

Numerical Investigation of the Electrical Performance of Broken Skirt Glass Insulators in Suspension Strings

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KEYWORDS

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ABSTRACT

Broken skirt glass insulators are commonly encountered in overhead transmission systems due to mechanical damage while remaining in service because their metallic cap and pin continue to provide mechanical support. However, the influence of broken skirt insulators on the electrical performance of an insulator string remains insufficiently understood. This study numerically investigates the effects of broken skirt insulators on the voltage distribution, surface charge distribution, and string efficiency of a glass suspension insulator string using Finite Element Method Magnetics (FEMM). A comparison with QuickField was first performed to verify the consistency of the numerical results before subsequent analyses were conducted using FEMM. In addition, the electrical behaviour of a broken skirt insulator was compared with that of a smaller intact disc insulator to evaluate the influence of the reduced insulating profile. The results show that the presence and location of the broken skirt significantly affect the voltage distribution, surface charge distribution, and string efficiency of the insulator string. The lowest string efficiency was observed when the broken skirt was located nearest to the high-voltage conductor, whereas the small disc insulator exhibited electrical characteristics that were much closer to those of the healthy insulator string. The findings provide useful insight into the electrical behaviour of damaged glass insulators and contribute to a better understanding of their influence on transmission line insulation performance.

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1. INTRODUCTION

Electricity is essential to modern society and is delivered to end users through generation, transmission, and distribution networks. Transmission is the most crucial stage where overhead lines are primarily used to transfer the electric energy to substations continue at a higher voltage levels for efficient operation. If overhead insulators string fails to function properly, the electricity transmission will be disrupted and may threaten the reliability of power system network. Thus, the reliability of a transmission network can be said as partly

dependent on the performance of insulators available in the electrical power transmission system [1].

Overhead insulators can be considered cheap when compared with other high voltage (HV) equipment; however, they play an important role in protecting the most expensive equipment which subsists in the power system network. During overvoltage events, the insulation system may experience flashover before more vulnerable equipment is affected; therefore, its insulation performance is an important consideration in system protection and reliability [2]. An overhead transmission line consists mainly of conductors,

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insulators, and supporting tower structures. Conductors operating at high voltage require mechanical support while maintaining adequate electrical clearance from the grounded structure, which is provided by the insulator string.

To date, overhead insulators have provided long-term service in transmission and distribution networks, with typical operating lifetimes exceeding 25 years [3]. The insulators used in these systems are generally manufactured from ceramic or polymeric materials, with glass being one of the commonly used materials for suspension insulators [3]. Previous studies have reported that high voltage (HV) glass insulators can experience ageing and mechanical damage during service [4–6]. Broken glass insulators may result from events such as lightning strikes and external mechanical impacts, including projectile impacts [7].

Broken glass insulators frequently remain in service after mechanical damage because the metallic cap and pin continue supporting the conductor. Although previous studies have investigated contamination, ageing and flashover characteristics of glass insulators, limited attention has been given to the electrical behaviour of broken skirt insulators using finite element analysis, particularly in comparison with small-sized replacement insulators. Therefore, this work investigates the voltage distribution, surface charge distribution and string efficiency of glass insulator strings containing broken skirt units.

In practical transmission line maintenance, damaged glass insulators may require replacement to maintain system reliability. From an electrical perspective, comparing a broken skirt insulator with a smaller intact disc provides a useful basis for determining whether the reduced insulating profile of a damaged unit produces electrical characteristics similar to those of a smaller intact insulator. Such a comparison may provide useful insight into the electrical implications of different insulator geometries and the assessment of damaged units.

2. BROKEN SKIRT (STUB) EFFECT

It is worth stating that the simulation studies for overhead transmission line insulators is not only limited on polluted conditions but the effect of broken insulators in a string has also become a major concern. Studies on broken glass insulator shown in Figure 1 has started to become a favorite among researchers throughout the world as early as 1920s [8].



Fig. 1. Example of broken glass insulator.

