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Electromagnetic Spectrum of the Corona Discharge and Their Fundamental Frequency

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Abstract

Historically, the Electromagnetic Compatibility (EMC) began with the disturbances at the radio navigation systems generated by the electrical power distribution lines; hence it was referred to as Radio Interference (RI). This disturbance is an Electromagnetic Interference (EMI). Although this type of EMI has been studied since the first decades of the past century, it still maintains a continued interest of the researchers, especially with the Corona Discharge (CD), generated by High Voltage Direct Current (HVDC) systems. Because of its design criterion and the concern that this phenomenon may affect the new radio communication systems in the very high frequency (VHF), ultra high frequency (UHF), and microwave bands, interest in their studies continues. In this chapter, an analysis of the electromagnetic spectrum of the CD is presented. The CD is generated at a short transmission line located within a semi-anechoic chamber. To be sure of the phenomenon, the CD is identified by its current pulse, which is well studied. The instruments used are an oscilloscope of 2 GHz and 2 GS/s, a spectrum analyzer, and an EMI test receiver. The results show that the CD concentrates its energy at frequencies below 70 MHz. In the UHF band, only narrowband signals very separated were found, with levels that cannot affect radio communication systems.

Keywords: corona discharge, electromagnetic spectrum, radio interferences

1. Introduction

The issue of electromagnetic coexistence of the Corona Discharge (CD) generated by High Voltage (HV) systems, with broadcasting, especially with the Amplitude Modulated (AM), can be said to be thoroughly studied. However, disturbances persist because the CD is an inherent part of HV systems. Now, broader spectrum must be analyzed, due to possible effects on all electronic systems, including the radio communication by their high sensitivity at the VHF, UHF, and microwave band, that may be in the presence of said systems, especially at HVDC systems [1–3]. In addition, this issue is a design requirement for high voltage transmission lines [4–6]. These problems are subjects of Electromagnetic Compatibility (EMC), which were born from the beginning of AM radio [7]. Nowadays, radio communication technologies have changed, as well as services and their applications. Thus, Electromagnetic Interferences (EMI) have increased because there is a higher

density of high sensitivity systems [8]. The EMI is identified in the high voltage power distribution area as Radio Interference (RI).

The HV power and radio communication systems are every day in human life. Therefore, all of them should be coexist, and they must comply with the conformity assessment of the EMC. However, the rules are not yet very clear with respect to CD at frequencies greater than 30 MHz [9]. In the frequency range of 30 MHz–1 GHz, there are several investigations about RI, but some of them are associated with CD since the detection, in general, corresponds to partial discharges (PD) because the measurements are made in uncontrolled electromagnetic environments [8, 10]. Within the literature on Direct Current Corona Discharge (DC-CD), there are no reports of the frequency spectrum; they only exist for AC [11]. In general, the measurements reported are related to the electromagnetic radiation of the DC-CD. They have been carried out as a function of time, whose data are processed by software to determine the electromagnetic spectrum of the phenomenon [12, 13]. In the analytical part, the developments that have served as a reference for both AC and DC corona discharge are reported in [14, 15].

With respect to the standards, these must be developed in accordance with technological advances. However, they are always delayed, e.g., with the change that is taking place in the transmission of high voltage from AC to DC and with the increase of radio communication services. The CISPR-18 standard [9] in its recent version covers the range of 150 kHz–3 GHz, but it does not define the limits at frequencies greater than 30 MHz due to the great uncertainty that exists. This fact indicates that there are challenges for researchers on the subject since now it is had much more sensitive and complex electronic systems, such as electric vehicles and smart grids, among other systems. Therefore, it is first necessary to know the levels of electromagnetic emissions of CD in the frequency range specified by the CISPR in order to define the interference levels that exceed the immunity level of high-sensitivity systems.

