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Analysis of the Light Radiation Spectra Emitted by Electrical Discharges in Insulation Oil

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The paper presents the measurement results of the optical spectrum of the light emitted during disruptive electrical discharges in the plane-point system. Optical spectra are presented for the electrode of various point inclinations. The measurements were taken using a spectrometer with a diffraction grating with a semiconductor CCD. An interpretation is presented of the occurrence of extrema in optical spectra coming from the change of energetic state of elements that are part of an electrode and occur as a result of free gas generation. For comparison, the optical spectrum run for electrical discharges of the surface type is presented.

Keywords: optical spectrum, electrical discharge, surface.

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I. Introduction

The formation of PDs in solid, liquid and gaseous dielectrics is accompanied by a number of physical phenomena, the most important of which are the occurrence of a current pulse and emission of an electromagnetic wave, chemical insulation changes, percussive elastic strain and the generation of an electromagnetic wave that accompanies it.

Based on these phenomena various diagnostic methods have been developed for the detection, measurement and location of the PDs that can occur in insulation systems of power appliances [10]. At present, the following non-destructive methods have found their technical application in estimating electrical discharges: electric, gas chromatography and acoustic emission (AE) methods. Also the comparative estimate measurements are taken of the amount of the heat produced, the light emitted and the changes of pressure in the area of PD generation [1, 2].

The subject matter of this paper is the evaluation of the possibility of applying the optical method for detection and evaluation of the degree of hazard to oil insulation systems of power appliances due to electrical discharges.

The particular aim, however, is to determine the type of energy released to the environment as different forms of radiation. This includes both mechanical energy measured by acoustic spectroscopy (the measurement of amplitude changes of acoustic waves between 300m and 3 km long, which correspond with frequencies from 105 to 103 Hz) and high-frequency radiation within the optical spectroscopy range (wave length from 10 nm to 30 mm). The power participation of the waves generated depends on the length the wave generated and is the

highest in the range of ultraviolet (10-380) nm ; in the visible range (380-780 nm) the participation of energy is lower. The cause of wave occurrence in particular ranges of length is connected with the character of the phenomena taking place. In the ranges of ultraviolet and visible light, the waves are connected with the passage of valence electrons between atomic envelopes. In the infrared range, the waves are connected with the rotation of particles, which is the effect of particle stretching and bending. Determining the participation of the particular phenomena taking place during electrical discharges requires the use of the spectral emission method. In this method the following processes can be distinguished: excitation of atoms and radiation emission, fission of the radiation emitted, registration and interpretation of a spectrum (identification of spectral lines) [7-9, 11].

This paper presents an analysis of the optical spectra generated in spark gaps modeling electrical discharges of the point-plane and surface types occurring in insulation oil. For electrical discharges of the point-plane type, the results of the spectral analysis, including the particular phases of a discharge formation, are presented, and the influence of the geometry change of the point electrode on the characteristics obtained is evaluated. Moreover, for comparison, an analysis of optical spectra emitted by electrical discharges of the surface type is presented.

II. Characteristics of emission spectra

The emission spectrum is closely connected with the electron structure of an atom. Under normal temperature and pressure conditions, atoms are in a ground state. A minimum of the energy emitted corresponds with this state. After providing an atom with an energy quantum,

an electron transfer onto a higher power level takes place, and the atom is in an excited state of a higher energy than the energy in the ground state. After some time, an electron transfer from the higher onto a lower level takes place. This transfer is connected with energy emission in the form of electromagnetic radiation. The frequency of this radiation is:

$$\nu = \frac{c}{\lambda} = \frac{E_e - E_g}{h} \quad (1)$$

where c , h – are constants denoting the speed of light and the Planck number, λ is the length of the wave generated, E_e is the atom energy in the excited state, E_g is the atom energy in the ground state.

