Determination of Critical Cavity Size on Stator Bar Insulation System Using a Finite Element Method Model

Alander R. Ribeiro *. Reinaldo. C. Leite**
Marcus. V.A. Nunes***

**UFPA - Universidade Federal do Pará, Belém, PA Brazil (Tel: 91 993569506; e-mail: alanderribeiro@gmail.com).*
*** UFPA - Universidade Federal do Pará, Belém, PA Brazil (e-mail: reinaldo.leite1913@gmail.com)*
**** UFPA - Universidade Federal do Pará, Belém, PA Brazil (e-mail: mvan@ufpa.br)*

Abstract: Partial discharge (PD) inside cavities causes aging of a stator bar groundwall insulation system that can generates a breakdown leading to equipment failures. One of the conditions to a PD occurrence is that the electric field (EF) within the cavity must exceed an inception field that mainly depends on the cavity size and pressure. A stator bar model has been simulated using Finite Element Method (FEM) in order to study the presence of a spherical cavity within the insulation. Simulation results and inception field calculation were used to determinate critical cavity size.

Keywords: partial discharge modelling; electric field; insulation system; finite element method; simulation.

1. INTRODUCTION

Partial Discharges (PD) measurement is a diagnostic tool that aids maintenance engineers in life cycle management of stator bar groundwall insulation. PD activity degrades the insulation system and can lead the equipment to fail when protrusions and electrical trees are formed from the cavity wall giving rise to a fast breakdown of the insulation system (Montanari et al., 2019). The PD activity can be tolerated for entire expected life of a generator for epoxy-mica insulation if these discharges are not abnormally high, but some cavities can cause more significant PD events and accelerate aging. (Turgeon et al., 2011). The cavity size also plays a significant role for PD attainment because for the avalanche turns into a streamer a critical length must not be exceeded and this length depends on the cavity diameter (Niemeyer, 1995).

Modeling the PD process can bring a better understanding of the phenomenon. The main objectives of PD modelling for condition monitoring are: (i) increase the knowledge about the PD phenomenon; (ii) identify critical parameters and physical mechanisms that influence PD occurrence and (iii) obtain relations between defect characteristics, insulation project parameters and test conditions and the partial discharges (Ilias; Chen; Lewin, 2017). The critical cavity size is a parameter that can be obtained by simulation.

The first approach used to model PD process was the three-capacitance model (Kreuger, 1989). In this model C_a represents the sound part of the dielectric between the test electrodes, C_b is the leakage capacitance between the electrodes and the cavity and C_c represents the capacitance of the cavity. Pedersen et al. (1991) criticized this model because according to the authors the PD phenomenon is a field problem and as such, could not be treated as a circuit problem. The cavity cannot be seen as a capacitor because it has no metallic electrodes limiting it. Pedersen proposed an approach based on the field theory to assess the PD process. Application examples of the Pedersen approach can be found in Leite (2021) and Lemke (2012).

The Niemeyer model (Niemeyer, 1995) is an evolution of Pedersen model based on physical characteristics of the PD phenomenon, such as: defect geometry, field behavior at the defect, charge carrier generation (surface emission and volume generation), streamer process and PD charge. This model is capable of predicting measurable PD characteristics as: inception voltage, inception delay, measurable charges, statistical characteristics and distribution of PD events over the ac phase.

A method for determining the critical cavity size is proposed on Turgeon et al. (2011). The proposed method consists in calculating the electric field in a cavity present in the ground wall insulation of a generator bar using the boundary element method (BEM) and once having the EF inside the void, determine the critical size capable of causing dielectric breakdown on gas using the Paschen Law. There are two critics to this approach: the use of Paschen Law for the calculation of the inception field and the use of BEM as numerical method to solve the problem. The problem in using Paschen Law for inception field determination is that the authors considered the EF uniform inside the cavity. This assumption does not hold, because after a PD event a volumetric charge appears inside the cavity distorting the field transforming a Laplacian problem into a Poissonian problem (Niemeyer, 1995), (Pedersen, 1991). In what concerns the use of the BEM as numerical method the problem is that it is not efficient at handling non linear materials and the type of matrix formed is not amenable to efficient solution. On the other hand, the Finite Element Method (FEM) is well suited for modeling of non-linear materials and as the matrix formed is sparse, an efficient solution is obtained (Haddad, 2004).

