AC Flashover Voltage Model for Polluted Suspension Insulators and an Experimental Investigation in Salt Fog

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Abstract: In recent years, the electrical performance of polluted suspension insulators operating in coastal foggy regions has attracted wide attention because of the occurrence of flashover. Surface wetting by salt fog accretion increases the surface conductivity and degrades the flashover voltage of insulators. Normally, the effect of conductivity under fog condition and pre-contamination on the flashover of polluted insulators are analyzed separately. Therefore, this does not reveal the flashover characteristic in salt fog, which requires further research. This paper describes salt fog experiments with an AC test voltage conducted using suspension insulators in a 110-kV power system. The electrical strength performance of insulators with salt fog treatments is analyzed, and the effects of salt deposit density (SDD) and the fog water conductivity (FWC) on the flashover of three types of suspension insulators are studied. The concept of additional SDD is proposed to quantify analyze the effects of salt fog. The results show that there is less dependence on FWC at higher pollution levels than at lower pollution levels. That is, the effect of FWC on 50% AC flashover voltage ($U_{50}$) can be neglected for SDD >0.15 mg/cm$^2$, whereas FWC has a strong effect on $U_{50}$ for SDD <0.15 mg/cm$^2$. FWC has a greater influence on $U_{50}$ of ceramic insulators than on that of silicone rubber insulator. A model for calculating the critical flashover voltage of insulators is proposed by considering the combined effect of FWC and pre-polluting SDD.

Index Terms: Insulator, fog accretion, additional salt deposit density, pollution level, flashover voltage.

Abbreviation

- SDD: salt deposit density
- ESDD: equivalent salt deposit density
- FWC: fog water conductivity
- FV: flashover voltage
- NSDD: no soluble deposit density
- $U_{50}$: critical flashover voltage
- SDD$_t$: total equivalent salt deposit density

I. INTRODUCTION

Flashover in polluted insulators endangers the safe and stable operation of power systems [1], [2]. Due to atmospheric pollution, contamination accumulates on the surface of insulators that operate in outdoor environments. After long exposure, the contamination on the insulator surface can be severe. The long-term reliability of electrical insulation becomes uncertain in the event of water or air contamination; namely, the pollution affects the electrical performance of power transmission equipment when subjected to adverse weather conditions [3], [4]. In most coastal areas, the collision of seawater and the rising and falling tides of the coast cause salt droplets and bubbles in seawater to diffuse in the air, eventually forming salt fog. In southern China, a large number of suspension insulators have been installed in coastal areas with a salt fog environment, and the researchers have observed some performance changes in these insulators [5]. Environmental problems caused by urban modernization and
industrial development may also be severe. Therefore, salt fog and haze fog frequently occur together, reducing the outdoor insulation performance of power equipment. There has been a decrease on the flashover voltage of insulators in salt fog, and salt fog is known to have an effect on this downward trend [6]. Moreover, shed surface wetting by salt fog accretion increases the surface conductivity and degrades the flashover voltage of insulators [6], [7]. Therefore, the flashover performance of insulators in salt fog should be considered in the design stage of power lines.

On the standards of IEC 60507 and IEEE Std. 4-2013, the contamination is categorized into the solid pollution and the highly conductive liquid electrolytes, which are the main pollution components accreted on the insulator surfaces [8]–[10]. The solid pollution, normally with a non-soluble component, is most often associated with inland, desert or industrially polluted areas. When a dry slat layer forms and then rapidly becomes wetted by dew, mist fog or drizzle. The highly conductive liquid electrolytes are frequently associated with coastal areas where saltwater or conductive fog is deposited onto the insulator surface or other pollution sources such as crop spraying, chemical mists or acid. During adverse weather, particularly the haze or salt fog, a large number of tiny water droplets or aerosol particles are suspended in the air, which contain certain amounts of soluble salts. Deposition of the soluble salts on insulators surface leads to the increase of soluble salt on its surface, making the flashover more likely to happen in the high humidity and moisture condition [11]–[13].

