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Calculation of leakage current density of silicone rubber insulators under accelerated aging conditions

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ABSTRACT

The paper presents two different methods to calculate the current density along silicone rubber (SiR) insulator surface under salt-fog testing conditions. The first method which is based on field theory approach uses the commercial software COMSOL® to compute the current density. The conductivity of the contamination layer used in the calculations was extracted from the measured equivalent salt deposit density (ESDD) separately for different regions of the insulator surfaces. The second method is based on circuit theory approach. The insulator surface was divided into different sections for resistance calculations to account for different contamination levels. Rankings based on the calculated current densities based on segmentation of the insulator surface for ESDD measurements match with those extracted from measured leakage currents.

1. Introduction

It is well known that aging, which leads either to tracking/erosion or to flashover under contaminated conditions at normal operating voltage, is still the main cause of failures for non-ceramic insulators [1]. Although considerable work has been done with regards to new material compositions to resist aging, and understanding the mechanism of aging [2,3], there exist only few investigations to study the influence of the non-ceramic insulators profile both theoretically and experimentally on their aging performance [4,5]. On the other hand, several studies have been conducted to understand the effect of the insulator profile on ceramic insulators. In desert conditions, and with respect to shed profile, open profile, or aerodynamic designs have performed well, whereas, in fog conditions, insulators with more corrugated ribs (fog insulators) have been employed. In addition, the shed spacing to shed diameter ratio, the shed inclination angle, and the protected creepage distance are other profile parameters that have been examined [6,7].

LC is one of the most important causes of aging in non-ceramic insulators. When a large LC bridges the two ends of the insulator, flashover occurs. While several attempts have been reported to measure the LC at both field and laboratory investigations, few studies have been conducted to calculate the LC on non-ceramic insulators' surfaces. The effect of shed diameter, shed angle and rod diameter on surface resistance and hence on current density were calculated for non-ceramic insulator profiles based on circuit theory by Young et al. [8,9]. It was found that the surface resistance dropped with increased shed diameter, and the shed angle had only a small effect in reducing the surface resistance. However, in their computations the authors assumed that the surface resistance was uniform as it was assumed to have uniform wetting of the insulator surface, which is contrary to what has been observed in the field or in laboratory studies. The experimental studies show that there is a significant difference in wetting of the upper and lower surfaces of the insulator sheds [10].

As the insulator ages in the field, the quantity of pollution on its surface increases. The most frequently measured and well-accepted parameter to quantify the level of contamination of insulator surface is the equivalent salt deposit density (ESDD) [10]. As such ESDD has been used in pollution performance studies. A correlation has been found between the ESDD and the leakage impedance of ceramic insulators [11]. However, no such studies have been performed to correlate ESDD with the surface resistance for non-ceramic insulators [12].

The paper presents two different approaches to calculate the leakage current density on polluted non-ceramic insulator surfaces of different profiles. The first method is based on field theory, which uses the finite element based simulation technique. The second approach is based on circuit theory and uses the approach considered in the earlier work by Young et al. [8]. Both methods use the independently measured ESDD for upper and lower regions of

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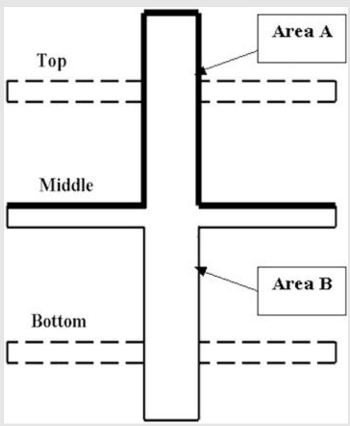
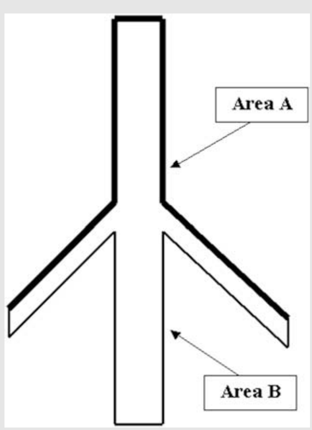
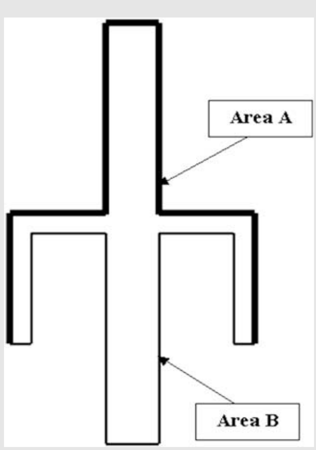
the insulator surfaces for calculating the surface resistances separately.