To overcome this problem, this paper proposes to implement the Niemeyer model using the FEM to calculate the EF distribution inside cavity using the geometry of the generator bar proposed on Turgeon et al. (2011). Also, both simulated and experimental results from Illias (2011) are used in order to obtain a great accuracy for this work, considering that the study of the size and location of cavities and its consequences are a large contribution for maintenance of equipments. The paper is outlined as follows: section 2 describes the model proposed by Niemeyer, Section 3 describes the geometry and the modeling steps and at last on section 4 the results are discussed.

2. THE NIEMEYER MODEL

The detailed model presented on Niemeyer (1995) shows the mathematical representation and classification of different streamer discharge phenomena in gases and along gas insulator interfaces. This type of discharges are the ones generally detected in PD measurements. The defect parameters considered in this model are related to: (i) the size and location of the defect within the insulation; (ii) the properties of the materials involved in the PD and (iii) the modification of the gas characteristics during the whole event of discharge. Among the different classifications of PD defects, spherical cavities within insulation materials are widely used by researchers (Illias, 2011). Fig. 1 shows an example of a cavity on a solid insulation system composed of high voltage electrode connected to the voltage source, the dielectric material in gray, the cavity represented by the circle, the partial discharge and the ground electrode connected the ground of the voltage source.

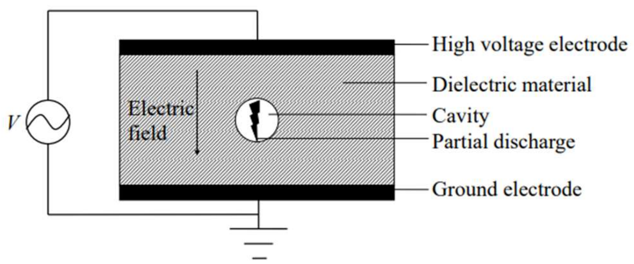

Fig.1 Spherical cavity within a solid insulator system.

2.1 Partial Discharges in Spherical Cavities

Partial discharges are driven by a field enhancement located within the spherical cavity that contains gas. The mainly parameters for this type of defect are the relative permittivity of the gas and the surrounding dielectric, the diameter of the cavity and the pressure of the gas (Niemeyer, 1995).

For the PD to occur, two conditions are necessary. The first one is that the electric field (EF) at the cavity must exceed the critical electric field strength of the discharge. The inception field (E_{inc}) can be defined as (1) where p is the pressure of the gas inside the cavity, d is the diameter of the cavity and the constant parameters $\left(\frac{E}{p}\right)_{cr}$, B and n are related to the ionization process in the gas and in air the values are 24.2 $VPa^{-1}m^{-1}$, 8.6 $Pa^{1/2}m^{1/2}$ and 0.5, respectively. The E_{inc} is the minimum EF value that can guarantee the self-sustaining of the PD process (Wang et al., 2021).

$$E_{inc} = \left(\frac{E}{p}\right)_{cr} p[1 + \frac{B}{(pd)^n}] \quad (1)$$

The second condition is that inside the cavity there must exist a free electron causing electron avalanche. The main mechanisms for this initial electron generation are by surface emission and volume ionization. The availability of free electrons within the cavity causes the statistical characteristic of the PD activity that directly affects the delay of the event, frequency of occurrence and distribution of the PD process (Wang et al., 2021). However, for this probability exist, the inception field must be reached within the cavity. Thus, it will be the focus of the next sections.

2.2 Finite Element Method Simulation

The Niemeyer model is consolidated and widely used in researches along with Finite Element Method (FEM) in order to study and learn about the PD process. In Illias (2011), the complete PD process is simulated using an interface between software COMSOL and MATLAB code. Experimental tests were performed on five samples with different cavities size and data were used in order to improve the simulation results. The purpose was to simulate PD activity and the effects of applied voltage, frequency, cavity size and temperature.

In this paper, FEM is used to calculate EF and some conclusions from Illias (2011) are used in order to find the critical cavity size present in the ground wall insulation of a generator bar. Table 1 shows the initial E_{inc} at 20°C for the five samples tested and simulated, the values are defined through the experimental tests. This parameter is mainly influenced by temperature change in the cavity due to cavity pressure change and the cavity size.

