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A Feasibility Study of the Application of Signal Processing Techniques to Corona Discharge Characterization on HVDC Systems †

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Abstract: This paper presents an initial and feasibility study of corona discharge characterization on HVDC systems through the application of signal processing techniques. In the corona discharge test, high voltages varying from ±30 kV to ±80 kV were applied through a DC high-voltage generator and corona discharges around the conductor were measured by means of a data acquisition prototype system equipped with a metal electrode device for the purpose of corona current measurement. The signals collected were subjected to digital signal processing parameters to extract the most relevant information related to corona discharge occurrence. The results reveal that the proposed method was able to detect the corona discharge characteristics following the changes in the signal content, especially, for narrow frequency ranges. The results indicate the feasibility of the proposed method to detect and characterize the occurrence of corona discharge in a simple way, which expands the research field in corona discharge characterization in HVDC systems by means of digital signal processing and feature extraction.

Keywords: HVDC; corona discharge; digital signal processing; pattern recognition; fault diagnosis

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1. Introduction

High-voltage direct-current (HVDC) systems are emerging as a promising technology for long-distance bulk power delivery due to their lower cost and reliability compared to high-voltage alternating-current (HVAC) systems [1–3]. On the other hand, the effectiveness of HVDC systems is, however, significantly defined by the application of inspection and condition monitoring procedures, which are necessary to guarantee the HVDC transmission efficiency, diagnose faults, enable personnel safety during maintenance roadmaps, and meet the environmental requirements [4–7]. In this context, the measurement of corona current plays an essential role within HVDC systems because it provides important information such as corona discharge occurrence, electromagnetic interferences, HV and electrical current intensity, among other features [8,9].

On the other hand, researchers have been made efforts to promote new strategies of monitoring and inspection of HVDC systems through the use of contact and non-contact measurement solutions. This way, many approaches have been proposed to establish HVDC detection sensing devices based on corona current measurement [6,9–11]. Likewise, the use of indirect measurement sensing devices, such as electrical current sensors, electromagnetic field measurement approaches, and the use of electric field mill devices, has also been considered [4,7,12,13].

Due to the importance of corona current measurement to the HVDC systems, especially in terms of corona discharge occurrence detection, the present research work performs an initial and feasibility study of the corona discharge characterization on HVDC systems by means of the application of signal processing techniques. Although the popular use of digital signal processing techniques for corona discharge monitoring in electrical systems [14], the present particular focus on the HVDC is an approach that has not been reported in the literature. Corona measurement experimental tests were conducted applying different high voltages values through a DC high-voltage generator and corona discharges around the conductor were measured utilizing a data acquisition prototype system equipped with a metal electrode device. The signals collected were subjected to digital signal processing parameters, such as time-domain and frequency-domain analysis based on raw signals, fast Fourier transform (FFT), digital filters, and peak value, to extract the most relevant features related to corona discharge occurrence The proposed approach effectively contributes to the improvement of HVDC corona current measurement and corona discharge detection.

2. Experimental Setup

To assess the feasibility of the proposed approach, experimental tests were carried out in a laboratory, under a controlled environment and conditions. The HV tests were conducted applying voltages of ±30 kV, ±50 kV, and ±80 kV through a 110 kV PGK 110/HB Baur DC power supply. For the purpose of corona current measurement, a data acquisition prototype system equipped with a metal electrode device was used. The corona detector device was mounted on an aluminum rod fixed at 60 cm and 90° in relation to the DC generator, and the electrical measurements were carried out under load conditions with a fixed distance of 1.5 m between the positive and negative electrodes. The proposed experimental setup framework is shown in Figure 1. The data acquisition system is composed of an infrared communication that allows an interface between the measurement device and PC through an optical link (irDA2) and USB. The electrical current data were collected for each condition tested on the experiments at a 2 MHz sampling rate. During the experiments, the environmental influences, such as temperature and humidity, were kept constant, allowing a proper comparison between the signals collected under different conditions (30 kV, ±50 kV, and ±80 kV).

For signal processing and feature extraction, the procedure was conducted according to Figure 1, from which the analyzes were performed in both time and frequency domains by using Matlab® software. Firstly, a time-domain analysis was carried out upon the raw signals. Secondly, a spectral analysis was performed, using fast Fourier transform (FFT), to select the most appropriated frequency bands. Finally, a statistical analysis was performed through the application of Butterworth digital filters and the computation of peak values for each condition. The later analysis was supported by the coefficient of determination R^2 (R-squared), whose value was used to determine the most appropriate trend on the process of band frequency choice.