The excitation of atoms can take place in a thermal way through the mechanical (kinetic) energy transfer or through providing electromagnetic energy (optical). In the system under study, the excitement is of a thermal character. Under the influence of high voltage, at a certain distance between the electrodes a spark-over takes place. The electrons propelling in a spark collide with atoms occurring both between the spark gaps and on the plane (point) material. The excitement takes place when the kinetic energy of a propelling electron is at least equal to the excitement energy of the first spectral line of an atom. During the collision with the atom of an electron of the energy higher than the excitement energy it loses a part of the kinetic energy which is used for exciting the atom; the electron, however, keeps on propelling, retaining the rest of energy (inelastic collision). The duration time of the atom in an excited state is short: 10^{-8} s. Immediately after the excitement, the radiation emission connected with the electron transfer from the higher power level onto the lower one takes place. The return from the higher power level can be direct or gradual through lower states of excitement. The atom excited thermally can collide again with the electron before the energy emission – then it will be additionally excited. Also, the process reverse to excitement can take place, i.e. the return of the excited atom to the normal state due to the collision with an electron in the result of which the energy of the atom increases. The excitement energy depends on the atom structure and especially on the duration of the valence electron bonding in an atom [7-9, 11].

III. Characteristics of the measuring set-up used

In the research work carried out by the authors a set-up modeling PDs of the point- grounded plane and surface in oil type was used. In the distance of 3 cm in the direction perpendicular to the spark gap axis an outlet of the optical waveguide coupled with the spectrometer was mounted. The spectrometer was mated with a computer equipped with proper software. In the measurements a spectrometer AVS-USB2000 by the AVANTES firm was used, the main element of which is a multistage diffraction grating which makes it possible to analyze the spectrum in the range of (270-1600) nm with the resolving power of about 0.5 nm. The signal is

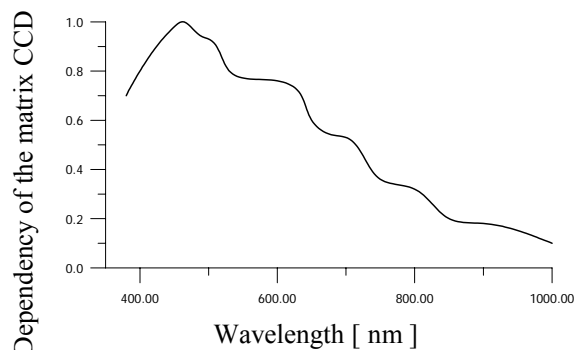


Fig. 1. Dependency of the spectrometer matrix sensitivity on the radiation wave length.

brought to the grating by the optical waveguide. After the fission the radiation falls on a CCD matrix (Sony ILX511). The integration time can be changed in the range from 3 ms to 60 seconds. An analogue - digital transducer of a 12- bite resolving power at the sampling time of 1 MHz was used for processing the signal into the digital form. The device is coupled with the computer by the UBS series connector.

The measurement in the particular element of the CCD matrix (2048 elements sized 12.5 x 200 micrometers) is based on the photon counting in a time unit. One counting corresponds with the activation by 86 photons, which is the equivalent of the sensitivity of $2.9 \cdot 10^{-17}$ J/pulse. The relative sensitivity depends of the length of the wave analyzed. The dependency of the relative sensitivity on the wave length is shown in fig. 1. The root-mean-square value of the dark current is from 2.5 to 4 countings [5, 6].

IV. Characteristics of the built spark gaps modeling electrical discharges

Fig. 2 shows an idea diagram of a spark gap which makes generation of electrical discharges of the point-plane type in insulation oil possible. The distance between the electrodes is 3 cm. In order to evaluate the influence the point electrode geometry on the runs of the optical spectra generated by electrical discharges in the

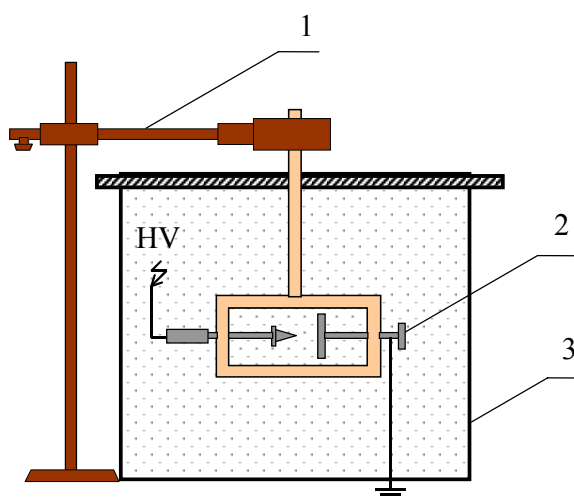


Fig. 2. Schematic of a point-grounded plane spark gap 1 - structure fastening the gap, 2 - point and flat electrodes, 3 - insulation oil tank.