A comparative study conducted on breakdown voltage measurements in a glass insulator string containing several units with broken glass part of a string of 16 units glass insulators was studied in [6]. It is found that different locations of broken insulators in a string affects the electrical breakdown

voltage of the glass insulator strings. A comprehensive approach to the electrical characteristics of a broken glass insulator taken individually or in a string in [9] and found that the electrical characteristics and properties of a stub certainly differs to a healthy insulator string. The existence of broken insulators or defective units in a string of porcelain and glass was examined in [10] to observe the switching overvoltage effect. Determination of critical flashover level based on the insulator types, number and position of broken units [11] are of prime important criteria to allow live work maintenance [10]. In the meantime, simulation studies on the broken insulators also began to grow whereby the electric field distribution profile was investigated using boundary element software and in [12] shows that the broken insulators possess high electric field.

Exploration on the voltage distribution profile across single and ten units of glass insulator string with different locations of broken insulators has been conducted by [13] using QuickField software. It is proven from the simulation results that the presence of broken insulators definitely alters the voltage distribution profile along the glass insulator string. Although there is significant difference in the voltage distribution between perfect and broken insulator, the remaining healthy insulators available in the string are less affected. Motivated by the continued operation of broken skirt insulators in service, this study evaluates whether a smaller intact disc insulator can provide electrical performance comparable to that of a broken skirt insulator. The comparison focuses on voltage distribution, surface charge distribution, and string efficiency to assess the feasibility of using smaller replacement insulators from an electrical performance perspective.

2.1 Finite Element Method Magnetics (FEMM) Modelling

Two commercially available glass suspension insulators, namely the N70/146 type B and CT4/140 [14], were selected for this study. The N70/146 type B was used as the reference healthy insulator, while the broken skirt model was derived from the same insulator by removing the glass skirt. The CT4/140 insulator was selected as a smaller intact reference to evaluate whether the electrical behaviour of a broken skirt resembles that of a reduced-size insulator. The selection of CT4/140 insulator is mainly because its smaller dimensions provide a suitable basis for comparison with the broken skirt configuration. Although the broken skirt and small disc insulators differ in geometry, both exhibit a reduced insulating profile compared with the standard N70/146 insulator. This comparison enables the influence of the missing glass skirt on the electrical performance of the insulator string to be evaluated independently of the healthy insulator configuration. Figure 2 shows three types of insulators to be modelled in Finite element method magnetism (FEMM) version 4.2 to observe their voltage distribution effect. The parameters of modelled Sediver toughened glass suspension insulators particularly nominal creepage distance, suspension length and shed diameter is presented in Table 1.

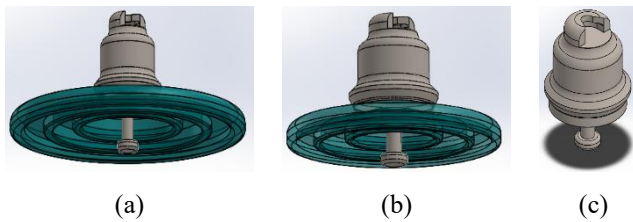


Fig. 2. The illustration of insulator in (a) perfect condition; (b) small disc insulator and (c) stub insulator.

Table 1. Insulator parameters.

Insulator condition	Insulator Type	Creepage distance (mm)	Suspension length (mm)	Shed diameter (mm)
Perfect	N70/146 type B	320	146	255
Small disc	CT4/140	190	140	160
Stub	Broken N70/146 type B	$\approx 0^*$	146	$\approx 0^*$

*Note: The stub configuration retains its metallic hardware and mechanical string length (146mm) but loses its functional glass shell.

[†]Minimal effective profile remaining around the cap/cement boundary.

