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Research Article

Experimental Investigation of High-Frequency Effect on Ignition and Damping of Corona Discharges

İlker ARI[1*], Fevzi HANSU[2]

[1] Siirt University, Motor Vehicles and Transportation Technologies Department, ilkerari89@gmail.com, Orcid No: 0000-0002-1171-5533
[2] Siirt University, Electrical-Electronics Engineering Department, f_hansu@hotmail.com, Orcid No: 0000-0002-5325-5459

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* Corresponding author

ABSTRACT

The impact of high-frequency voltage/current oscillations on the corona discharge's ignition and damping in electrical networks were experimentally investigated as part of this study. Internal and external overvoltages caused by short-circuit faults or circuit opening/closing in the generation, transmission and distribution lines cause voltage/current oscillations on the lines at different frequencies. At frequencies of 50, 150, 250, 350, and 500 Hz in different electrode systems such as Sphere-Plane and Needle-Plane, the effects of these oscillations at various frequencies in the networks on the ignition and damping of corona discharges on transmission lines have been investigated. The results showed that the ignition and damping voltages of corona discharges are greatly influenced by high-frequency voltage/current oscillations, and that an increase in the frequency value significantly speeds up the corona discharge's ignition.

Introduction

In parallel with the rapid development of technology, efficient use of energy is gaining more and more importance day by day. Among the energies with high strategic value, electrical energy, which is the most widely used, has become one of the most popular research topics with its feature of being an indispensable energy source for human beings today. Considering the factors such as the increasing need for electrical energy in recent years, the limited energy resources and the limited number of energy types, the importance of the efficient use of electrical energy has increased significantly. The concept of increasing electrical energy efficiency can be considered as reducing losses in practical terms [1]. In this context, the issue of minimizing or completely eliminating the losses occurring in the electrical energy generation, transmission and distribution stages has taken its place among the current problems and has attracted the attention of researchers especially in recent years. In addition to trying to find new energy sources to fulfill the growing demand for energy, researchers are additionally attempting to minimize energy losses in present energy systems [2]. When the studies in the literature are examined, it is seen that the losses occurring in the intermediate systems from the generation of the electrical energy to the consumption show a large number of variations. Therefore, it is possible to find many studies conducted in these areas. When these studies are examined, it can be seen that many issues have been clarified, but it is possible to encounter many problems that still have not been solved.

There are many factors that affect the amount of losses in electrical energy generation, transmission and distribution lines. The most important of these factors can be listed as atmospheric conditions, line length, conductor cross-section, conductor type, variety of loads connected to the network, voltage level, and ionization events on the lines [3-4].

There are various studies on corona discharge in the literature. In [5], the frequency characteristics of corona discharge in a low pressure environment have been studied. In the study, tests were carried out at different pressure values and it was concluded that the discharge current, which is an important parameter of the frequency spectrum, showed a significant change depending on the pressure. In [6], The effect of voltage and load current on DC bipolar corona pulses was examined. In the study, laboratory-scale digitizing oscilloscopes were connected to a bipolar HVDC transmission line to observe the anode and cathode corona pulses. As a result of the study, it was found that the corona pulse amplitude increased with increasing transmission line voltage; It also has the effect of reducing the corona pulse duration for both the anode and cathode; With the addition of load current, the corona pulse amplitude decreases and the corona pulse time ratio for the anode increases; On the other hand, it has been determined that the ratio of cathode corona pulse amplitude and pulse time decreases with the addition of load current. In [7], corona losses occurring in monopolar DC transmission lines were examined. In the study, a charge simulation-based method is presented to solve the equations defining the ionized field around monopolar transmission lines. The method has been applied to calculate the current density profile between the corona power loss and ground level of conductor bundles with two and three subconductors. As a result of the study, it was seen that the corona power loss calculated for bundle conductors and the current density at ground level were in full agreement with experimental measurements. In [8], the effect of DC polarity and Alternating Current (AC) electromagnetic field intensity on corona onset voltage and corona discharge was investigated using some test objects such as high voltage needle-plane, needle-internal defect, surface discharge, headless underground cable, bare overhead conductor. Therefore, it is emphasized that the effect of the polarity of the DC transmission line on the initial voltage and discharge voltage of the corona must be determined. As a result of the study, the discharge waveform of the positive polarity measured has a larger amplitude with a single discharge pulse, while the wave width of the negative polarity has less amplitude with a higher frequency of occurrence or a higher repetition rate; It has been found that the initial voltage of positive DC is generally larger than that of negative polarity and AC voltage.In [9], experimental observations and some mathematical modeling were made by taking into account the corona discharge occurring at the ends of grounded rods, tip height, radius of curvature, magnitude and polarity of the applied electric field. As a result of the research, it has been suggested that the electric field intensity of the corona current exceeds the penetration limits in the air environment and depends on the active volume to a certain extent. Within the scope of the study, the results of mathematical modeling and experimental observations are compatible; It has been determined that the corona current depends on the rod tip height, tip radius, applied electric field strength and geometry. In [10], The effect of atmospheric humidity on corona discharges has been investigated experimentally. As a result of the study, it was determined that corona discharges occurring in transmission lines due to atmospheric humidity had a significant effect on the limit values of ignition and damping voltages; It has been observed that the current values corresponding to the ignition voltage of the discharge are directly proportional to the humidity rate in the environment, and the effect of increasing the humidity rate becomes more evident in wide electrode gaps.

