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Anomalous flashovers of silicone rubber insulators under the artificial rain test

Krystian Leonard Chrzan[1], **Henryk Marek Brzeziński**[2]

[1] *Wroclaw University of Technology*
Poland

[2] *Łukasiewicz Research Network – Institute of Electrical Engineering*
Poland

e-mail: krystian.chrzan@pwr.edu.pl, henryk.brzezinski@iel.lukasiewicz.gov.pl

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Abstract: The wet flashover voltage of medium voltage insulators made of a silicone rubber is 8% lower than the wet flashover voltage of a porcelain insulator with an identical profile. These surprising results, obtained in 2012, were confirmed again in 2019. The flashover development on the composite insulator is very short (less than 30 ms). On the other hand, on the porcelain insulator, the flashover develops longer (1–3 seconds). The Koppelmann equation was modified, and the Obenaus model to calculate the flashover voltage of insulators under the artificial rain was presented. Attention was paid to the importance of insulator diameters and the phenomenon of water cascades.

Key words: flashover, leakage distance, porcelain insulator, silicone rubber insulator

1. Introduction

The artificial rain test is the oldest test method of overhead insulators, and was first used at the beginning of the 20th century [1, 2]. The procedure and the stand for the artificial rain test are described in standards and publications (e.g. [3–5]). The flashover voltage of ceramic long rod insulators or cap and pin insulators under a standardized rain test (precipitation 3 mm/min and the conductivity of water 100 μS/cm) is reduced by approximately 20% when compared to the flashover voltage in dry conditions. A much greater decrease in electrical strength occurs with rainwater conductivity greater than 1 mS/cm [6], or when insulators are contaminated and the surface conductivity exceeds 10 μS. In the late 1980s and early 1990s, flashovers were recorded on the light polluted bushing insulators of ultra-high voltage DC substations during heavy rains [7]. An effective solution to the problem was to increase the leakage distance and use hydrophobic silicone coatings.

In standard pollution tests, the flashover voltage of silicone insulators is approximately 30% higher than the flashover voltage of porcelain insulators. However, there are two important points: the insulator profile and the wetting intensity.

In the above-mentioned experiments, typical composite insulators with a much smaller shank diameter than the shank diameter of porcelain insulators were used.

Under intense artificial rain, the flashover voltage of polluted silicone insulators may be even lower than the flashover voltage of these insulators (with the same pollution) when they are wetted by steam or fog [8].

Our previous work examined silicone and porcelain insulators of an identical shape, with the same leakage distances, and with the same diameters of shanks and sheds. It was surprising that the flashover voltage of the silicone insulator under the artificial rain was 7% lower than the flashover voltage of the porcelain insulator [9]. In the second series of measurements presented here, special attention was paid to the preservation of test conditions and the repeatability of the results. The second measurements confirmed the results of the first tests.

2. Test objects and experimental procedure

Two 24 kV composite insulators with 6 sheds made of HTV (high temperature vulcanized) silicone sheath, and one porcelain insulator of identical shape were tested. The dimensions of the insulators are given in Table 1. The set up was built at the Łukasiewicz Research Network – Institute of Electrotechnical Engineering in Wroclaw and was equipped with the original multiple nozzles with 19 jet tubules with the diameters of 0.6 mm (Fig. 1). Several multiple nozzles are located on one side near the test insulator.

Table 1. Dimensions and parameters of the silicone and porcelain insulators LP25/6

Parameter	Dimensions
leakage distance	612 mm
arcing distance	304 mm
shed/shank diameter	95/25 mm
slope of the upper surface shed	13°
slope of the bottom surface shed	3°

Two series of measurements were made with the same water conductivity of 100 μS/cm and under the same climatic conditions: an atmospheric air pressure of 1010 hPa, an air temperature of 20°C, a water temperature of 20°C. In the first series, measurements were made in accordance with the standard [3] – with a precipitation intensity of 1.5 mm/min (equal horizontal and vertical components). After a week, the surface of the insulators was not conditioned by wetting and electrical discharges, and the precipitation intensity was reduced to 0.3 mm/min. The discharges on the insulators were filmed using the popular Samsung SM-A202F/DS smartphone. After the next two weeks, the contact angles were measured in several places on the insulator shank using the SeeSystem Standard from Advex Instruments.