2. Materials and methods

2.1. Simulation method

The two approaches investigated to calculate the leakage current density along the polluted non-ceramic insulator surfaces are described in brief. The first approach is based on the field theory. Finite element method software, COMSOL®, was used for calculating the current density. The relative permittivity (ε_r) for SiR material was set to 3.6 while its conductivity is set to 10^{-15} S/m. The thickness of the wet layer was set to 0.5 mm. The number of triangles, especially in the areas of interest, was increased till a steady state solution is achieved. For all simulation cases, quasi-static and axi-symmetry options were selected and the potential for the outside boundaries was set to zero. The electric field and current density were calculated by the following equations:

Table 1
Tested cases for single-shed design.

Design No.	Shed Profile	Shed Position	Shed Inclination Angle (degree)	Shed Diameter (mm)
1		Top	0	80
		Middle	0	40
		Middle	0	60
		Middle	0	80
		Middle	0	100
		Bottom	0	80
2		Middle	20	80
		Middle	50	80
		Middle	50	100
3		Middle	0	100

$$\nabla^2 V = 0, \tag{1}$$

$$E = -\nabla V, \tag{2}$$

and

$$J = \sigma E. \tag{3}$$

Unlike in previous work [8,9], the wet layer was divided into two different sections for the single-shed design, and three different sections for the other designs as indicated in Tables 1–3. The salt deposited on the surface of each area was washed with de-ionized water, and the conductivity of the washed water was measured using a conductivity meter. The salt deposit density was calculated by using the following formulas [16]:

$$\sigma_{20} = \sigma_T[1 - b(T - 20)], \tag{4}$$

$$S_a = (5.7\sigma_{20})^{1.03}, \text{ and} \tag{5}$$

$$S_{\mathrm{dd}} = (S_{\mathrm{a}}V/A) \tag{6}$$

Where:

σ_{20} is the layer conductivity at a temperature of 20 °C (in S/m); σ_T is the layer conductivity at a temperature of T °C (in S/m); Sa is the layer salinity (in kg/m^3);

Table 2
Tested cases for two-shed design.

