ABSTRACT Ultra-high voltage at transmission systems enables to reduce the electrical power losses due to the Joule effect. However, if the environment is not the proper (i.e., polluted, high humidity, high temperatures, etc.) this fact may lead to an air ionization causing a Corona discharge. As a result, electromagnetic parameters in the transmission line may be affected causing reduction in power transfer capacity on the line, or in critical situations, it may cause interruption of the electrical service. To face these challenges, this manuscript presents an innovative mechanism that can be attached to the transmission lines and suppress the impact due to the Corona discharge. Such mechanism contains dielectric oil that is released when the Corona discharge takes place, producing an isolated layer that protects the line from the high electrical fields. The manuscript includes the quantification of the impact of the Corona discharge on the electrical features of the transmission line through COMSOL Multiphysics 5.6 software. Then, the impact of the Corona discharge and the line are modelled as a two-port network in such a way that the operation of the line is analyzed in a circle power diagram. The results reveal that the incorporation of the innovative mechanism reduces or mitigates (in the best-case scenario) the impact of the Corona discharge, opening a pathway to future applications in the power systems protection field.

INDEX TERMS Corona discharge, dielectric oil, parameters of transmission lines.
ionization and partial discharge due to extreme electric field intensity [8]. More sophisticated methods include the use of on-line monitoring that enable to anticipate the appearance of potential discharges [9]. While the presented approaches look promising, their main drawback is the high inversion required for their development.

The occurrence probability of Corona discharge increases under severe weather conditions (i.e., pollution, high humidity, high temperature, etc.) [10]. For this reason, in some situations the presence of corona effect is inevitable and the impact on the power system operation can be plausible. In first instance, the Corona discharge affects the capacitance transmission line parameter, driving to voltage variations on system bus. Another consequence of the Corona effect lies in power transfer capacity on the line. With a view to keep the system voltage on the power systems buses, the automatic voltage regulator, and the power system stabilizer act in conjunction [11]. Nevertheless, for such action, it is required to adjust the injected power to supplied load, and in some cases, this maybe limited due to the thermal limits of the lines [12]. Therefore, there is a need to incorporate innovative strategies or mechanism to suppress the Corona discharge at low cost.

This paper proposes a novel mechanism that releases dielectric oil to reduce the impact of the Corona effect. Details regarding the mathematical expressions to model the Corona effect and impact quantification on transmission line parameters and transmission line transfer capacity are presented in Section 2. In Section 3, the architecture design and operation of the proposed mechanism is described. To show the effectiveness of the proposed mechanism, simulations with finite elements and power flow circle diagram are presented in Section 4. Finally, Section 5 brings the conclusion and future applications of the proposed approach.

II. CORONA EFFECT MATHEMATICAL MODEL

The Corona discharge is a phenomenon that depends on several factors, such as, bundle configuration of the conductors, weather conditions, potential gradient, among others, which are discussed in this section.

A. ELECTRON AVALANCHE AND BREAKDOWN

During the ionization process, some electrons are in free state and may interact with the electric field density. Consequently, the electrons are accelerated, and an electron shedding to other atoms could take place, leading to a chain effect (see Figure 2) [13]. This occurs as long as the kinetic energy of electrons does not exceed the dielectric breakdown energy limit.

During the electron avalanche there are three key drivers that lead to the Corona effect: 1. electric field distribution; 2. applied voltage waveform; 3. polarity. In this context, there is a potential gradient denoted as disruptive critical voltage $V_C$, which refers to the potential difference that the electrons must overcome to migrate from the conductor surface to air. Even though literature presents several studies [14]–[18] to quantify the disruptive critical voltage, most of them are based on the quasi-experimental model proposed by Peek [19]. This model is considered as a milestone due to the factors that are considered on it. The first factor that Peek incorporates in the model is the critical field intensity, which has been experimentally determined as $84 \text{ kV/cm}$. The second parameter is the relative density of the air $\varphi$, which emerge as a function of the relative pressure $h$ given in cm-Hg, and the temperature $\Theta$ given in °C, then the relative density is computed using (1).

$$\rho = \rho_0 \exp \left( \frac{-g}{\Theta h} \right)$$

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$$U_C = \frac{E_C m_r m_s}{m_t}$$
\[
\varphi = \frac{3.9211 h}{273 + \Theta} \tag{1}
\]
\[
\log h = \log 76 - \frac{y}{18336} \tag{2}
\]
\[
U_C = 84m_c m_t \varphi \log \left(\frac{GMD}{r}\right) \tag{3}
\]