When the studies in the literature are examined, it is seen that many studies have been carried out especially in the field of visual line losses. In addition, from the point of view of ion-electron technology, it is known that corona losses constitute an important place among the current losses [11]. However, it has been observed that the studies on some important causes that form the basis of corona losses are very limited. Corona discharges, which are basically electrical discharges that occur in a certain gaseous environment, have a critical importance in terms of losses in electrical power transmission lines. In order to examine the corona losses, the mechanism of corona discharges should be well known and modeled correctly. In order to fully understand corona discharges, first of all, knowing the mechanisms of electrical discharges occurring in gases can be considered as a prerequisite [12-14].

It is considered that the effect of frequency on the limit values of corona discharge’s ignition and damping voltage so is crucial and cannot be disregarded. Since discharges in the fixed range are generally capacitive, increasing the frequency value is very important for the ignition of the discharge [15-18]. The determination of the frequency parameter, which is important for the ignition and development of the discharge, is important in controlling the losses in the energy transmission lines and in eliminating the disadvantages of the harmonics at different frequencies caused by the voltage fluctuations occurring in the transmission lines due to various (internal and external) factors and the effects of the components of these harmonics.

In this study, a number of studies have been carried out to experimentally investigate the effect of high frequency voltage/current oscillations on the ignition and damping of corona discharges that occur in electrical energy transmission lines. The effect of the harmonic or current oscillations with various frequencies, on the supply voltage of corona discharges occurs on the networks have been experimentally investigated in terms of 50, 150, 250, 350 and 500 Hz frequencies at the Needle-Plane and Sphere-Plane electrode systems that corresponding to the transmission line model. By using obtained experimental measurement results, the generated Voltage-Current graphs at certain frequencies of corona discharges were interpreted comparatively. As a result of the study, high frequency voltage/current oscillations have a significant effect on the ignition and damping voltages of corona discharges, and the increase in the frequency value has facilitated the ignition of corona discharges considerably.

Materials and Methods

System description

Specially designed Needle-Plane and Sphere-Plane electrode systems, which are seen as equivalent models for some electrical equipment, were used to examine corona discharges, which cause significant losses in energy transmission systems, under laboratory conditions. Parameters such as the type of material from which these electrode systems are made, the geometric shape, the gap between the electrodes and the type of gas in the environment, the application voltage and the frequency of the applied voltage are important for the ignition, development and damping of the discharge [19-21]. The electrode system used in the study is made of stainless steel material in the form of a circular disc with smooth surfaces. These electrodes were properly mounted on a C-shaped insulating material designed using fiberglass material, fixed with an electrode opening of 5 mm, and the necessary experiments were carried out. Experimental studies were carried out in atmospheric conditions and at room temperature.

