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EFFECT OF VACUUM DRYING THE INSULATION PRESSBOARD ON PARTIAL DISCHARGE CHARACTERISTICS UNDER RIPPLE VOLTAGE CONDITIONS

The object of the research is partial discharges arising in a sample of the insulation pressboard. In most modern high-voltage direct current transmission schemes based on voltage-source converters six-pulse or twelve-pulse converters are used. The signal waveform on the direct current voltage side of a high-voltage direct current transmission is not pure direct current voltage and it has alternating current component. Since the partial discharge activity under distorted voltage is much different than that under pure direct current voltage, voltage ripples and voltage harmonics are the subject of various studies.

This article examines the effect of vacuum drying the insulation pressboard on partial discharge characteristics at direct voltage ripples. The insulation pressboard was dried in a vacuum chamber with a residual pressure of 1 mm Hg.

Among all the characteristics of a partial discharge, the main focus has been on the apparent charge of a partial discharge. The greater is the apparent charge value, the stronger is the destructive effect on high-voltage insulation. It was shown that drying the insulation in a vacuum chamber has the greatest effect on reducing the apparent charge of a partial discharge at direct current voltage than at alternating current voltage. After drying the insulation in a vacuum chamber, the amplitude of the partial discharge pulses was decreased by 99.3 % at direct current voltage in comparison with the moistened sample. After vacuum drying, at DC voltage, rare and very low magnitude partial discharges were recorded.

The conducted research contributes to the development of methods for partial discharge detection under non-standard voltage conditions.

Keywords: *partial discharge, ripple voltage, insulation pressboard, vacuum drying.*

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1. Introduction

Currently, high-voltage direct current (HVDC) technology of electric power transmission is on the rise worldwide. Applicability of high-voltage alternating current (HVAC) technology for transmission of electric power over long distances is limited due to the influence of inductive reactance and, therefore, inductive losses in transmission lines. HVDC transmission has considerably lower losses compared to HVAC over long distances. Another fact is large-scale cascading power outages. All biggest cascading blackouts that have happened around the world in the past [1, 2] have happened in HVAC systems. HVDC systems are protected from such cascading outages [3]. HVDC links and transmissions provide asynchronous connection between interconnected power systems, allowing independent frequency control in each of them. In such a case, different failures (short circuits, power outages) in one power system have little effect on the performance of the other one. Obviously, HVDC transmissions are most relevant for countries with long distances between sites of electricity consumption and production. That is why, HVDC technology is considered as a solution to increase transmission capacity in power system, as well as to obtain a stable power system in India [4, 5]. Various phenomena that affect the insulation electrical strength of HVAC systems have been studied over the years. But the effect of the same physical phenomenon on insulation at AC voltage and DC voltage is significantly different. Study of partial discharges (PD) at DC voltage [6, 7] assumes significance due to a global rise of equipment used in HVDC systems. According to [8], a PD is a localized electrical discharge that bridges only a part of insulation located between different electrodes. It should be noted that according to the modern classification of partial discharges, corona discharge, as well as surface discharge, also belong to PD [9]. The PD is considered as the main cause of insulation failure in different power equipment and among other factors, voltage waveform has significant impacts on PD characteristics [10]. This influence is so significant that recently studies of PDs have been carried out for practically all possible waveforms of the influencing voltage, which differ from the AC voltage. In most modern HVDC transmission schemes based on voltage-source converters (VSC) six-pulse or twelve-pulse converters are used. The signal waveform on the DC voltage side of a HVDC transmission is not pure DC and it has AC component [11]. This undesired component is referred to as «voltage ripple» or «DC voltage ripple». Ripple occurrences can be caused by periodic switching operations of thyristor valves or incomplete suppression of the AC waveform after rectification. Since the PD activity under distorted voltage is much different than that under pure DC, voltage ripples and voltage harmonics are the subject of various studies [12]. In [13] it was shown that PDs tend to cluster around the DC voltage ripple peaks mainly on the rising slopes of the DC voltage ripples. Common insulating materials used in HVAC power transformers such as paper and pressboard are also used in HVDC converter transformers [14]. Insulation pressboard based on pure cellulose is a very convenient insulating material for laboratory experimentation. For this reason, the insulation pressboard has already been used to study PD performance when exposed to not pure DC voltage containing ripples [13].