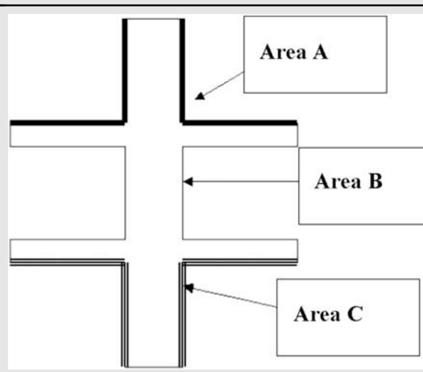
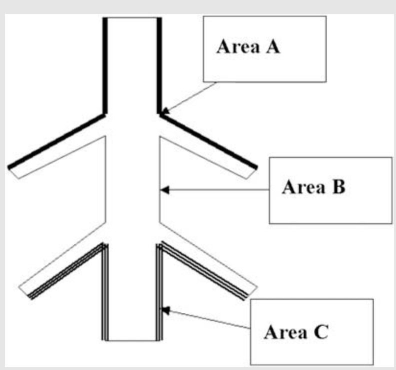
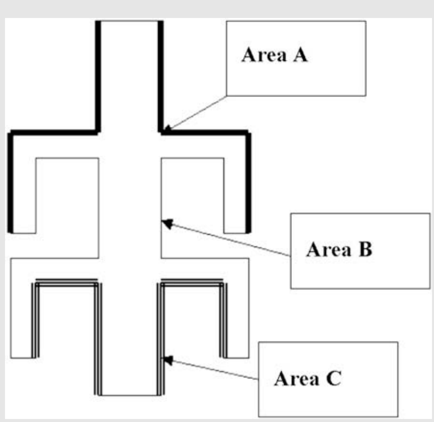
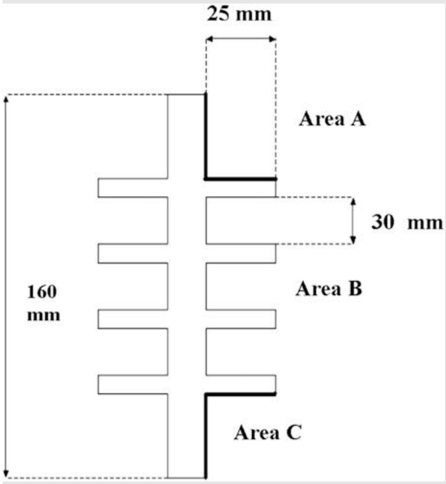
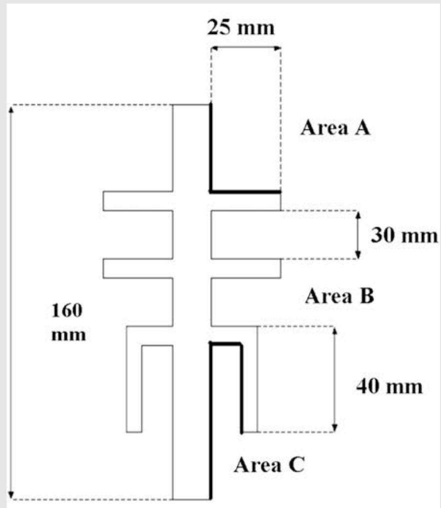
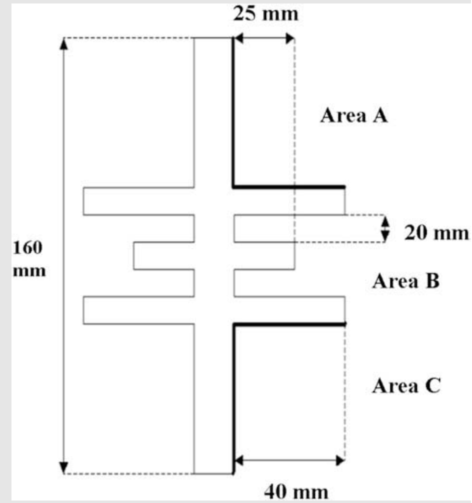
Design No.	Shed Profile	Shed Diameter (mm)	Shed Spacing (mm)
1		100	80 50 30
2	Same as design No. 1	80	60 36
3	Same as design No. 1	60	45 27
4		100	50
5		100	50

Table 3
Tested cases for 15-kV design.

Design No. 1	Design No. 2	Design No. 3
		

S_{dd} is the salt deposit density (in mg/cm^2); T is the temperature of the insulator surface (in C);
b is a factor depending on temperature; V is the volume of the slurry (in cm^3);
A is the area of the cleaned surface (in cm^2).

By dividing the insulator surface into separate regions, it allows in accounting for the difference in wetting, hence the accumulation of pollutants on the surface.

The second approach is based on the circuit theory model developed by Young et al. [8]. The surface resistance derived by Young et al. is as follows:

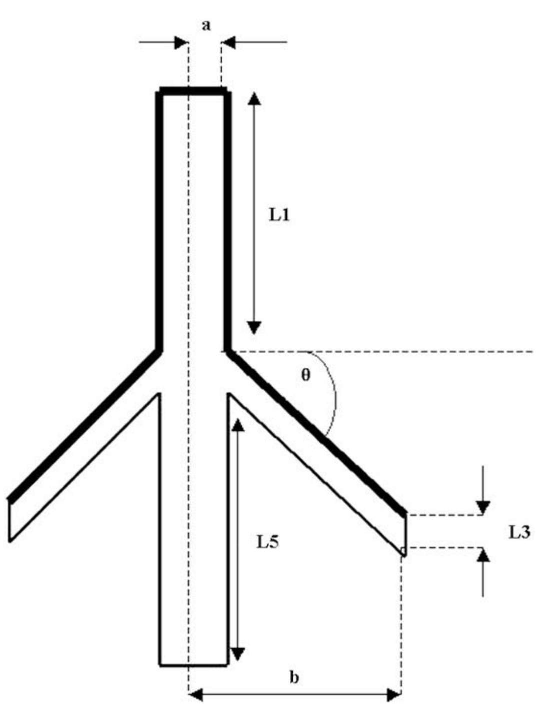


Fig. 1. Schematic diagram of a sample insulator for single-shed design with inclined profile showing all the dimensions for calculating the surface resistance.