An important part of the test system is the Needle-Plane electrode system. The distance between the tip of the needle and the plane used in this electrode system was adjusted to be 5 mm constant, and this value was used for all experiments. The diameter of the plane electrode is 25 mm and its thickness is 5 mm. The electrode system was formed by mounting the electrodes with stainless steel screws to the transparent fiberglass dielectric material of 10 mm thickness, which was cut in a C-shape in principle. The image of the designed Needle-Plane electrode system is given in Figure 1.

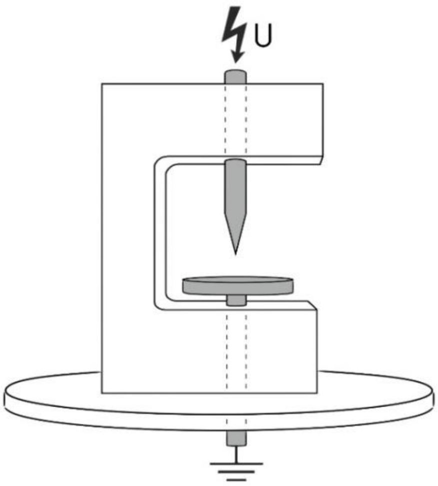

Figure 1. Needle-Plane electrode system image

Another electrode system used in the study is the Sphere-Plane electrode system. The diameter of the sphere used in this electrode system is 15 mm and is made of stainless iron material. The plane electrode is made of stainless iron material with a diameter of 25 mm and a thickness of 5 mm. The electrode opening of the Sphere-Plane electrode system was set to 5 mm. The electrode system was formed by mounting the electrodes with stainless steel screws to the transparent fiberglass dielectric material of 10 mm thickness, which was cut in a C-shape in principle. The image of the designed Sphere-Plane electrode system is given in Figure 2.

The established experimental set was supplied with a 500 VA source with a fixed frequency of 50 Hz and an output voltage adjustable in the range of 0-220 v. Images of the discharge current and voltage waves were obtained with the help of an analog oscilloscope.

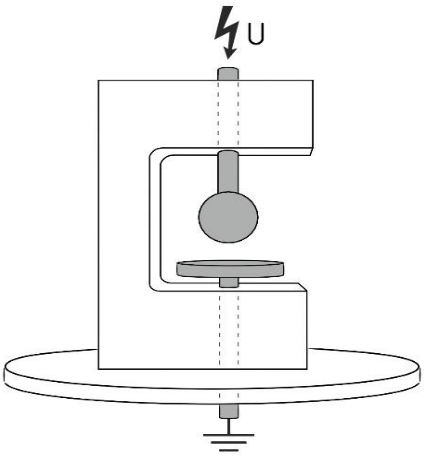

Figure 2. Sphere-Plane electrode system image

The circuit diagram of the experimental set is given in Figure 3.

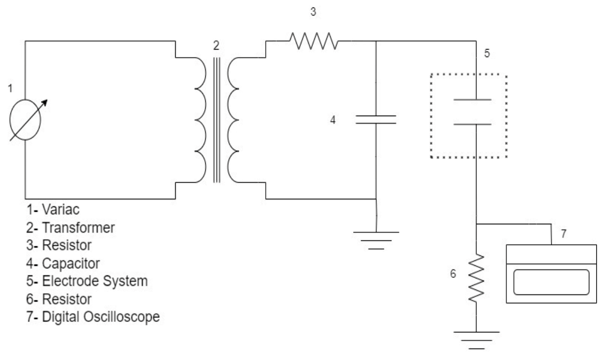

Figure 3. Circuit diagram of the experimental setup

Experiment methods

Within the scope of the experimental study, voltage and current values were measured and recorded independently of each other by applying various voltages at different frequency values to the e electrode systems such as Sphere-Plane and Needle-Plane. For each selected frequency value, the application voltage was increased with certain steps and the current values corresponding to each step were recorded. Current values initially showed an increase in microampere levels in accordance with Ohm's Law. However, after a certain increase limit of the application voltage, discharge occurs and with the ignition of the discharge, the current increased with a sudden jump from Microampere levels to Ampere levels. The voltage value at this point of rise was recorded and called the ignition voltage of the discharge. It has been observed that after the ignition of the discharge, the application voltage is reduced in slow steps, and the discharge extinguishes at a certain voltage value (a value lower than the ignition voltage value). The voltage value corresponding to this point is also recorded as the damping voltage of the discharge.