Fig. 1. The multiple nozzle with 19 jet tubules with diameters of 0.6 mm

3. Test results

Measurements of the flashover voltage are given in Table 2. The flashover voltages under a water precipitation of 1.5 mm/min are about 6% lower than the flashover voltages under a water precipitation of 0.3 mm/min. In both series, the flashover voltage of the silicone insulators is 8% lower than the flashover voltage of the porcelain insulator. Wetting angles (taken two weeks after the end of the second series of flashover voltage measurements) of 91° on the silicone rubber, and 60° on the glazed porcelain are typical values for these surfaces. A photograph of the droplets on the silicone insulator taken immediately after the voltage test shows that the surface has not lost its water repellency (Fig. 2(a)). During the test there is accumulation of drops under the shed edges, which is especially characteristic for silicone insulators (Fig. 2(b)).

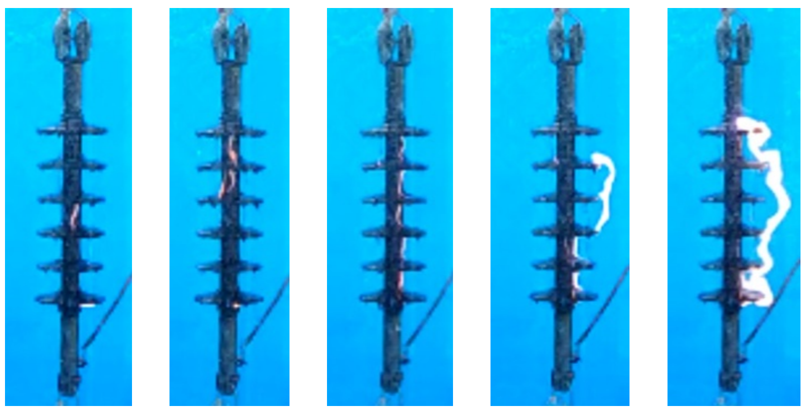
Table 2. The results of measurements of the flashover voltage

Tests with precipitation of 1.5 mm/min						
Insulators	1	2	3	4	5	Average
Porcelain	108	104	110	108	110	108 kV
SIR1	96	92	84	107	110	98 kV
SIR2	96	101	95	98	107	99 kV
Tests with precipitation of 0.3 mm/min						
Porcelain	120	112	117	113	113	113 kV
SIR1	111	105	103	106	103	106 kV
SIR2	111	106	105	104	103	106 kV

The flashover on the porcelain insulator develops gradually within 1–3 seconds, and after ignition, the discharge is extended until a short circuit occurs (Fig. 3). On the silicone insulator, however, the flashover develops very quickly, in a time of less than 33 ms (Fig. 4). The shooting speed, which is 1 frame in 33 ms, is too slow to trace the development of discharge on the silicone insulator.

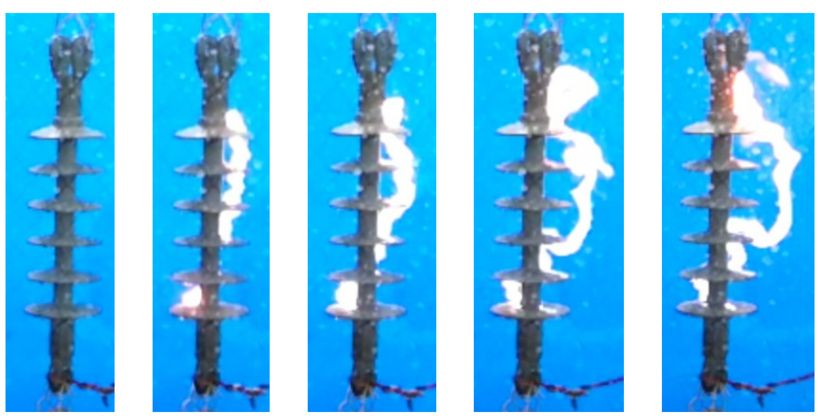
(a) (b)

Fig. 2. Drops on the sheds of the silicone insulator after the voltage test (a), drops under the sheds' edges during wetting without the voltage applied (b)



t = 160 ms 570 ms 1390 ms 1430 ms 1500 ms

Fig. 3. Development of the flashover on the porcelain insulator, t time measured from the first discharge ignition



t = 33 ms 0 ms +33 ms +100 ms +133 ms

Fig. 4. Rapid development of the flashover on the composite insulator, t time measured from the first discharge ignition (flashover)

The results of the measurements are surprising and contradict the well-known fact that a water-repellent surface under wet conditions has a higher electrical strength than a wet hydrophilic surface.