The object of research is partial discharges arising in a sample of the insulation pressboard. And *the aim of research* is to continue previous tests and study how vacuum drying the insulation affect PD under ripple voltage conditions.

2. Research methodology

The property of electrical insulating paper and pressboard is to reduce its electrical insulation strength when moistened. Relative humidity has an effect on the surface resistance of cavity and the PD characteristics at AC voltage [15]. With increasing relative humidity, the amplitude of the PD decreases. Therefore, when studying PD characteristics, it is advisable to evaluate the effect of moistening the pressboard at DC voltage too.

All detection circuits previously developed for the measurement of PDs at AC voltage, with minor modifications, are also suitable for use at DC voltage. A circuit diagram of experimental laboratory installation intended for PD measurement by electrical detection method is shown in Fig. 1.

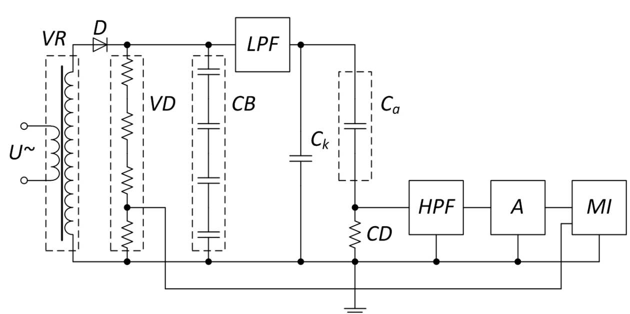

Fig. 1. Circuit diagram of PD measuring installation

In Fig. 1: *U*~ is high-voltage power supply; *VR* is voltage regulator; *D* is diode; *VD* is voltage divider; *CB* is capacitor bank; *LPF* is low-pass filter; C_k is coupling capacitor; C_a is test object; *CD* is coupling device (resistor); *HPF* is high-pass filter; *A* is amplifier; *MI* is measuring instrument (digital storage oscilloscope).

Regulated AC voltage source, diode and capacitor bank form a half wave rectifier circuit. Capacitor bank is used in rectifier circuit to get a DC signal with controllable level of pulsations. The general view of the measuring circuit is shown in the photographs in Fig. 2.

In PD measurement circuits at AC voltage, the coupling device is connected either in series with the test object, or in series with the coupling capacitor. In this experiment measuring circuit when coupling device is connected in series with the test object where PDs occurring is used (Fig. 1). As a metering instrument the XDS3102A dual-channel series digital storage oscilloscope (China) [16] was used. The general view of the measuring instrument is shown in the photographs in Fig. 3.

a *b*

Fig. 2. General view of partial discharge: *a* – measuring installation; *b* – capacitor bank

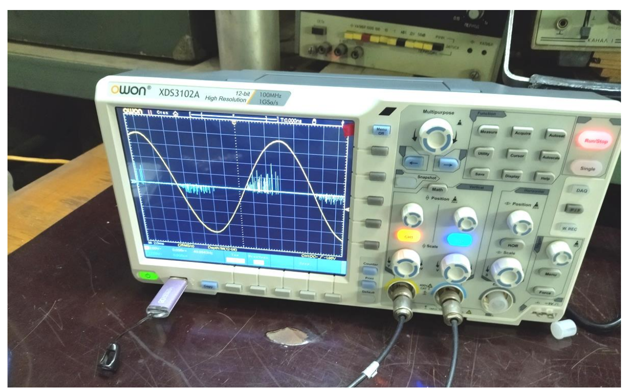

Fig. 3. Dual-channel oscilloscope during PD measurement at AC voltage

As a test object, a sample of insulation pressboard containing cavities on its surface was selected, which was placed between two cylindrical electrodes. Diameter of the lower electrode is 75 mm and upper electrode is 10 mm. Such an object is a fairly simple source of partial discharges when a high voltage is applied to it. When a rectified high voltage is applied to the electrode system, PDs are generated near the upper electrode with a smaller diameter. A photograph of this object and pressboard used has been repeatedly shown in previous articles, for example, in [13], therefore, to save space, it is not shown in this paper.

Since the PD actual charge cannot be measured, the maximum values of the PD apparent charge were measured and studied. The apparent charge of a single PD is the charge that, if injected between the electrodes of the object under test, would give the same voltage on the measuring instrument as a single PD itself.