The electrical insulation problem of polluted insulators in China and abroad has been studied for some time [14]. Previous results show that FV is influenced by several factors, such as the pollution level, insulator parameters, atmospheric pressure, temperature [15]–[17]. The general relation between FV and ESDD can be represented by a power curve [18], [19], as can the relationship between FV and the NSDD [20]. The effect of air pressure on FV can be written as a power function, showing that FV decreases as the air pressure decreases [21], [22]. FWC is the key parameter in simulating the influence of salt fog or haze fog on the outdoor insulation performance: the relationship between FV and FWC can also be represented by a power curve, such as \( U = B \times \gamma^{20} \) [23] or \( U = B \times e^{-b \gamma^{2}} \) [14], where \( B \) is a coefficient related to the insulator geometry and material, \( b \) is an exponent related to FWC, and is taken as 2.718. The leakage current can be used to estimate the pollution degree and predict the flashover voltage of insulators, as well as to monitor the insulation performance under salt fog conditions [24], [25].

To date, the effect of conductivity on flashover under fog conditions has not been fully considered, despite its importance, especially in typical salt fog environments. Normally, the effect of FWC and pre-contamination on the flashover of polluted insulators are analyzed separately, but this does not reveal the flashover behavior in salt fog [6], [14]. The effect of salt fog cannot be quantitatively estimated. Moreover, it seems more appropriate to study the flashover characteristics of insulators by considering the combined effects of FWC and the pre-polluting SDD, as this is closer to the operating conditions than clean fog. Flashover in salt fog is treated as a new kind of flashover, and the underlying connection between fog flashover and pollution flashover is ignored.

The key influences of salt fog or haze fog on the flashover performance of polluted insulators is to enhance the degree of pollution on insulators surface and wet the contamination layer. In this paper, the concept of additional SDD is proposed to quantitatively analyze the effect of salt fog on pollution severity. Common methods of analyzing the pollution flashover characteristics can be applied in salt fog. In addition, the introduction of additional SDD reveals that the fog flashover is a special kind of pollution flashover. A large number of tests are carried out on porcelain, glass and composite insulators under salt fog conditions. The changes in \( U_{50} \) and SDD are studied, and the influence of salt fog is analyzed. The results provide a valuable reference for the selection and design of outdoor insulation layers in coastal areas and areas that are frequently afflicted by salt fog and haze. They will also be useful during the insulation coordination process in the design stage of transmission equipment.

II. EQUIPMENT, SPECIMENS AND METHODS
A. EQUIPMENT

Fig. 1 shows a circuit diagram in which the voltage supply components are a TDTY-10kV/100A variable-voltage auto-regulator (T) and a YDJ-900/150 test transformer (B). The technical parameters of the voltage supply comply with the requirement introduced by the relevant testing standards [8]–[9]. In this circuit, S represents the test objects, H represents a wall bushing, and F is an AC capacitive voltage divider with a ratio of 10 000:1 (the ratio of capacitance at the high capacitor \( C_{1} \) to capacitance at the low terminal \( C_{2} \)).

B. SPECIMENS

The specimens are one silicone rubber composite insulator FXBW-35/70 (Type A) and two seven-disk ceramic insulators, i.e. XP-160 (Type B), LXY-160 (Type C). The dimensions and geometry of the specimens are presented in both Table 1 and Fig. 2, where \( h \) is the unit spacing, \( D \) and \( d \) are the big and small shed diameter, respectively, \( L \) is the leakage distance, and \( A \) is the surface area.
TABLE 1. Insulator parameters.

| Type | Unit spacing (h, mm) | Shed diameter (D/d, mm) | Leakage distance (L, mm) | Surface area (A, cm²) |
|------|---------------------|------------------------|--------------------------|----------------------|
| A    | 670                 | 150/100                | 1100                     | 2586                 |
| B    | 155                 | 255                    | 305                      | 1691                 |
| C    | 146                 | 280                    | 380                      | 2098                 |

C. TEST METHODS

1) POLLUTING INSULATOR

The specimen surfaces are initially cleaned carefully with deionized water and trisodium phosphate (Na₃PO₃), and then allowed to dry naturally. Pollution was applied to the specimen surfaces using quantitative brushing method, in which sodium chloride and kieselguhr provide the conductive and inert materials, respectively [6], [8], [9]. ESDD ranged from 0.03-0.30 mg/cm² in order to simulate pollution levels from light to heavy, and the ratio of ESDD and NSDD is 1/6 [6], [8], [23].