4. Discussion

4.1. Koppelmann model

The first tests of porcelain long-rod insulators under the artificial rain were carried out in Germany in the 1930s. Koppelmann studied the effects of the diameter, distance and inclination of the sheds and proposed an equation for the flashover voltage under the artificial rain with a water precipitation of 3 mm/min and a water conductivity of 100 μS/cm [10]:

$$U_{\text{Wet}} = 3.9 \sum \text{Dry} + 1.1 \sum \text{Wet}, \tag{1}$$

where: U_{Wet} is the flashover voltage of a long rod insulator (kV), Dry is the length of the air discharges bypassing the protected parts of the insulator (cm), Wet is the leakage distance wetted by rain (cm) (Fig. 5).

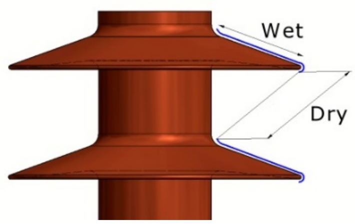


Fig. 5. The method of determining the length of Wet and Dry sections in Koppelmann equation

Similar equations proposed by Steyer, Kull and Boening are also known [10]. Assuming that the wet part is 21 cm long and the dry part is 24 cm long, the flashover voltage calculated from Formula (1) is equal to 117 kV. This value is higher than 108 kV measured for a porcelain insulator at a precipitation of 1.5 mm/min. Observation of the insulator tested under the artificial rain suggests that three zones can be distinguished in the leakage distance: Dry, Wet (water film) and Intermediate I (separate droplets). Assuming that the electric strength of the intermediate zone is 2 kV/cm [11], the Koppelmann equation can be modified to the form:

$$U_{\text{Wet}} = 3.9 \sum \text{Dry} + 1.1 \sum \text{Wet} + 2.0 \sum I. \tag{2}$$

On the porcelain insulator, the intermediate zone only covers a small strip on the shank, and therefore has a little effect on the flashover voltage.

4.2. Obenaus model

The Obenaus model can be used to calculate the flashover voltage of the insulators under the artificial rain. This model was proposed in order to describe the pollution flashover, and it assumes that a single arc burns on a narrow strip. In this simplified case, the critical flashover voltage can be represented as follows:

$$U_c = A^{\frac{1}{n+1}} \cdot r_p^{\frac{n}{n+1}} \cdot L, \tag{3}$$

where: U_c is the critical voltage (kV), A, n are the dimensionless arc constants, L is the leakage distance (cm), r_P is the resistance of the pollution layer per unit length (kΩ/cm).

The line insulator is a three-dimensional figure and the r_P resistance is a function of its height. The unit surface resistance (or a surface conductivity) can be calculated from the value of the total resistance of the pollution layer and the coefficient of the insulator shape f.

$$U_c = A^{\frac{1}{n+1}} \cdot \kappa_s^{\frac{n+1}{n}} \left(\frac{f}{L}\right)^{\frac{n}{n+1}} \cdot L, \tag{4}$$

where: f is the dimensionless form factor of an insulator, κ_S is the surface conductivity (μS).

The shape of the insulator in Eq. (4), represented by the form factor and a surface conductivity, is taken into account in a simplified manner. It is assumed that the pollution layer is uniform and that only one arc burns on the insulator. However, several arcs usually burn, so the current concentration near the arc foot and the multiple dry bands along the leakage distance should be taken into account [12]. More advanced models for the calculation of the flashover voltage of insulators under rain conditions were designed by Streubel [13] and Gorur [14].

Surface conductivity under the artificial rain test is approximately 1 μS. With such small surface conductivity values (and low current), the arc parameters A and n must be determined. They are different from the parameters of the arc burning on a heavy polluted insulator.

