmonic in loss current

It is known that dielectric dissipation factor of cable insulation increases and its breakdown voltage decreases with the growth of water trees in the cable insulation [5], therefore one of the oldest techniques still frequently used for diagnosis insulation condition is the dielectric loss tangent measurement. The ratio of loss current to capacitive current (tanδ) is extremely important as property for showing the insulation loss.

The technique using tanδ is an effective diagnostic technique in cases where deteriorations are uniform. Therefore it cannot discriminate between the occurrence of numerous water trees with slight deteriorations, and a few water trees with serious deterioration [7].

Measurement of the harmonic distortion of the insulation loss current also has been used as a diagnostic tool to detect and quantify the degradation level. The THD values exhibits much stronger dependence with electric stress than the dielectric losses. This results suggests that tanδ in the case of the insulation with predominantly medium size water tree may be unable to detect the presence of less frequent but longer trees. The Total Harmonic Distortion of loss current would better detect the long trees than by the tanδ values due to the correlation between the average water trees length with the THD is better than the correlation with the tanδ. The THD measurement can better differentiate the degradation of various stages of water tree than the loss tangent measurement [8].

Furthermore, examining the third harmonic loss current waveform parameters (i.e., amplitude $I_3$, phase angle $\theta_3$) it is possible to evaluate the water tree degradation. As the deterioration advances, the $I_3$ tends to grow and the $\theta_3$ decreases, showing a trend to a fixed direction [7].

Moreover, there is an extremely good correlation of $\theta_3$ with the extent of development of water trees and degradation of the breakdown strength [9]. The loss current technique is a diagnostic method that can be used to identify the un-bridged water tree, which can induce the sudden breakdown [10]. Then for the high-voltage class power cable, an accurate detection of this un-bridged water tree becomes important due its higher operating stress.

In addition, as the deterioration progresses, the insulation resistance usually decreases [11] and the shunt capacitance of the cable increases [12]. This behavior can be used as a signal of insulation deterioration in XLPE cables.

## 3. Experimental loss current measurement circuit

The loss current technique requires the identification of the loss current flowing in the insulation layer which is used as reference to identify the degree of the cable insulation degradation. A schematic diagram [13] of the experimental which is used for identify the loss current circuit is shown in Fig. 3.

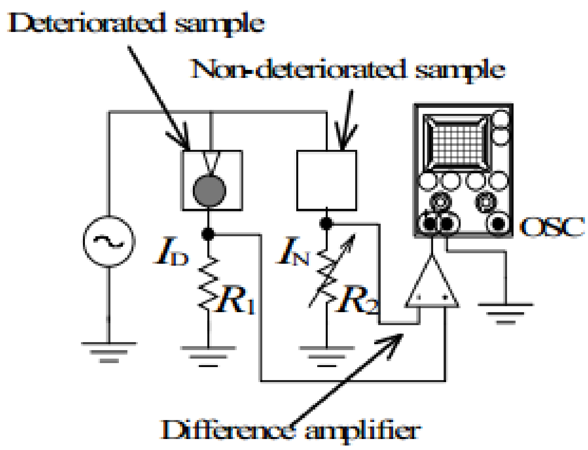



Fig. 3. Loss current measuring circuit – procedure 1 [13]

The basic operating principle of the above scheme is described below.

First, it is necessary to identify the currents flowing in each branch of the circuit, as follows: $I_N$ (t) corresponding to the non-degraded sample current, $I_D$ (t) corresponds to a degraded sample current and [$I_N$ (t) - $I_D$ (t)] is the output current of the differential amplifier. The same sinusoidal voltage is applied to non-degraded and degraded samples. The voltages across the $R_1$ and $R_2$ resistors are connected to a differential amplifier. By observing the waveform current in the differential amplifier on a oscilloscope is possible to identify the loss current by adjusting the resistance used for detecting the current through the non-degraded sample to make the difference current, $I_N$ (t) - $I_D$ (t), in phase with the applied voltage [14].

If the applied voltage is defined as a standard vector V the vectors $I_N$ and $I_D$ for the changing currents through the non-degraded and water-treed samples, respectively, are shown in Fig.4.