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3. Research results and discussion

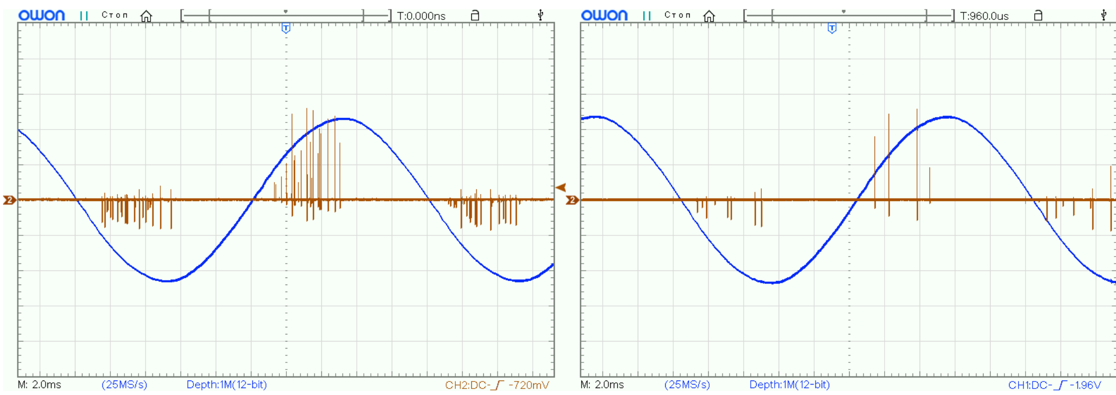
The results of measuring the characteristics of PD that arise both in moistened and dried sample when the voltage rises with different ripple levels are shown in oscillograms below. Fig. 4, *a* shows initial PD pulses in the insulation sample at AC voltage with 4.5 kV peak value before vacuum drying. How vacuum drying reduces the number of PD pulses is shown Fig. 4, *b*.

Here and thereafter, the detected PD pulses are shown in brown color, and the blue color shows the waveform of voltage applied to the test object.

Similar oscilloscope display screenshots were also saved when the amplitude of the applied voltage was increased to 7.3 kV. Similarly, Fig. 5, *a* shows high PD repetition rate for moistened sample and its noticeable decrease after vacuum drying in Fig. 5, *b*.

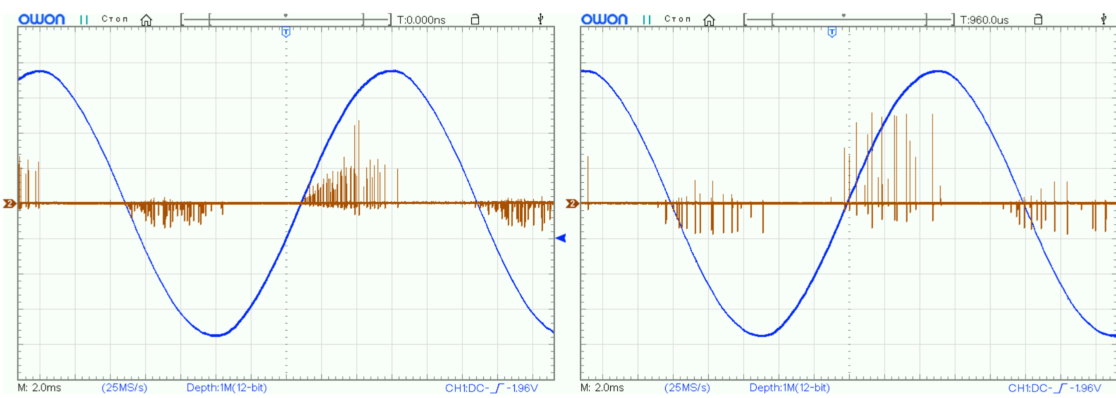
A noticeable effect of vacuum drying on the decrease in the amplitude of PD pulses at AC voltage was not recorded.

Similar studies were carried out for pulsating DC voltage with the same maximum values (4.5, 7.3 and 9.0 kV). In this case, two series of experiments were carried out: with a large level of pulsations (3.3 to 5.3 kV) and a small one (1.1 to 2.3 kV). Fig. 6, *a* shows initial PD pulses in the moistened insulation sample at pulsating DC voltage with maximum pulsations in the experiment (5.3 kV ripple-to-ripple peak value). In Fig. 6, *a* PDs are concentrated in the time domain where rectified ripples rise to maximum, as it was experimentally established in [13]. Significant effect of vacuum drying on PD repetition rate reduction is shown Fig. 6, *b*.