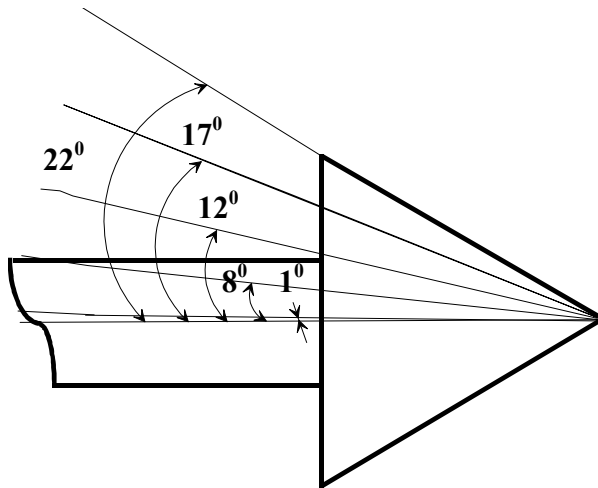


Fig. 3 Pictorial presentation of the point electrodes used of the given angle values of their curvature.

point-plane system, the measurements for five various angles of its curvature and their corresponding five diameters of the point ends were taken. Copper point electrodes were made for testing purposes of the following sizes of the point curvature angles and of their ending diameters (the values are given in round brackets): 22° (0.6 mm), 17° (0.54 mm), 12° (0.4 mm), 8° (0.23 mm), 1° (0.06 mm). Fig. 3 shows in a pictorial way the values of the angles and the way they were determined. The spark gaps made were placed in a transformer tub size: 1.5 m x 2.0 m x 2.0 m. The model set-ups used were placed in special fixing grips ensuring the repeatability of the PD generation place. The geometric measurements of the spark gaps made were over 15 times smaller than the transformer tub size in which they were placed.

The spark gap diagram making the generation of electrical discharges of the surface type possible is shown in Fig. 4. The electrode, to which high voltage was supplied, was a metal cylinder (1) of a diameter of 3 cm and length of 9 cm. The other electrode was a metal plane (3) sized 16 cm x 13 cm with a thickness of 2 mm, which was grounded. The spark gap electrodes were separated by an insulation layer, and the research range included various types of resins and papers that can be used in insulation technology [3, 4].

The set-ups under study modeling electrical discharges of the point-plane and surface types were supplied from a standard test set-up which made fluent adjustment of the voltage from 0 to 60 kV possible. The optical transducer was placed in a specially profiled ebonite pipe, the terminal opening of which placed in transformer oil directly over the area of electrical discharge generation was tightly closed with a quartz glass. The transformer tub was tightly closed with the upper lid, in which an opening enabling the introduction of the pipe with the measuring transducer was made. The measurements were taken in a darkened room without access of any additional sources of light radiation [3, 4].

The paper will present the measurement results of

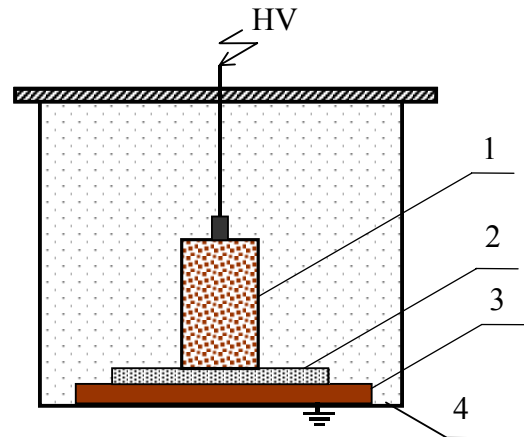


Fig. 4. Schematic of a 'cylinder-grounded plane' spark gap, with a pressboard insulation, to generate surface PD
1 - cylinder electrode, 2 - pressboard insulation, 3 - flat grounded electrode, 4 - insulation oil tank.

the optical spectrum emitted by electrical discharges in the point-plane spark gap in insulation oil for two extreme values of the curvature angle of the point electrode 22° and 1° , with which the diameters of the point electrode endings 0.6 mm and 0.06 mm, respectively, corresponded.