$$R = \left(\frac{1}{2\pi t}\right)\left\{\left(\frac{1}{\sigma}\right)\left(\frac{L1+L3+L5}{a}+\frac{2}{\cos(\theta)}\ln\frac{b}{a}\right)\right\} \tag{7}$$

Where: σ is the surface conductivities, t is the thickness of the pollution layer and the other parameters are shown in Fig. 1.

However, in our work, the surface resistance for each section of the insulator is calculated separately using the ESDD values for the respective sections as described earlier.

For single-shed design, the modified formula to calculate the surface resistance is as follows:

$$R = \left(\frac{1}{2\pi t}\right)\left\{\left(\frac{1}{\sigma_1}\right)\left(\frac{L1+L3}{a}+\frac{1}{\cos(\theta)}\ln\frac{b}{a}\right) + \left(\frac{1}{\sigma_2}\right)\left(\frac{L5}{a}+\frac{1}{\cos(\theta)}\ln\frac{b}{a}\right)\right\} \tag{8}$$

Where: $\sigma 1$ and $\sigma 2$ are the surface conductivities for sections I and II respectively, t is the thickness of the pollution layer and the other parameters are shown in Fig. 1. After calculating the surface resistance, the current density can be calculated using Ohm's law. For

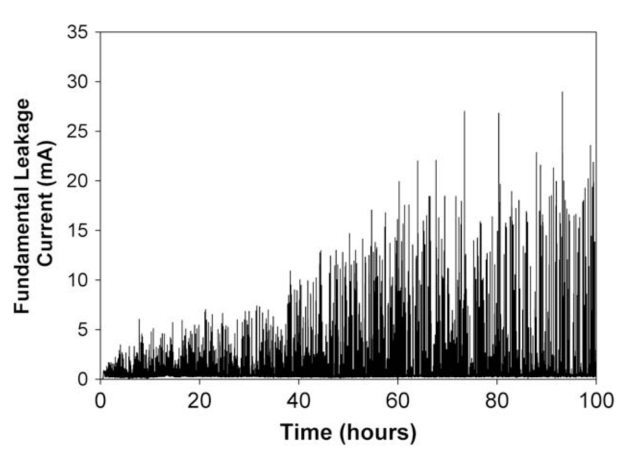


Fig. 2. Fundamental component of LC as a function of time measured during salt-fog test.

Table 4
Measured ESDD for different samples of single-shed design.

Shed diameter	Shed position	ESDD	
80	Top	0.055	0.12
40	Middle	0.21	0.22
60		0.073	0.29
80		0.053	0.26
100		0.062	0.15
80	Bottom	0.21	0.21

designs with more than one shed, equation (8) was modified appropriately.

2.2. Salt-fog tests

Samples of the physical dimensions given in Tables 1 and 2 were prepared using silicone rubber. The samples consist of a sleeved high temperature vulcanized (HTV) silicone rubber (SiR) rod and either a single or two-moulded room temperature vulcanized (RTV) SiR sheds. The sample insulators were tested in salt-fog and the leakage current was measured continuously. The current density is calculated by dividing the LC average value during salt-fog test with the insulator surface area. The salt-water flow rate was 1.5 L/min with the air pressure of 0.35 MPa and the water conductivity was selected to be 0.25 S/m. Such relatively low water conductivity was selected to ensure that the arcing will be on the insulator surface [13,14]. A 15-kVA single-phase distribution transformer (480 V/16 kV) with leakage reactance of 4% was designated as the high voltage source. The test was conducted for 100 h and the fundamental component of leakage current was recorded once in every 30 s.

3. Results and discussion

The leakage current density along the insulator surfaces were both measured and calculated. A typical leakage current measurement curve during salt-fog test is depicted in Fig. 2. In this study only the average value of the leakage current will be considered and compared with the calculated value.