Table 1. Initial inception field at 20°C of different cavities size

Sample	Cavity diameter (mm)	Initial Inception Field (kV/mm)
1	1.55	3.02
2	1.1	3.35
3	2.35	2.83
4	1.7	3.53
5	1.4	3.35

The results from Illias (2011) are of great importance for this paper, since the data of the experimental tests carried out on the samples are consolidated in literature and very important to characterize parameters of a partial discharge. From the data in Table 1 and using (1) is possible to assume that at same

ISSN: 2177-6164

DOI: 10.20906/sbse.v2i1.3057

initial temperature, the pressure inside the cavity does not change greatly with cavity diameter change and it can be calculated and used in order to find initial E_{inc} values for different cavity diameters.

3. STATOR BAR MODEL

For simulating the EF inside a cavity in a stator bar ground wall insulation of a rotating machine, the geometry model used is presented in Turgeon et al. (2011) and simulated in FEM software COMSOL in a 2D component system with Electrostatics physics. Fig. 2 shows the geometry, materials information, domains and the four different positions of the spherical cavity.

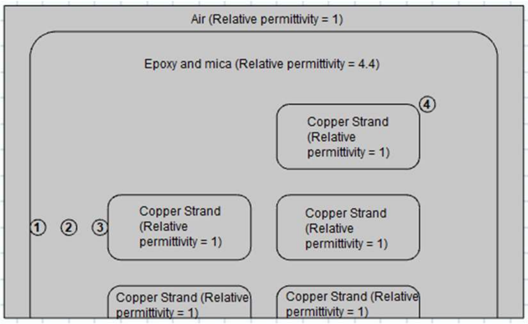

Fig. 2 Stator bar geometry, materials and cavities positions.

The boundary selection for Electric Potential and Ground are shown in Fig. 3 and Fig. 4, respectively. As in Turgeon et al. (2011), the voltage value used is 8 kV RMS which has a peak value of 11.28 kV.

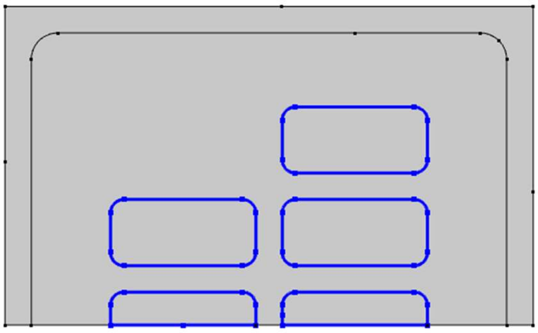

Fig.3 Electric Potential boundary selection of stator bar model.

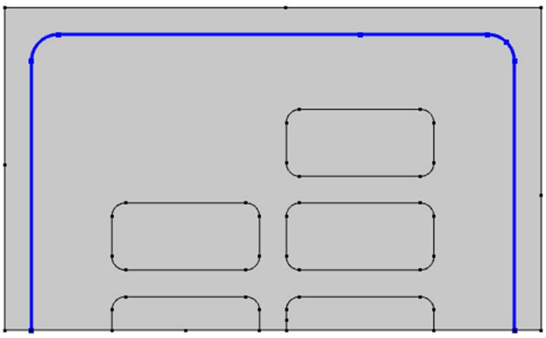

Fig.4 Ground boundary selection of stator bar model.

In order to obtain an accurate result, the mesh for simulation is defined as extremely fine with small elements. It is shown in Fig. 5.

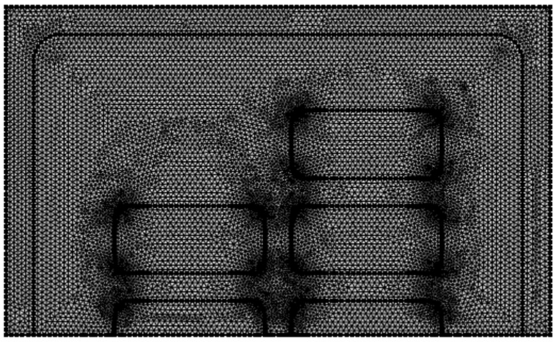

Fig. 5 Mesh selection of stator bar model.

First, a simulation without spherical cavity were performed and in Fig. 6 it can be seen that for a voltage peak value of 11.28 kV, the maximum EF is equal to 91.96 kV/cm.