4.3. Influence of insulator diameter

Erler conducted the first studies on the effect of the insulator diameter on its pollution flashover voltage [15]. The unit resistance r_p in (3) decreases with an increase in an insulator diameter, and therefore the flashover voltage also decreases. The formula for the flashover voltage of relatively thin cylinder-shaped insulators (without sheds) is very simple. On such an insulator, only one arc is burned (no parallel arcs) if its circumference is shorter than 2/3 of its height. In this case, the flashover voltage can be calculated from a very simple equation [12].

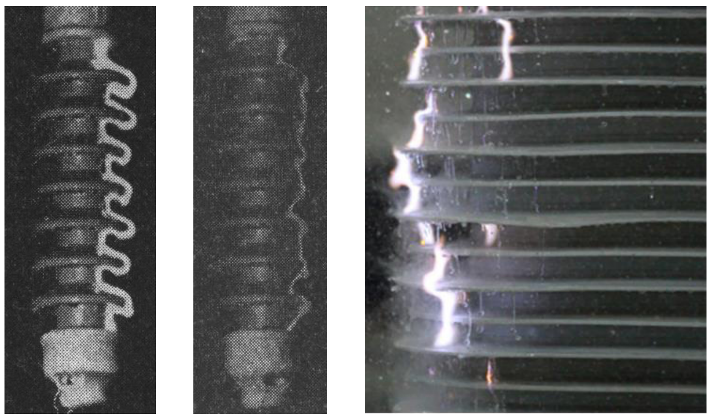
$$U_F = 1.6 \cdot D^{-0.25} \cdot \kappa_S^{-0.25} \cdot L, \tag{5}$$

where: U_F is the flashover voltage (kV), L is the cylinder length (cm), D is the diameter (cm).

Consider two types of insulators with the same leakage distance: the porcelain with shed diameters of 15 cm and a shank diameter of 7.5 cm, and a similar composite insulator with shed diameters of 13 cm and a shank diameter of 2.5 cm. Their equivalent diameters are 10.7 cm and 7.25 cm, respectively. Using Eq. (5), it can be estimated that the flashover voltage of the insulator with the smaller diameter is 10% higher. The well-known fact that the flashover voltage of composite insulators under polluted conditions is 30% higher than the flashover voltage of porcelain insulators is due partly to their different shapes. Moreover, only 20% is due to the hydrophobic properties of the silicone rubber.

4.4. Water cascading

The so-called effective leakage distance of an insulator depends on the degree of pollution. This behavior is shown in photos of the porcelain insulator flashover under the rain test with the standard precipitation of 3 mm/min carried out by Hari Streubel. When the water conductivity was low (150 μS/cm), the arc developed along the insulator surface (Fig. 6(a)). When the water conductivity was 2100 μS/cm, the arc length was shorter and the effective leakage distance was smaller than the real leakage distance of the insulator (Fig. 6(b)).



(a) (b) (c)

Fig. 6. Flashover on a porcelain insulator in the negative half-period of the test voltage: (a) U = 135 kV, a water conductivity of 150 μS/cm; (b) U = 87 kV, a water conductivity of 2100 μS/cm [6]; (c) DC arc propagation along the composite post with a large diameter under a rainfall intensity of 10 mm/min [16]

During rain, the water collected on the sheds can run off as single drops. When the intensity of the rain is high and the distance between the sheds is small, the water column can sometimes bridge the adjacent sheds. A water cascade can initiate an arc that burns between the sheds' edges (Fig. 6(c)). This phenomenon significantly reduces the flashover voltage. The use of booster sheds with a diameter larger than the diameter of the sheds interrupts the development of the water cascade and significantly increases the flashover voltage [17, 18].

In extreme cases, the water cascade can shorten the flashover path to the dry arcing distance (Fig. 7), which means that the flashover can develop from the air breakdowns between the edges of the sheds. In this case, the flashover voltage calculated from (1) is reduced from 117 kV (calculated in paragraph 4.1) to 86 kV.