Result and Discussions

Results

In order to carry out experimental analyzes of corona discharges and to obtain more realistic results, the electrode systems model, which largely correspond to the model in electrical power transmission lines, were used. Experimental studies were carried out in atmospheric conditions. During the studies, in order to minimize measurement errors, many measurements were taken in the same experiment, the average of these measurements was taken and recorded.

Needle-Plane electrode system

Corona discharges in power transmission lines normally occur at the surface of the conductor or near the surface of the conductor. Especially in alternating voltages, discharges tend towards the conductor in positive alternance, while in negative alternance they move from the conductor surface to a weak area. Trichel current oscillations occurring on positive alternans during discharge develop depending on the electrode geometry and polarization. The image of the current oscillations of the positive corona at 500 Hz frequency of the Needle-Plane electrode system photographed on the oscilloscope screen is given in Figure 4. It can be seen from the figure that the current oscillations of the positive corona are more numerous per unit area and exhibit a more stable state.

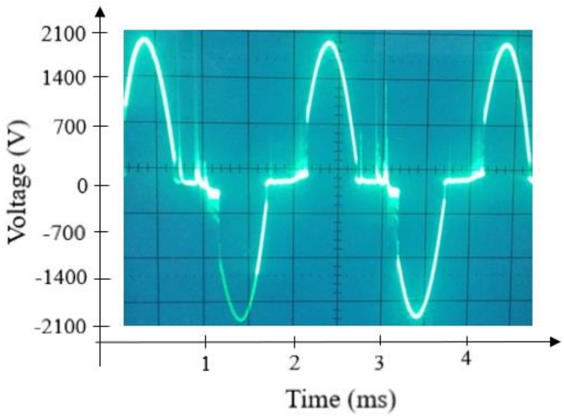

Figure 4. Image of positive corona current oscillations of the Needle-Plane electrode system at 500 Hz frequency

The photographed image of the corona discharge occurring at low frequencies (50-150 Hz) and non-homogeneous electric field in the Needle-Plane electrode system is given in Figure 5. As can be seen from the figure, the geometric structure of the discharge is spread out in a cone shape depending on the geometric structure of the electrode system.

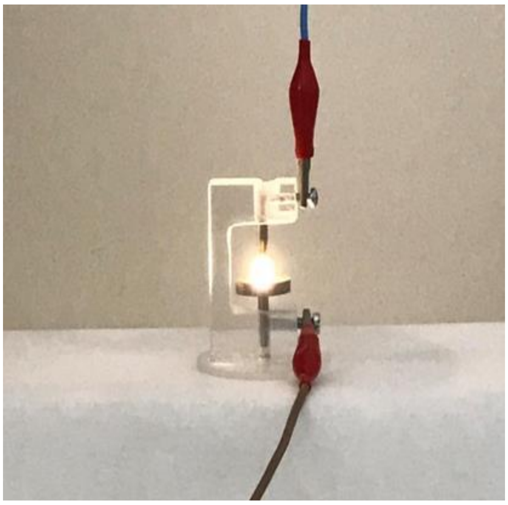

Figure 5. Corona discharge image at low frequencies in the electrode system of Needle-Plane

While one end of the discharge channels is concentrated around the needle electrode, the other ends are spread over the plane electrode surface. For this reason, it was observed that the discharge channels on the surfaces close to the plane electrode exhibit a less frequent behavior. The photographed image of the corona discharge occurring at high frequencies (350-500 Hz) and in a non-homogeneous electric field by using the Needle-Plane electrode system in cases where the frequency values are further increased is given in Figure 6. As can be seen from the figure, the geometric structure of the discharge is realized as a narrow channel depending on the geometric structure of the electrode system. While one end of the discharge channel lets is concentrated around the needle electrode, the other ends are only in the middle of the plane electrode surface and take the form of a narrow channel. For this reason, the charge density in the discharge channel is higher and a significant increase in the number of charges striking the unit surface has been observed. This situation was interpreted by utilizing the destruction effect on the electrode surface.

