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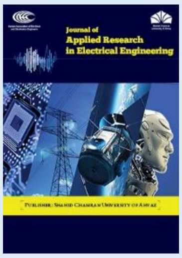

Research Article

Investigating the Flashover Probability of Transmission Network Insulators During Dust Storms

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Abstract: In recent decades, the probability of natural disasters has increased due to climate change. As a result, the discussion of resilience in the power system literature was raised. One consequence of these events is the unwanted operation of some power system equipment, which causes unexpected blackouts and increases the value of energy not supplied (ENS) in the system. Insulators are important components of the power system that have a great impact on the continuity of supply. Electrical flashover in insulators causes a decrease in their insulation strength and might lead to short-circuit faults in the power system. In this paper, the effect of dust storms and humidity on the probability of transmission network insulators flashover is investigated. The studied insulator is simulated in Electrical AutoCAD software, and after applying pollution and moisture in COMSOL-Multiphysics software, the distribution of potential and electric field on the studied insulator is obtained using the finite element method (FEM). In order to determine the probability of insulation flashover, the candidate points for arc occurrence are selected using the roulette wheel method in MATLAB software, and the insulation flashover probability curve is determined in different amounts of dust pollution and three humidity levels of 65%, 80%, and 95%. The effects of increasing the creepage distance and using silicone rubber materials that have hydrophobic properties are investigated, and various sensitivity analyses are conducted. The results indicate that both solutions can significantly reduce the flashover probability of transmission insulators.

Keywords: Humidity, dust storm, transmission network, insulator, fragility curve**.**

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NOMENCLATURE

Symbol	Description
C	capacitance of each insulator
C_E	capacitance of the insulator relative to the ground
C_L	capacitance of the insulator relative to the line
H	the length of the insulator
x	the distance from the ground electrode
S_a	the hardness of the solution in g/cm3
σ_{20}	the electrical conductivity of the solution in µs⁄cm at 20℃
V	the volume of the pollution solution in cm^3
A	the surface area of the insulator in cm^2
d	the distance between the two nodes of interest
Δv	the voltage difference between the given nodes
Ec	the electric strength of the air gap (3 kV/mm)

N	the number of iterations
$N_{No-Flashover}$	the counter of no arc conditions
$N_{Flashover}$	the flashover counter
$P_{Flashover}$	the flashover probability

1. INTRODUCTION

1.1. The Effect of Dust Storm on The Resilience of Power System

The main purpose of operating the power system is to provide stable electricity [1]. The stability of power systems is a critical requirement for modern societies. Natural events such as storms, floods and earthquakes, as well as cyber-attacks that are man-made, have destructive effects on the operation and control of the power system. Accurate modelling of these events is very difficult due to their random nature. Each of these events affects a part of the power system. In most researches, forecasts and historical data available in meteorological organizations have been used for modelling purpose [2]. Power system blackout is one of the challenges of the electricity industry and consumers. The loss of electrical power can be linked to three sources: power outages caused by natural disasters, technical problems, and human-made power outages. According to the reports provided by the US Department of Energy, among these blackout sources, the role of natural disasters is more severe. Due to climate change in recent decades, the number and severity of climate change related incidents have increased worldwide. It can be concluded that most outages originate from low-probability events that have a large impact on power systems and are known as high-impact, low-probability (HILP) events [3].

Dust storm is defined as solid particles resulting from surface soils that are suspended in the air and remain in the air for a long time due to their small dimensions and are easily moved by air flow [4]. The phenomenon of dust storm is one of the most important challenges in North Africa and the Middle East. According to the environmental standards, the permissible concentration of dust storm in the air is 150 $\mu gr/cm^3$ during 24 hours. The diameter of dust storm with different origins is between 10 and 50 microns. If their diameter is less than 10 microns, they are harmful to human and animal health. Dust storm particles with a diameter of less than 2.5 microns have an unnatural origin and are usually caused by human factors [5].

1.2. Literature Review

In [6], the phenomenon of dust storm is investigated. Spatial analysis of this phenomenon shows that the main areas of dust activities are deserts, including sand dunes that have been destroyed by humans. Geographical location and climatic conditions are also other factors affecting the possibility of this phenomenon. In reference [7], the author investigated the effects caused by the phenomenon of dust storm on the insulation surfaces of the equipment and artificial contamination on the insulation surface was simulated using the IEC60507 standard. By applying low voltage to the insulator and measuring the amount of leakage current, the conductivity coefficient is calculated and the amount of pollution is determined from it. Reference [8] argues that the increase in pollution affects the performance of insulators, and therefore, it is necessary for network operators to continuously wash insulators. The results showed that the leakage current does not increase significantly with the increase of pollution at noon. In [9], the test of uniform and non-uniform pollution in new and old polymer insulators have been evaluated. The results show that polymer insulators have higher endurance in uniform pollution than in non-uniform pollution. Moreover, aging in polymer insulators has reduced the arc voltage in them. In reference [10], the technical and economic issues related to washing insulators and applying RTV coating to combat dust were evaluated. It is shown that the number of washing cycles, the washing method, the level of contamination and the type of contamination in the area affect the cost of washing insulators. Moreover, it is argued that factors such as the quality of the selected coating, the volume of materials required and the quality of the applied coating affect the cost of using RTV coating. In paper [11], an analysis was conducted on the contaminating microparticles. The presence of moisture creates an electric current path on the insulator surface. The presence of contamination on the insulator is necessary to form a conductive path, but it is not sufficient. In other words, contamination and moisture alone cannot cause the insulator to fail. The results show that as the leakage current increases, the temperature of the insulator surface increases as a result of the passage of this current. In article [12], it was stated that the presence of sufficient moisture on the contaminated insulator creates a conductive layer on the insulator surface by converting dry salt into electrolyte, and causes leakage current which is one of the factors of insulator failure. Using nanoparticles to create a coating on glass and ceramic insulators can prevent dirt and pollution from adhering, prevent deep absorption of contaminants on the surface, make insulators easy to clean and resistant to acid rain, increase resistance to surface scratches, improve insulating properties and help insulators remain clean for a long time. In paper [13], electric arc voltage tests conducted on 20 kV polymer insulators under uniform and non-uniform contamination, and different humidity levels were examined. The results showed that in presence of non-uniform contamination along with humidity, the insulators break down occurs earlier than in the case of uniform contamination. Moreover, increasing the degree of non-uniformity of contamination causes an increase in the surface conductivity in the insulators and as a result, the occurrence of a complete arc is accelerated. In article [14], it was stated that the contamination layer will not have much effect on the insulation resistance of the insulation as long as it is dry, and if it gets wet, it causes the dissolution of particles, and the formation of a conductive layer on the surface of the insulator. The results show that by having an insulator leakage current monitoring system, it is possible to compare the performance of high-voltage insulators with different profiles and materials in real environmental conditions, and with timely notification, washing and repair and maintenance operations will be carried out in a timely manner. In [15], a reduced experimental model is used to simulate a practical insulator washing equipment. The leakage current is measured using a current transformer. The results show that the leakage current increases first and then decrease during the washing process. In reference [16], the porcelain (PI) and silicone rubber insulators (SRI) used in the distribution network are modelled using COMSOL-Multiphysics software. The results indicate that at a certain level of humidity, for the same level of pollution on the insulators, the intensity of electrical flashover on silicon rubber insulators is lower than porcelain insulators. The influence of climatic and environmental conditions on high voltage insulators have been discussed in [17]. The results show that even by observing the appropriate creepage distance in these environmental conditions, the insulation strength against power frequency voltages is compromised, and electrical flashover has occurred in the insulators. In [18], the behavior of aging and electrical failure of silicone rubber insulators under pollution and dry tape conditions are investigated, and the breakdown voltage and electric field distribution at different levels of pollution intensity have been measured. The practical results and simulation show that with the reduction of the intensity of pollution, the strength of failure and the probability of electrical failure decreases. In [19], the fragility curve of transmission line conductors against storms has been estimated. Uncertainties related to the behavior of transmission line conductors due to the conductor capacity and the random nature of wind fluctuations are considered. In reference [20], the authors state that the majority of distribution network failures during storms are related to tree branches hitting network conductors, trees falling on distribution network feeders, bird bodies hitting distribution feeders, and breaking bridges due to strong winds. In order to estimate the probability of equipment failure, the concept of fragility curve is used. In [21, 22], the importance of hardening distribution feeder lines and installing distributed generations (DGs) has been discussed. Harding of the distribution network is one of the most effective methods to improve the resilience of distribution networks against natural events [22]. The use of DGs has increased due to their effect in improving the voltage profile, reducing power losses, reducing greenhouse gas emissions, increasing power quality, and increasing the reliability and resilience of the distribution system [21, 22]. By comparing the results, it is possible to show the effect of increasing the resilience of the distribution system and reducing the risk of the system by hardening the line conductors and optimal installation of distributed generation resources [22]. Paper [23] proposes a resilience assessment framework focused on planning to increase the level of resilience of the transmission system. The probabilistic model of the storm is presented with respect to the wind field and using the uncertainty in the intensity and track of the storm by the probability distribution. In Ref [24], the importance of evaluating system components to improve resilience in strengthening the network structure and designing a recovery strategy is discussed. Firstly, the component failure rate model under wind storm conditions is presented. Based on this model, the state of the system in the conditions of wind storms is sampled using the non-sequential Monte Carlo (MC) simulation method. After sufficient sampling of the system state, the repair time of the components is obtained. Copeland's ranking method is used to rank the importance of the components. In article [25] the necessity of using energy storage systems with the aim of increasing the reliability of the network and its use during off-peak as well as on-peak times is stated. In this model, the failure of components such as generators, pumps, turbines, control and protection systems is considered. The results show that the use of energy storage systems increases the reliability of the power system. In paper [26], the importance of using clean energy has been emphasized due to its advantages such as low cost and ease of installation. Moreover, the problem of Generation Expansion Planning (GEP) in presence of demand response has been examined. Using the Weibull distribution function, the uncertainty of wind power plants and rewards and penalties have been modeled. Using the genetic algorithm in the proposed model, the optimal number of turbines has been determined and the results show that the expected unsupplied energy index has decreased. The paper [27] proposes a quantitative resilience assessment framework for power transmission systems operating under typhoon conditions that considers both the spatial and temporal impacts of the typhoon. Finite element component modelling is developed to model component failure probability. The simulation results have highlighted the capability of the proposed method in assessing and quantifying the resilience of power transmission systems against hurricanes.