This chapter presents an experimental analysis of the electromagnetic spectrum of CD, covering the frequency range from 150 kHz to 1 GHz. The aim is to respond to the problems that are constantly manifested with regard to interference from radio communication systems. Despite, it is known that the CD effect is very strong in the AM frequency band, be it analog or digital, but in the frequency bands above 30 MHz, many questions remain. The experimentation is carried out within an electromagnetically controlled environment that is a semi-anechoic chamber, and a short transmission line is used as the source. Measurements were carried out in the time domain and the frequency domain, using three antennas to cover the specified frequency range. Filters based on the Wavelet Transform (WT) were applied to the results obtained to smooth or minimize the noise in order to better appreciate the levels of the radiated signal from the CD, according to the procedure of [14]. WT was applied to the time domain response to obtain a spectrogram and better observe the distribution of energy levels. The results present information that can be compared with the sensitivity levels of electronic systems, including radio communication systems, in order to define whether these can be interfered with in a corona discharge environment.

2. Experimental setup

The measurements for analysis of CD electromagnetic spectrum on-situ or at HV laboratories are not reliable because the environment is contaminated by various RF signals and reflection multiples. Thus, it is necessary for these measurements to use a controlled environment, such as an anechoic or semi-anechoic

Antenna	Mark	Model	Wide band (MHz)
Loop-antenna	ETS Lindgren (EMCO)	6507	0.001–30
Biconical antenna	ETS Lindgren (EMCO)	3110B	30–300
SAS 521-1 hybrid biconical/log periodic antenna	A. H. Systems, Inc.	SAS-521-2	25–2000

Table 1.
Antenna’s characteristics.

Figure 1.
Experimental setup scheme and short transmission lines. (a) Experimental setup. (b) Short transmission lines [16].

chamber. In our case, we used a semi-anechoic chamber of EMC. As a CD source, a short transmission line was used, which was supplied with a positive DC high power supply (Bertan 205B Series). The measurement of the conducted corona current pulse is carried out with a high-frequency current transformer, which has

an operating range of 4.8 kHz–400 MHz (Bergoz CT-E5.0). To cover the frequency range of the radiated emission, three antennas were used, which characteristics are shown in **Table 1**. As measurements instruments are used: oscilloscope (204Xi Lecroy, 2 GHz, 10 GS/s), signal analyzer (N9010A EXA X Keysight, 10 MHz–7GHz), and EMI test receiver (ESPC EMI Test Receiver Rohde & Schwarz, 9KHz–1GHz).

The schemes of the experimental setup and a picture of the short transmission line short are shown in **Figure 1**.

The scheme of the experimental setup is shown in **Figure 1a**, and a picture of the short transmission line short is shown in **Figure 1b**.

The short transmission line was made with a magnetic wire 28-gauge AWG of long 1 m and a ground plane with 0.3 m of separation. The line is fixed on a wood table with a dimension of $0.8 \times 1.2 \times 0.8 \text{ m}^3$, high, long, and wide, respectively. The current transformer (CT) is placed at the return plane cable, and the antennas were fixed at 1.5 m of the corona source. This kit was placed inside the semi-anechoic chamber.

3. Procedure

Measurements were carried out in a semi-anechoic chamber located at a latitude of 2250 m and pressure of 585 mmHg (Mexico City). The temperature inside the chamber was 25°C with a relative humidity of 50%. To start the measurements, the electromagnetic environment was first analyzed in the range of measurement frequencies under test in order to ensure that there would not be a presence of spurious signals.

CD onset corona voltage is well identified for the different configurations of needle plane, corona cage, and others [17, 18]. A good reference for the presence of the phenomenon is the corona current pulse, which is detected in the conducted form [18]. The detection of such as current may be carried out between the power supply and configuration under test or in return plane. In the first case, a coupling circuit is needed, which is a complex method of measurement. The measurement of corona current at the return plane is simpler because measurements with a current probe are enough as a CT.

The rise time of the corona current pulse gives information of the phenomenon, and the fall time is a function of the parasitic electrical components of the configuration. Therefore, to have a better shaped pulse, it is necessary to optimize the circuit of the discharge configuration. Knowing the rise time of the corona pulse, the fundamental frequency can be determined, both for conducted and radiated radio electric emissions [19].