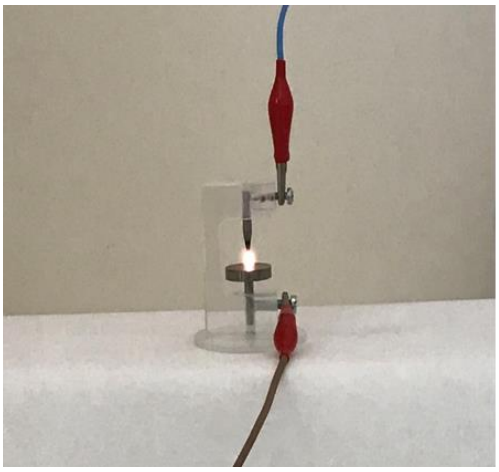

Figure 6. Corona discharge image at high frequencies in the Needle-Plane electrode system

In order to compare the experimental results obtained in the Needle-Plane electrode system, the collective representation of the Voltage-Current graphics at the supply voltage frequencies of 50, 150, 250, 350 and 500 Hz is given in Figure 7. As can be seen from the figure as the frequency value of the supply voltage increases, the ignition voltage limit values of the corona discharge show a smooth decrease in inverse proportion to this. According to the results measured in the experimental studies, it has been observed that the current values of the discharge before ignition at 50 Hz supply voltage frequency are higher than the currents at other frequency values. The possible reason for this is that the supply source used for 50 Hz frequency value is different from the supply source used for other frequency values.

From the graph in Figure 7. in order to compare the experimental results of the corona discharges in the Needle-Plane electrode system, corona discharges' ignition and damping voltage values obtained at the supply voltage frequencies of 50, 150, 250, 350 and 500 Hz are frequency dependent; but it is seen that they exhibit an inversely proportional change. In addition, it is obvious that the discharge currents at voltage values that are smaller than the ignition voltages of the discharges formed at different frequencies also show a frequency-dependent change.

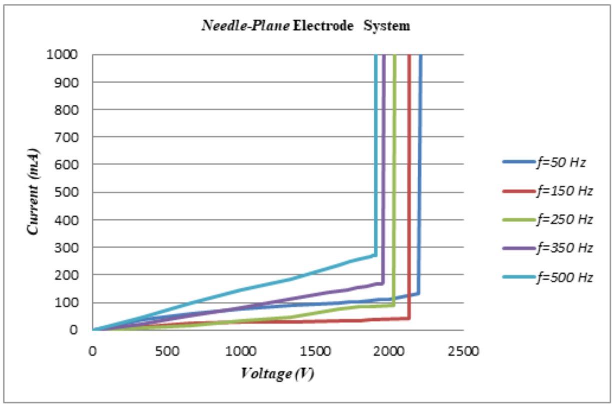

Figure 7. Graph of collective Voltage-Current changes taken at different supply voltage frequency values for the electrode system of Needle-Plane

The corona discharges' ignition and damping voltage and current values, which were experimentally measured at the different supply voltage frequencies, in the electrode system are given in Table 1. When the data in table is examined, the limit values of the ignition voltage of the discharge decrease as the frequency values of the supply voltage increase. On the other hand, the discharge damping voltage limit values have increased. This clearly indicates the frequency impact on corona discharge ignition.