1.3. Methodology and Contributions

Since most of the power system customers are fed from the distribution network, it is essential to have a high level of reliability and resilience at the distribution network level. Considering that the transmission network is located upstream of the distribution network and the transmission of energy from power plants to consumers is the responsibility of the transmission network, the need to have an acceptable level of stability and resilience is crucial to meet the needs of customers on the distribution network side. Therefore, it is necessary to evaluate the reliability and resilience of transmission network against various types of unforeseen natural events to help system operators determine preventive and corrective measures. Review of the above-mentioned researches reveals that the importance and impact of the dust storms, especially in the transmission network, have been rarely discussed. Meanwhile, a number of Middle Eastern countries such as Iran, Iraq, Saudi Arabia, etc. are currently dealing with this phenomenon. Moreover, the historical investigation of the occurrence of dust storm in Khuzestan province in Iran in 2017 shows that the impact of this phenomenon on the distribution and transmission network was high and it resulted in a lot of damages, blackouts and ENS [7]. In most of the studies conducted, the impact of wind storm was examined, while due to the climatic conditions of the Middle East, the occurrence of dust storms has increased significantly in recent years. According to the explanations given, the main problems in previous articles are:

• Less attention is paid to modeling the impact of dust storm phenomenon on power system.

• Failure probability of transmission system equipment during dust storm is not evaluated.

Therefore, in this paper we will evaluate the probability of transmission network insulators failure during dust storms and in various levels of humidity. In Table 1, the features of the reviewed articles are discussed and the features of the presented model are also shown.

On this basis, the main goal of this paper is to find the flashover probability of transmission network insulators in different levels of humidity and fine dust pollution. It is necessary to firstly examine the equations and relationships between the electric field and the electric potential distribution on the surfaces of the insulators.

Table 1: Comparison between the reviewed articles and the proposed model.

Feature	Network		Resilience				Reliability
	T	D	I	II	III	IV	
[8]	✓	×	×	×	×	×	✓
[15]	✓	×	×	×	×	×	×
[16]	×	✓	×	×	×	✓	×
[19]	✓	×	×	✓	×	×	×
[20]	×	✓	×	✓	×	×	×
[21]	×	✓	×	✓	✓	×	×
[22]	×	✓	×	✓	×	×	×
[23]	✓	×	×	✓	×	×	×
[25]	✓	×	✓	×	×	×	×
[27]	✓	×	✓	×	×	×	×
Proposed Model	✓	×	×	×	×	✓	×

T: Transmission Network, D: Distribution Network, I: Wind, II: Storm, III: Flood, IV: Dust storm & Humidity.

On this basis, the main goal of this paper is to find the flashover probability of transmission network insulators in different levels of humidity and fine dust pollution. It is necessary to firstly examine the equations and relationships between the electric field and the electric potential distribution on the surfaces of the insulators. Then, a sample transmission insulator is created in simulation software, and by applying different amounts of moisture and fine dust on its surface, the possibility of electrical breakdown is examined. Finally, the effect of different levels of fine dust and humidity on transmission insulators is investigated.

Based on this, the contributions of this paper can be listed as follows:

• Simulating a sample 230 kV insulator in AutoCAD software, and applying moisture and fine dust to the designed insulator in COMSOL software.

• Investigating the flashover probability of the studied insulator in MATLAB software.

• Investigating the effects of fine dust and humidity on the flashover probability of different models of transmission network insulators.

The remainder of this paper is organized as follows: In Section 2, the role of the insulator in power system and its types, as well as how the electric field and potential are distributed on its surface are discussed. In Section 3, the process of calculating the probability of electrical failure in the modelled insulator is examined. Numerical results are provided in Section 4 and conclusions are presented in Section 5.

2. Insulator Modelling

2.1. Insulator Types

An insulator is a device that has a high electrical strength and is installed between the live conductor and supporting structures such as transmission towers and distribution poles. In addition to insulating the conductor from the pole, insulators also form a mechanical connection between the conductor and the supporting structure [28]. The main functions of insulators include:

• Insulators must isolate the conductor from the pole while being able to withstand the highest voltage under normal conditions without any leakage current. They should also have the necessary electrical strength when overvoltage occurs.

• The insulator must have the ability to withstand the mechanical forces caused by the weight of the conductor and the applied force caused by wind and ice on the conductor, without reducing the permissible distance of the conductor from the body and the base arm.

• The insulator must be resistant to severe weather changes and temperature changes and not lose its electrical and mechanical properties over time [28].

Classification of types of insulators is done based on the type of insulating material used in them and they are classified into three main categories of ceramic, glass and polymer insulators [28]. In the following, we briefly review the characteristics of different insulators.

2.1.1. *Ceramic insulator*

These types of insulators have high electrical strength against discharge caused by electric arc and corona phenomena, because the ceramic used in them has a high melting temperature of about 1500℃. Due to being brittle, special care should be paid when carrying these types of insulators. A special type of ceramic insulators is used in areas with high pollution, where a type of semiconductive glaze is used instead of the usual insulating glaze [7, 28]

2.1.2. *Glass insulators*

Raw materials such as silica, feldspar, dolomite, etc. are used to make this type of insulator. These materials are melted, homogenized and moulded in special furnaces. Then they are cooled by air jets for hardening. The mechanical endurance of this type of insulator is 1.5 times that of porcelain insulators. Moreover, the electrical strength of this type of insulator is higher than that of porcelain insulators. Moisture is easily distilled from the surface of these types of insulators; But these insulators attract more dust. The most widely used types of glass and ceramic insulators in the world are cap and pin insulators [7, 28].