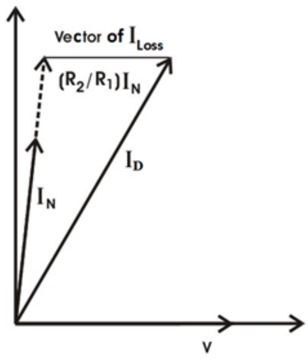



Fig. 4. Definitions of loss current [14]

It is noteworthy that, although the recognition that the waveform associated with the degradation process of the insulation gives rise to non-sinusoidal currents, the vector representation merely show the process of the composition's currents components presented in the study.

Note that this procedure does not consider the possibility of harmonic capacitive current, because only the fundamental frequency is considered in the capacitive current. Fig.5 shows the waveform of the loss current component of the leakage current obtained using the measurement circuit presented in Fig. 3. In this case, a voltage of 5 kV peak-to-peaks (1 kHz) was applied and the growth of the water tree in the sample is 90% [13].

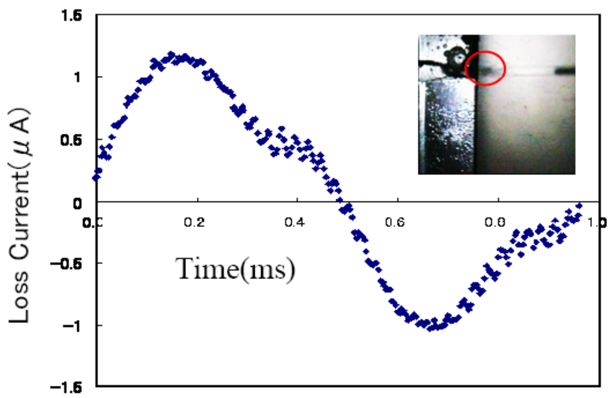



Fig. 5. Water tree deterioration and measured loss current [13]

Another procedure also used to determine the loss current of the leakage current in a degraded sample cable is shown below. In this case instead of using the operational amplifier circuit based on capacitive bridge as shown in Fig.6. A no-loss standard capacitor is connected in parallel with the sample and a bridge circuit maintains the current balance in both components. The loss current is obtained by subtracting the capacitive current of the total current flowing in the sample. Loss current waveforms are obtained as discrete numerical data using a digital oscilloscope. A test voltage of 1 kV (50 Hz) was used in current loss measurement [7].

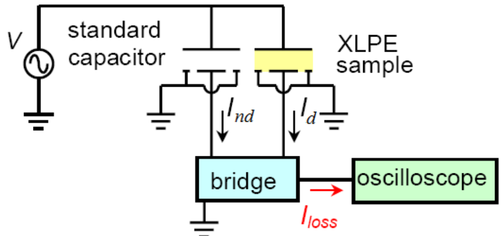



Fig. 6. Loss current measuring circuit – procedure 2 [7]

On the other hand the Fig. 7 shows loss current waveform obtained from degraded sample using the measurement circuit presented at Fig.6. The water trees were generated by forming a liquid electrode of 1 mol/1 of NaCl solution on one side of an XLPE sheet sample (0.5 mm thick) and applying a voltage of 3 kV (1 k Hz) for 500 hours, causing a degradation that reached significant portion of the sample used in the experiment. This loss current waveform was obtained from the original measured waveform as discrete numerical data by means of specific software developed by the authors.

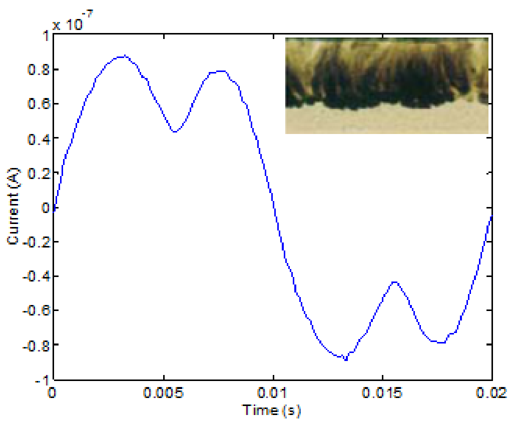



Fig. 7. Water tree deterioration and loss current waveform [7]

Observing the waveform shown in Fig. 7, procedure 2, and comparing it with the waveform shown in Fig.5, procedure 1, there is a significant difference from one to another. The hypothesis for this discrepancy is that the loss current obtained by the procedure 1 contains capacitive harmonics. To eliminate these capacitive harmonics in order to prove this hypothesis, is used a mathematical procedure that was developed by the authors and tested with success to recovery the loss current waveform, reported in [15]. This is feasible because through this mathematical procedure it is possible to identify the capacitive current that flows in the insulation due to water tree, as shown below.