Table 1. Voltage-Current discharge values for the *Needle Plane* electrode system's ignition and damping

	50 Hz	*150 Hz*	*250 Hz*	*350 Hz*	*500 Hz*
$U_{ignition}$ (v)	2266,78	2140,11	2060,10	2010,10	1913,43
$U_{damping}$ (v)	866,71	Null	873,37	1073,38	1140,05
$I_{ignition}$ (mA)	4200,00	4000,00	3810,00	2910,00	1910,00
$I_{damping}$(mA)	800,00	Null	1000,00	1042,00	1131,00

Sphere-Plane electrode system

The Sphere-Plane electrode system is an additional electrode system used to determine the limit voltage values of corona discharge's ignition and damping. The image of the 50 Hz frequency current oscillations of the Sphere-Plane electrode system photographed directly from the oscilloscope screen during the experimental studies is shown in Figure 8. As can be seen from the figure, the number of current oscillations of the positive and negative corona per unit area is quite dense and stable.

The photograph of the changes in the measured current and voltage values relative to each other during the ignition of the corona discharge occurring in the Sphere-Plane electrode system, taken directly from the oscilloscope screen, is given in Figure 9. As can be seen from the figure, the variation of the discharge voltage with respect to the discharge current is in the form of a stable Lysajous diagram.

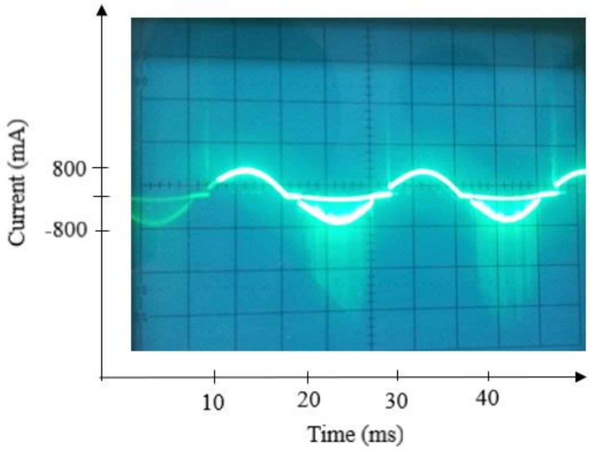

Figure 8. Image of current oscillations at 50 Hz frequency of the Sphere-Plane electrode system

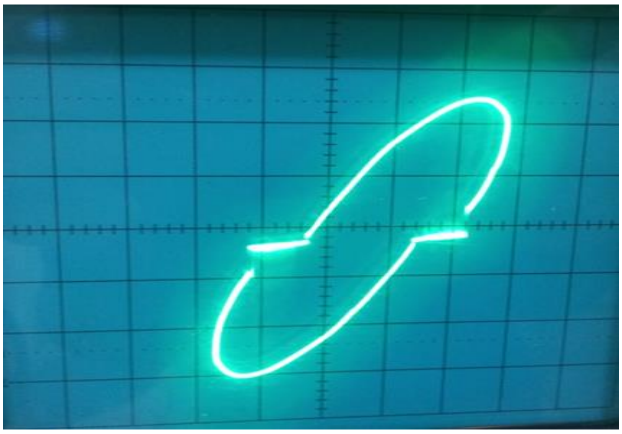

Figure 9. The graph of the variation of the discharge voltage of the Sphere-Plane electrode system at 50 Hz versus the discharge current

The photographed image of the corona discharge occurring at low frequencies (50-150 Hz) and in the non-homogeneous electric field in the Sphere-Plane electrode system is given in Figure 10. Since the electric field strength in the Sphere-Plane geometry is more homogeneous than the Needle-Plane electrode system (as seen in the figure), the geometric structure of the discharge has an ellipsoidal structure. In this case, since the discharge occurs at low frequencies, the number of discharge channels exhibited a less frequent structure.

The photograph of the corona discharge occurring at high frequencies (350-500 Hz) and in the non-homogeneous electric field in the Sphere-Plane electrode system is shown in Figure 11. In this case, since the discharge takes place at high frequencies, the number of discharge channels exhibited a denser and narrower structure.