2.1.3. *Polymer insulators*

The body of this class of insulators is made of organic materials and hydrocarbons. These types of insulators have weaker electrostatic strength than ceramic and glass insulators. Over time, they lose their electrical and mechanical properties and become worn-out. Since organic materials have low energy, they are not easily wetted by water and have high hydrophobic properties. Compared to ceramic and glass insulators, it is lighter and less brittle [7, 28].

2.2. Potential Distribution on the Insulator Surface

The potential distribution on the surface of the insulator is non-uniform due to the presence of metal parts. Fig. 1 shows the capacitance model of the insulator chain, where C is the capacitance of each insulator, C_E is the capacitance of the insulator relative to the ground, and C_L is the capacitance of the insulator relative to the line. H is the length of the insulator, and x is the distance from the ground electrode.

We assume that the capacities C, C_E and C_L are constant, and their relationship with the length of the insulator is shown

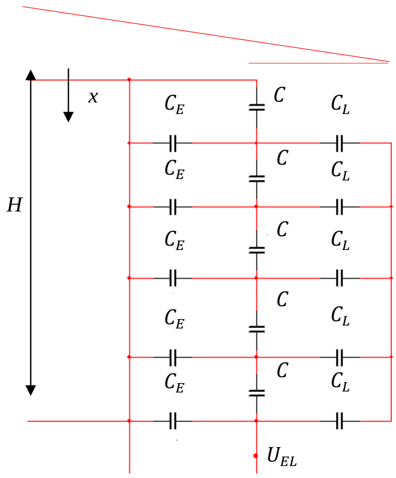

Fig. 1: Insulator capacitance model [29].

as (1) to (3) [30]:

$$C' = C \times H \quad (1)$$

$$C'_L = \frac{C_L}{H} \quad (2)$$

$$C'_E = \frac{C_E}{H} \quad (3)$$

The voltage and current equations will be in the form of (4) and (5) [30]:

$$\frac{dU_x}{dX} = \frac{1}{j\omega C'} \quad (4)$$

$$\frac{dI}{dX} = U_x\, j\omega C' + (U_x - U_{EL}\,)\, j\omega C' \quad (5)$$

2.3. Electric Field

In the design of high voltage equipment, it is very important to know the electric field distribution, because the field intensity must be tolerable for electrical insulation at all points. The critical value of electric field intensity (Ec) refers to the maximum electric field intensity that can be tolerated without causing electrical failure in insulating materials. This value depends on the physical and chemical characteristics of the insulators, including their composition and structure. Humidity is one of the important factors that can affect the critical value of electric field intensity. In conditions where the humidity in the environment increases, water can act as a poor conductor and thus reduce the insulation resistance. Studies show that the critical value of electric field intensity in the air should not exceed 3 (kV/mm) [31]. Some electric fields, such as homogeneous fields, can be obtained analytically, but if the geometrical shape of insulators and electrodes is complicated, it will be difficult to perform calculations analytically, and as a result, it is done using numerical methods and iterative calculations. The intensity of the electric field is considered as the gradient of the electric potential, and we will have [32]:

$$E = -grad\ V = -\nabla V \quad (6)$$

Since the field is created by the presence of electric charges, the divergence of the electric flux density will be equal to the volume density of the electric charge [32]:

$$div\ \bar{D} = \rho \quad (7)$$

If there is no charge in the space under study, the relationship between E and D is obtained from (8) [32]:

$$D = \varepsilon E \quad (8)$$

$$div\ \bar{E} = \frac{\rho}{\varepsilon} \quad (9)$$

Using (6) and (8), we will have [32]:

$$div\ \nabla V = -\frac{\rho}{\varepsilon} \quad (10)$$

Moreover, the divergence of the gradient is equal to the Laplacian [32]:

$$\nabla^2 V = -\frac{\rho}{\varepsilon} \quad (11)$$

Using Poisson's equation, equation (11) in Cartesian coordinate axes will be as follows [32]:

$$\nabla^2 V = \frac{\nabla^2 V}{\partial x^2} + \frac{\nabla^2 V}{\partial y^2} + \frac{\nabla^2 V}{\partial z^2} = -\frac{\rho}{\varepsilon} \quad (12)$$

It is very difficult to solve voltage equations in non-homogeneous field distribution, and for this purpose, an iterative numerical method is used. Among the numerical methods, we can mention finite difference method, finite element method, charge simulation method and boundary element method [32].

2.3.1. Finite Difference Method

The finite difference method (FDM) is one of the numerical techniques used to solve partial differential equations (PDEs). To use this method, the desired domain is divided into a discrete network and the coordinates of each point in the network are determined as (i,j). Then the spatial derivatives in the equations are approximated using finite differences. By replacing the approximated derivatives in the original equations, a set of linear equations is obtained which can be represented as a matrix, and can be solved by different numerical methods such as Gauss-Seidel. Finally, the results should be analysed and checked to confirm their accuracy [32].

2.3.2. Finite Element Method

The main idea of the finite element method is to divide the object or area under analysis into a large number of finite elements. These elements may be one, two or three-dimensional. The classic and popular type of element for the two-dimensional case is the triangular element. The nodes of this type of element are conveniently located at the vertices of the triangle. In the two-dimensional case, rectangular elements can also be used, but triangular elements are more suitable for meshing complex shapes. After discretization, it is time to obtain the stiffness matrix for each element. In this method, a digital computer is required due to the high computational burden. Solving problems with this method is done using commercial finite element software such as COMSOL, ANSYS, Abaqus, CATIA, etc [32].

2.3.3. Charge Simulation Method

Charge simulation method is one of the simple and effective techniques in the analysis of electric fields. This method is based on the principle of superposition, which states that the electric field caused by several point charges is equal to the sum of the electric fields caused by each charge. In this context, the charges in the system are identified and their positions are determined, and then the associated electric fields are calculated and aggregated to yield the total field [32].

2.3.4. Boundary Element Method

The boundary element method (BEM) is based on the principle of superposition and the theory of potentials. In this method, physical fields are expressed as integral equations on the boundary of the domain. Firstly, the boundary conditions and the field type are determined. Then the governing equations of the field are written in integral form. Then, using the boundary conditions and basic functions, the integral equations are established, and solved using numerical techniques to obtain the field values at the boundary points. In this method, due to the fact that only the boundaries are analysed, the number of variables required to solve the problem is reduced. In many problems, BEM can provide higher accuracy than other methods [32].

Table 2 shows the advantages and disadvantages of each of the presented methods. Due to the complex and different geometric shapes in the structure of the insulator cap and pin, and since we use COMSOL software, which is one of the most powerful engineering software in analysis, and considering the other advantages of the finite element method over other methods stated in Table 2, FEM has been chosen to conduct electrostatic field studies.

2.4. Insulator Modelling

2.4.1. Introduction of the studied insulator

The modelled insulator is shown in Fig.2, which is a porcelain type with a rated voltage of 230 kV from the catalogue of 120 kilonewton insulators of POWER TRIGOLD. Using the insulator catalogue in Table 3, its exact dimensions are extracted. This insulator is called type 1 insulator in this paper.

2.4.2. Calculation of Electrostatic Fields

According to the review of the literature, the presence of dust alone does not cause an electric arc on the insulator

Table 2: Advantages and disadvantages of the introduced methods [33-35].

Method	Advantage	Disadvantage
Finite difference method	• Understandable and simple • Fast calculations in simple problems • Can be used to solve ordinary and partial differential equations	• Low accuracy • Difficult to implement on problems with complex geometry • Reduced accuracy at boundary points
Finite element method	• Suitable for complex geometries and different boundary conditions • High accuracy of results with proper discretization • Usable for problems with variable material properties	• More complex to learn and implement • Requires long computation time • Requires the use of specialized software
Charge simulation method	• Easy to understand and use • Can be used for quick and approximate analyses	• Dependence of the accuracy of the results on the assumptions • Inability to solve problems with complex geometries
Boundary element method	• Reduces the dimensions of the problem because it only considers the boundaries • High accuracy in non-local problems with specific boundary conditions • Usable for problems with variable material properties	• Requires a deeper understanding of mathematics and physics • Difficult for complex and multidimensional geometries • Dependence of the accuracy of the results on the assumed boundary conditions

Fig. 2: Type 1 insulator cap and pin model [36].