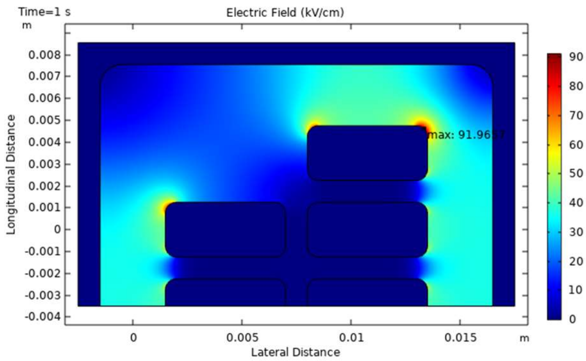

Fig. 6 Electric field distribution in stator bar model without cavity.

In order to discover the critical diameter, the cavities were placed separately in the four different positions shown in Fig. 2. It is assumed that the cavities are filled with air. From this, the EF inside the cavity is calculated using FEM software. Initially, a cavity with diameter 0.03 cm is placed in the position and using (1), the inception field is calculated. After, the diameter is gradually changed in order to calculate the inception field that matches the average value of EF within the cavity from the Finite Element Analysis. Once this diameter value is found, it represents the critical cavity size in the respective position.

4. RESULTS AND DISCUSSION

Table 2 shows the values of critical cavity diameter and respective average electric field within the spherical defect at an initial temperature of 20°C in all four positions previously defined. It is noticed that between positions 1, 2 and 3, the cavity closest to the conductor has the highest value of EF and consequently, the smaller value of critical diameter. This result was expected since in (1), decreasing cavity diameter generates an increase of inception field. The cavity in position 4 is located near the highest stator bar model value of EF as shown in Fig. 6. For this reason, it can be assumed that in this location, the probability of a PD to occur is greater.

Table 2. Critical cavity diameter and average electric field for different cavities location at 20°C

Cavity position	Critical cavity diameter (cm)	Average electric field (kV/cm)
1	0.0312	48.6
2	0.017	59.6
3	0.015	62.4
4	0.0021	138

Also using the results of temperature effects in the inception field presented in Illias (2011), it is possible to determine the values of critical cavity diameter and average EF at a temperature of 100°C that are summarized in Table 3. As in the results of Table 2, the cavity located in position 4 presents the higher probability for a PD to occur due to the high value of average EF. Therefore, has the smaller critical diameter.

Table 3. Critical cavity diameter and average electric field for different cavities location at 100°C

Cavity position	Critical cavity diameter (cm)	Average electric field (kV/cm)
1	0.114	47.7
2	0.0476	59
3	0.04	61.9
4	0.0046	130

Comparing the results for the two different temperatures, it is noticed that increasing the initial temperature from 20°C to 100°C caused an increase in the critical cavity diameter in all four positions. This happens because with a higher temperature inside the cavity, the pressure is also higher and consequently, the inception field is increased (Illias et al. 2010). Therefore, in order to match EF within the cavity with Inception field calculated using (1), critical diameter is increased. In position 1, the change is the highest one and has a ratio of 3.653. Fig 7 shows the difference.

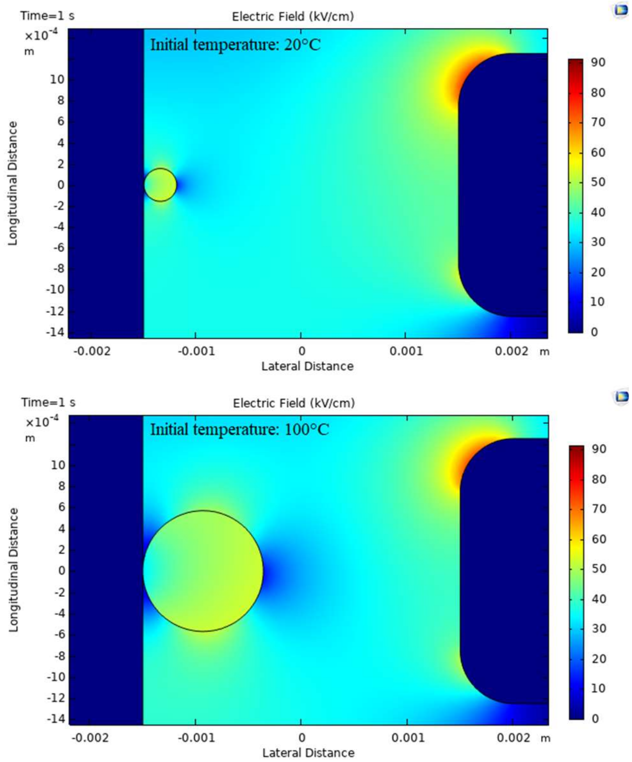

Fig. 7 Critical cavity at 20°C and 100°C in position 1.