B. CORONA CAPACITANCE AND CONDUCTANCE

In order to represent Corona’s behavior on the transmission line capacitance, it is common to develop a charge-voltage curve (q-V curve). Authors in [22] determined that for a voltage between zero and \(U_c\), \(q\) linearly increased. Then, for voltages that exceed \(U_c\) the behavior of \(q\) exponentially increases. This fact is attributed to the space charges generated by the corona discharge. Once the discharge is mitigated, \(V\) decreases and then a hysteresis phenomenon is observed, as shown in Figure 3. This fact reveals that the rate between \(q\) and \(V\) of the line can not be considered as constant during Corona discharge. Therefore, the capacitance of the line can be described as [23]:

\[
C = \begin{cases} 
C_0 = V \frac{\partial \Gamma}{\partial \varphi}, & \text{if } V < U_c \\
C_r = V \frac{\partial \Gamma}{\partial t}, & \text{if } V \geq U_c 
\end{cases} \tag{4}
\]

where \(C_0\) is the geometrical capacitance per unit length of the transmission line, \(C_r\) is the space charge generation capacitance per unit length due to Corona discharge, and \(\Gamma\) represents the arithmetic relation between \(q\) and \(V\).

On the other hand, heat is released when the Corona effect takes place. Based on the given fact, literature [24] establishes that if the line rated voltage \(U_r\) times a security factor (that by standards is set on 1.15) is greater than \(U_c\), then the one-phase power losses expressed in watts per unit length due to Corona can be quantified using (5). Then, the conductance of the line due to Corona can be calculated using (6) [24].

\[
P_c = \frac{241}{\delta} \left( f + 25 \right) \sqrt[3]{\frac{1}{GMD}} \left( \frac{1.15 U_r}{\sqrt{3}} - \frac{U_c}{\sqrt{3}} \right)^2 \times 10^{-8} \tag{5}
\]

\[
G = \frac{P_c}{U_r^2} \tag{6}
\]

The expressions (4) and (6) enable to quantify the impact of Corona discharge on transmission line modelling as presented in next section.

C. CORONA AND TRANSMISSION LINE MODELING

A transmission line of longitude \(\ell\) can be represented by its resistance \(R\), inductance \(L\), and capacitance \(C\) per unit length. If a Corona discharge takes place at some section \(\Delta x\) on the line, then by using two-port network theory, the system can be represented as shown in Figure 4.

The two-port network representation is useful to relate in a simple manner the system as a function of the sending voltage \(V_{in}\) and current \(I_{in}\), and the receiving voltage \(V_{out}\) and current \(I_{out}\). Mathematically such relationship is as given in (7), then \(A, B, C, D\) parameters are obtained using (8) [25].

\[
\begin{align*}
V_{in} &= A V_{out} + B I_{out} \\
I_{in} &= C V_{out} + D I_{out}
\end{align*} \tag{7}
\]

\[
\begin{align*}
A &= \left. \frac{V_{in}}{V_{out}} \right|_{I_{out}=0}; & B &= \left. -\frac{I_{in}}{V_{out}} \right|_{I_{out}=0} \\
C &= \left. \frac{I_{in}}{V_{out}} \right|_{I_{out}=0}; & D &= \left. -\frac{I_{in}}{V_{out}} \right|_{I_{out}=0}
\end{align*} \tag{8}
\]
By applying the definitions established in (7) on the Corona discharge modelling, the result is (9). Following the analysis, literature reports that for a long transmission line a matrix as given in (10) [25],

\[
\begin{bmatrix}
A_T & B_T \\
C_T & D_T
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
y & 0
\end{bmatrix}
\]

(9)

\[
\begin{bmatrix}
A_{\Psi(i)} & B_{\Psi(i)} \\
C_{\Psi(i)} & D_{\Psi(i)}
\end{bmatrix} = \begin{bmatrix}
cosh \gamma \ell_1 & Z_c \sinh \gamma \ell_1 \\
1/Z_c \sinh \gamma \ell_1 & \cosh \gamma \ell_1
\end{bmatrix}
\]

(10)

where \( y = \sqrt{y^2} \); \( Z_c = \sqrt{z/y} \)