Table 3: Data of type 1 insulator [36].

IEC Class		U120BS
Type		XP-120
Porcelain Disc Diameter, D. mm		245
Unit Spacing, H. mm		146
Standard Coupling to IEC 120		16B/16A
Creepage Distance, mm		320
Combined M & E Strength, kN		120
Routine Test Load, kN		48
Power Frequency Flashover Voltage	Dry, kV	78
	Wet, kV	45
50% Impulse Flashover Voltage	Pos., kV	120
	Neg., kV	125
Power Frequency Withstand Voltage	Dry, kV	70
	Wet, kV	40
Impulse Withstand Voltage, kV		110
Power Frequency Puncture Voltage, kV		110

surface, and when the insulator surface is also covered with moisture in addition to dust, a path for the creation of an electric arc is created. This path is modeled as a conductive layer. As a result, to model the effect of dust on the insulator, a conductive layer with a thickness of 2 mm has been created on the insulator surface. Table 4 shows information related to the levels of contamination based on different standards. According to the IEC standard, if the level of contamination exceeds 0.6 mg/cm^2, the contamination level will be very heavy.

Finite element method has been used to simulate and calculate electrostatic fields. To simulate dust on the insulator, an outer layer with a thickness of 2 mm is considered on the surface of the insulator. By changing the conductivity of the outer layer, the effect of different environmental conditions of humidity and pollution can be simulated on the surface of the insulator. Fig.3 shows the conductive layer created on the insulator, the conductivity of which is determined based on the data in Table 5.

The characteristics of the pollution layer change due to different pollution intensities. Table 5 typically presents the characteristics of different levels of pollution.

Therefore, by increasing the ESDD value in the present study, the effect of various pollutants such as industrial and marine pollution can be calculated in determining the probability of failure of electrical insulators located in the vicinity of these areas.

From (11) and (12), we have [31]:

$$\nabla.\varepsilon\nabla V = -\rho_s \Rightarrow \varepsilon\nabla^2 V + \rho_s = 0 \quad (13)$$

In (13), ρ_s is the flux density and ε is the permeability coefficient; As a result, the voltage distribution in the presence of contamination will be as follows [31]:

$$(\sigma + j\omega\varepsilon)\nabla^2 V + j\omega\rho_s = 0 \quad (14)$$

In (14), σ is the conductivity and ω is the angular frequency ($\omega=2\pi f$). Since the surface charge density along the length of the insulator is zero (ρ_s=0), equation (14) is rewritten as (15) [31]:

$$S_a = (5.7 \times 10^{-4} \times \sigma_{20})^{1.03} \quad (15)$$

S_a is the hardness of the solution in g/cm^3 and σ_{20} is the electrical conductivity of the solution in µs⁄cm at a temperature of 20℃, V is the volume of the pollution solution in cm^3, and A is the surface area of the insulator in cm^2.

As a result, the pollution intensity index is extracted from (16) [7]:

$$ESDD = \frac{S_a \times V}{A} \quad (16)$$

Table 4: Different levels of pollution based on common standards [7].

Pollution Level	IEC	IEEE	CIGRE
Very Light	-	0-0.03	0.015-0.03
Light	0.03-0.06	0.03-0.06	0.03-0.06
Medium	0.1-0.2	0.06-0.1	0.06-0.12
Heavy	0.3-0.6	>0.1	0.12-0.24
Very Heavy	>0.06	-	0.24-0.48
Special	-	-	>0.48

Table 5: Information about different pollution levels [18].

Pollution Level	ESDD (mg/cm^2)	Counductivity (S/m)
Light	0.035	1.4
Medium	0.1	4
Heavy	0.2	8
Very Heavy	0.4	16

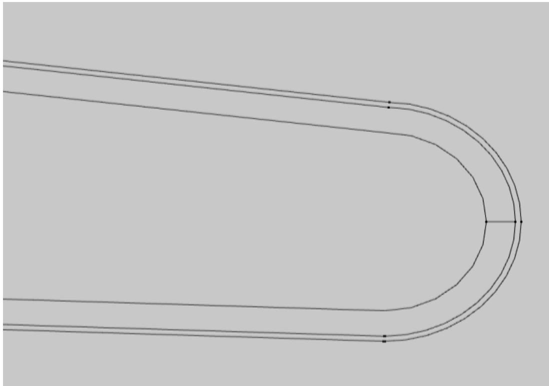

Fig. 3: Conductive layer created on the insulating shed to simulate dust.

2.4.3. Simulation of the Studied Insulator

At first, the studied insulator is designed in AutoCAD software. Fig.4 shows the pin and cap of the studied insulator in the AutoCAD Electrical software environment. Then we use Multiphysics 6.2 COMSOL program to simulate the pollution and moisture layer on the insulator. This program is one of the powerful tools for simulating physical and engineering phenomena. This software is especially used in the fields of electromagnetism, fluid mechanics, heat transfer and structural analysis. Fig.5 shows the electric potential distribution on the insulator designed in COMSOL software. Due to axial symmetry along the length of the insulator, two-dimensional modeling has been used for simulation. The electric field distribution on the studied insulator is shown in Fig.6.

In the next step, we determine the type of insulating material and the characteristics of the space around it. We put the material around the chain as air, cap and pin as iron, and silicon as the shackle. Table 6 shows the specifications of the materials used in the design of the insulator.

The boundary conditions of the problem are determined as the known potential of the high voltage electrode and the zero potential of the ground electrode. Fig.7 shows the meshing of the insulator and the space around it.

3. Calculating the Flashover Probability

Using the Finite Element Method (FEM), the electric field and potential distribution throughout the insulator is calculated. Complete electrical breakdown occurs when the average electric field between two points is greater than the critical value of electric field intensity (E_c), equation (17) shows this concept [16].

$$\Delta v(E) > E_c(H) \times d \quad (17)$$

To calculate the probability of electric arc jumping from one point to other points on the surface of the insulator, first the voltage difference between the desired point (such as point x) and its surrounding points should be calculated in

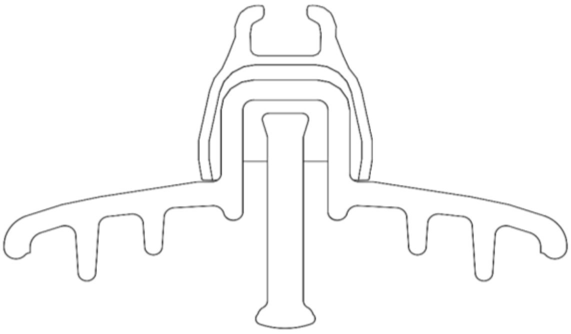

Fig. 4: Cap and pin modeling of type 1 insulator in AutoCAD software.

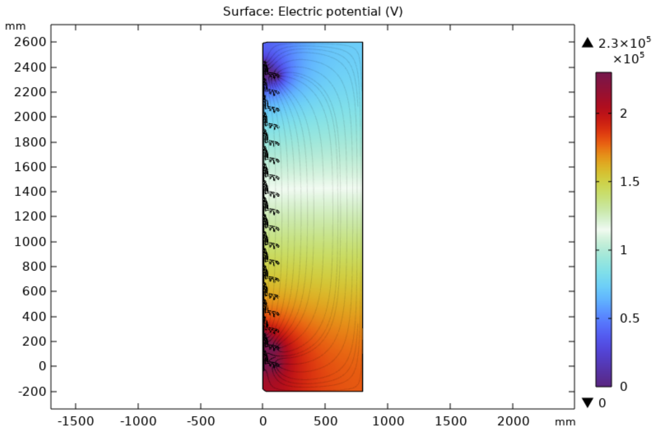

Fig. 5: Electric potential distribution on type 1 insulator in COMSOL software.

each step. Then, all the points whose voltage difference with the desired point is greater than the critical value are considered as possible points for electric arc jump [16]. Fig.8 shows the process of selecting candidate points.