Also, Fig. 8 and Fig. 9 display the change in critical size when the initial temperature is increased in positions 2 and 3, respectively. The smallest difference with a ratio of 2.19 was found in position 4, as shown in Fig. 10. At his location, the average EF within the cavity decreased from 138 kV/cm to 130 kV/cm which is the biggest change compared to the others positions.

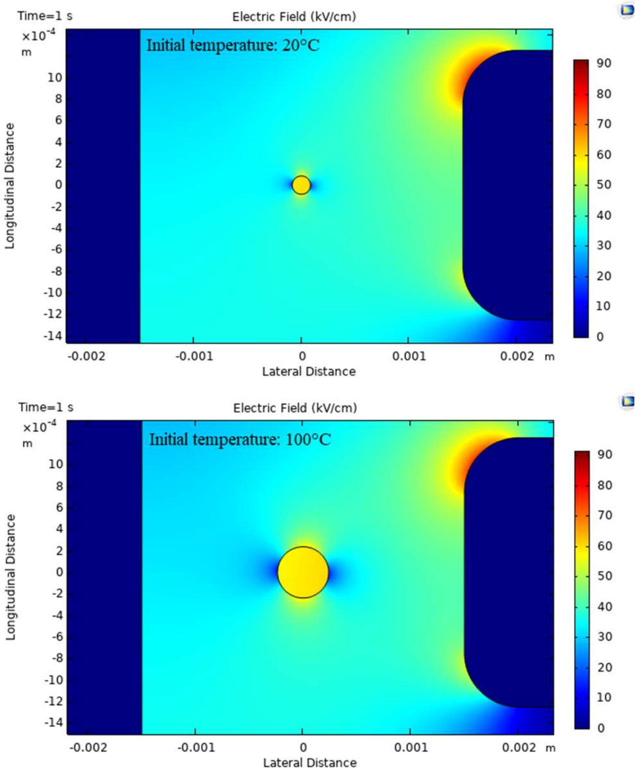

Fig. 8 Critical cavity at 20°C and 100°C in position 2.

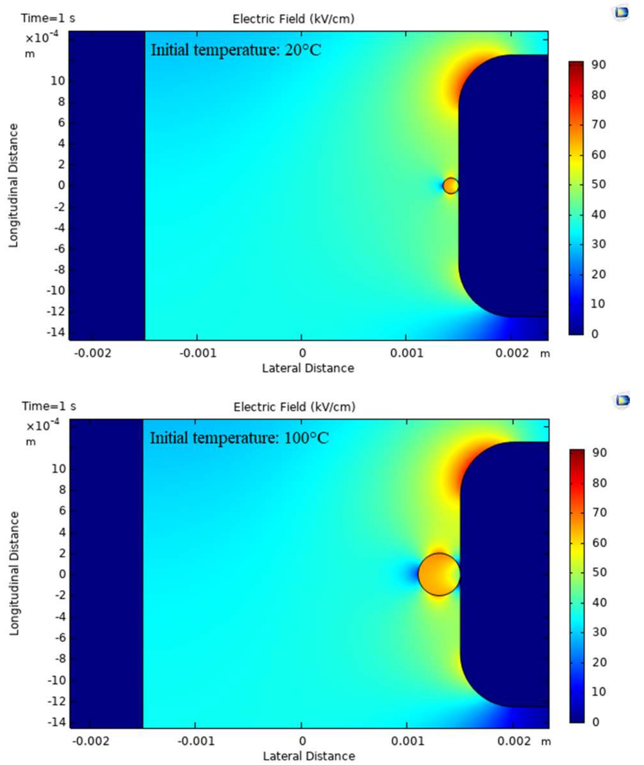

Fig. 9 Critical cavity at 20°C and 100°C in position 3.