Such leakage current constitutes the composition of capacitive current and the loss current, fundamental and harmonics, the total current flowing in the insulation is:

$$i_{total}(t) = i_0 + i_{wt}(t) \tag{1}$$

Where

$i_0$ = fundamental leakage current
$i_{wt}$ = harmonic leakage current

Using Fourier series it is possible to conclude that:

$$\begin{aligned} i_{wt}(t) &= c_1 \sin(\omega t+\theta_1) + c_3 \sin(3\omega t+\theta_3) \\ &+ c_5 \sin(5\omega t+\theta_5) + c_7 \sin(7\omega t+\theta_7) \\ &+ \ldots \end{aligned} \tag{2}$$

Equation (3) expresses the harmonic components of the total current.

$$\begin{aligned} i_{h\_wt}(t) &= c_3 \sin(3\omega t+\theta_3) + c_5 \sin(5\omega t+\theta_5) \\ &+ c_7 \sin(7\omega t+\theta_7) + c_9 \sin(9\omega t+\theta_9) \\ &+ \ldots \end{aligned} \tag{3}$$

The harmonic components may also be presented by their orthogonal components as given by equation (4).

$$i_{h\_wt}(t) = i_{h\_c}(t) + i_{h\_r}(t) \tag{4}$$

Where

$$\begin{aligned} i_{h\_c}(t) &= c_3 \sin(3\omega t+\theta_3) + c_3 \sin[3\omega t + (\theta_3-90°)] \\ &+ c_5 \sin(5\omega t+\theta_5) + c_5 \sin[5\omega t + (\theta_5+90°)] \\ &+ c_7 \sin(7\omega t+\theta_7) + c_7 \sin[7\omega t + (\theta_7-90°)] \\ &+ \ldots \end{aligned} \tag{5}$$

And

$$\begin{aligned} i_{h\_r}(t) &= c_3 \sin[3\omega t+(\theta_3+90°)] \\ &+ c_5 \sin[5\omega t+(\theta_5-90°)] \\ &+ c_7 \sin[7\omega t+(\theta_7+90°)] \\ &+ \ldots \end{aligned} \tag{6}$$

Therefore, the loss current will be calculated through (7).

$$i_{loss}(t) = i_{wt}(t) - i_{h\_c}(t) - i_{\Delta C_0}(t) \tag{7}$$

Where

$$i_{\Delta C_0}(t) = [i_{wt}(0) - i_{h\_c}(0)] \cos(\omega t) \tag{8}$$

Fig.8 shows the vector diagram, containing the currents involved in the determination of the loss current from the total leakage current, considering the fundamental current and the third harmonic current.

It was also pointed out in this case that the use of components at different frequencies is only to show the process of the composition of the current involved in this methodology. Note that the $I_{wt}$ and $I_{loss}$ are not phasor because the modules vary with time.

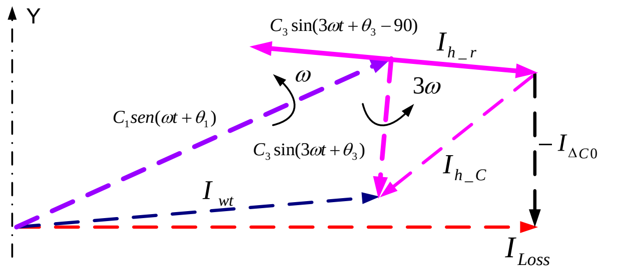



Fig. 8. Currents components involved in the methodology

Figure 9 was obtained from the original waveform, Fig. 5, by means of specific software developed by authors, considering the fundamental and the third harmonic.