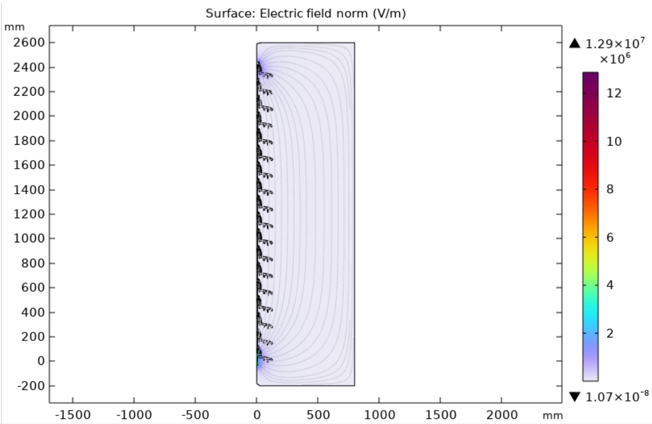

Fig. 6: Electric field distribution on type 1 insulator in COMSOL software.

Table 6: Characteristics of the materials used in the design of type 1 insulator [31].

Material	Silicone rubber	Iron	Air
Counductivity (S/m)	1×10^{-18}	1.4×10^{-7}	0
Permittivity (F/m)	3.6	100~500	1

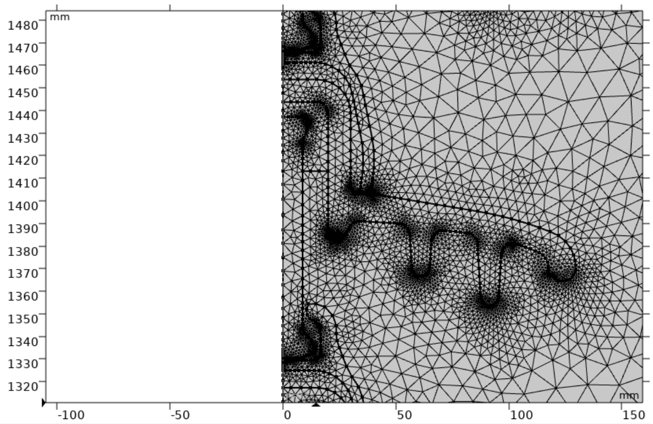

Fig. 7: Type 1 insulator meshing in COMSOL software.

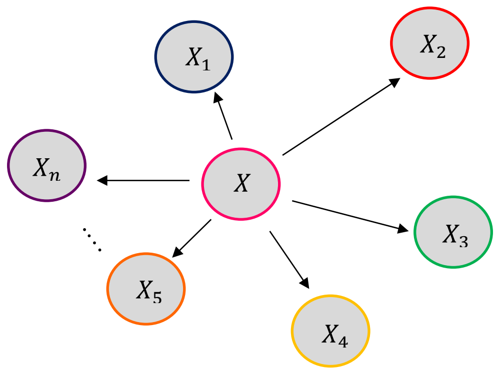

Fig. 8: Determining the initial point (X) and checking the probability of arc to each of the surrounding points.

The possible points for jumping the arc are placed randomly in a roulette wheel. The probability of arc jump depends on the intensity of the voltage difference and the distance between the points. Fig.9 shows an example of the process of selecting the next candidate point to check the probability of arc.

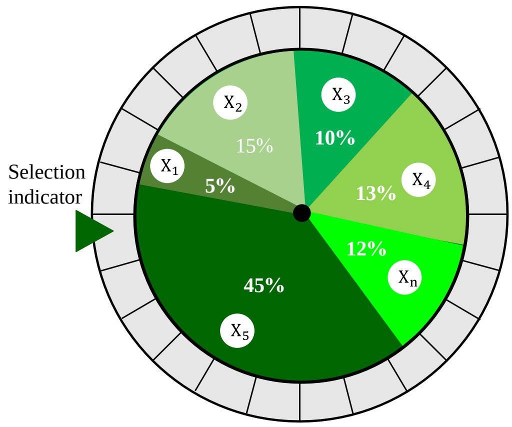

Fig. 9: Using the roulette wheel to determine the next point in consecutive arcs.

Finally, to calculate the flashover probability ($P_{Flashover}$), a certain number of arc jump processes must be repeated. Flashover probability is calculated using the ratio of the number of complete flashovers ($N_{Flashover}$) to the total number of flashovers (N_{All}).

$$P_{Flashover} = \frac{N_{Flashover}}{N_{All}} \quad (18)$$

In general, the relationship between AutoCAD, COMSOL and MATLAB software is shown in Fig.10. First, we design the insulator in AutoCAD Electrical software. From the Geometry section, using the Import option, we import the designed CAD file into the COMSOL software. Then, in the Materials section, enter the materials used in the insulation and apply the desired pollution and humidity in the Electric Current section. At the end, we extract the output text file in the Result section. By calling the text file in MATLAB software and using the procedure mentioned in Fig. 11, the probability of insulation failure is calculated. Fig.11 shows the process followed to calculate the probability of electrical breakdown in the insulator. We indicate the total number of iterations with N and set it equal to 100. At first, it is necessary to call the coordinates and voltage value of all the points in the text file taken from COMSOL software in MATLAB. Then, the point with the highest voltage is selected as the starting point for checking successive arcs. After finding this point using (17), the probability of arc occurrence is calculated for all the surrounding points. If the probability of arc occurrence to the surrounding points is equal to zero, we add one to the counter of no arc ($N_{No-Flashover}$) in this iteration. On the other hand, if the calculated probability is not equal to zero, that means the field difference between two points is greater than Ec (3 kV/mm), the next candidate point is selected using the roulette wheel, and this process continues until the voltage of the point where the arc is struck is equal to zero, in other words, the arc has reached the end point of the insulator. In this case, the flashover counter ($N_{Flashover}$) is incremented by one. Finally, if 100 repetitions for the insulator at a certain level of pollution and humidity are examined, the probability of failure will be calculated based on (18). To obtain the probability of failure in each level of humidity and different amounts of pollution in each step, the text output file taken from COMSOL software was called and the probability of failure for each level of humidity and pollution was calculated according to the flowchart in Fig.11.

4. Numerical Results

4.1. Model Validation

Most of the reviewed articles have considered the calculation of leakage current in different levels of dust and humidity. In articles [16] and [31], the probability of failure at different pollution levels and humidity of 80% has been investigated for 36 kV and 66 kV insulators. On the other hand, reference [37] have not mentioned the humidity level used for investigating the failure probability of 138 kV insulators. Given that the detailed data of the insulator model and humidity level in [31] and [37] are not provided. we have investigated the probability of failure of the silicone rubber insulator introduced in [16]. For this goal, we have modelled the insulator according to the explanations mentioned in the article. Subsequently, the failure curve was extracted for the modelled insulator. In Fig. 11, the curve reported in [16] and the curve that we extracted by simulation are compared.

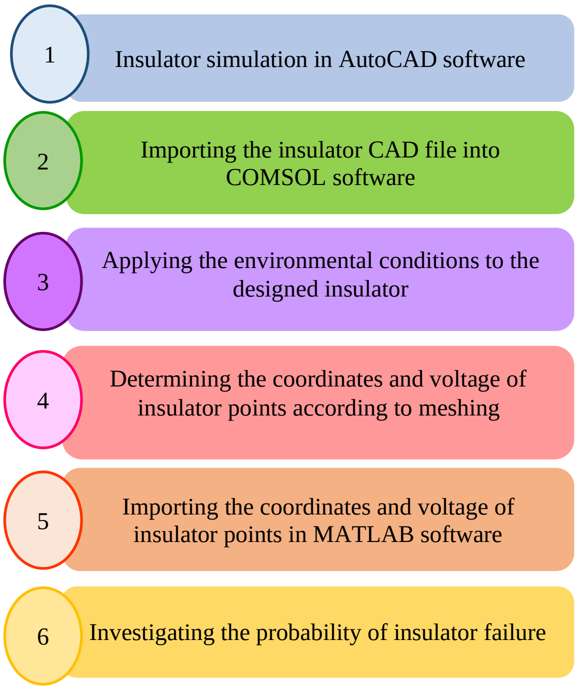

Fig. 10: Established links between software packages.