2) WETTING PROCEDURE

Once the contamination layer on the insulator surface was totally dry, the specimens were mounted vertically in the center of an artificial chamber [7]. The cold fog method was applied to study the flashover performance of polluted insulators [6], [14], [23]. The contamination layer on the insulator surface was wetted using four YC-G030T ultrasonic fog generators, which were placed at the four corners of the artificial fog chamber. FWC was measured by the DD810-E conductivity meter to an accuracy of ±1 µS/cm. The natural FWC can reach 3.080 mS/cm in seriously polluted districts, 0.457 mS/cm in suburbs, and 0.076 mS/cm in outer suburban districts [14]. In view of FWC of areas with low regional pollution and high industrial pollution, FWC ranged from 0.01-3.00 mS/cm in the experiments, as measured at 20°C ambient temperature.

3) CRITICAL FLASHOVER VOLTAGE

The 50% AC flashover voltage stresses were obtained by the up-and-down method, as recommended by IEC-60507 [8]. In this method, the contamination layer on the insulating surface is applied over a period of time, and then the surface is totally wetted by cold fog. The applied voltage level is then maintained for 30 min or until flashover. Then, the estimated test value was increased or decreased by one step depending on whether the last test result was withstanding (about 15 min) or flashover. If the insulator withstands this voltage, it is retested at a higher voltage. If a flashover occurs, the insulator is retested at a lower voltage. The step of each voltage increases or decrease was about 5% of the initial voltage. Each insulator string was only tested to flashover or withstand once. Typically, the critical flashover voltage ($U_{50}$, kV) is given by ‘valid’ tests (>10) in an up-and-down sequence. The formula for $U_{50}$ with a relative standard deviation $\sigma$ (%) is derived as follows:

$$U_{50} = \frac{N}{\sum_{i=1}^{N} U_i}$$

$$\sigma(\%) = \frac{100\% 	imes \frac{\sum_{i=1}^{N} (U_i - U_{50})^2}{N - 1}}{U_{50}}$$

where $U_i$ is the applied voltage in the valid tests, $N$ is the numbers of valid tests.

III. RESULTS AND ANALYSES

A. RESULTS

Fig. 3 shows $U_{50}$ (kV) of the three types of insulators with SDD values from 0.03-0.30 mg/cm² as FWC ($\gamma$, mS/cm) varies from 0.01-3.0 mS/cm.

B. INFLUENCE OF SDD ON $U_{50}$

Many studies show that $U_{50}$ (kV) reduces nonlinearly with increasing SDD (mg/cm²) for various insulators. Moreover, $U_{50}$ has a general relation with SDD is derived [18], [19]:

$$U_{50} = A \times SDD^{-a}$$
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FIGURE 3. Results of the critical flashover voltage ($U_{50}$, kV) versus fog water conductivity ($\gamma$, S/cm), salt deposit density (SDD, mg/cm$^2$) for insulators. (a) Type A. (b) Type B. (c) Type C.

where $A$ is a constant for each insulator related to geometry, material and dimension, $a$ is an exponent relating SDD and $U_{50}$ varies. The value of $a$ is depending on insulator dimension, and test method including type of $U_{50}$.

According to the results in Fig. 3, the relationship between $U_{50}$ and SDD is illustrated in Fig. 4. Table 2 presents the constant $A$, exponent $a$, and correlation coefficient $R^2$ for the variation in FWC for ceramic insulators.

1) EFFECT OF SDD ON $U_{50}$

Analyzing both Fig. 4 and Table 2, the following conclusions can be stated.
1) For the same FWC, $U_{50}$ decreases nonlinearly as SDD increases. Moreover, the relation between $U_{50}$ and SDD can be expressed as a negative exponential curve, and a power curve exponent of $a$ fits the data well. The values of $R^2$ are consistently greater than 0.93.

2) The exponent $a$ relating SDD and $U_{50}$ decreases as $\gamma$ increases. That is, the variation of $U_{50}$ with SDD decreases as $\gamma$ increases, especially in high-conductivity and high-concentration fog.

3) The combined effect of increases in both SDD and $\gamma$ is to substantially reduce $U_{50}$.

2) EFFECT OF FWC ON EXPONENT

Based on Table 2, the exponent $a$ is further examined in Table 3. The relative deviation of the exponent $a$ relating SDD and $U_{50}$ is given by

$$\Delta_a \text{%} = \left| \frac{a - a_{\text{ave}}}{a_{\text{ave}}} \right| \times 100\%$$

where

- $a$ is an exponent relating SDD and $U_{50}$,
- $a_{\text{ave}}$ is the overall mean value of exponent $a$.