Once every component is expressed as a two-port network, it is possible to applied properties that leads to a reduced representation of the system. The configuration is denoted as a cascade connection, therefore, according to the two-port network theory [26], the equivalent system is obtained by performing the matrix multiplication of every individual matrix, resulting in expression (11).

\[
A_Y = (\cosh \gamma \ell_1 + Z_c y \sinh \gamma \ell_2) \cosh \gamma \ell_2 \\
B_Y = (\cosh \gamma \ell_1 + Z_c y \sinh \gamma \ell_2) Z_c \sinh \gamma \ell_2 \\
C_Y = (1/Z_c \sinh \gamma \ell_1 + y \cosh \gamma \ell_2) \cosh \gamma \ell_2 \\
D_Y = (1/Z_c \sinh \gamma \ell_1 + y \cosh \gamma \ell_2) Z_c \sinh \gamma \ell_2
\]

(11)

As presented, the \( A, B, C, D \) parameters are affected due to Corona discharge. This fact will have repercussions on the transmission line transfer capacity, which is discussed in next section.

D. CORONA AND TRANSMISSION LINE CAPACITY

For the following analysis, let’s assume a simplified two bus power system as given in Figure 5. With a view to get an expression that relates the voltage angle \( \delta \), voltage magnitudes \((|V_{in}|, |W_{out}|)\), transmission line parameters with Corona discharge \((A_Y, B_Y, C_Y, D_Y)\), demand active power \( P \) and demand reactive power \( Q \), the expression presented in (7) employed. Then, solving for \( I_{in} \) and expressing the quantities in polar form, the result is the following:

\[
I_{in} = \left( \frac{|V_{in}|}{|B_Y|} e^{j\delta - \beta} - \frac{|A_Y||V_{out}|}{|B_Y|} e^{j\alpha - \beta} \right)
\]

(12)

On the other hand, it is well known that the apparent power \( S \) demanded by the load is proportional to the product of the voltage and conjugate current, both at the receiving end. Under the given definition and employing (12), the expression (13) is derived.

\[
|S_{load}|e^{j\theta} = \left( \frac{|V_{in}| |V_{out}|}{|B_Y|} e^{j\delta - \beta} - \frac{|A_Y||V_{out}|^2}{|B_Y|^2} e^{j\beta - \alpha} \right)
\]

(13)

The mathematical expression in (13) enables to determine the transmission line transfer capacity from the sending to the receiving end. In addition, it can be appreciated that in order to keep constant the voltage at the receiving end (which is the purpose of the automatic voltage control at generation station), the parameter \( A \) and \( B \) are the drivers that defines the power limits. It is expected that under Corona discharge condition the transmission line ampacity reduces. This fact is demonstrated in Section IV part b.

III. NOVEL MECHANISM WITH DIELECTRIC OIL

High temperatures combined with other climate parameters result in a Corona discharge. Such high temperatures are commonly manifested in zones where junction points exist (i.e., insulator ended clamp). Under this context, a mechanism is designed to be attached on critical points of the conductor. Figure 6 shows the mechanism coupled to ACAR 1300 MCM conductor with a chain of insulators.

The mechanism has a housing armor grid, strap, bolt, lock washer and lock nut, which are made of galvanized steel to ensure their strength and durability, capable of withstanding the mechanical stresses exerted by the wind and conductor’s weight, as well as the different climatic conditions that may arise. The housing armor grid is used to hold both, the dielectric oil and the polymer in place through a cylindrical coating. In addition, it enables coupling the insulators’ chain with the two terminals protruding from the center. The strap, bolt, lock washer and lock nut, are intended to engage the housing armor grid with the insulators’ chain so that it is tight enough to prevent movement that will wear out the material surfaces and affect the performance of the mechanism. Regarding the dimension of the mechanism, Figure 7. shows different views with the corresponding dimensions. It is relevant to mention that all the parts that formed the mechanism follow the IEC 61284:1997 standard [27].

The operation of the mechanism is based on a thermosetting polymer that contains the dielectric oil combined. When the conductor reaches a temperature higher than the degradation temperature of the polymer, this is degraded and releases the dielectric oil, forming a layer that covers the conductor at the critical point. To select the thermosetting polymer, the dynamic thermal limit of the conductor under rated conditions (\( \approx 333 \) K) [28] and high temperature (\( \approx 1723 \) K) during Corona effect are considered [29], resulting in a 0.1 mm thick coating of melanin resin with a degradation temperature of 160 °C with a 1.5 mm thick dielectric coating is selected. In addition, the resin contains a fluorescent blue chemical that allows easy detection in the zone where the Corona occurs.