V. Analysis of the measurement results obtained

Figs 5-6 show optical spectra of light impulses generated at disruptive discharges of the point-plane type for the point electrode with a curvature angle of 22° . These spectra are characteristic of a wide power band active in the visible range (400-780)nm. In the infrared range a bigger power participation occurs in the second phase of a discharge, which is connected with a slower release of heat compared with optical wave generation. A spectral wide-band response is connected with a large number of particle structures. In the initial period (Fig. 5) there occur extrema at the values of 510 and 654 nm. A relative value of the radiation intensity of such lengths changes in the second phase of a discharge (Fig. 6).

Fig. 7 shows the magnification of the optical spectrum in the initial phase of a discharge in the range of ultraviolet close radiation (280-380 nm). The characteristic features are a rotational shape of the spectrum and the extremum occurring at the length of 324 nm. It is a spectral line of copper (green of a theoretical length of 324.7 nm), which results from the transfer from the state of excitement to the ground state (Fig. 9). A spectral line 510 nm is also typical for copper, which results from the transfer from the excitement level 3.817 eV to the level of lower energy 1.389 eV. Such a

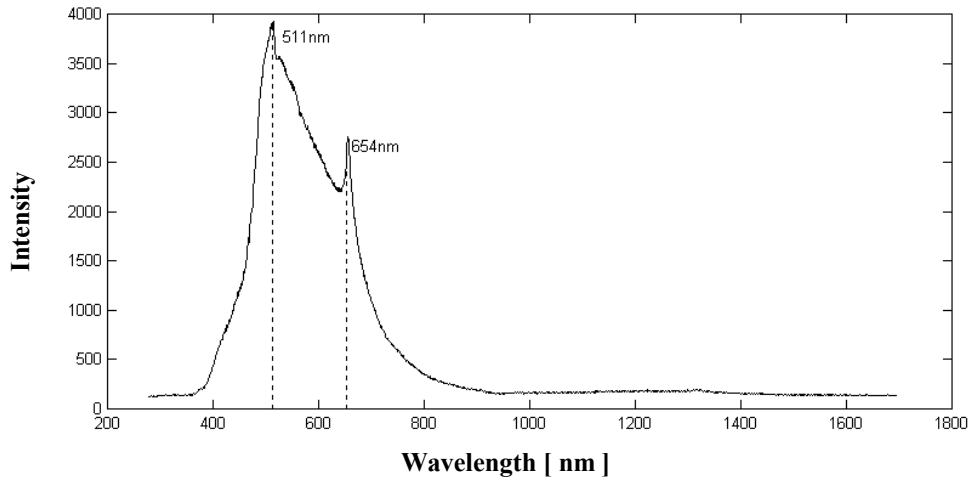


Fig. 5. Optical spectrum of light generated at a discharge in the point 22^0 –plane set-up; the initial stage of the disruptive electrical discharge.