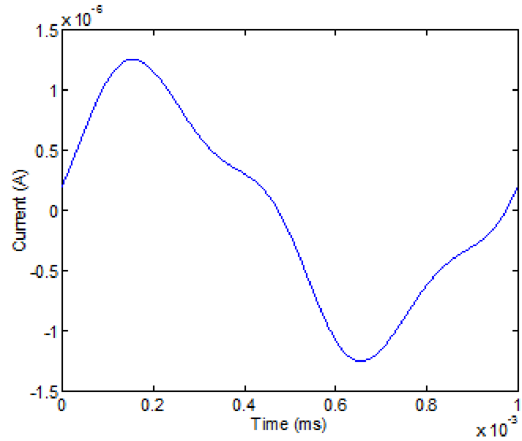



Fig. 9. Loss current waveform without scattering

This procedure can be summarized in the following steps:

a) Shift the measured loss current to make it on stage with a sign sinusoidal supply with angle phase equals zero;
b) Elimination of harmonic contribution of capacitive nature;
c) Elimination of residual contribution of capacitive current at the fundamental frequency.

Applying these steps in the waveform presented in Fig.9 resulting in a loss current waveform shown in Fig.10.

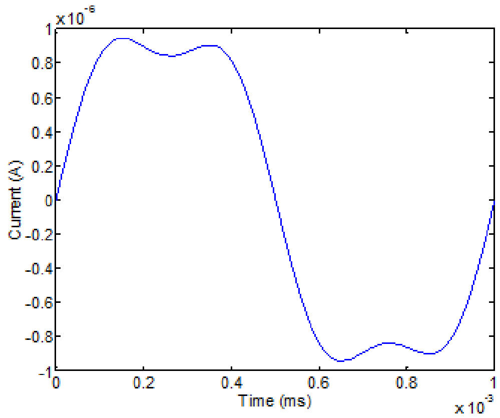
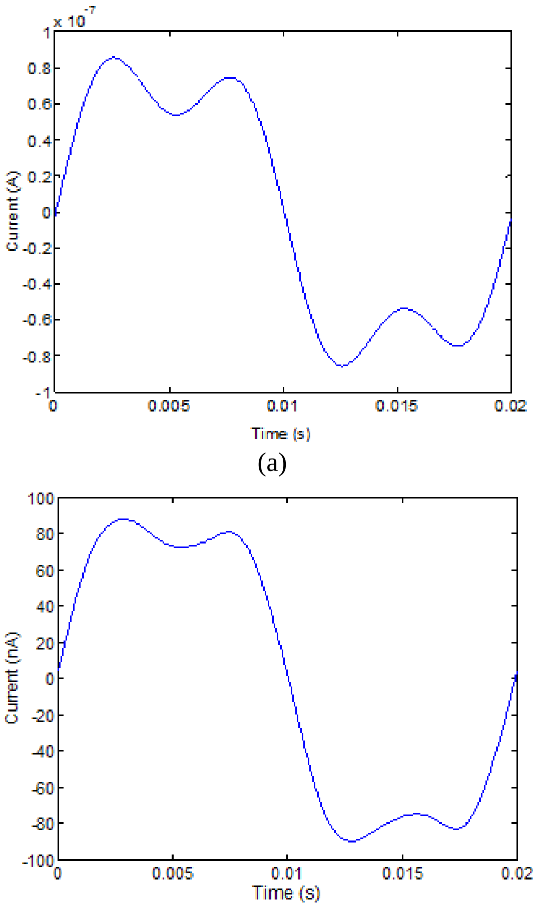



Fig. 10. Loss current waveform without capacitive harmonics

Note that current waveform shown in Fig.10 has significant similarity with the waveform shown in Fig. 11 (a) obtained from the original measured waveform [7], and in Fig. 11 (b), obtained by theoretical model for a sample with water tree extended to 80% [16], considering only the fundamental and the third harmonic.

Taking in to account the results obtained in reference [15] it is possible to ensure that the difference between the curves obtained by the procedures mentioned above is due to the existence of capacitive harmonic components in the loss current measured by the procedure 1.




(a)

(b)

Fig. 11. Loss current waveform: a) measured; b) calculated

By having the loss current and the capacitive current it is possible to determine the following parameters: total harmonic distortion, power loss, tanδ, $I_3$ and $\theta_3$. These constitute the necessary data to estimate the degree of insulation degradation. Moreover, the equivalent resistor and capacitance can be obtained throughout the relationship between the applied voltage and fundamental component of loss current and fundamental component of capacitive current, respectively.

It is worth noting that in this study, the equivalent capacitance ($C_{eq}$) and the dielectric loss tangent (tanδ) were not considered due the unavailability of the total leakage current, corresponding to the experiments considered here.