IV. CORONA EFFECT IMPACT SUPPRESSION

To quantify the influence of the proposed mechanism a case study is presented. The conductor to be used is ACAR 1300 MCM made of Aluminum 1350 H19 with a core of Aluminum 6201 T81. For more details regarding the features

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of the conductor, Table I is presented. Concerning the system voltage rate and frequency are 800 kV and 60 Hz, respectively.

![Figure 6. One phase proposed mechanism to storage and release dielectric oil](image)

**Figure 6.** One phase proposed mechanism to storage and release dielectric oil

![Figure 7. Novel mechanism dimensions given in mm: (a) Front view; (b) Side view](image)

**Figure 7.** Novel mechanism dimensions given in mm: (a) Front view; (b) Side view

**Table I**

| Feature          | Symbol | Value       |
|------------------|--------|-------------|
| Longitude        | ℓ      | 270 km      |
| Area             | A      | 659 mm²     |
| Diameter         | φ      | 33.33 Mm    |
| Strands          | Nₛ    | 18/19       |
| Max. resistance AC 60 Hz 75°C | R | 0.057 Ω/km |
| Inductance       | L      | 0.9693 mH/km|
| Capacitance      | C      | 13.5751 nF/km|
| Ampacity         | I      | 1150 A      |

**A. ELECTROMAGNETIC LINE PARAMETERS**

To quantify the electromagnetic parameters $A, B, C, D$ of the transmission line, a finite element assessment using COMSOL Multiphysics 5.6 is conducted. COMSOL Multiphysics is a computational modeling tool that incorporates Partial Differential Equations (PDEs), and a mathematical description of various physical phenomena based on the laws of science [30]. For the purpose of this paper, the transmission line is modeled with an exact 3D geometry that includes all the physical parameters (i.e., conductivity, permeability, density, etc.), which is given as an input in COMSOL. Several electromagnetic and thermodynamic parameters, including electrical field gradient, magnetic flux density and temperature distribution are studied under normal operation (see Figure 8). The resistance, inductance, and capacitance are computed based on such parameters. To validate the model, the results obtained from COMSOL are compared with the datasheet given by the manufacturer, rising in a relative error of less than 1%, as presented in Table II.

![Figure 8. COMSOL Multiphysics: (a) electrical field gradient; (b) magnetic flux density; (c) temperature distribution](image)
TABLE II
PROPOSED MODEL VS REAL MODEL AT 50C

| Parameter        | Datasheet | COMSOL  | Relative error % |
|------------------|-----------|---------|------------------|
| Resistance [Ω/km] | 0.0570    | 0.0571  | 0.1754           |
| Inductive reactance [Ω/km] | 0.3654    | 0.3659  | 0.1368           |
| Capacitive reactance [MΩ·km] | 0.1954    | 0.1970  | 0.8188           |

TABLE III
ABCD OF THE PARAMETERS UNDER DIFFERENT CONDITIONS

| Parameter | Normal Operation Ψ | Corona Discharge Ψ | Corona discharge suppressed Δ |
|-----------|--------------------|-------------------|-----------------------------|
| A         | 0.9326             | 0.9514            | 0.9333                      |
| B         | 97.6026            | 98.1886           | 97.6251                     |
| C         | 481.34°            | 482.44°           | 481.34°                     |
| D         | 0.0014             | 0.0017            | 0.0013                      |
|           | 0.9326             | 0.9514            | 0.9333                      |
|           | 481.34°            | 482.44°           | 481.34°                     |

TABLE IV
POWER SYSTEM INPUT DATA

| Feature                                    | Symbol Value |
|--------------------------------------------|--------------|
| Voltage magnitude at the sending end       | $V_{in}$ 800/\sqrt{3}$ kV |
| Voltage angle at the sending end           | $\delta$ unknown |
| Voltage magnitude at the receiving end     | $V_{out}$ 792/\sqrt{3}$ kV |
| Voltage angle at the receiving end         | $\delta$ 0° |

The analysis continues with the investigation of two scenarios: 1. Corona discharge; 2. Corona discharge suppressed by the released dielectric oil. This modeled in COMSOL by setting the weather conditions of the environment that are favorable to Corona discharge, and so the electrical equations described in the Section II. For each scenario, the resistance, inductance, capacitance, and conductance are obtained. Then, the transmission line is modeled as a two-network port with the parameters given in TABLE III.