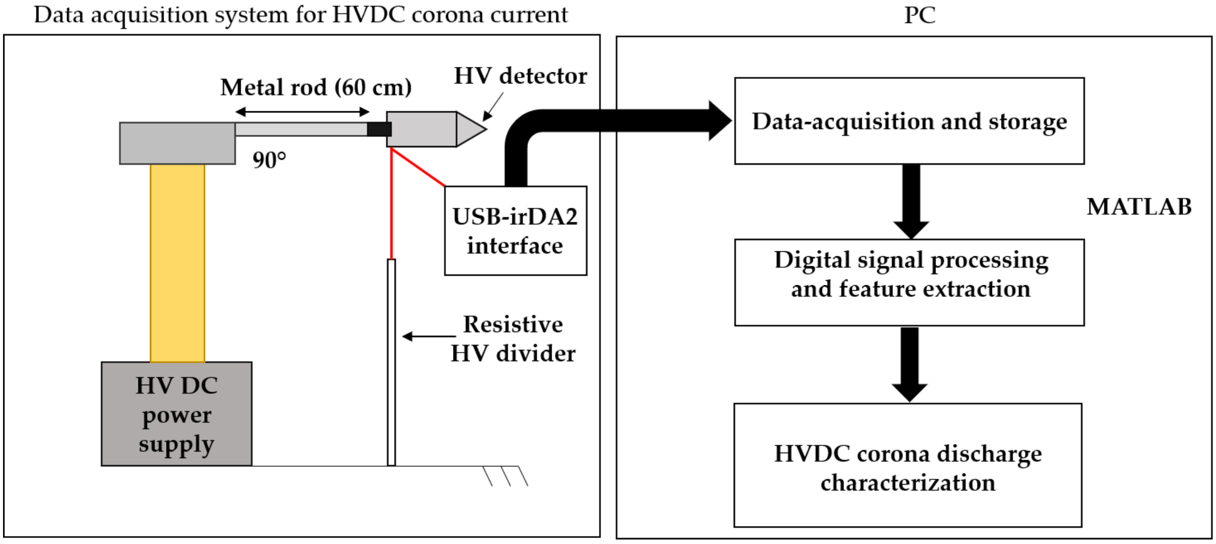
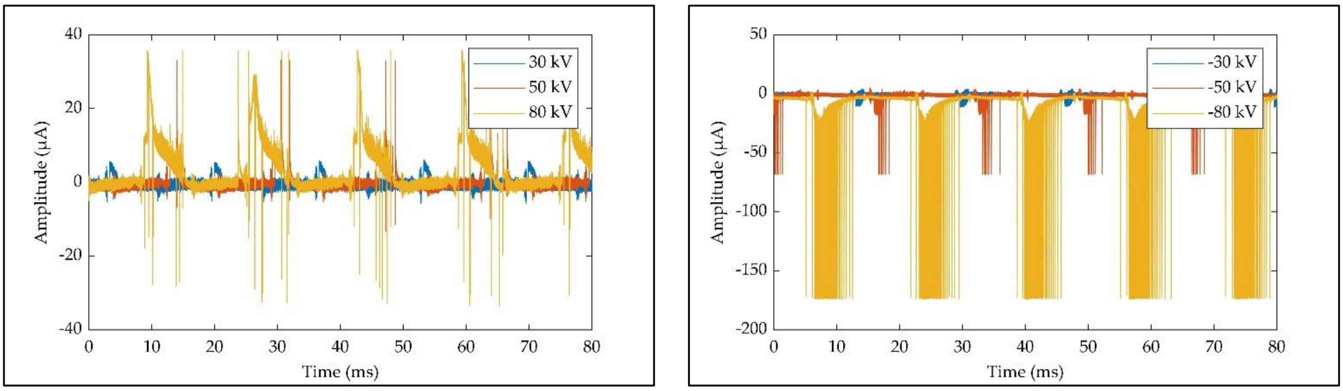


Figure 1. Experimental setup proposed framework.

3. Results and Discussion

3.1. Time-Domain Analysis

The raw signals, i.e., without any digital processing, corresponding to the electrical current of ±30 kV, ±50 kV, and ±80 kV are shown in Figure 2. This way, Figure 2a shows the measurements at the positive pole and Figure 2b shows the measurements at the negative pole.