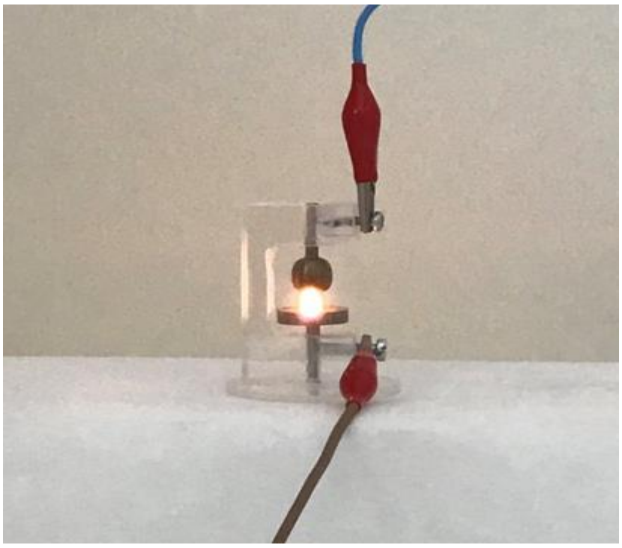

Figure 10. Corona discharge image at low frequencies in the Sphere-Plane electrode system

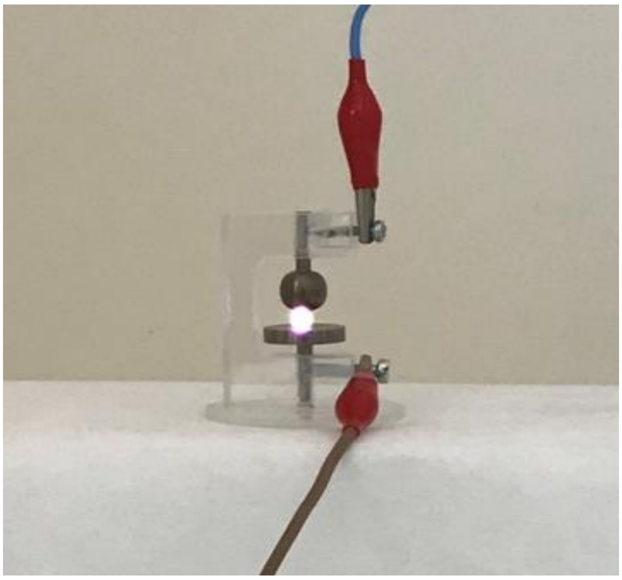

Figure 11. Corona discharge image at high frequencies in the electrode system of Sphere-Plane

In order to compare the experimental results in the Sphere-Plane electrode system, the collective representation of the Voltage-Current graphics at the supply voltage frequencies of 50, 150, 250, 350 and 500 Hz is given in Figure 12. As can be seen from the figure, as the frequency value of the supply voltage increases, the ignition voltage limit values of the corona discharge show a smooth decrease in inverse proportion to this. According to the results measured in the experimental studies, it has been observed that the current values of the discharge before ignition at 50 Hz supply voltage frequency are higher than the currents at other frequency values. The possible reason for this is that the supply source used for 50 Hz frequency value is different from the supply source used for other frequency values.

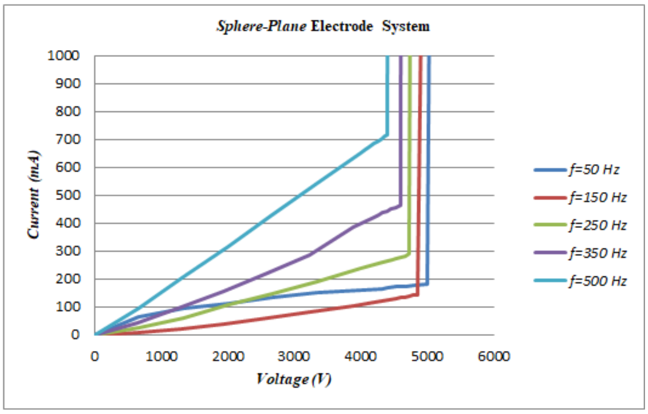

Figure 12. Voltage-Current change graph for the electrode system of Sphere-Plane, obtained at various supply voltage frequencies.