To carry out the electromagnetic spectrum analysis of the corona discharge, we did the following:

1. Equipment installation: Inside the semi-anechoic chamber, the short transmission line was installed, as well as the antennas were fixed at 1.5 m in front of the line.
2. Measurement of corona current conducted: The corona current was measured in the return plane with the CT and the oscilloscope. With the presence of the pulse, we ensure that the corona phenomenon is present. This was done at every measurement.
3. Measurement radiation of the corona discharge: Due to the dimension of the short transmission line and the semi-anechoic chamber dimensions, we could not perform measurements in the far field. Therefore, the measurements were

carried out in the near field. The results are presented in dB μ V; from these, the current can be calculated to predict the far field.

4. Measurement of frequency spectrum: This measurement is carried out in accordance with the frequency ranges, where are more activities of EMI: 0.15–30 MHz, 30–300 MHz, and 470–950 MHz, as is specified in the CISPR-18-1 [20]. For the first range, the loop antenna is used; for the second range, the biconical antenna is used, and for the third range, the hybrid biconical/log periodic antenna is used. These antennas used the signal analyzer and EMI test receiver for covering the frequency band of 150 kHz until 1 GHz. The signal analyzer has several functions; in this case, it is used as a spectrum analyzer.
5. Measurement of corona current radiated in the time domain: The corona current in the time domain was determined by the antennas specified in **Table 1** and the oscilloscope.
6. Antennas polarization: For the case of the loop antenna, the three components of the field were measured (x, y, z), and the total field was obtained. For the other antennas, the two polarizations considered were vertical and horizontal.
7. Presentation of the results: All results were smoothed by filters using the wavelet transform to estimate the emissions radiated by corona discharge in time and frequency domains simultaneously.

4. Results

4.1 Conducted emission

The CD analyzed in the laboratories is identified in different ways. As already mentioned, one of the ways is by means of the conducted current. Therefore, we connected the CT to the return plane, and we observed in the oscilloscope the pulse. With this, we identified the presence of the discharge for an onset voltage of 12 kV $\pm$ 100 V. The current of corona pulse obtained of conducted way is shown in **Figure 2**, where **Figure 2a** corresponds to the pulse shape, and **Figure 2b** is the spectrogram obtained by WT.

In accordance with the spectrogram of **Figure 2**, the energies are concentrated at the range of 7 MHz and 16 MHz. In this last range is where there is the greatest amount of energy.

4.2 Radiated emission

The electromagnetic radiation of the CD generated by the short transmission line under test was measured in the time and frequency domain covering the frequency ranges in accordance with CISPR 16-1-1 (**Table 2**) [21]: band B, C, and D. For the time domain an oscilloscope was used, and for the frequency domain a signal analyzer in spectrum analyzer mode and an EMI test receiver were used. In both cases, the antenna factors were considered.

In order to cover the frequency intervals, three antennas were used, which are specified in **Table 2**. Whose frequency bands are the basis for displaying the results.

The results of the antennas are presented in dB μ V vs. frequency, which can be converted to current, to predict the far field using the expression of a short dipole in the first instance [22].

Figure 2.
Corona discharge pulse conducted. (a) pulse shape; (b) WT spectrogram.

Antenna	Frequency bands
Loop antenna	Band B (300 kHz–30 MHz)
Biconical antenna	Band C (30–300 MHz)
SAS 521-1 hybrid biconical/log periodic antenna	Band D (300–1000 MHz)

Table 2.
Antennas and frequency band accordance with CSPR 16-1-1 [21].

4.2.1 Frequency band B (0.3–30 MHz)

In this frequency range, the loop antenna was used. The result corresponds to the total field formed by the three components (x, y, z). For the temporal part, an oscilloscope was used, whose data was processed using the WT to obtain its spectrograms; these results are shown in **Figure 3**. In the frequential part, we made two measurements: one with the spectrum analyzer and the other which EMI test receiver. The results are expressed in dBμV for both instruments, as shown in **Figure 4**, where graph (a) corresponds to the spectrum analyzer and graph (b) corresponds to EMI test receiver.