As already mentioned, the knowledge of the leakage current, allows the determination of a set of indicators to find operational condition of the insulating layer degraded by water tree. In the next item will be discussed if there are significant discrepancies in these indicators, when the loss current is measured by the two measurement circuits focused on this study.

## 4. Insulation parameters for diagnostic of power cables due water tree degradation

By knowing, the total leakage current is possible to calculate the following performance parameters:

1) Equivalent insulation resistance $R_{eq}$ is determined by the relationship between the peak values of voltage and loss current in the fundamental frequency.

2) Insulation equivalent capacitance $C_{eq}$ is determined by the ratio between the peak values of voltage and reactive power in the fundamental frequency.

3) The dissipated power (P) is calculated as (9)

$$P = R_{eq} I_{ef}^2 \qquad (9)$$

Where

$I_{ef}$ = true rms value of loss current.

4) The total harmonic distortion THD, obtained by (10)

$$THD_I = \frac{\left(\sum_{i=2}^{\infty}(I_i^2)\right)^{0,5}}{I_1} \qquad (10)$$

Being Ii the amplitude of the *ith* harmonic contribution, corresponding to the frequency fi = (i x 50) Hz.

5) The dielectric dissipation factor, determined as (11)

$$\tan\delta = \frac{1}{2\,\pi\, f\, R_{eq}\, C_{eq}} \qquad (11)$$

Where

f = the fundamental frequency.

These performance parameters were calculated for the loss current obtained in each of the aforementioned procedures and the results are shown in Table I.

TABELA I. INSULATION PARAMETERS

| | Procedure1 | Procedure 2 |
|---|---|---|
| **THD (%)** | 20,49 | 20,6 |
| **P (mW)** | 1,33 | 1,31 |
| **$I_3$ (μA)** | 0,21 | 0,21 |
| **$\theta_3$ (°)** | -96,91 | -6.91 |
| **$R_{eq}$ (GΩ)** | 2,45 | 2,48 |

The results presented in Table I indicate that the difference between the values of the parameters is less 1.6%, except for $\theta_3$, comparing the values of the two procedures. Therefore, the two measuring circuits permit the same diagnosis of the operating condition of the insulating layer. Moreover, it is important to note that both circuits, by itself, do not apply to real cases. However, this result shows that in real cases is possible to separate the fundamental capacitive current of the total leakage current using the conductance G such was referred to by Fryze as equivalent conductance (12).

$$G = \frac{P}{V_{rms}^{2}} \qquad (12)$$

Where

P = active power
$V_{rms}$ = true rms value of applied voltage

The following steps are adopted to determine the capacitive fundamental current flowing through the total current:

a) Determine the magnitude of the fundamental active current using the Fryze's equivalent conductance;

b) Varying the angle of the fundamental active current such that the fundamental capacitive current is a cosine wave with a zero degree phase shift.

This procedure allows to calculate the capacitive current when the active current not in phase with the applied voltage. The authors in theoretical nonlinear loads have identified this situation.

Note that this procedure can be applied in cases where the supply voltage presents distortion because the Fryze's equivalent conductance also applies to systems with distorted voltages.

## 5. Conclusions

This investigation presented a comparative analysis of the loss current determined by two measuring circuits that are commonly used to identify the loss current in the leakage current that flows through a sample of XLPE cable degraded by water tree. The results show for the case considered the two measuring circuits lead to the same diagnostic of the power cable insulation because the values of the indicators calculated based on the leakage current have very close except for the third harmonic angle that differs ninety degrees from one circuit to another. The method considered is based on various performance parameters, which are obtained from the loss current that flows in the degraded sample. Furthermore opens the possibility to use in real cases the Fryze's equivalent conductance to eliminate the fundamental capacitive current in the total leakage current and perform online diagnosis, only from the voltage supply and total leakage current measurements, without using specific measurement circuits to determine the orthogonal leakage current components. One aspect to be considered in future studies concerns the elimination the harmonic current contribution in leakage current due to distorted supply voltages.

## *References*


[1] IEEE Guide for Partial Discharge testing of Shielded Power Cables System in a Field Environment. (IEEE Std 400.3tm -2006).

[2] S. Priya and A. Mubashira Anjum, "Analysis of Water Trees and Characterization Techniques in Xlpe Cables", Indian Journal of Science and Technology, Vol. 7(S7), 127–135, ISSN: 0974-6846, November 2014.