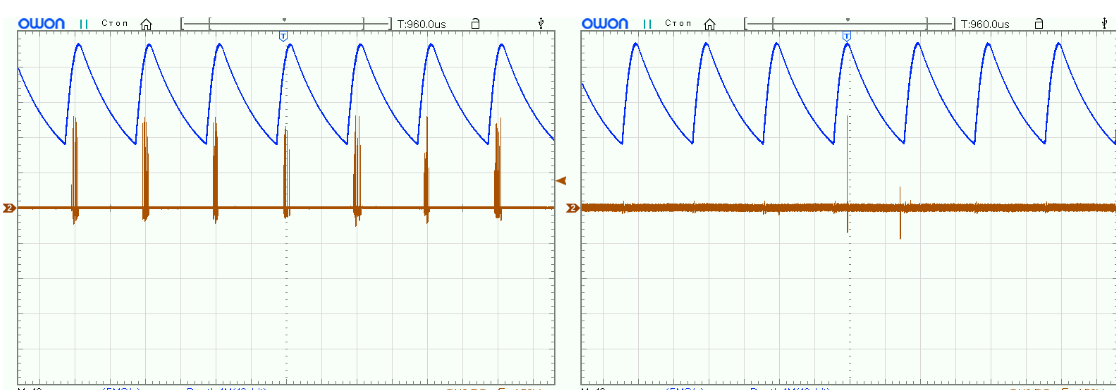
a *b*

Fig. 4. Comparison of PD pulses at AC voltage with peak value of 4.5 kV: *a* – without vacuum drying; *b* – after vacuum drying



a *b*

Fig. 5. Comparison of PD pulses at AC voltage with peak value of 7.3 kV: *a* – without vacuum drying; *b* – after vacuum drying



a *b*

Fig. 6. Comparison of PD pulses at pulsating voltage with ripple-to-ripple peak voltage of 5.3 kV: *a* – without vacuum drying; *b* – after vacuum drying

Fig. 7, *a* shows PD pulses in the moistened insulation sample at DC voltage with ripple-to-ripple peak voltage of 1.9 kV. Fig. 7, *b* shows the effect of drying the insulation and PD pulse with the smallest amplitude recorded in the experiment after vacuum drying under the same applied voltage.

Fig. 8, *a* shows PD pulses in the insulation sample at pulsating voltage with 9.0 kV peak value before vacuum drying, and Fig. 8, *b* after it.

Fig. 6 and Fig. 8 correspond to the same magnitude of the pulsating voltage (9.0 kV), but different ripple factor. A comparison of the oscillograms in these illustrations shows that for dried insulation the decrease in the amplitude of the PD pulses mainly depends on the decrease in the level of pulsations.

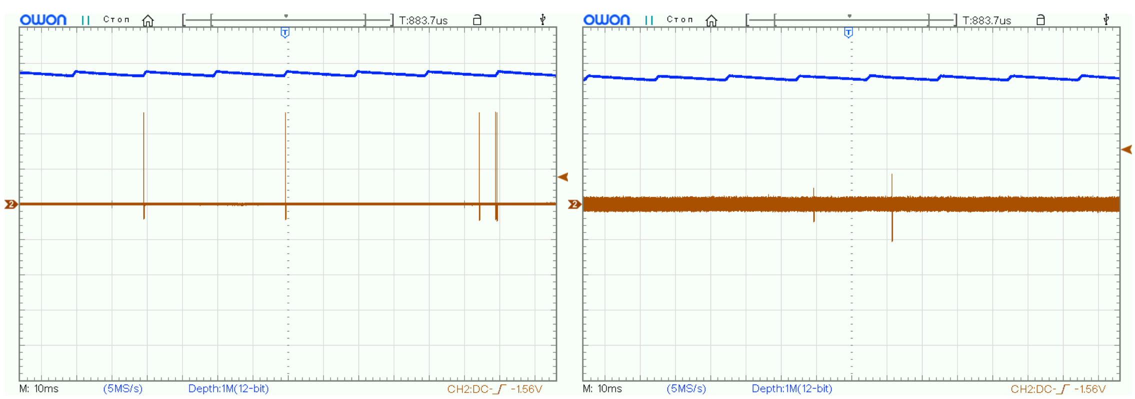
The results of measuring the apparent charge of PDs that arise in moistened sample when the voltage rises with different ripple levels are shown in Table 1.