In this work, the string was applied with 66 kV at the pin of insulator 1, while the top insulator cap 4 was grounded. It is worth mentioning that the insulator number represents the positions of the insulator itself as shown in Figure 3. An attempt was first made by simulating three units of perfect insulators with one stub insulator in a string using QuickField and FEMM software. The same insulator configuration was analysed using QuickField and FEMM to verify the consistency of the numerical solutions obtained from two independent finite element platforms. Similar voltage distribution trends were observed, providing confidence in the modelling approach. Due to its computational efficiency and modelling flexibility, FEMM was selected for the subsequent analyses.

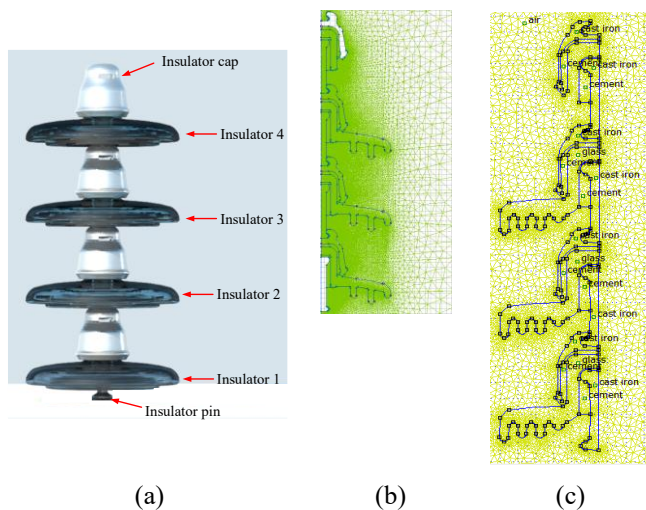


Fig. 3. (a) Insulator positions, (b) QuickField software modelling and (c) FEMM software modelling.

It is important highlighting that the location of the stub was changed from position 1 to 4. One of the insulator string that has been modelled with the stub located near to ground terminal in both software is presented in Figure 3b and 3c. Considering the symmetrical shape of HV insulator, the simulation was performed in an axisymmetrical two-dimensional (2D) which need only the cross-section of the insulator to represent the 3D modelling [15]. To save the computation time of the simulation process, the transmission sub-system (such as the guard ring,

supporting structures, conductors and other accessories) is neglected. The present analysis is based on a two-dimensional axisymmetric finite element model. Although this approach effectively captures the voltage and charge distribution characteristics, experimental validation is required to further verify the numerical predictions under practical operating conditions.

3. RESULTS AND DISCUSSION

3.1 Voltage Distribution Analysis

Figure 4 shows that QuickField and FEMM produce similar voltage distribution trends for all broken skirt locations. Although slight differences in voltage magnitude are observed, both software predict the same redistribution pattern along the insulator string. The percentage difference between both software for the healthy insulator string is approximately 33%, whereas the difference decreases to about 13% when a broken skirt is introduced. Since both software provide comparable voltage distribution trends, the simulation was subsequently carried out using FEMM because of its computational efficiency and modelling flexibility. The close agreement between both software indicates that the predicted voltage redistribution is primarily influenced by the broken skirt geometry rather than by differences in the numerical implementation of the finite element solver [16].

The simulation was then extended to compare the voltage distribution of the healthy, broken skirt, and small disc insulator strings, as presented in Figure 5. It is observed that the distribution of voltage is dramatically distorted in the presence of stub insulator in a string. The distortion is attributed to the removal of part of the glass dielectric, which changes the local capacitance between adjacent insulator units. Consequently, the electric potential is redistributed along the string, producing higher electrical stress on neighbouring insulators.

The greatest voltage redistribution occurs when the broken skirt is located at Position 1, nearest to the HV conductor. At this location, the electric field intensity is inherently higher, causing the missing glass skirt to have a greater influence on the surrounding potential distribution. As the broken skirt is moved toward the grounded end of the string, its influence on the overall voltage distribution gradually decreases.

In contrast, the voltage distribution of the small disc configuration remains very close to that of the healthy insulator string, with a percentage difference of less than 5%. This indicates that reducing the insulator dimensions alone does not produce the same electrical behaviour as the loss of the glass skirt, highlighting the importance of the defect geometry rather than the overall insulator size. A similar redistribution trend was reported in [13,17], although the present study further demonstrates that the electrical behaviour of a broken skirt differs from that of a geometrically smaller intact insulator.