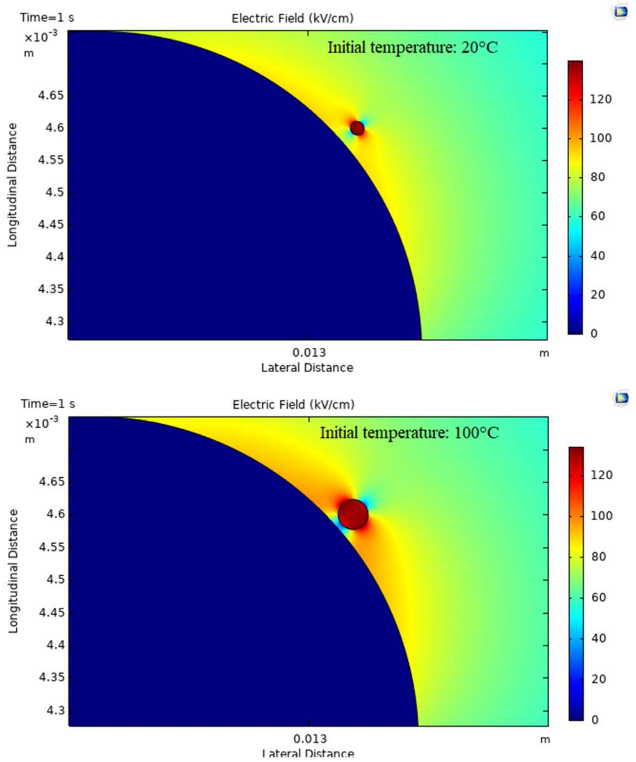

Fig. 10 Critical cavity at 20°C and 100°C in position 4.

5. CONCLUSION

This paper proposed an approach to define the critical size of a spherical cavity filled with air within a stator bar insulation system using theoretical definitions of partial discharge phenomena, experimental tests data and Finite Element Method simulations. The presented results show the smallest cavities sizes at which the probability of a partial discharge becomes existent. This is done by calculating the inception field which is the first condition for the phenomenon to happen. It was shown that the position of the cavity has an important influence on critical size since, depending on it, the average electric field within the void can undergo large variations. Also, the initial temperature plays a great role as it affect the pression inside the cavity and, consequently, the inception field. The validation on the results is based on the accuracy of the inception field equation, the experimental data evidences and on the refinement of the Finite Element Analysis and simulation.

REFERENCES

Haddad, A., Haddad, M., Warne, D. F., & Warne, D. (Eds.). (2004). Advances in high voltage engineering (Vol. 40). IET.

Illias, H. A., Chen, G., & Lewin, P. L. (2010). Modelling of temporal temperature and pressure change due to partial discharge events within a spherical cavity in a solid dielectric material using finite element analysis. *In 2010 International Conference on High Voltage Engineering and Application* (pp. 501-504). IEEE.

Illias, H. A. (2011). Measurement and simulation of partial discharges within a spherical cavity in a solid dielectric material. *Doctoral dissertation, University of Southampton*.

Illias, H. A., Chen, G., & Lewin, P. L. (2017). Comparison between three-capacitance, analytical-based and finite element analysis partial discharge models in condition monitoring. *IEEE Transactions on Dielectrics and Electrical Insulation*, *24*(1), 99-109.

Kreuger, F. H. (1989). Partial discharge detection in high-voltage equipment. Butterworth-Heinemann.

Leite, Reinaldo Corrêa (2021). Quantificação de descargas parciais em geradores usando modelo matemático baseado na teoria de campo. *Revista Principia - Divulgação Científica e Tecnológica do IFPB*, [S.l.], n. 56, p. 248-258, dez. 2021. ISSN 2447-9187.

Lemke, E. (2012). A critical review of partial-discharge models. *IEEE Electrical Insulation Magazine*, v. 28, n. 6, p. 11-16.

Montanari, G. C., Seri, P., & Dissado, L. A. (2019). Aging mechanisms of polymeric materials under DC electrical stress: A new approach and similarities to mechanical aging. *IEEE Transactions on Dielectrics and Electrical Insulation*, *26*(2), 634-641.

Niemeyer, L. (1995). A generalized approach to partial discharge modelling. *IEEE transactions on Dielectrics and Electrical insulation*, *2*(4), 510-528.

Pedersen, A., Crichton, G. C., & McAllister, I. W. (1991). The theory and measurement of partial discharge transients. *IEEE Transactions on Electrical Insulation*, *26*(3), 487-497.

Turgeon, A., Hudon, C., & Nguyen, D. N. (2011, June). Critical cavity size producing internal discharges in stator bar ground wall insulation. *In 2011 Electrical Insulation Conference (EIC)*. (pp. 318-322). IEEE.

Wang, W., & Shi, Z. (2021, November). A Finite Element Model of Partial Discharge in Solid Medium. *In Journal of Physics: Conference Series* (Vol. 2087, No. 1, p. 012066). IOP Publishing.