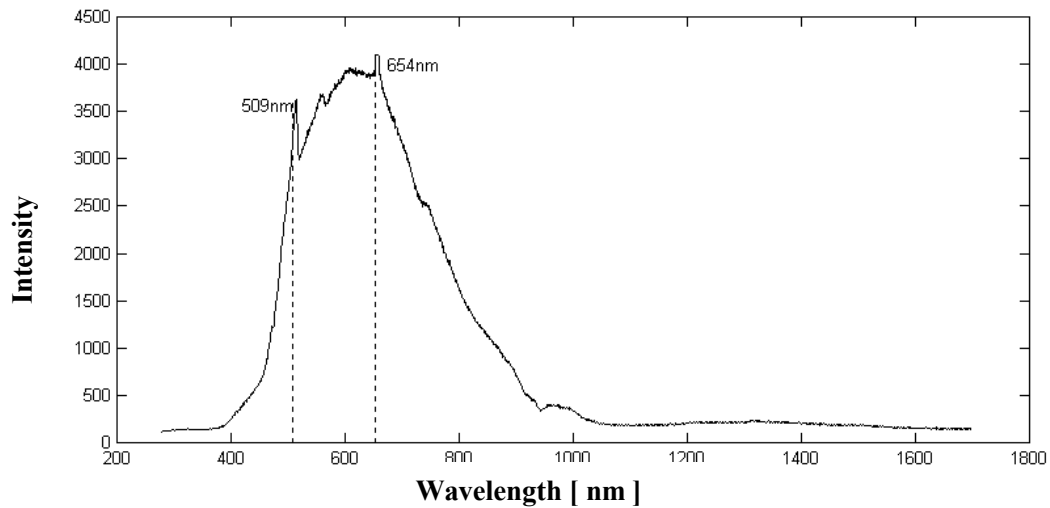


Fig. 6. Optical spectrum of light generated at a discharge in the point 22^0 –plane set-up; the interim stage of the disruptive electrical discharge.

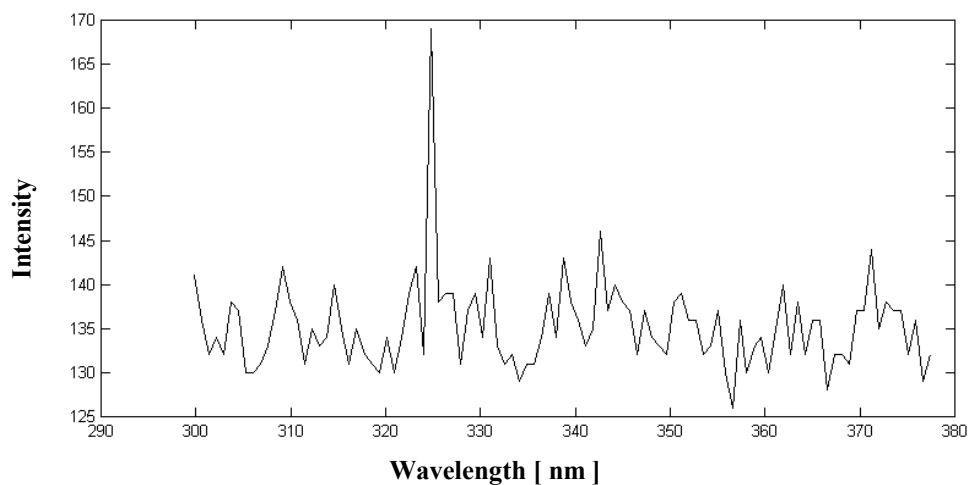


Fig. 7. Magnification of the optical spectrum for the set-up with the point 22^0 – plane in the range of close ultraviolet; visible is a spectral line occurring at the return of copper atoms from the state of excitement to the ground state (of zero energy).