The results show that most amount of energy is concentrated in the 8 MHz, 11 MHz, 18 MHz and 25 MHz range; this agrees both in the temporal part and in the frequency part. At frequencies below 15 MHz, the EMI test receiver exhibits a higher signal level because it responds to the envelope and has a higher fall time constant on the input filter. An appropriate resolution bandwidth (RBW) in the spectrum analyzer allows a sweep so that the peaks of the RI are seen with greater definition, which makes the frequencies higher than 15 MHz the graphs of both instruments coincide.

4.2.2 Frequency band C (30–300 MHz)

The antenna used in this frequency range is biconical, which is recommended for this application by international standards. This antenna is basically a dipole with conical shape elements and has linear polarization. The results of the radiated emissions in the 30–300 MHz frequency range are shown for vertical and horizontal polarization. For the temporal response, the pulse with its spectrogram is shown in

Figure 3.
Temporal answer of the corona discharge at B band (0.3–30 MHz) measured with a loop antenna.

Figure 4.
Frequency spectrum of the corona discharge at B band (0.3–30 MHz) measured with a loop antenna: (a) spectrum analyzer, (b) EMI test receiver.

Figure 5. The frequency response measured with a spectrum analyzer and with the EMI test receiver are shown in **Figure 6**.

In this frequency band, we have the following:

In the spectrogram, it can be observed that the energy concentration for vertical polarization covers the range from 10 to 65 MHz. In this case, the measurement frequency range is not limited, and it is understood that the antenna responds outside its operating band.

With the frequency behavior, the measurement with the spectrum analyzer in vertical polarization shows that there are signal levels in almost the entire band, concentrating in the 30–60 MHz range. In EMI test receiver also the energy of RI is concentrating at 30 MHz and 60 MHz, but there is no signal at higher frequencies. For horizontal polarization, both measuring instruments present the same behavior, concentrating the greatest number of electromagnetic emissions in the 30–60 MHz interval; the energy is most high, around 40 MHz.

Figure 5. Temporal answer of the corona discharge at C band (30–300 MHz) measured with a biconical antenna. (a) Vertical polarization. (b) Horizontal polarization.

According to the above, the highest amount of electromagnetic energy radiated by a corona discharge generated by a short transmission line is in the range of 30–60 MHz for both polarizations. In vertical polarization, some significant emissions at frequencies greater than 100 MHz, such as in 120 MHz, are only identified with the spectrum analyzer due to their higher resolution.

The noise floor of each instrument is an important part. In the case of the spectrum analyzer, the noise is greater due to the used span. In EMI test receiver, the noise is less and can not identify narrowband signals, because detect only the envelope and the filters are not able to resolve those signals. The signal levels in the high activity band of RI are almost equal, considering the background noise in both instruments.

4.2.3 Frequency band D (300–1000 MHz)

This frequency band is important because there are lots of portable radio communication services. For example, some of the services are the trunk radio, which

a)

b)

Figure 6.
Frequency spectrum of the corona discharge at C band (30–300 MHz) measured with a biconical antenna.
(a) Vertical polarization. (b) Horizontal polarization.

is a typical means of communication used by those who maintain the high-voltage transmission lines, the open digital television, the first cell phone band that one continues to apply, systems 5G and others. Therefore, it is necessary to analyze the levels of electromagnetic emissions from the corona phenomenon. In this case, a hybrid biconical/log periodic antenna was used to cover the D band frequency range. The results in the time domain for vertical and horizontal polarization are

presented in **Figure 7**, including the spectrogram. For the frequency domain part at both polarities with the spectrum analyzer and the EMI test receiver, the spectra are shown in **Figure 8**.

From the temporal results in this band, it is observed that there is noise only for vertical polarization. Then, it is difficult to identify if this corresponds to the corona discharge. As the measurement is made with an oscilloscope, the time base that is set is where the maximum amount of energy of the phenomenon occurs. What we see corresponds to the distribution of the noise signal at frequencies related to the time base of the oscilloscope. However, for horizontal polarization, the energy is concentrated in the frequency bands where the corona is identified.

Regarding the frequency part, in this case, the measurement with the spectrum analyzer and the antenna at vertical polarization, the spectrum shows a signal at the frequency of 336 MHz and noise. The same signal of 336 MHz is present with the horizontal polarization and one at 960 MHz. These signals are not seen with the EMI test receiver because they are narrowband. Therefore, in both polarizations, only the background noise is seen.