As mentioned earlier, first the ESDD measurement was conducted along the insulator surface. The single-shed test sample was divided into two sections (areas A and B, Table 1) while the other designs' samples were divided into three sections (areas A, B and C, Tables 2 and 3). Samples of the results for the ESDD measurement for both single and two-shed designs are shown in Tables 4 and 5 respectively. It is very clear from both tables that the distribution of ESDD is not even along the insulators' surface and hence the distribution of conductivity. The measured ESDD values for the bottom part of the insulator, area B in single-shed design and area C in the two-shed designs, compared to the rest of the insulator was higher for certain cases by 400%, Tables 4 and 5. This distribution agrees with the visual observations during the salt-fog test as more arcing concentrated at the bottom part of the insulators [15].

Table 5
Measured ESDD for different samples of two-sheds design.

Shed diameter	Shed spacing	ESDD		
		Area A	Area B	Area C
100 mm	80 mm	0.015	0.036	0.072
	50 mm	0.010	0.038	0.12
	30 mm	0.009	0.022	0.079
80 mm	60 mm	0.03	0.08	0.079
	36 mm	0.024	0.074	0.079
60 mm	45 mm	0.053	0.12	0.33
	27 mm	0.056	0.15	0.20

Table 6
Calculated and measured current densities for single-shed design.

Shed Diameter in mm (Middle Shed Position)	Experimental (Per Unit)	Simulation Results (Per Unit)		
		Field Theory	Circuit Theory	Young et al. [6,7]
40	1	1	1	1
60	0.33	0.64	0.31	0.69
80	0.32	0.67	0.28	0.62
100	0.087	0.45	0.19	0.56
Shed Position (80-mm Shed Diameter)				
Top	0.26	0.48	0.40	1.0
Middle	0.33	0.65	0.42	1.0
Bottom	1.0	1.0	1.0	1.0
Shed Profile (80-mm Shed Diameter)				
0 – degree	1.0	1.0	1.0	1.0
20 – degree	0.37	0.47	0.67	0.99
50 – degree	0.20	0.41	0.63	0.98
Shed Profile (100-mm Shed Diameter)				
0 – degree	1.0	1.0	1.0	1.0
50 – degree	0.49	0.77	0.46	0.92
Cup design	0.29	0.70	0.46	0.92

The calculated current densities using both methods described earlier along with those estimated average values from measurements are shown in Tables 6–8. For comparisons, the calculated current densities using the approach by Young et al. [8] are also listed.

Instead of comparing the absolute values based on the magnitudes, the various designs of insulator profiles considered in this study are ranked and compared based on the measured and calculated current densities independently. From Tables 6–8, it can be noted that the rankings of the different insulators based on field theory approach are in the same order as those measured for all tested samples. For example, for 15-kV class insulator, design no. 1 had the highest level of LC current both experimentally and based on field theory. On the other hand, design no. 2 had the lowest level of both measured and calculated level of LC.

Rankings based on circuit theory approach also match with those measured only when the proposed correction based on ESDD for different sections is applied. For example, for single-shed design, regardless of the shed position, all the calculated current densities are the same when uniform wetting was assumed. This is because the conductivity was assumed uniform

Table 7
Calculated and measured current densities for two-shed design.

Shed Spacing in mm (100-mm Shed Diameter	Experimental (Per Unit)	Simulation Results (Per Unit)		
		Field Theory	Circuit Theory	Young et al. [6,7]
80	0.29	0.53	0.32	0.82
50	0.19	0.36	0.23	0.82
30	0.15	0.32	0.17	0.82
Shed Spacing in mm (80-mm Shed Diameter)				
60	0.36	0.57	0.53	0.91
36	0.27	0.44	0.42	0.91
Shed Spacing in mm (60-mm Shed Diameter)				
45	1.0	1.0	1.0	1.0
27	0.93	0.90	0.94	1.0
Shed Profile (100-mm Shed Diameter, 50-mm Shed Spacing)				
0 – degree	1.0	1.0	1.0	1.0
50 – degree	0.48	0.88	0.34	0.85
Cup design	0.18	0.76	0.33	0.76

Table 8
Calculated and measured current densities for 15-kV design.