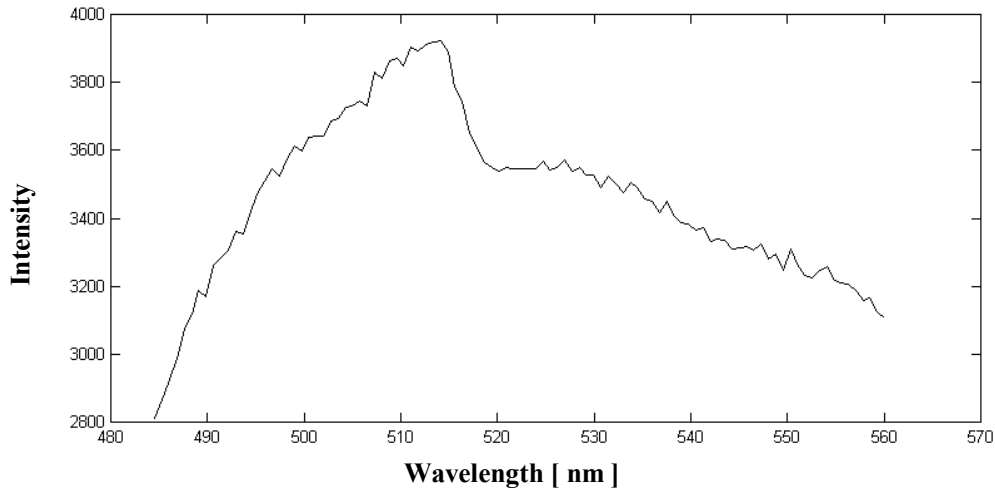


Fig. 8. Magnification of the optical spectrum for the set-up with the point 22^0 – plane in the range of green light; visible is a spectral line 510 nm connected with the electron jumps of copper atoms to the level of a lower energy.

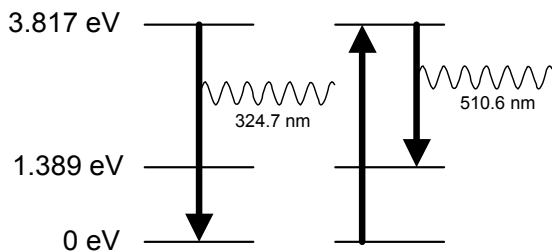


Fig. 9. Generation of the electromagnetic radiation for copper at the transfer to the states of lower energy.

line can be observed in Figs 5 and 6 and on magnification in the range of green light (480 – 560)nm shown in fig. 8.

The other of the extrema observed (Figs. 5, 6) of a length of 656 nm is enlarged in fig. 10 in the range of red light (620-700 nm). A clear extremum is connected with the change of the excitement state of hydrogen atoms. A

spectral line of a length of 656.47 nm (wave number 15233 cm^{-1}) occurs as a result of the transfer of hydrogen atoms from level 3 (of the energy 12.03 eV) to level 2 (resonance level of the energy 10.15 eV). It is the first line from the Balmer series (line α). The consecutive lines from this series (434 nm, 410 nm etc.) and from other series (Lyman, Paschen, Bracket) are unnoticeable or immeasurable. It can result from too low energy, which does not lead to the excitement of the hydrogen atoms.

Fig. 12 shows an optical spectrum of the light emission pulses generated during disruptive discharges in the point set-up of the inclination angle of 1^0 in the initial phase of a discharge. This spectrum is of a similar shape as the spectrum observed for the point of the inclination angle of 22^0 . Both the radiation participation generated in the visible band and the thermal radiation are close. Similar results were obtained for the point of an intermediate inclination angle.