B. TRANSMISSION LINE TRANSFER CAPACITY

For the following analysis, the power system presented in Figure 5 with the system features presented in TABLE IV are utilized, under the condition that the magnitudes at the sending and receiving end are desired to be constant. Then, the expression given in (13) can be employed to analyze the power limits transfer capacity of the transmission line. For simplicity, the following variables are defined:

$$S_1 = \frac{|V_{in}|V_{out}|}{|B|} e^{\beta - \delta}$$

$$S_2 = \frac{|A||V_{out}|^2}{|B|} e^{\beta - \alpha}$$

Therefore, (13) can be simply written as

$$S_{load} = S_1 - S_2$$

Notice that (16) can be represented graphically as a power phasor sum. For this purpose, let’s start by defining the x-axis and y-axis as the active and reactive power, respectively. Since the voltage magnitudes $|V_{in}|$ and $|V_{out}|$ and the parameters $A$ and $B$ are given as input data, negative $S_2$ is first to draw. Intuitively, next to draw is the power $S_1$, nevertheless this is not easy to graph since the voltage angle at the sending end is unknown and requires to be adjusted depending on the operating condition. An important issue to consider is the fact that the magnitudes voltages at the sending and receiving end constants requires to keep constant, and for this goal, it is mandatory to keep $S_1$ magnitude also as constant as presented in (14). This fact leads to the creation of a circle diagram with center on the end of phasor $S_2$ and with a radius of $S_1$ magnitude. This circle exemplifies all the operating conditions of the transmission line [25].
With a view to get the maximum active power that can be transmitted through the line, let’s assume that a load purely resistive is installed at the receiving end. Therefore, in the graph, the operating point is defined by the interception of the circle with the x-axis. Then, the power $S_2$ and $S_{load}$ can be plotted, and maximum active power is determined. The described process is followed for the conditions of Corona discharge and Corona discharge suppressed, resulting in the development of two circle diagrams as presented in Figure 9. The results reveal that the Corona discharge limited the active power transfer capability of the line by an approximate amount of 34% compared to the scenario in which the released oil suppresses the Corona discharge. This is attributed to the impact of the Corona discharge on the transmission line that affects the $A, B, C, D$ parameters. The influence of the Corona discharge is extended to the reactive power since the reactive power transfer capability of the line is reduced by an approximate amount of 33% in comparison with the scenario in which the Corona discharge is suppressed by the released oil.

VII. CONCLUSION
The inclusion of the Corona discharge in the transmission line modeling is essential to predict maximum voltages and reduce insulation levels. Attending to this need, this manuscript presents an innovative mathematical framework to quantify the impact of the Corona discharge on the transmission line at ultra-high voltage, which is based on the two-port network theory. The approach incorporates the fact that Corona discharge affects the capacitance of the transmission line. Moreover, due to the heat released during Corona discharge, a conductance may be added to the line modeling.

Until an efficient wireless transmission electrical system is developed, it is necessary to implement new ways to deal with the Corona discharge. This manuscript proposes a novel mechanism to suppress Corona discharge impact. The operation principle of the mechanism is simple, it contains dielectric oil in a resin that is broken at temperatures that may precipitate the Corona effect. As a result, the dielectric oil is released and it isolates, cleans, and cools down the conductor, leading to an unfavorable environment for Corona discharge.

The effectiveness of the mechanism is validated through two studies. Firstly, the topology of the mechanism and the mathematical equations that describe the electromagnetic and thermodynamic physic of the transmission line (including Corona discharge) are incorporated into the COMSOL Multiphysics 5.6 software. Under normal conditions, the results obtained in COMSOL are compared with the datasheet given by the manufacturer, presenting a relative error of less than 1%, concluding with the validation of the model. Then, an analysis with Corona discharge and Corona discharge suppressed are conducted, resulting in the $A, B, C, D$ parameters for every scenario. In the second study, a power circle diagram is performed. The result concludes that the released oil enables more transfer power capability up to 34%.

It is relevant to highlight that the presented mechanism does not mitigate the occurrence probability of the Corona discharge, however, the mechanism enables to reduce its impact. Although the mechanism is applied to transmission lines, the approach can be extended to other power system components subject to Corona discharges. This fact opens to a range of opportunities for future research development.

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