The corona discharge's ignition and damping voltage and current values of that were experimentally measured at the different supply voltage frequencies in the electrode system of Sphere-Plane are given in Table 2. When the data in table is examined, the limit values of the ignition voltage of the discharge decrease as the frequency values of the supply voltage increase. On the other hand, the discharge damping voltage limit values have increased. This clearly indicates the frequency impact on corona discharge igniting. When the current values are examined, it is seen that the ignition current values of the discharge have increased correspondingly with the decrease of the frequency. Since the electric field strength in the Sphere-Plane electrode system is more uniform than the field strength in the Needle-Plane geometry, the ignition voltage limit values of the discharge occurring in the electrodes opening are larger. Accordingly, the ignition current values of the discharge are also higher. Therefore, considering the maximum power values of the supply sources used in the system, the limit values of the discharge damping currents could not be determined.

Table 2. Voltage-Current values for the discharge's ignition and damping in the electrode system of Sphere-Plane

	50 Hz	*150 Hz*	*250 Hz*	*350 Hz*	*500 Hz*
$U_{ignition}$ (v)	5133,59	5066,92	4800,24	4766,91	4426,89
$U_{damping}$ (v)	1200,06	Null	Null	Null	1373,40
$I_{ignition}$ (mA)	4440,00	4200,00	4000,00	3800,00	3600,00
$I_{damping}$(mA)	Null	Null	Null	Null	Null

Discussions

In order to determine the parameters of electrical discharges in gases, a supply source with high output power, output current and output voltage is needed. The geometry and surface roughness of the electrode system also have an important place in order for experimental studies to yield realistic results. In addition to these conditions, environmental parameters such as humidity, temperature, pressure, spacing between electrodes and electrical properties of the gas in the environment have important effects on the ignition and damping of electrical discharges. Therefore, it is of great importance to regulate the ambient conditions depending on the type of electrical discharges while conducting experimental studies. As a result, the correct analysis and interpretation of data received during experimental studies is important for modeling and accurately characterizing discharge.

Several experimental investigations have been conducted in Needle-Plane and Sphere-Plane electrode systems at the same electrode gap and in the same ambient circumstances to ascertain various corona discharge parameters. According to the test results measured in the Sphere-Plane electrode system, the ignition and damping voltages of the discharge's limit values were observed to be higher than the results that were obtained in the Needle-Plane geometry. This can be interpreted as an indication that the electrode geometry has a significant effect on the electric field strength, and therefore the electric field strength has a large effect on the characterization of the discharge.

Corona discharge ignition is greatly affected by the electrode's radius of curvature., which cause significant power losses in power transmission lines. The degree of homogeneity of the electric field is also of great importance in discharges that occur at fixed electrode gaps. As can be seen from the studies mentioned above and the experimental results given, the effect of the radii of curvature of the electrode tips can be clearly seen as a result of the comparison of a Needle-Plane electrode system and a Sphere-Plane electrode system. The decrease in the radius of curvature increases the degree of non-homogeneity of the electric field strength. In transmission lines, it is seen that the corona losses will increase inversely as the conductor radius decreases.

Conclusions

Current-voltage oscillations or harmonics at various frequencies occur on the lines due to circuit on-off, short-circuit faults, the effect of internal and external overvoltages caused by various reasons, and balanced or unbalanced loads that are momentarily activated and released in the energy generation, transmission and distribution lines. The impact of these high-frequency harmonics on the initiation and dampening of corona discharges in high-voltage power transmission lines has been studied experimentally. The results show that the levels of the ignition and damping voltages are strongly affected by the frequency of corona discharges that occur in high voltage transmission lines, and the limit value of the ignition voltage decreases with the increase in frequency. Thus, it was observed that the corona losses in the lines increased with the increase in frequency. In addition, it was concluded that the radii of curvature of the electrodes have a significant effect on the formation of the corona discharge, and the increase in the radius of curvature has an effect in the direction of complicating the ignition of the corona discharge. As a result, in order to eliminate high-frequency harmonics that have the effect of facilitating corona losses in electrical energy transmission lines, filtering processes should be done very well or Soft-Start systems should be preferred as much as possible instead of On/Off type switching in network systems.

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