To assess the effect of moisture on the PD performance, the insulation pressboard was dried in a vacuum chamber with a residual pressure of 1 mm Hg. As in paper [17], the PD maximum apparent charge was chosen as the main criterion for the efficiency of drying. Vapor phase drying method used in [17] combined heat and vacuum processing. The longer drying time may lead to initial degradation of cellulose insulation due to excessive heating. Prolonged drying and excessive heating lead to accelerated aging of the paper insulation and pressboard in particular. In current paper only vacuum drying without heating was used. The vacuum chamber used in the study is shown in Fig. 9.

For the vacuum dried insulation pressboard, similar measurements of apparent charge were carried out for the same applied voltage values s for the moistened pressboard. The results of measuring the apparent charge of PDs that arise in vacuum dried sample with different ripple levels are shown below in Table 2.

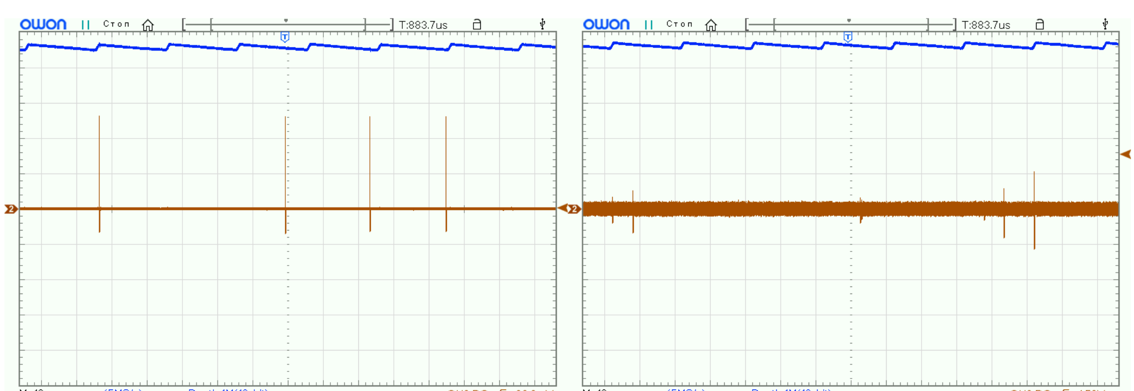
Unlike AC voltage, phase-resolved patterns cannot be obtained for DC voltage case. During PD measurement at DC voltage there are two available parameters: magnitude of PD pulses and time interval between two consecutive PD pulses. Therefore, oscillograms remain a visual representation approach of PDs at DC voltage.

There are studies [15] on the effect of different relative humidity of the air surrounding the test object on PD magnitude. There are also studies [17] on the effect of vacuum drying and heating of test object on PD magnitude. In this study two identical samples of insulation pressboard were used for the study. Then one of the samples was placed in a vacuum chamber, unlike other studies, without additional heating. After that, PD pulses were measured in these two samples during one day at the same humidity of the surrounding air. Analysis of the data in Table 1 and Table 2 shows that for a moistened sample, the apparent charge tends to rise with increasing applied voltage of any waveform. Vacuum drying the insulation has a greater effect at DC ripple voltage applied to a test object than at AC voltage. At the same humidity of surrounding air and at AC voltage, vacuum drying of the insulation has practically no effect on the maximum apparent charge of a PD. However, in this case, the total number of observed PD pulses is reduced.



a *b*

Fig. 7. Comparison of PD pulses at pulsating voltage with ripple-to-ripple peak voltage of 1.9 kV: *a* – without vacuum drying; *b* – after vacuum drying



a *b*

Fig. 8. Comparison of PD pulses at pulsating voltage with ripple-to-ripple peak voltage of 2.3 kV: *a* – without vacuum drying; *b* – after vacuum drying