Figure 7. Temporal answer of the corona discharge at D band (300–1000 MHz) measured with a hybrid biconical/log periodic antenna. (a) Vertical polarization. (b) Horizontal polarization.

a)

b)

Figure 8. Frequency spectrum of the corona discharge at D band (300–1000 MHz) measured with a hybrid biconical/log periodic antenna. (a) Vertical polarization. (b) Horizontal polarization.

The difference in the levels observed in the graphs is because the background noise of the spectrum analyzer is high by the span, which does not happen with EMI test receiver.

5. Discussion

The measurements of the electromagnetic radiation generated by corona discharge at media electromagnetically controlled (semi-anechoic chamber) give us information secure in time and frequency domains about the energy amount emitted by this

phenomenon to the environment. In such as environment, only the signal referring to the corona was present. We ensure the presence of the corona by measuring the conducted current, which is a well-known parameter. This current was monitored in all measurements. The emissions radiated in dB μ V are indicated, and those are compared to observe the frequency behavior, where are shown the band of most activity of RI.

In frequency band B, we measure one decade from 0.3 MHz to 30 MHz. The antenna used is a loop, so its three components (x, y, z) were measured. In the time domain, the current pulse was obtained, and the wavelet transform was applied in order to obtain information on the energy distribution. In the frequency domain, measurements were made with a spectrum analyzer and an EMI test receiver with the peak detector. In this case, the information coincides with the frequency. At frequencies lower than 6 MHz, what is observed is the background noise in both instruments. The spectrum analyzer presented less noise since the span and RBW were conditioned for this decade, which implies less bandwidth in both parameters. In this regard, the frequency peaks are matching.

For the C frequency band that corresponds to 30–300 MHz, a biconical antenna was used. The answer of the time domain that corresponds to the current pulse was processed by the transform wavelet, which is shown the energy distribution. For this case, the major amount of energy is below that of the 70 MHz. The vertical polarization presents more activity of emission than polarization horizontal, which is also shown with both the spectrum analyzer and the EMI test receiver. The answers at both instruments are similar, where the greatest amount of energy is found. In vertical polarization, the spectrum obtained with the spectrum analyzer shows two peaks at 120 MHz and 260 MHz, which are not shown in the measurements with EMI test receiver. For the horizontal polarization, the spectrums of both instruments have the same performance.

Measurements in the D frequency band (300 MHz–1GHz) with vertical polarization, only a signal in the 335 MHz frequency was obtained, with a low amplitude level; the rest is the background noise. This is corroborated with the EMI test receiver and with temporal measurements, where the distribution in the spectrogram is observed. In the case of horizontal polarization, in the temporal part, a more defined signal can be seen with respect to the corona, keeping the energy concentration at 16 MHz and 32 MHz, as observed in the spectrogram. In the response of the spectrum analyzer, there are two signals, one at 335 MHz and the other at 960 MHz; the first is also presented with vertical polarization, the rest is background noise. Measurements with the EMI test receiver in this frequency range do not present information; only the background noise is seen.

As an important part of this work analysis, we can say that the measurements of the electromagnetic radiation of corona discharges are concentrated below 70 MHz, which has already been reported. However, it does not present a spectrogram like we do, which gives information on the distribution of radiation both in time and in frequency. It was also determined that, for frequencies greater than 30 MHz, the most appropriate is to use a spectrum analyzer since the bandwidth resolution can be adjusted to obtain more frequency components. With the EMI test receiver, the envelope of the signal is obtained by its filter; it has a large recovery constant.

The measurements of the corona discharge in a semi-anechoic chamber and safely verify the presence of the phenomenon gives the certainty that the emissions only correspond to this discharge and that it can also be ensured that there are no interfering signals in the band from 300 MHz to 1 GHz. Therefore, radio communication systems that are highly sensitive cannot be affected by this phenomenon. This leads us to ensure that the measurements that have been reported regarding this problem both on-site and the development of antennas have a complete spectrum of partial discharges where corona discharge may be included.

