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Using the light emission measurement in assessment of electrical discharge development in different liquid dielectrics under lightning impulse voltage

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ABSTRACT

This article presents the results of studies concerning the assessment of propagation modes of electrical discharges developing in different liquid dielectrics. This assessment was performed on the basis of measurements of light emitted during discharge development. For liquid dielectrics such as natural ester, synthetic ester and mineral oil tested under standard lightning impulse voltage of both polarities, two propagation modes of discharges were identified: slow developing discharges of propagation velocities of few mm/μs and fast developing discharges of velocities of tens mm/μs. Comparing the results concerning the liquids tested in synthetic ester and natural ester fast discharges appeared at much lower testing voltage than in the case of mineral oil. Simultaneously, at the same voltage level, the frequency of light pulses corresponding with the discharges developing in esters was higher than frequency of pulses observed when discharges developed in mineral oil. Thus the results showed that both esters are less resistant to the appearance of fast and energetic discharges, which means that esters may have a lower ability to protect against the lightning impulses in real insulation systems. It is suggested that this disadvantage of the ester liquids should be necessarily taken into account during the design process of transformers filled by them.

1. Introduction

A growing interest in liquid dielectrics being an alternative to the mineral oils in the field of eco-friendly properties has been observed for several years in the transformer industry. This is because the trends related to the production of environmentally friendly products have also been aroused in the area of power transformers and liquid insulation used in them [1–5]. The above mentioned alternative liquids are specially produced synthetic esters and manufactured from legume seed natural esters. Both of these are characterized by a level of biodegradability equal to around 90% which makes them, in accordance to the OECD 301 standard, fully biodegradable. Thus in the case of unexpected leakage to the environment these liquids do not pose a threat. With the introduction of the esters in the transformer market a series of the studies on their physico-chemical and dielectric properties have been performed. These studies have confirmed the possibility of using the esters in electrical applications but with indication that some negative features exist, especially in the area of an electrical strength at lightning impulse voltage [2,6–13]. More precisely, a problem of lower ability of the esters than the mineral oils to protect insulating systems against the appearance of fast and energetic electrical discharges initiated as a result of lightning overvoltages, has been observed. In this respect, having the variety of experimental methods commonly used in the analyzes of electrical discharge propagation in mineral oil a comparison of the results of the measurements of light emission generated by the partial discharges developing under standard lightning impulse voltage 1.2/50 μs has been proposed in this paper. The stress of such type may occur in the insulating systems of power transformers and behavior of the liquids under such stress may influence the design process, thus the insulation coordination of the transformers [7–15].

In general, there are many measurement techniques used in the studies of electrical discharges in liquid dielectrics under lightning impulse voltage. These techniques are based either on the optical methods which allow the investigation of the spatio-temporal development of the discharges or on the electrical methods which enable the measurement of current, charge as well as voltage that is applied to the tested electrode system immersed in liquid [7–9,11–17]. The necessity for using the above mentioned