Drying the insulation in a vacuum chamber has the greatest effect on reducing the apparent charge of a PD at DC voltage. When a DC voltage was applied to the test object after drying the insulation in a vacuum chamber, the amplitude of the PD pulses decreased by 99.3 % in comparison with the moistened sample. After vacuum drying, at DC voltage, rare and very low magnitude PD was recorded. The magnitudes of these PD pulses depend on the magnitude of ripple-to-ripple peak voltage. Comparison of the results was carried out under the same external conditions, specifically, at the same relative humidity of the ambient air of 68 % before and after vacuum drying. The results show that theoretically, at a DC voltage, PDs in the insulation can be practically eliminated. Obviously, the method that was applied in the article cannot help in case of outdoor insulation. However, the results obtained show that research aimed at obtaining electrical insulating materials that are resistant to pollution and moisture is relevant and important. Future efforts should also be focused on carrying out experiments similar to this research, but at greater applied voltage magnitudes.

Table 1

Apparent Charge Measured During 1-Hour Partial discharge Test at 68 % Relative Humidity (No Vacuum Drying)

Voltage type (ripple-to-ripple peak voltage, kV)	Peak voltage U_{max}, kV	Maximum apparent charge Q_{max}, pC	Oscillo-grams
AC, 50 Hz	4.5	21870	Fig. 4, *a*
AC, 50 Hz	7.3	23858	Fig. 5, *a*
AC, 50 Hz	9.0	23937	–
DC (3.3 kV)	4.5	19160	–
DC (4.4 kV)	7.3	23724	–
DC (5.3 kV)	9.0	23850	Fig. 6, *a*
DC (1.1 kV)	4.5	14370	–
DC (1.9 kV)	7.3	23935	Fig. 7, *a*
DC (2.3 kV)	9.0	24950	Fig. 8, *a*

Fig. 9. General view of vacuum chamber

Table 2

Apparent Charge Measured During 1-Hour Partial discharge Test at 68 % Relative Humidity (After Vacuum Drying)

Voltage type (ripple-to-ripple peak voltage, kV)	Peak voltage U_{max}, kV	Maximum apparent charge Q_{max}, pC	Oscillo-grams
AC, 50 Hz	4.5	21820	Fig. 4, *b*
AC, 50 Hz	7.3	23865	Fig. 5, *b*
AC, 50 Hz	9.0	23910	–
DC (3.3 kV)	4.5	no partial discharges	–
DC (4.4 kV)	7.3	no partial discharges	–
DC (5.3 kV)	9.0	920	Fig. 6, *b*
DC (1.1 kV)	4.5	no partial discharges	–
DC (1.9 kV)	7.3	165	Fig. 7, *b*
DC (2.3 kV)	9.0	184	Fig. 8, *b*

4. Conclusions

Partial discharge, like any other complex phenomenon, can be described by a set of characteristics. In this article, among all the characteristics of a PD, the main focus have been on the apparent charge of a PD. PDs have a damaging effect on insulation. The greater the amplitude of the pulses of PDs, the correspondingly greater the value of the apparent charge and the stronger the destructive effect on the high-voltage insulation. Insulating paper and pressboard are moisture sensitive. It was shown that drying the insulation in a vacuum chamber has the greatest effect on reducing the apparent charge of a PD at DC voltage than at AC voltage. Space charge can be accumulated in a solid dielectric when the DC voltage is applied. Space charge distorts electric field distribution. Drying the insulation in a vacuum chamber removes moisture, as one of the factors leading to the accumulation of space charge in the insulation under DC voltage conditions. When exposed to a DC voltage, the number and intensity of PDs in the insulation definitely depends on the insulation condition and pulsation level of DC voltage. The results obtained show that with the help of vacuum drying the DC insulation, it is possible to practically reduce the amplitude of PD pulses, and completely eliminate them in some cases. So, in three cases at a pulsating voltage of 4.5 kV (with 3.3 kV ripple), 7.3 kV (with 4.4 kV ripple) and 4.5 kV (with 1.1 kV ripple) after vacuum drying, no PD pulses were registered at all. In three cases at a pulsating voltage the amplitude of the PD pulses were decreased by more than 96 % after vacuum drying. Specifically, at a pulsating voltage of 9.0 kV (with 5.3 kV ripple) it was reduced by 96.1 % and by 99.3 % at a pulsating voltage of 7.3 kV (1.9 kV ripple) and also 9.0 kV (2.3 kV ripple). HVDC technology has a number of advantages over HVAC. Due to the high dependence of electrical insulating properties on moisture and pollution, it is critical to keep the insulation of HVDC systems dry. Research aimed at obtaining new electrical insulating materials that are resistant to pollution and moisture is relevant and necessary.