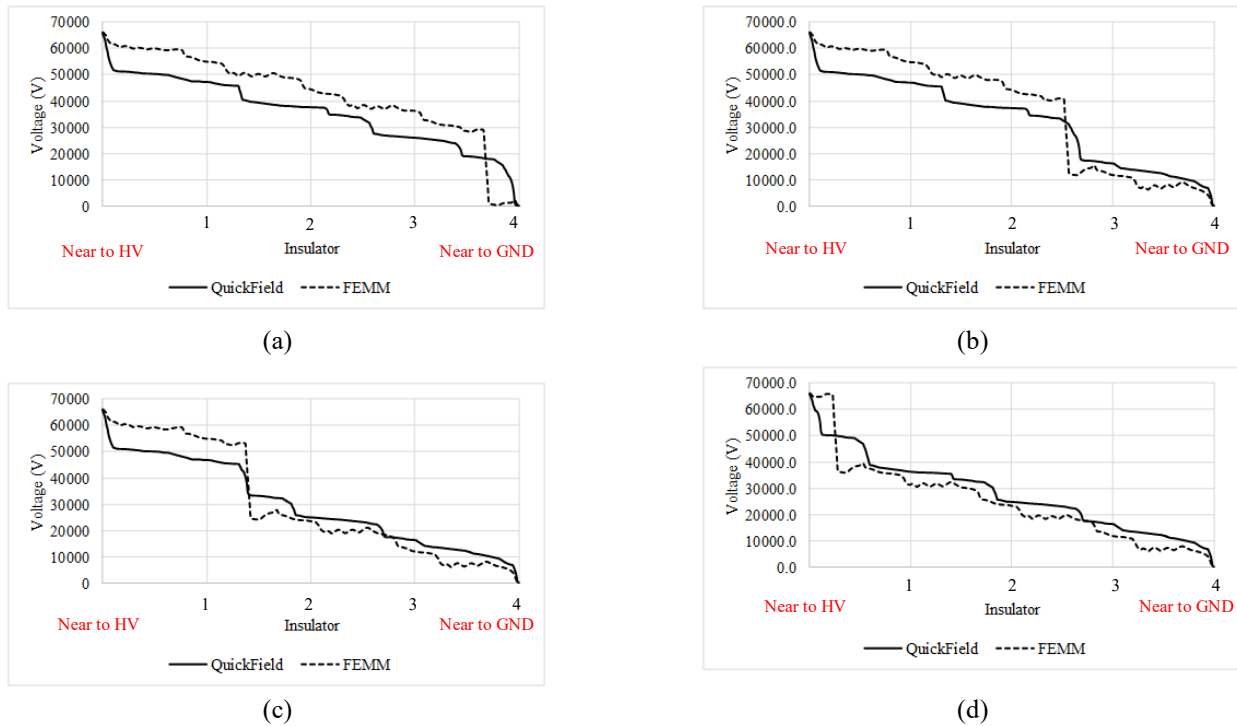


Fig. 4. Comparison of voltage distribution obtained using QuickField and FEMM for a glass insulator string containing a broken skirt located at (a) position 4; (b) position 3; (c) position 2 and (d) position 1.