Design No.	Experimental (Per Unit)	Simulation Results (Per Unit)		
		Field Theory	Circuit Theory	Young et al. [6,7]
1	1.0	1.0	1.0	0.91
2	0.16	0.45	0.16	0.84
3	0.22	0.48	0.25	1.0

over the insulator surface, and the surface area remained same irrespective of the shed position. Whereas, if the correction is applied to account for the differences in the salt deposition, the rankings based on circuit theory approach also compare well with those measured like the rankings based on field theory approach.

While the ranking of the designs matches very well between the field theory and measured LC, the actual level of LC does not match properly. This could be attributed to several factors like:

- The measured LC is the average value of LC during the whole 100 h. During the test the surface conductivity of the insulator will be continuously changing. However, the conductivity used for the calculation is the one measured at the end of the test.
- The thickness of the conductive layer on the insulator surface where assumed constant, but in real life it will be changing.

Although it has been previously reported that the ESDD measurement may not be suitable to be used as an index for non-ceramic insulators surface resistance measurement, the results presented in this paper show a good correlation between ESDD and leakage current measurement. This is because once the hydrophobic property of SiR insulators is lost in salt-fog, the SiR insulators act more like the ceramic insulators and hence the ESDD can be correlated with the surface resistance [11]. However, if the hydrophobic nature of the SIR insulator exists, which prevents the formation of continuous path for leakage current, the measured ESDD may not represent the actual conductive surface on the insulator.

Finally, it has been observed that when a failure occurs to the insulator, the level of ESDD may not reflect the severity of the LC because part of the deposited salt might have been wiped out due to the complete erosion of the insulator. For example, for single-shed insulator, the level of LC for the 40 mm shed diameter is the highest compared to the other three designs as shown in Fig. 3. However, the level of the ESDD at the bottom part was found to be 0.22 which is less than other insulators, Table 4. Complete damage to the bottom and top part of the insulator as shown in Fig. 4 has lead to the low level of ESDD. So, whenever there is significant erosion to the insulator surface, the level of ESDD may not correlate properly with the level of LC.

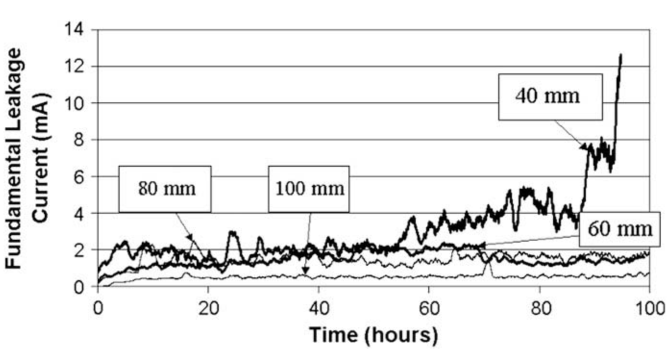


Fig. 3. The level of LC for different single-shed designs during 100 h salt-fog test.

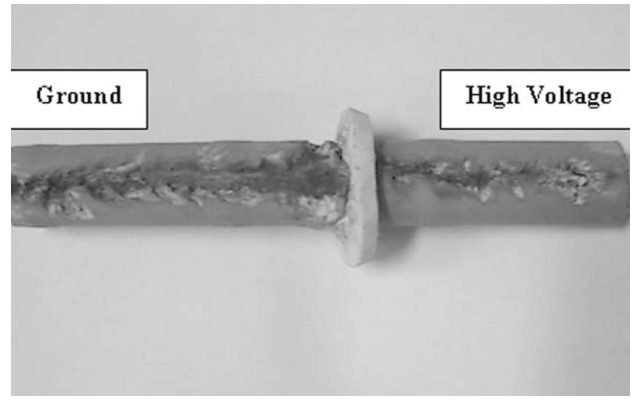


Fig. 4. 40 mm diameter single-shed insulator after 100 h salt-fog test.

4. Conclusions

- ESDD measurement by segmenting the insulator surface into different sections provides more insight into salt deposition as arcing leads to the damage of the insulator surface, which further enhances the salt deposition.
- Precaution should be taken while using the measured ESDD as an index for conductivity as the level of the measured salt on the insulator surface will be less in the case of failed insulator.
- The calculated current densities on wet and polluted surfaces using both field theory and circuit theory approaches agree with those measured when corrected conductivity for pollution layer is obtained from the proposed ESDD values for different sections of the insulator.

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