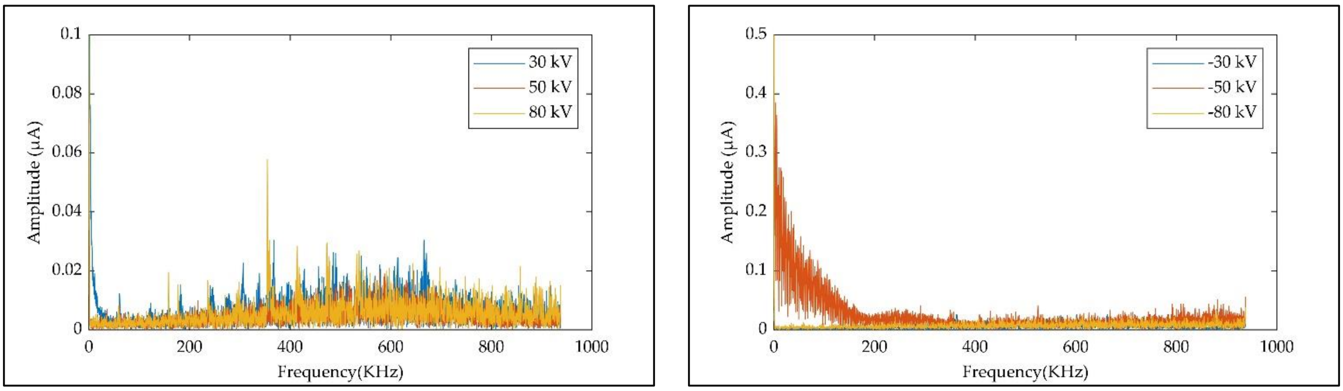
(**a**) (**b**)

Figure 2. Raw electrical current signals in time domain: (**a**) positive pole; e (**b**) negative pole.

It is possible to observe the trend of the signals in terms of amplitude and behavior over time. The time duration of 80 ms and the periodical occurrence of certain patterns, such as pulses, characterize the occurrence of events as in this case the corona discharges. Likewise, the signals present different patterns and trends between positive and negative poles. In addition, it is possible to note the signal evolution in terms of intensity for the different measurements of ±30 kV, ±50 kV, and ±80 kV. This analysis is also important to determine the electrical current intensity variation, which was below 10 μA to the HV values of ±30 kV and ±50 kV as well as above 30 μA to the HV of ±80 kV.

3.2. Frequency Domain Analysis

As previously mentioned, to analyze the frequency bands most sensitive to the corona discharge occurrence, an appropriate spectral analysis was conducted on the basis of the FFT calculation. The result is shown in Figure 3. This way, the frequency content of the signals corresponding to the electrical current under ±30 kV, ±50 kV, and ±80 kV is presented in Figure 3a (measurements at the positive pole) and 3b (measurements at the negative pole).



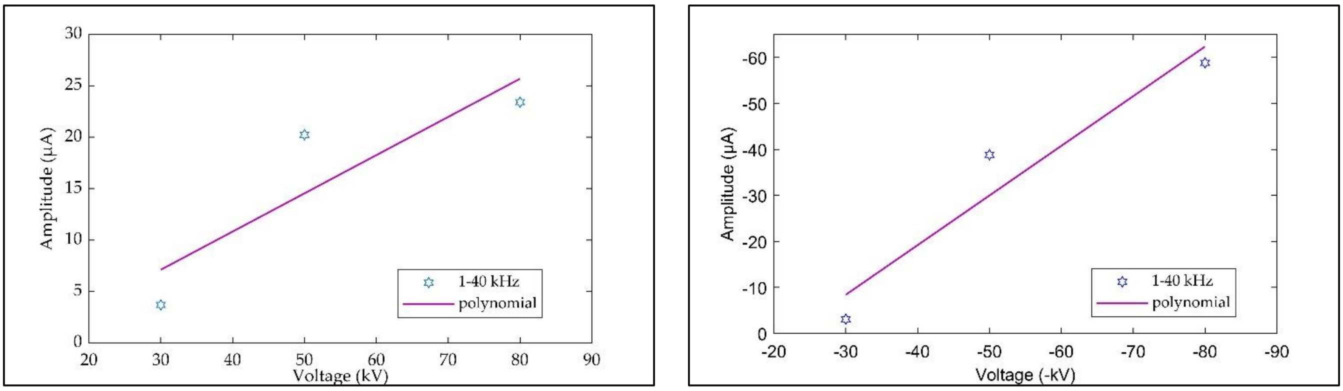
(**a**) (**b**)

Figure 3. Spectral content of the electrical current signals: (**a**) positive pole; e (**b**) negative pole.