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References

1. Dagle, J. E. (2004). Data management issues associated with the August 14, 2003 blackout investigation. *IEEE Power Engineering Society General Meeting, 2,* 1680–1684. doi: http://doi.org/10.1109/pes.2004.1373160
2. Rampurkar, V., Pentayya, P., Mangalvedekar, H. A., Kazi, F. (2016). Cascading Failure Analysis for Indian Power Grid. *IEEE Transactions on Smart Grid, 7 (4),* 1951–1960. doi: http://doi.org/10.1109/tsg.2016.2530679
3. Carlsson, L. (2005). HVDC. A firewall against disturbances in high-voltage grids. *ABB Review*, 3, 42–46.
4. Kamalapur, G. D., Sheelavant, V. R., Hyderabad, S., Pujar, A., Baksi, S., Patil, A. (2014). HVDC Transmission in India. *IEEE Potentials, 33 (1),* 22–27. doi: http://doi.org/10.1109/mpot.2012.2220870
5. Joshi, N., Sharma, J. (2021). An overview on high voltage direct current transmission projects in India. *2021 6th International Conference on Inventive Computation Technologies (ICICT)*, 459–463. doi: http://doi.org/10.1109/icict50816.2021.9358704
6. Fard, M. A., Farrag, M. E., McMeekin, S. G., Reid, A. J. (2017). Partial discharge behavior under operational and anomalous conditions in HVDC systems. *IEEE Transactions on Dielectrics and Electrical Insulation, 24 (3),* 1494–1502. doi: http://doi.org/10.1109/tdei.2017.006469
7. Guo, R., Wang, K., Xu, Z., Li, J., Sun, J., Cheng, H. (2016). Partial discharge characteristics and classification in oil-paper insulation under DC voltage. *2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*. doi: http://doi.org/10.1109/ichve.2016.7800629
8. *High-voltage test techniques – Partial discharge measurements* (2000). International standard IEC 60270:2000, 1–99.
9. Gulski, E. (1995). Digital analysis of partial discharges. *IEEE Transactions on Dielectrics and Electrical Insulation, 2 (5),* 822–837. doi: http://doi.org/10.1109/94.469977
10. Dong, G., Liu, T., Zhang, M., Li, Q., Wang, Z. (2018). Effect of voltage waveform on partial discharge characteristics and insulation life. *2018 12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*, 144–147. doi: http://doi.org/10.1109/icpadm.2018.8401151
11. Meisner, J., Schmidt, M., Lucas, W., Mohns, E. (2011). Generation and measurement of AC ripple at high direct voltage. *XVII International Symposium on High Voltage Engineering*, 1–4.
12. Fard, M. A., Reid, A. J., Hepburn, D. M., Gallagher, H. (2016). Influence of voltage harmonic phenomena on partial discharge behavior at HVDC. *2016 IEEE International Conference on Dielectrics (ICD)*, 548–551. doi: http://doi.org/10.1109/icd.2016.7547663
13. Trotsenko, Y., Protsenko, O., Mykhailenko, V., Burian, S. (2020). Effect of direct voltage ripples on partial discharge activity in solid dielectric. *2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP)*. doi: http://doi.org/10.1109/paep49887.2020.9240799
14. Carlson, A. (1996). Specific requirements on HVDC converter transformers. *ABB Transformers AB*. Valhallavagen, 1–4.
15. Nawawi, Z., Muramoto, Y., Hozumi, N., Nagao, M. (2003). Effect of humidity on partial discharge characteristics. *Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials (Cat. No.03CH37417)*, 1, 307–310. doi: http://doi.org/10.1109/icpadm.2003.1218413
16. *OWON XDS3000 Dual-Channel Series Digital Storage Oscilloscopes (2019)*. LILLIPUT Company. *User Manual*, 149.
17. Siswanto, Indarto, A., Rahmatullah, R., Hudaya, C. (2018). The effects of drying time during manufacturing process on partial discharge of 83.3 mva 275/160 kv power transformer. *MATEC Web of Conferences, 218,* 04008. doi: http://doi.org/10.1051/matecconf/201821804008

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