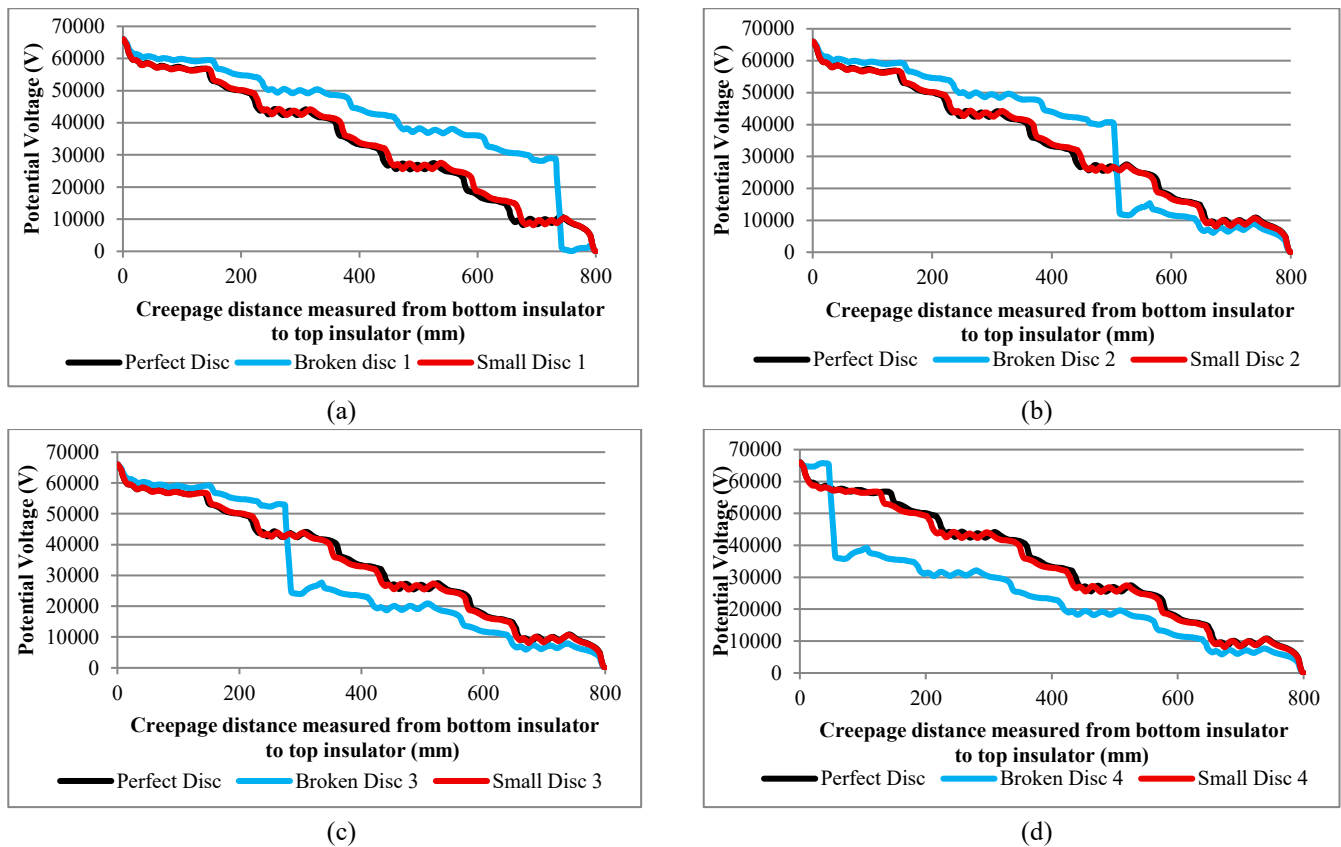


Fig. 5. Comparison of voltage distribution for healthy, broken skirt, and small disc insulator strings with the modified insulator located at (a) position 4; (b) position 3; (c) position 2 and (d) position 1.

3.2 Charge Distribution Analysis

Figure 6 depicts the magnitude of charge distribution across each insulator when a broken insulator exists as a part of complete string. It is observed that the distribution of charge on the insulator surface is affected at both electrodes of a perfect string. The increase in surface charge near the adjacent healthy insulator is caused by electric field enhancement around the discontinuity introduced by the missing glass skirt. The concentrated electric field promotes greater charge accumulation at the neighbouring electrode regions. However, the distribution of charge is dramatically affected in the presence of broken insulator; where the insulator next to broken insulator has the highest magnitude of charge at each condition. It is also apparent from Figure 6 that the magnitude of charge at the broken insulator is increased when located far away from HV electrode. However, the distribution of charge for healthy insulator seems unstable for insulator near to electrode. This situation is believed due to the charge injection and extraction process occurred at both electrodes [18]. This behaviour is expected because charge injection and extraction predominantly occur near the energized and grounded electrodes, where the electric field intensity is highest.