It is possible to observe that the frequency spectrum is limited to the range of 0–937.5 KHz (Nyquist frequency). Therefore, it is possible to study the frequency ranges that are predominant in terms of phenomena occurrence, as well as determine the frequency range from which the signals are attenuated. A significant difference between the signals corresponding to each applied voltage value (±30 kV, ±50 kV, and ±80 kV) is noticeable in Figure 3, as can be seen in the different amplitude values obtained over the frequency ranges. Differences between the voltages applied at the positive pole and those at the negative pole are also noticed. In addition, it is possible to note that the predominant activity relating to the corona discharge occurrence is concentrated up to 200 kHz for the present case, from which an attenuation above 100 kHz is noticed. An analysis based only on the graphics of Figure 3 is, however, insufficient to indicate the most appropriated narrow frequency bands because they present considerable overlap between signals and conditions. To overcome this problem, a statistical analysis was conducted, whose results are presented in the next section.

3.3. Statistical Analysis to Determine the Most Relevant Features Related to Corona Current Measurement

As previously mentioned, the purpose of the statistical analysis conducted in this study is to extract the optimal features related to the occurrence of corona discharges with a particular focus, however, on the specific and narrow frequency bands. To achieve this goal, digital filters were applied in several frequency bands to verify which is the most sensitive to characterize the occurrence of corona discharges in a simple way. Subsequently, the peak value was computed for ±30 kV, ±50 kV, and ±80 kV based on the selected frequency range. The selective criteria were based on the coefficient of determination R^2 calculation, to determine which trend was closest to a linear polynomial fit (45°). Therefore, the frequency band of 1–40 kHz was chosen, which proved to be adequate and representative. This way, the results of the peak values of the filtered signals corresponding to the voltages applied to the positive (Figure 4a) and negative (Figure 4b) poles are presented. The coefficient of determination was R^2 was 0.77 to the HV positive values and 0.925 to the HV negative values. The latter is a more suitable result since the increasing trend was more appropriate and closest to the linear fit. However, is possible to note similar trends between the signals corresponding to the positive and negative poles shown in Figure 4. Therefore, the results indicate that the frequency band of 1–40 kHz was suitable to determine the corona discharge that occurs in the electrical current signals, which is supported by the appropriated trend of the peak values in Figures 4a and 4b. These results also indicate the feasibility of the proposed approach to detect and characterize the occurrence of corona discharge in a simple way.



(**a**) (**b**)

Figure 4. Peak values of the filtered electrical current signals: (**a**) positive pole; e (**b**) negative pole.

4. Conclusions

In this work, an initial and feasibility study of corona discharge characterization on HVDC systems through the application of signal processing techniques was performed. The electrical current signals collected from experimental corona tests were subjected to digital signal processing parameters, such as time-domain and frequency-domain analysis based on raw signals, fast Fourier transform (FFT), digital filters, and peak value, to determine the most appropriated features related to the occurrence of corona discharges in HVDC systems. The analyzes conducted in the present study were important to determine the electrical current intensity variation between the different conditions (positive and negative measurements) and HV values (±30 kV, ±50 kV, and ±80 kV) applied to the system, its trend, and a specific frequency band of 1-40 kHz suitable to the corona discharge occurrence characterization. In addition, the results reveal that the proposed approach can be adequate for practical implementation in HVDC transmission lines because of its simplicity and low cost because of the low-frequency range selected. Future research work will go deeper into the experimental conditions to include different environmental variations and test parameters as well as higher HV values (e.g., ±600 kV and ±800 kV) applied to the system. Likewise, the effectiveness and reliability of the proposed approach can also be tested for corona current measurement in HVDC transmission lines and equipment.