Different flashover development rates on porcelain and silicone insulators have been documented before. The discharges on the polluted porcelain insulator develop slowly, and the current gradually increases for 0.3 seconds until the flashover (Fig. 8(a)). However, a flashover on the silicone insulator probably involves air breakdowns between the sheds, which are initiated by the water cascade. The flashover on the polluted silicone insulator occurs very quickly, and the current of only 50 ms after ignition reaches the value 5 A of the short-circuit current (Fig. 8(b)). Rapid flashovers, known as "sudden flashovers", on polluted silicone rubber insulators have already been tested in the laboratory [20]. These studies, however, concerned polluted composite

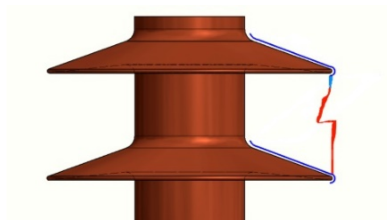


Fig. 7. Breakdown triggered by a water cascade

insulators, and used the wetting with the clean fog (steam fog) method. On the other hand, the authors' research concerns clean porcelain and composite insulators tested under an artificial rain.

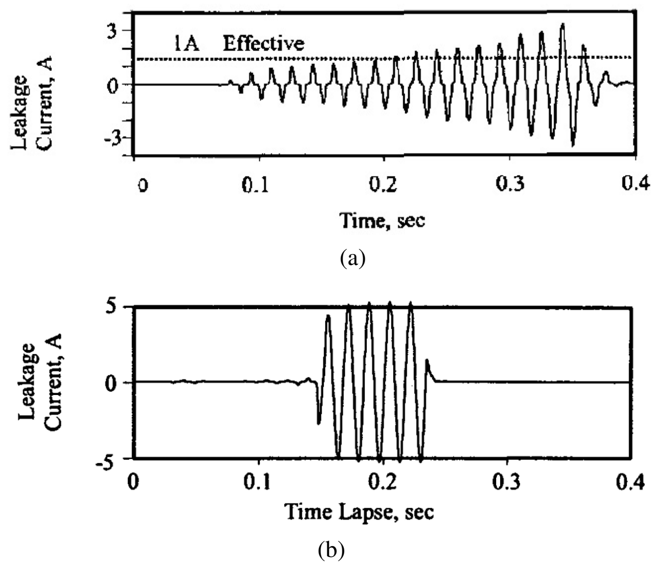


Fig. 8. Leakage current on the polluted long rod porcelain insulator (a) and on the polluted composite insulator, ESDD = 12 mg/cm^2 (b) [19]

The measured flashover voltages are surprising, and the authors did not find papers publishing similar results in the available literature. Hartings observed discharges on hydrophilic and hydrophobic post insulators by means of an UV camera [21]. He measured the electrical field close to the insulator, and also the capacitive and resistive components of leakage current. On the hydrophobic insulator, the capacitive field distribution was observed, which is similar to the field distribution under dry conditions. However, the highest applied voltage of 170 kV was about two times lower than the flashover voltage. Wang and Liang conducted tests of medium-voltage silicone insulators under the artificial rain with an intensity of 1.5 mm/min [22]. Half of the silicone insulators were pretreated immediately before the test to a temporally hydrophilic status by applying a dried kieselghur. With a water conductivity of 100 μS/cm, the flashover voltage of the hydrophobic insulator was 115 kV and was only 5% higher than the flashover voltage of the hydrophilic insulator.

Undoubtedly, our results are important in terms of the insulator flashover theory. However, they are not of a practical importance and do not undermine the importance of the hydrophobic properties of silicone insulators. The resulting flashover voltages of the order of 100 kV are very high when compared to the operating voltages. These insulators work on the 24 kV line with a phase voltage of only 14.5 kV. In the event of an earth fault, the healthy phase voltage may temporarily rise to the phase-to-phase voltage. Even in this case, it will be 4 times lower than the measured flashover voltage under artificial rain. Only with intense contamination (ESDD = 0.2–0.4 mg/cm^2) does the electrical strength drop to a dangerously low values of 0.4 kV/cm [23], which at the leakage length of 61 cm gives the flashover voltage of 24 kV.

5. Conclusions

Under the artificial rain, the flashover voltage of insulators with a hydrophobic surface is about 8% lower than the flashover voltage of insulators of identical shape, but with a hydrophilic surface.

The observed effect is caused by a sudden flashover on silicone insulators initiated probably by a water cascade bridging the space between adjacent sheds.

However, the flashover voltage is about 4 times higher under standard artificial rain than the operating voltage, and therefore under field conditions this effect is not very important.

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