[3] Skoršepová Terézia, "The growth of water trees in XLPE cable's insulation", Journal *Elektrotechnika,* Ročník 6, číslo 9, Portál pre odborné publikovanie ISSN 1338-0087, Set, 2013.

[4] R. Ross, "Inception and Propagation Mechanism of Water Treeing", IEEE Trans.Electr.Insul., Vol. 5, Nº5, pp. 660-680, 1998.

[5] S. Yamaguchi, S. Soda, N. Takada, "Development of a New Type Insulation Diagnostic Method for Hot-Line XLPE Cables", IEEE Transactions on Power Delivery, July, Vol. 4 Nº 3, pp. 1513-1520, 1989.

[6] Hussain, N.; Nor, N.M. ; Abdullah, M.F. ; Ashraf, K.; Usman Baloch, M, "Review of Third Harmonic Current Characteristic based Diagnostic Methods of medium Voltage Power Cables Insulation". Sustainable Utilization and Development in Engineering and Technology (STUDENT), IEEE Conference on, 2012.

[7] T. Tsujimoto, M. Nakade, Y. Yagi, K. Adachi, H. Tanaka, Egasaki-cho, Tsurumi-ku, Yokohama, Kanagawa, Yawata-kaigandori, Ichihara, Chiba, Higashi-shinagawa, Shinagawa-ku, "Development of on-site Diagnostic for XLPE Cable by Harmonics in AC Loss Current" Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials, June 1-5, Nagoya, pp 73-76, 2003.

[8] A. T. Bulinski, E. So, S. S.Bamji, "Measurement of the Harmonic Distortion of the Insulation Loss Current as a Diagnostic Tool for High Voltage Cable Insulation," 0- 7803-5935-6/00/$10.00 © 2000 IEEE, pp. 1615-1620, 2000.

[9] Y. Yukihiro., T. Hideo and K. Hitoshi., "Study on Diagnostic Method for Water Treed XLPE Cable by Loss Current Measurement," 0-7803-53035-9/98/$10.00© 1998 IEEE, pp. 653-656, 1998.

[10] T. Furuhashi, K. Tohyama, T. Imai, Y. Murata, "Dissipation Current Waveform of Water Tree Deteriorated Low Density Polyethylene Sheet". Electrical Insulation and Dielectric Phenomena, 2006 IEEE Conference on, Oct. 15-18, pp. 529-532, 2006.

[11] Wei. Zhang, Yutao Zhau, Baitun Yang, Yaonan Liu, "A Study on DC Component Method for Hot-Line XLPE Cable Diagnosis," IEEE International Symposium on Electrical Insulation, Pittsburgh – PA USA, June 5-8, pp. 95- 98, 1994.

[12] T. Ozaki, N. Ito, I. Sengoku, J. Kawai, and S. Nakamura, "Changes of capacitance and dielectric dissipation factor of water-treed XLPE with voltage,", Electrical Insulating Material, 2001. Proceedings of 2001 International Symposium, Himeje, Japan, pp. 459-462, 2001.

[13] Suzuki, M.; Itoh, A.; Yoshimura, N. "Three-dimensional Equivalent Circuit Analysis of Water tree". Power and Energy Systems (ICPS), 2011 International Conference on, pp .1 – 4, 2011.

[14] N. Ito, T. Ozaki, I. Sengoku, J. Kawai,"Relation between the AC loss current method and PEA method for water-treed length", IEEE Electrical Insulating Materials. Proceedings of 2001 International Symposium on, Himeji, Japan, pp. 524-527, November 2001.

[15] F. N. Lima, J. C. Oliveira, D. A. Andrade, B. C. Carvalho, A. P. Finazzi, R. M. T. Silva, "Modeling Water Tree Phenomenon for Insulated Cable Loss Current Estimation", Transmission and Distribution Conference and Exposition Latin America, 2008 IEEE/PES, August 13-15, Bogotá, Colombia, pp. 1-6, 2008.

[16] Suzuki, M., Itoh, A., Yoshimura, N., "Loss Current Analysis of Water Tree Degradation in Polyethylene using Equivalent Circuit Model", IEEJ Transactions on Fundamentals and Materials, Volume 125, Issue 4, pp. 367- 372, 2005.