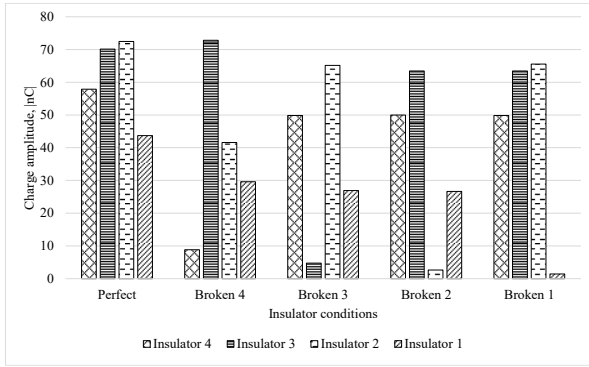


Fig. 6. Distribution of charge across each insulator when the broken disc exists in the string.

3.3 String Efficiency Analysis

Table 2 shows the string efficiency of the healthy insulators and when the stub and small size insulator exists in a complete string. The string efficiency is defined as a ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the high voltage line and as given in equation (1).

$$\eta = \frac{V_{total}}{\eta \cdot V_{HV}} \times 100 \quad (1)$$

(where V_{total} is total voltage across the string, η is the number of insulator units, and V_{HV} is the voltage across the unit nearest to the high voltage conductor).

Table 2. String efficiency.

Condition of Insulator	Location of stub/ small size insulator	String Efficiency, η (%)
Healthy insulator	-	27.96
Stub Insulator	4	26.97
	3	27.02
	2	27.08
	1	25.41
Small Disc Insulator	4	27.72
	3	27.70
	2	27.69
	1	27.50

It is well known that there are three ways [19, 20] to improve the string efficiency particularly (1) by using longer cross-arm where the shunt capacitance to mutual capacitance can be reduced; (2) by grading the insulator where different dimensions of insulators are assembled in a string to equalize the potential distribution across the units in the string; and (3) by using guard or grading ring where insulator at the bottom of string is surrounded by a large metal ring which electrically connected to the line.

It is obvious from Table 2 that the healthy insulator string has the highest string efficiency of 27.96%. However, the string efficiency is reduced if the stub exists between healthy insulators string. On the contrary, only very little difference can be observed when the small size insulator exists between healthy insulator strings. It is observed that the lowest string efficiency is found when the stub located at position 1 followed by position 4 where at the position 2 and 3 the string efficiency can be considered similar. The reduction in string efficiency indicates a less uniform voltage distribution along the insulator string. From an engineering perspective, lower string efficiency implies that a greater proportion of the applied voltage is concentrated across a small number of insulator units, increasing the likelihood of localized electrical stress and long-term insulation degradation [21].

4. CONCLUSION

This study investigated the effect of broken skirt glass insulators on the voltage distribution, surface charge distribution, and string efficiency of suspension insulator strings using finite element analysis. The results showed that the presence and location of the broken skirt significantly influence the electrical characteristics of the insulator string. A broken skirt altered the voltage distribution and increased the surface charge concentration on the adjacent insulator, resulting in reduced string efficiency, particularly when located nearest to the HV conductor. In contrast, the small disc insulator exhibited voltage distribution and string efficiency that were much closer to those of the healthy insulator string.

These findings provide useful insight into the electrical behaviour of broken glass insulators and may assist in evaluating suitable replacement strategies for damaged insulator strings. The present study is limited to two-dimensional finite element simulations without experimental validation. Therefore, future work will focus on experimental verification and the investigation of additional operating conditions to further validate the proposed findings.

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