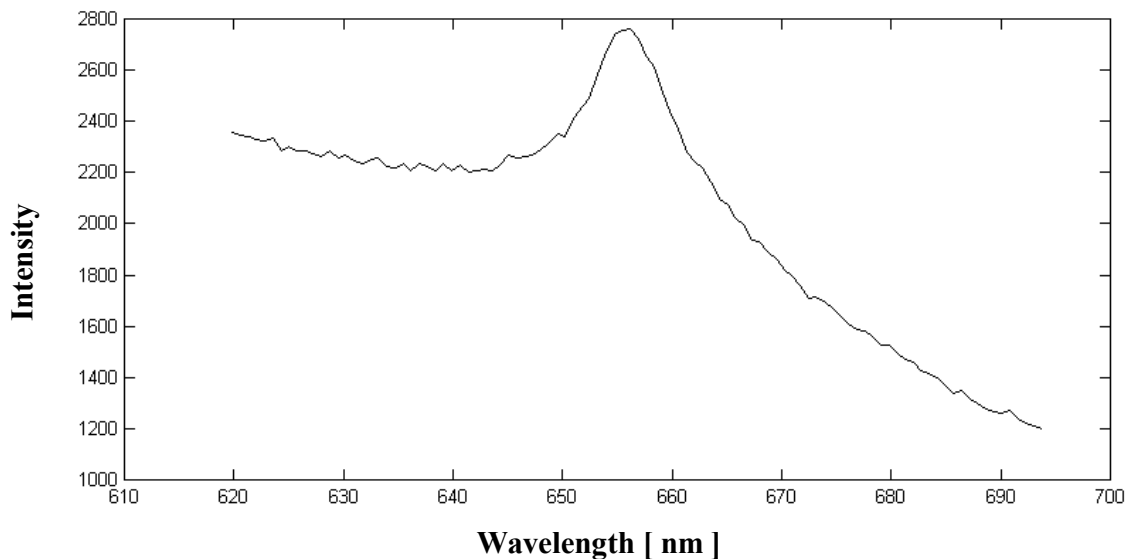


Fig. 10. Magnification of the optical spectrum for the set-up with the point 22^0 – plane in the range of red light; visible is a spectral line 656 nm characteristic for hydrogen (line α of Balmer series).

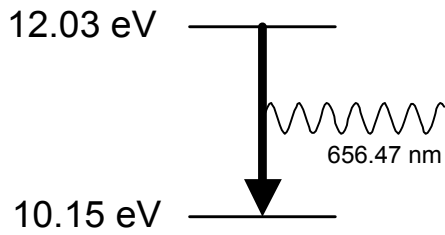


Fig. 11. Generation of the red electromagnetic radiation for the first line of the Balmer series for hydrogen at the electron transfer from level 3 to level 2.

For comparison, Fig. 13 shows the run of the optical spectrum generated by electrical discharges of the surface type in the initial phase of a discharge formation. For discharges of this type, a different character of the runs determined was obtained, which was characteristic of a bigger number of observable extrema (309, 512, 588, 616, 926) nm and a wider power band in the range from 300 to 926. It can find a practical application in the form identification of electrical discharges that occur in the insulation system under study.

Currently, research is being carried out by the authors into other generation set-ups of electrical discharges; their aim is determining the possibilities of using the optical method for identification of electrical discharges that can occur in oil insulation systems of power appliances.

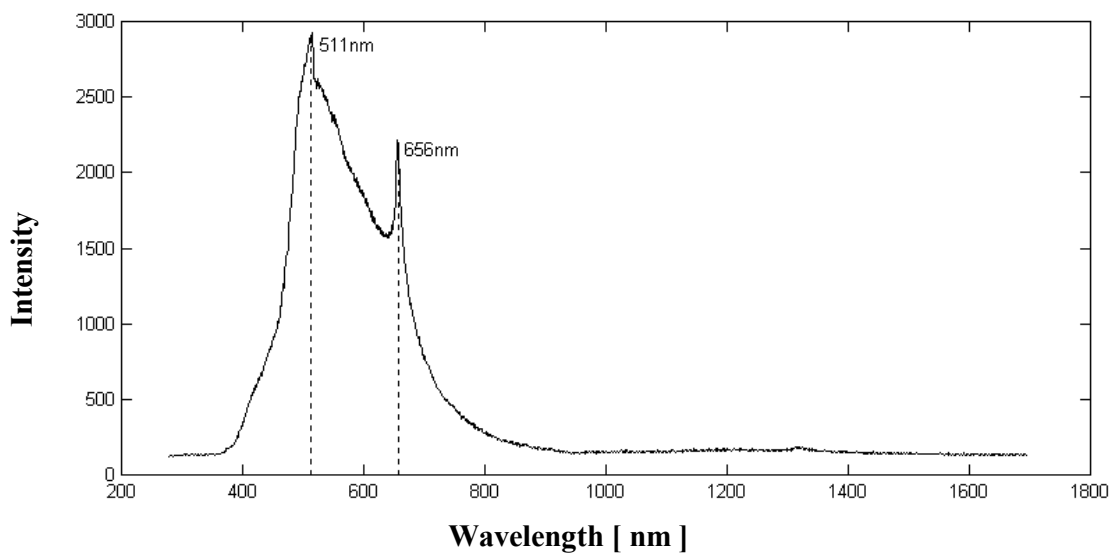


Fig. 12. Optical spectrum of light generated at a discharge in the point 1^0 - plane set-up.