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References

1. Ghislain Ogoulola, C.E.; Junqueira Rezek, A.J.; Fifatin, F.; Silva, V.Z.; Gonzatti, R.B.; de Oliveira, J.C.; Lorenzo Correa, R. Di An alternative proposal for HVDC transmission systems using 24-pulse AC/DC converters based on three-winding non-conventional transformers. *Electr. Power Syst. Res.* **2020**, *182*, 106230, doi:10.1016/j.epsr.2020.106230.
2. Alassi, A.; Bañales, S.; Ellabban, O.; Adam, G.; MacIver, C. HVDC Transmission: Technology Review, Market Trends and Future Outlook. *Renew. Sustain. Energy Rev.* **2019**, *112*, 530–554, doi:10.1016/j.rser.2019.04.062.
3. Tosatto, A.; Weckesser, T.; Chatzivasileiadis, S. Market Integration of HVDC Lines: Internalizing HVDC Losses in Market Clearing. *IEEE Trans. Power Syst.* **2020**, *35*, 451–461, doi:10.1109/TPWRS.2019.2932184.
4. Cui, Y.; Yuan, H.; Song, X.; Zhao, L.; Liu, Y.; Lin, L. Model, Design, and Testing of Field Mill Sensors for Measuring Electric Fields under High-Voltage Direct-Current Power Lines. *IEEE Trans. Ind. Electron.* **2018**, *65*, 608–615, doi:10.1109/TIE.2017.2719618.
5. Wijeweera, G.; Bahreyni, B.; Shafai, C.; Rajapakse, A.; Swatek, D.R. Micromachined Electric-Field Sensor to Measure AC and DC Fields in Power Systems. *IEEE Trans. Power Deliv.* **2009**, *24*, 988–995, doi:10.1109/TPWRD.2008.2008427.
6. Xin, E.; Yuan, H. Development of a sensor for corona current measurement under high-voltage direct-current transmission lines. *Int. J. Distrib. Sens. Netw.* **2016**, *12*, 155014771666424, doi:10.1177/1550147716664243.
7. Suo, C.; Sun, H.; Zhang, W.; Zhou, N.; Chen, W. Adaptive Safety Early Warning Device for Non-contact Measurement of HVDC Electric Field. *Electronics* **2020**, *9*, 329, doi:10.3390/electronics9020329.
8. Otto, A.J.; Reader, H.C. Wideband and Narrowband HVDC Conductor Corona Test Methods for Radio Noise Prediction. *IEEE Trans. Power Deliv.* **2010**, *25*, 2950–2957, doi:10.1109/TPWRD.2010.2051689.
9. Yuan, H.; Yang, Q.; Liu, Y.; Lu, J.; Akhtar, S.A. Development and Application of High-Frequency Sensor for Corona Current Measurement under Ultra High-Voltage Direct-Current Environment. *IEEE Trans. Instrum. Meas.* **2012**, *61*, 1064–1071, doi:10.1109/TIM.2011.2179337.
10. Zhu, L.; Liu, S.H.; Zhang, Y.; Huang, F.Y.; Zhu, H.J. Design of Sensor for Detecting Corona Discharge Signal in Specific Band. *Appl. Mech. Mater.* **2013**, *336–338*, 158–162, doi:10.4028/www.scientific.net/AMM.336-338.158.
11. Liu, Y.; Yuan, H.; Yang, Q.; Cui, Y. Design of the corona current measurement sensor with wide bandwidth under dc ultra-high-voltage environment. *Meas. Sci. Technol.* **2011**, *22*, 125202, doi:10.1088/0957-0233/22/12/125202.
12. Zhu, K.; Lee, W.K.; Pong, P.W. Non-Contact Voltage Monitoring of HVDC Transmission Lines Based on Electromagnetic Fields. *IEEE Sens. J.* **2019**, *19*, 3121–3129, doi:10.1109/JSEN.2019.2892498.
13. Wijeweera, G.; Bahreyni, B.; Shafai, C.; Rajapakse, A.; Swatek, D.R. Micromachined electric-field sensor to measure AC and DC fields in power systems. *IEEE Trans. Power Deliv.* **2009**, *24*, 988–995.
14. Ardila-Rey, J.A.; Cerda-Luna, M.P.; Rozas-Valderrama, R.A.; de Castro, B.A.; Andreoli, A.L.; Muhammad-Sukki, F. Separation Techniques of Partial Discharges and Electrical Noise Sources: A Review of Recent Progress. *IEEE Access* **2020**, *8*, 199449–199461, doi:10.1109/ACCESS.2020.3035249.