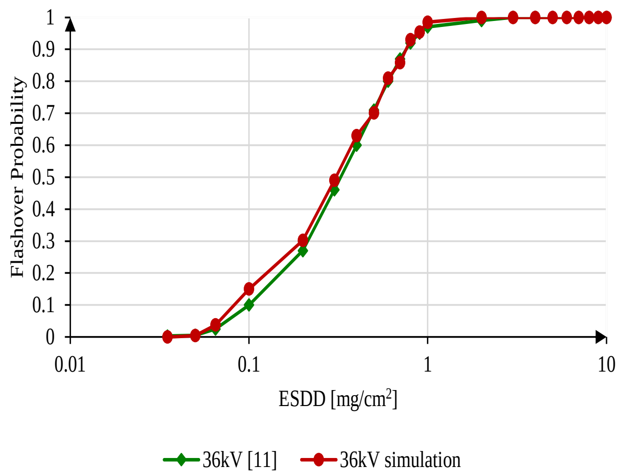

Fig. 11: Comparison of failure probability obtained from simulation and the curve reported in [11].

The results show that the obtained failure probability is in good agreement with the data in [11], and after validating the modelling process, we proceeded to examine the 230 kV insulator.

4.2. Calculation of Failure Probability in the Studied Insulator

In this section, we import the *x* and *y* values from the output of the text file taken from COMSOL software into MATLAB software. It is necessary to select insulator's high voltage point as the reference point to check possible arcs.
In the insulator, electric breakdown occurs completely when these arcs start from the high voltage point and reach the point that has zero voltage (the bottom of the insulator). In this case, a complete arc occurs, but in some cases, the arc may advance to a certain point, but not reach the end of the insulator. In this case, we will not have a complete arc. Fig.12 shows examples

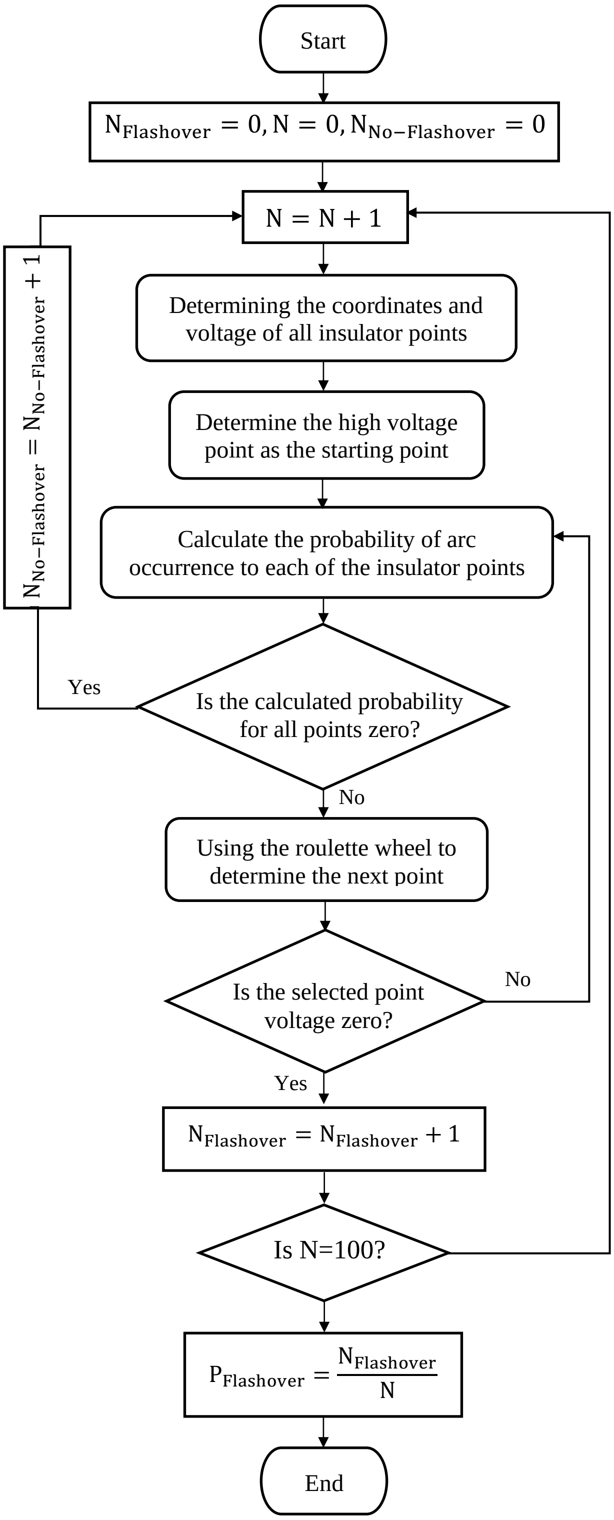

Fig. 11: Flashover probability calculation flowchart.

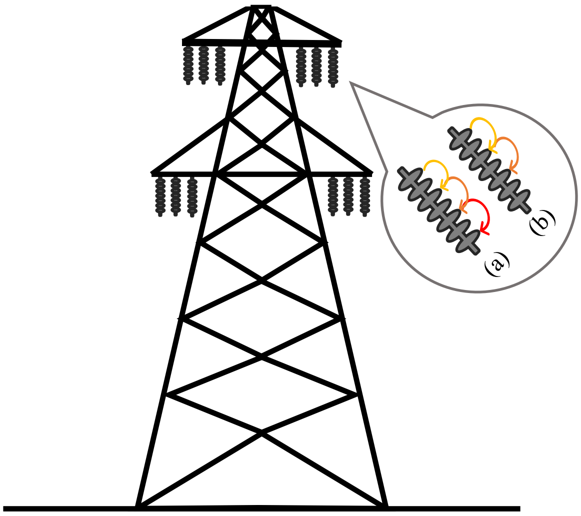

Fig. 2: (a) An example of a complete arc on an insulator surface, (b) An example of an incomplete arc on an insulator surface.

Table 7: Successive arcs in two complete and incomplete arc states for type 1 insulation in 65% humidity and ESDD of 0.2 (mg/cm^2).

Incomplete arc			
j	X	Y	V(V)
1	43.9163	47.2675	6.147×10^6
2	37.5892	90.9209	5.6652×10^6
3	93.4627	140.5593	4.5192×10^6
4	94.1069	192.20201	4.2863×10^6
5	154.2661	190.6057	4.1587×10^6
6	154.2661	190.6057	4.1587×10^6
Complete arc			
j	X	Y	V(V)
1	28.0634	2.3392×10^3	1.1104×10^6
2	22.6748	2.339×10^3	1.0908×10^6
3	22.7363	2.344×10^3	9.141×10^5
4	40.7162	2.3608×10^3	1.6772×10^5
5	37.9779	2.3581×10^3	8.0465×10^4
6	36.7238	2.359×10^3	0

of complete and incomplete arc. Table 7 shows two examples of complete and incomplete arc processes that are determined based on (18). After going through the process mentioned for each of the data extracted at different levels of humidity and pollution, the probability curve of the insulation failure under study is shown in Fig. 13.

4.3. Sensitivity Analysis

4.3.1. Case study 1

Firstly, we want to investigate the effect of pollution on the probability of failure on the surface of the insulator at a constant level of humidity. According to the curve obtained in Fig.13, it can be concluded that for a constant humidity level such as 65%, with increasing pollution, the possibility of flash over in the insulator has increased. For example, the probability of electrical failure in ESDD of 0.1 is about 4%, while in ESDD of 0.5, the probability of failure is 32%. This point shows the effect of micro dust on power grid elements, especially high voltage insulators, which reduces the stability and reliability of the power system due to the occurrence of arcing in these insulators. Table 8 shows the probability of arc occurrence in 65% humidity for type 1 insulator at different pollution levels.