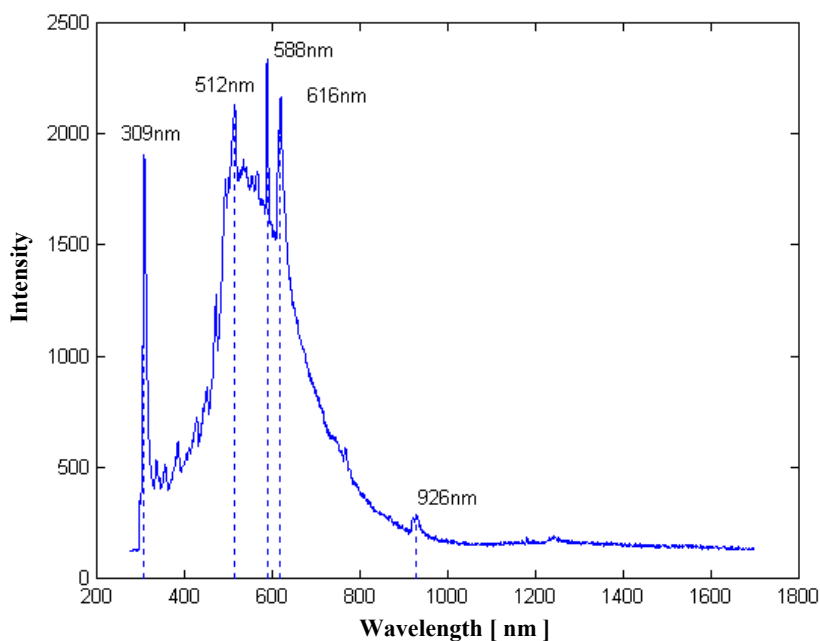


Fig. 13. Optical spectrum of the light generated at a discharge in the surface set-up.

VI. Summing-up

Optical spectra of light pulses generated by disruptive discharges in the point-plane set-up in insulation oil are characteristic of the occurrence of a wideband structure in the whole visible range. The radiation intensity is the biggest in the green and red ranges. Also, the local extrema are visible, which indicates the participation of a few elements in the physical and chemical reactions that take place. Hydrogen (the first visible spectral line from the Balmer series) and copper (two visible spectral lines, one in the band of the near ultraviolet, and the other in the green band). No particular differences were observed in the spectrum of the light signals emitted in various spark gaps. It shows an insignificant influence of the electrode shape on the radiation generated. There were observed differences in the spectrum depending on the development phase of a disruptive electrical discharge. In the initial stage of a discharge the radiation connected

with the electron jumps in copper participated more fully, whereas in the second stage of a discharge the bigger participation refers to the change of the hydrogen atomic excitation. Moreover, as a discharge develops the participation of radiation in the infrared range increases.

For electrical discharges of the point-plane and surface types generated in insulation oil optical spectrum runs were obtained which differed from one another. For surface discharges there occurs a bigger number of extrema corresponding with the following lengths of light waves: (309, 512, 588, 616, 926) nm than for the point-plane discharges, for which two extremum values are visible – for the waves 509 and 653 nm long. This observation can be useful in the process of PD form identification based on the light radiation generated.

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Т. Боцар, П. Фрац, Д. Змерзлий

Аналіз оптичного спектра світла, що випускається електричними розрядами в масляній ізоляції

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У статті представлено результати вимірювання оптичного спектра світла, випущеного руйнівними електричними розрядами в системі площина – точка. Оптичні спектри були представлені різними нахилами електродів в точці дотику. Вимірювання проводилися з використанням спектрометра із дифракційною решіткою з напівпровідниковим приладом з зарядовим зв'язком. Інтерпретацію здійснювали для екстремуму в оптичному спектрі, утвореному від зміни енергетичного стану елементів, які є частиною електроду і відбуваються в результаті вільної генерації газу. Для порівняння представлено оптичний спектр для електричних розрядах поверхневого типу.