For measurements of radiated emissions in open spaces, the fact of identifying the corona with an ultraviolet camera does not indicate that only the corona discharge is present, it may be the main discharge with frequencies of partial discharges, but as the corona has been verified, it does not emit high-frequency signals (UHF).

In HV systems greater than those used (>12 kV) in this work, of course, the corona discharge has levels of radiated emissions higher than those obtained. In the bands with higher activity (<60 MHz), their presence is significant, but at high frequencies (UHF and microwaves), this phenomenon is not a problem for radio-communication systems.

6. Conclusion

The energy of conducted emissions of the CD that can be affirmed is located in the frequency range of 8–32 MHz. The fundamental frequency is in 8 MHz, which indicates that the frequency fundamental of the corona discharge is independent of the source configuration.

A summary is presented in **Table 3** for the analysis of the spectrogram of radiated CD emissions.

The temporal and frequency responses of the radiated emissions of the CD present the energy concentration in the same frequency range, which indicates that the process used in the measurements is adequate.

In relation to the radiated emissions in the frequency range from 0.3 to 30 MHz, the three measurement processes agree, which indicates the RBW selected in both instruments is adequate (10 kHz). In the case of the 30–300 MHz frequency band, in both instruments, RBW of 120 kHz was set as specified in CSPR-1-1. However, there are differences according to the results. For this case, the EMI test receiver can be reliable up to 100 MHz. The opposite for the spectrum analyzer, which has a better resolution because narrowband emissions can be identified at 120 and 260 MHz. In the band from 300 MHz to 1 GHz, having the same RBW (120 kHz) on both instruments, the EMI test receiver is unresponsive; it only presents background noise. Instead, the spectrum analyzer makes it possible to determine narrowband emissions. Finally, the results show that in the 100 MHz–1 GHz band, the radiated emissions from corona discharge are not a threat to radio communication systems.

Antenna	Polatization	Frequency range MHz
Loop	x, y, z	8, 16, 16–32
Biconical	Vertical	16, 16–64
Biconical	Horizontal	16–64
Hybrid biconical/log periodic antenna	Vertical	8, 16, 24–64
Hybrid biconical/log periodic antenna	Horizontal	16–64

Table 3.
Concentration of energy in the spectrograms.

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Conflict of interest

The authors declare no conflict of interest.