4.3.2. Case study 2

In this case, we intend to investigate the effect of humidity on the possibility of insulation failure in the presence of pollution. It was mentioned in the reviewed papers that the presence of fine dust alone does not cause

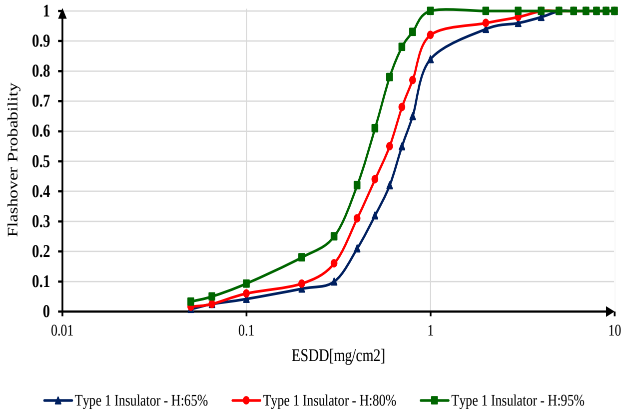

Fig. 13: Flashover probability of type 1 insulator at different levels of pollution and humidity.

Table 8: The flashover probability at 65% humidity for different amounts of pollution in type 1 insulator.

Humidity (%)	ESDD (mg/cm^2)	Flashover Probability (%)
65	0.1	4.2
65	0.5	32
65	1	84
65	5	100
65	10	100

arcing in insulators, and the presence of moisture along with fine dust creates the possibility of electrical breakdown in insulators. According to the results of Table 9, which are extracted from Fig. 13, we find that in a fixed level of pollution, by increasing the humidity, the probability of failure increases and this will affect the reliability of the power system.

4.3.3. Case study 3

In this section, we increase the number of discs from 18 to 23, and call it type 2 insulator. All the materials are similar to Table 6. We calculate the possibility of failure in 80 % humidity for different amounts of contamination for type 2 insulator. In Table 10, samples of complete and incomplete arc on type 2 insulator are provided. Fig. 14 compares the probability of type 1 and type 2 at humidity level of 80 %.

In Table 11, the probability of failure for type 1 and 2 insulators in 80% humidity and different levels of contamination is compared. As can be seen, with the increase in the number of disks and the increase in the creepage distance, the probability of electrical failure has decreased.

4.3.4. Case study 4

Among the ways to reduce the probability of arcing in power system insulators before natural disasters, predicting the probability of natural events [20], replacing worn-out elements of the network [2, 19], washing program of the insulators [8], using silicone rubber insulators [16], using organic paint coating to repair corrosion [29] and using insulators with more sheds [16]. As for the third study, we increase the number of sheds and set the type of insulating materials according to Table 12. The insulator studied in this section is called type 3 insulator. The potential distribution on the type 3 insulator in the COMSOL software environment is shown in Fig.15, and the electric field distribution on this

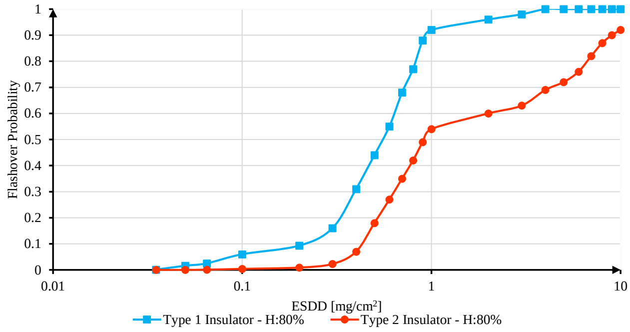

Fig. 14: Comparing the flashover probability of type 1 and type 2 insulators in 80% humidity for different amounts of pollution.

Table 9: The effect of humidity on the flashover probability of type 1 insulator.

Humidity (%)	ESDD (mg/cm^2)	Flashover Probability (%)
65	0.6	42
80	0.6	55
95	0.6	78

Table 10: Successive arcs in two complete and incomplete arc states for type 2 insulator in 80% humidity and ESDD of 0.3 (mg/cm^2).

Incomplete arc			
j	X	Y	V(V)
1	22.8496	1.3824×10^3	3.4535×10^5
2	43.4439	2.4347×10^3	2.5296×10^5
3	19.1831	2.3937×10^3	4.6612×10^3
4	19.1831	2.3937×10^3	4.6612×10^3
Complete arc			
j	X	Y	V(V)
1	9.7955	1.8878×10^3	2.148×10^6
2	9.6899	2.242×10^3	7.9706×10^5
3	130.659	2.3292×10^3	4.9211×10^4
4	12.3583	2.3273×10^3	7.5626×10^3
5	129.4585	2.328×10^3	0

Table 11: Comparing the probability of electrical breakdown of type 1 and 2 insulators for 80% humidity.

Insulator Type	ESDD (mg/cm^2)	Flashover Probability (%)
1	0.1	6
2		0.4
1	0.5	44
2		18
1	1	92
2		54
1	10	100
2		72

Table 12: The material used in the type 3 insulator [31].

Material	Silicone rubber	Fiberglass	Metal fittings	Air
Counductivity (S/m)	1×10^{-18}	1×10^{-18}	3.774×10^4	0
Permittivity (F/m)	3.6	4.2	1	1

insulator is shown in Fig. 16. Fig.17 shows the meshing on the surface of the type 3 insulator in the COMSOL software

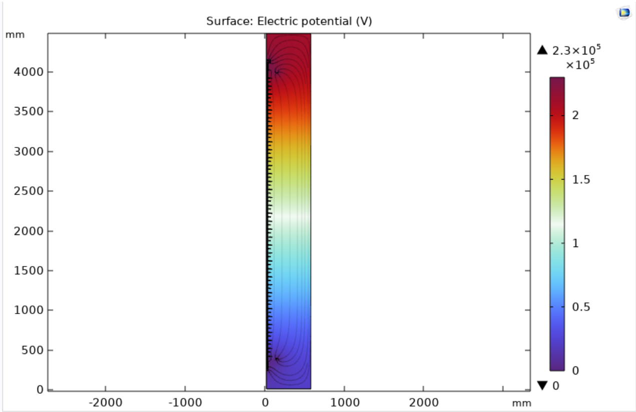

Fig. 15: Electric potential distribution on type 3 insulator in COMSOL software.

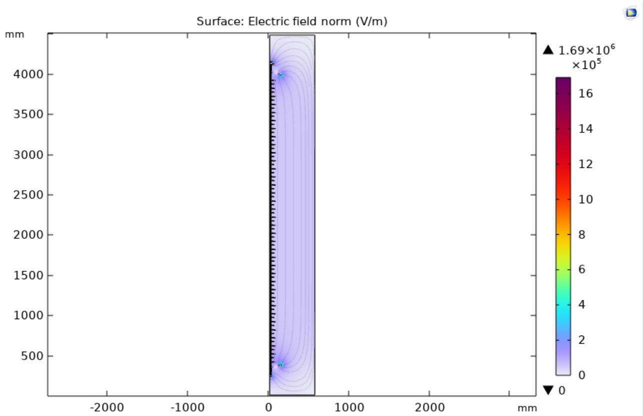

Fig. 16: Electric field distribution on type 3 insulator in COMSOL software.

Table 13: Specifications of type 3 insulator [38].

Voltage Level	kV	230
Tensile Strength	kN	160/80
Creepage Distance, mm	mm	11000
Arcing Distance	mm	2650
Section Distance	mm	2920
Lighting Impulse Withstand Voltage	Pos., kV	1050
	Neg., kV	1080
Power Frequency Withstand Voltage	Dry, kV	460
	Wet, kV	510

environment. The specifications of the type 3 insulator are reported in Table 13.

Fig. 18 compares the probability of failure of type 1 and type 3 insulators in 80% humidity. The effect of increasing the number of sheds as well as the materials used in insulation coating can be clearly seen in the probability of insulation failure. In type 1 insulator with ESDD of 1 and 80% humidity, the probability of electrical failure is more than 90%, while in type 3 insulator with the same pollution and humidity conditions, the probability of electrical failure is about 35%. Table 14 shows the probability of flashover for type 1 and 3 insulators for 80% humidity in different pollution levels.