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techniques has resulted from the fact that the processes of initiation and propagation of the discharges in liquids are very complicated and involve very complex phenomena. Thus, they require a multilayer analysis in order to assess their character. The long-term studies within the field of discharge development in the different hydrocarbon liquids have allowed for the elaboration of division of these discharges in the specific modes. These modes occur together with voltage increase in the given electrode system (with rising the electrical field stress resulting from the voltage applied) and each of the modes is characterized by its properties in terms of spatio-temporal development. In view of propagation velocity of the discharges they have been divided into two main modes: slow and fast. However within these two modes there are some sub-modes such as 1st and 2nd mode (characterized by propagation velocity of few mm/μs named commonly as slow) and 3rd and 4th mode (having propagation velocity from a dozen to tens of mm/μs and named as fast) [7,17–19]. The 1st mode discharges may appear only in specific conditions and that are in the systems with a point electrode of a very small radius of curvature. Hence in most experimental studies concerning discharges in liquid dielectrics under lightning impulses identification of such a mode in practice is very difficult. The 2nd mode discharges are however typical discharge modes developing at inception voltage V_0 and at testing voltages up to circa 2 times higher than this threshold value. It is important to note in this point that the range of the testing voltages, at which the 2nd mode discharges develop, depends on the type of dielectric liquid under consideration. For example in ester liquids and mineral oils of high content of aromatic molecules the maximum testing voltage multiples for development of 2nd mode discharges is lower than in the case of mineral oils of low content of these aromatic compounds. The 2nd mode discharges may lead to the breakdown in the given testing conditions. However the breakdown channel created on the basis of the developing discharge is not ionized strongly. Alternatively, when the electrodes are isolated or a grounded electrode is covered with an insulating plate, a so-called return channel is created as a result of capacitive coupling between the metal parts of the electrodes. This channel is also not ionized as much as it may damage the solid insulation [19]. Both the 1st and 2nd mode discharges develop as a result of gaseous phase ionization which means that the discharge channels are filled with ionized gas and next step lengthening of these channels are connected with ionization of the molecules of low ionization potential. With increase in the testing voltage the fast (3rd or 4th mode) discharges start to occur. The characteristics of these types of the discharges are significantly different to the slow developing discharges of 1st and 2nd mode. In addition to the clear difference in the spatial shape of the discharge forms, changes are observed first of all in the sudden increase of propagation velocity of the discharges. Thus recognition between the slow and fast discharges may be identified just on the basis of this feature. For this reason a term of acceleration voltage was introduced in the assessment of electrical discharges in liquids [7,8,17,18]. This term describes the threshold value of voltage at which the sudden change of propagation velocity follows with raising the testing voltage. A determination of the acceleration voltage for different liquid dielectrics may give the possibility to assess the resistance of a given liquid against the voltage stress of a given type. The current and charge of the fast discharges is also higher than the slow discharges similarly as frequency of light pulses recorded. The propagation is still in a step way, but the next steps occur in a shorter time. It is assumed that for fast discharges the dominant phenomenon is liquid phase ionization. In general, in the process of discharge development, the high number density main molecules are ionized, which do not participate in the propagation of 1st and 2nd mode discharges [7–9,16–19]. A higher propagation velocity and more intense ionization processes of fast discharges are also reflected in the created breakdown or return channel. The energy of these events is much higher than analogically events which occur as a result of slow discharge development. The appearance of breakdown or return channel in the insulating system may result finally in the destruction of the paper insulation. As was mentioned above among the fast discharges the 3rd and 4th sub-modes are extracted. The differences between these modes are connected mainly with intensity of ionization processes which is mapped also in propagation velocity. The 3rd mode discharges appear in mineral oil at voltages which are slightly higher than acceleration voltage and are characterized by velocity of 10–40 mm/μs depending on the oil gap. The 4th mode discharges are however characterized by extremely high velocity reaching even 100 mm/μs and appear at voltages which are much higher than acceleration voltage [17,18]. Anyway above findings concern mineral oils and their applications for ester liquids must be done with reserve.

One of the most important experimental methods providing information about the processes occurring during electrical discharge propagation in liquids is method of measurement of light emitted by the developing discharges. As has been mentioned the intensity of light is strictly connected with the intensity of ionization processes. By leaps and bounds developing discharges generate the pulsed light, which may be registered using proper detectors and then in the form of waveforms may be presented on the screen of an oscilloscope. The higher frequency of light pulses registered the more frequent step lengthening of the discharge channels occur. The higher peak values of the light pulses reflect in higher energy of discharge itself [7,8,11–19].

2. Methods and samples

2.1. Experimental technique description

Fig. 1 presents the general scheme of a laboratory system used in the studies of electrical discharge development in liquid dielectrics based on light emission measurement. The voltage source was a six-stage Marx generator of rated voltage 500 kV and storage energy of 2.2 kJ producing a standard lightning impulse of 1.2/50 μs. The peak value of the voltage waveform was measured using a resistive voltage divider and peak value meter. Simultaneously, the voltage waveform was registered on the screen of an oscilloscope in order to control the correctness of its shape. The lightning impulse was supplied through a limiting resistor to the electrode setup placed in the test cell. The tests were performed for a point-plane electrode arrangement, typical electrode system representing a strongly non-uniform electric field distribution. The highest electrical field stresses are obviously in the vicinity of the point electrode

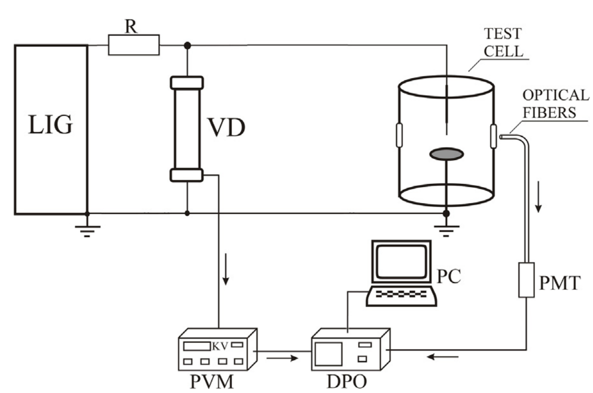

Fig. 1. General scheme of laboratory experimental system. LIG, lightning impulse generator, VD, voltage divider; R, limiting resistor; PMT, photomultiplier; PVM, peak value meter; DPO, digital phosphor oscilloscope; PC, computer.