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References

- [1] Lia X, Cuib X, Luc T, Wangd D, Wange Z, He Z. A platform for multiple DC corona effects measurements and analysis. In: Proceeding IEEE Instrumentation and Measurement Technology Conference (I2MTC); 11-14 May 2015, July 2015. Pisa, Italy: IEEE; 2015. pp. 181-186. DOI: 10.1109/I2MTC.2015.7151262
- [2] Radio Interference. 2010. Available from: <https://www.sciencedirect.com/topics/engineering/radio-interference> [Accessed: January 20, 2021]
- [3] Riba J-R, Gómez-Pau Á, Moreno-Eguilaz M. Experimental study of visual corona under aeronautic pressure conditions using low-cost imaging sensors. *Sensors*. 2020;**20**(2): 411. DOI: 10.3390/s20020411
- [4] Riba J-R, Morosini A, Capelli F. Comparative study of AC and positive and negative DC visual corona for sphere-plane gaps in atmospheric air. *Energies*. 2018;**11**:2671. DOI: 10.3390/en11102671
- [5] Tejada-Martínez C, Espino-Cortes FP, Ilhan S, Ozdemir A. optimization of radio interference levels for 500 and 600 kV bipolar HVDC transmission lines. *Energies*. 2019;**12**:3187. DOI: 10.3390/en12163187
- [6] Phillips DB, Olsen RG, Pedrow PD. Corona onset as a design optimization criterion for high voltage hardware. *IEEE Transactions on Dielectrics and Electrical Insulation*. 2000;**7**(6):744-751. DOI: 10.1109/94.891984
- [7] Tanner RL. Radio Interference from Corona Discharge. Technical Report No 37. SRI Project No 591. Air Force Contract No AF 19(604)-266. 1953
- [8] Moongilan D. Corona noise considerations for smart grid wireless communication and control network planning. In: Proceedings IEEE International Symposium on Electromagnetic Compatibility (EMC); 6-10 August 2012; Pittsburgh, PA. USA: IEEE; 2012. pp. 357-362. DOI: 10.1109/ISEMC.2012.6351822
- [9] CISPR TR 18-2. Radio interference characteristics of overhead power lines and high-voltage equipment—Part 2: Methods of measurement and procedure for determining limits. Edition 3.0. 2017
- [10] Xia Y, Song X, Jia Z, Wang X, Qi J, Xu Z. Research on antenna for detecting the corona discharge of transmission line. In: Proceeding the 14th IET International Conference on AC and DC Power Transmission (ACDC2018). United Kingdom; 19th September 2018. DOI: 10.1049/joe.2018.8392
- [11] Kysela A. Electromagnetic emissions of AC high-voltage corona. In: Intensive Programme, Renewable Energy Sources. Czech Republic: Železná Ruda-Špičák, University of West Bohemia; 2011. pp. 114-118
- [12] Madhar SA, Mráz P, Mor AR, Ross R. Study of corona configurations under DC Conditions and recommendations for an identification test plan. *International Journal of Electrical Power & Energy Systems*. 2020;**118**:1-10. DOI: 10.1016/j.ijepes.2020.105820
- [13] Korzhov AV, Okrainskaya IS, Sidorov AI, Kufel VD. A study of electromagnetic radiation of corona discharge near 500-kV electric installations. *Power Technology and Engineering*. 2004;**38**(1):57-60. DOI: 10.1023/B:HYCO.0000029636.31951.91
- [14] Robert GO, Bradley OS. Predicting VHF/UHF electromagnetic noise from corona on power-line conductors. *IEEE Transactions on Electromagnetic Compatibility*. 1988;**30**(1):13-22. DOI: 10.1109/15.19883

- [15] Chartier VL, Sheridan R, DiPlacido JN, Loftness MO. Electromagnetic interference measurements at 900 MHz on 230-kV and 500-kV transmission lines. *IEEE Transactions on Power Delivery*. 1986;**PWRD-1**(2):140-149. DOI: 10.1109/TPWRD.1986.4307944
- [16] Abdel-Salam M, Abdel-Sattar S. Calculation of corona V-I characteristics of monopolar bundles using the charge simulation method. *IEEE Transactions on Electrical Insulation*. 1989;**24**(4): 669-679. DOI: 10.1109/14.34202
- [17] Wang D, Lin D, Yao C. Statistical study on space charge effects and stage characteristics of needle-plate corona discharge under DC voltage. *Energies*. 2019;**12**:2732. DOI: 10.3390/en12142732
- [18] Huang C, Yin H, Xu P, Zhang B, He J, Liu J. Prediction of radio interference from HVDC transmission lines based on corona discharge characteristics. *High Voltage*. 2020;**5**(6):679-687. DOI: 10.1049/hve.2019.0050
- [19] Salazar-Hernández JC, Linares y Miranda R, Espino-Cortes FP, Ozdemir A. Far-field prediction for radio-interference produced by fundamental frequency of a DC corona discharge at a rod-plane configuration. *IEEE Electromagnetic Compatibility Magazine*. 2020;**9**(Quarter 3):37-43. DOI: 10.1109/MEMC.2020.9241549
- [20] CISPR TR 18-1. Radio interference characteristics of overhead power lines and high-voltage equipment—Part 1: Description of phenomena. Edition 3.0. 2017
- [21] CISPR 16-1-1. Specification for radio disturbance and immunity measuring apparatus and methods—Part 1-1: Radio disturbance and immunity measuring apparatus—Measuring apparatus. ED. 5.0 B. 2019
- [22] Shixiu C, Youlin S, Hengkun M. Characteristics of electromagnetic wave radiated from corona discharge. In: *Proceeding of the IEEE EMC International Symposium on Electromagnetic Compatibility* (Cat. No. 01CH37161); 13-17 August 2001; Montreal, QC. Canada: IEEE; 2001. pp. 1279-1282. DOI: 10.1109/ISEMC.2001.950630