4.3.5. *Case study 5*

In the following, different conductivity levels are applied to each of the 3 studied insulator types at 80% humidity. The results in Fig. 19 show that by increasing the amount of ESDD, the conductivity also increases, resulting in a higher flashover probability. Moreover, the probability of failure at each humidity level is higher in type 1 insulator, while type 3 insulator has the lowest probability.

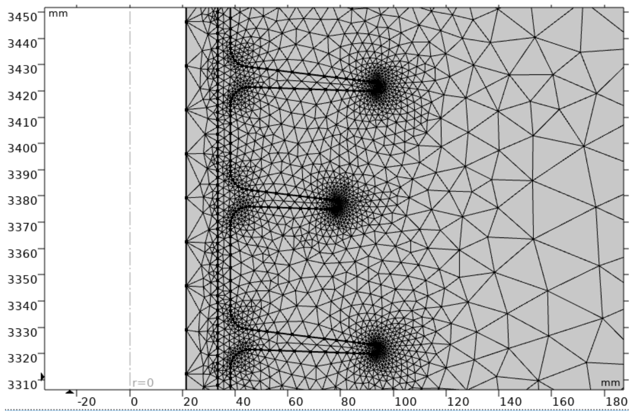

Fig. 17: Meshing on type 3 insulator in COMSOL software.

Table 14: Comparing the probability of electrical breakdown of type 1 and 3 insulators for 80% humidity.

Insolation Type	ESDD (mg/cm^2)	Flashover Probability (%)
1	0.1	6
3		0.025
1	0.5	44
3		11
1	1	92
3		35
1	10	100
3		89

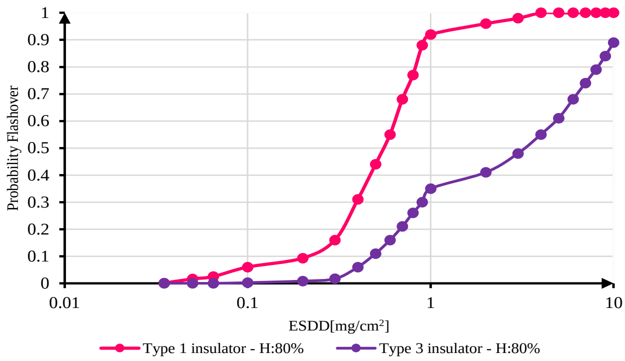

Fig. 18: Comparing the flashover probability of type 1 and type 3 insulators in 80% humidity for different amounts of pollution.

4.4. Curve Fitting Results

In order to use the obtained results more easily, using the curve fitting toolbox of MATLAB software, the equations of distribution probability function are obtained and reported in Table 15. In these equations, the probability of flashover is indicated by y and the value of ESDD is indicated by x. Fig. 20 shows an example of curve fitting in MATLAB software. In Fig. 20, the blue curve is the flashover curve of type 1 insulator at 65% humidity and the orange curve is the fitted probability distribution function.

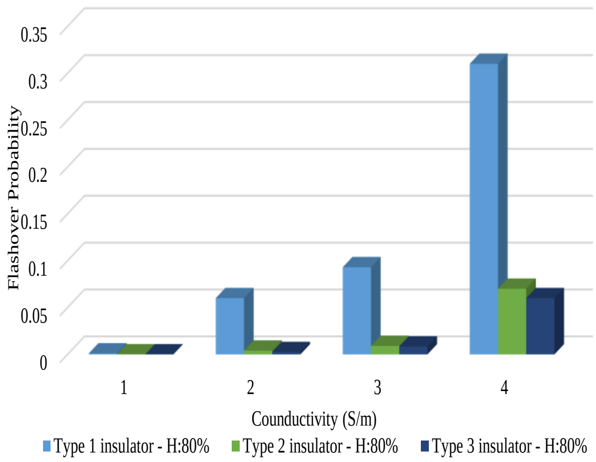

Fig. 19: Comparison of the failure probability of three types of insulators in different conductivities.

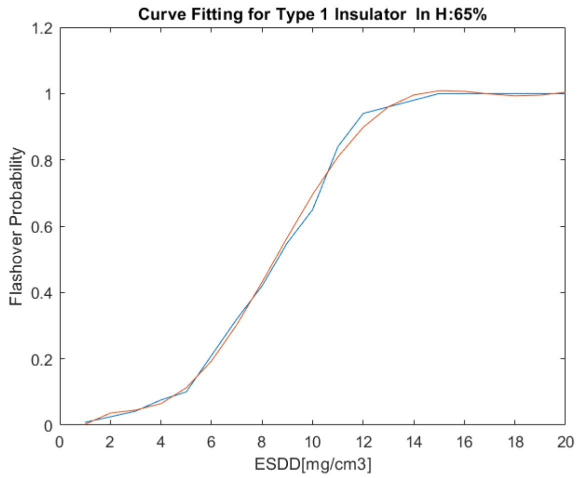

Fig. 20: Comparison of the flashover curve of type 1 insulator at 65% humidity with the fitted probability distribution function.

Table 15: Probability distribution function for the fragility curve of the studied insulator.

Type of insulation	Probability Ddistribution Function
Type 1 insulator - H:۶۵%	$y = 2.7563 \times 10^{-4}(x^5) - 0.0083(x^4) + 0.095(x^3) - 0.5037(x^2) + 1.2275x - 0.1018$
Type 1 insulator - H:80%	$y = -4.7881 \times 10^{-5}(x^5) + 0.0018(x^4) + 0.0279(x^3) + 0.2121(x^2) - 0.8371x + 1.5931$
Type 1 insulator - H:۹۵%	$y = -1.1648 \times 10^{-4}(x^5) + 0.004(x^4) - 0.0552(x^3) + 0.372(x^2) - 1.278x + 2.0473$
Type 2 insulator - H:80%	$y = 1.7018 \times 10^{-4}(x^4) - 0.0053(x^3) + 0.0615(x^2) - 0.3253x + 0.8041$
Type 3 insulator - H:80%	$y = 1.0215 \times 10^{-4}(x^4) - 0.0031(x^3) + 0.0343(x^2) - 0.1779x + 0.482$

5. Conclusion

The purpose of this article is to investigate the probability of failure of transmission network insulators in presence of micro dust phenomenon, as one of the adverse natural events that has become more intense in recent years due to climate changes. The presence of pollution alone does not cause arcing and electrical breakdown in insulators, whereas in the presence of humidity, the probability of electrical discharge increases. Failure of insulators affects the stability, reliability and resilience of the power system, and by reducing the probability of failure of insulators, the duration of blackout and the amount of unserved energy can be reduced. In this context, as the first step, type 1 insulator was investigated and it was shown that the probability of failure in the insulator increases with the increase in the amount of pollution at a certain level of humidity. Moreover, the results indicate that with the increase of humidity at a certain level of pollution, the probability of electrical discharge on the surface of the insulator has also increased. Finally, according to the proposed corrective measures, the number of discs has been increased, and a number of sheds have been placed among the discs, and the material used has also been changed to silicone rubber in order to investigate the possibility of insulation failure in this situation. The results show that by carrying out the above-mentioned corrective measures, the probability of electric failure in type 2 and 3 insulators has been greatly reduced, and this confirms the that replacement of grid insulators with silicon-rubber coated insulators, as well as the increasing their creepage distance, are effective solutions for improving the power system resilience against dust storms. Moreover, from the comparison of Fig. 7 and Fig. 17 in the paper, which show the meshing on the sheds of the type 1 and 3 insulators, it can be seen that in the type 1 insulator, based on its cap model, a finer meshing was used with more points compared to type 3 insulator. This is due to the existence of sharp points, which justifies a finer meshing than other points where the electric field is more uniform.

Credit Authorship Contribution Statement

Yasaman Abbasi Chahardah Cheriki: Data curation, Software, Visualization, Roles/Writing - original draft. **Hossein Farzin**: Conceptualization, Methodology, Validation, Writing - review & editing. **Elaheh Mashhour**: Validation, Writing - review & editing.

Declaration Of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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