Analyzing both Fig. 4 and Table 3, we may conclude the following.

1) The results indicate that the relationships between $U_{50}$ and SDD can be expressed as a power curve. Moreover, the value of the exponent $a$ varies from 0.345–0.409 for the Type B insulator and from 0.324–0.380 for the Type C insulator.

2) For $\gamma$<3.0 mS/cm, a power curve with an exponent of $a$ fits the data well. Additionally, the overall mean value ($a_{\text{ave}}$) of $a$ relating the pollution level to the flashover voltage varies with a standard deviation of 0.07.

1) For the same FWC, $U_{50}$ decreases nonlinearly as SDD increases. Moreover, the relation between $U_{50}$ and SDD can be expressed as a negative exponential curve, and a power curve exponent of $a$ fits the data well. The values of $R^2$ are consistently greater than 0.93.

2) The exponent $a$ relating SDD and $U_{50}$ decreases as $\gamma$ increases. That is, the variation of $U_{50}$ with SDD decreases as $\gamma$ increases, especially in high-conductivity and high-concentration fog.

3) The combined effect of increases in both SDD and $\gamma$ is to substantially reduce $U_{50}$.
a) When SDD is less than 0.15 mg/cm², \( U_{50} \) decreases considerably as \( \gamma \) increases. When \( \Delta U_1 \% > 10\% \), FWC has a strong effect on \( U_{50} \) in areas with limited development and low pollution.

b) For example, \( \Delta U_1 \%= 25.6 \) when SDD = 0.03 mg/cm² for Type A. For higher pollution levels (SDD > 0.15 mg/cm²), \( U_{50} \) does not vary at all as \( \gamma \) varies. For example, \( \Delta U_1 \%= 25.6 \) for SDD = 0.03 mg/cm², but \( \Delta U_1 \%= 4.1 \) when SDD = 0.3 mg/cm² for Type B. That is, the results at heavy pollution levels (SDD = 0.3 mg/cm²) do not show as much dependence on FWC as those at very light pollution levels (SDD = 0.03 mg/cm²). Again, the effects of \( \gamma \) on \( U_{50} \) can be neglected in areas of high contamination.

### D. TOTAL EQUIVALENCE MODEL

FWC can be characterized by the equivalent salt content. The approximate relation between ESDD (mg/m²) and FWC (\( \gamma \), \( \mu S/cm \)) for a clean insulator is [7]

\[
ESDD = \frac{0.42 V}{A_s} \left[ \frac{\gamma}{1 + C_t (T_W - 20)} \right]^{1.039} \tag{4}
\]

where \( V \) is the fog water volume (L) of the insulator, \( A \) is the surface area (m²) for each insulator, \( T_W \) is the fog water temperature (°C), \( \gamma \) is FWC at \( T_W \), and \( C_t \) is a temperature coefficient (≈0.02 °C⁻¹).

The equivalent NaCl content (\( \beta \), mg) per gram of fog water is

\[
\beta = \frac{ESDD \times A_s}{V \times \rho} \times 10^{-3}
\]

\[
= \frac{0.42 \left[ \frac{\gamma}{1 + C_t (T_W - 20)} \right]^{1.039}}{\rho} \times 10^{-3} \tag{5}
\]

where \( \rho \) is the density of fog water at \( T_W \) (kg/L).

It is assumed that the conductive materials are distributed evenly on the wetted insulator surface by fog accretion. When the amount deposited on each wetted insulator surface by fog accretion is \( W \) (g), the equivalent NaCl content (\( M \), mg) for each clean insulator surface is:

\[
M = \beta W = \frac{0.42 \times W}{\rho} \left[ \frac{\gamma}{1 + C_t (T_W - 20)} \right]^{1.039} \times 10^{-3} \tag{6}
\]

When the amount deposited on each wetted insulator surface by fog accretion reaches \( W \), the additional equivalent salt deposit density \( SDD_w \) (mg/cm²) is

\[
SDD_w = \frac{M}{A_s}
\]

\[
= \frac{0.42 \times W}{\rho \times A_s} \left[ \frac{\gamma}{1 + C_t (T_W - 20)} \right]^{1.039} \times 10^{-3} \tag{7}
\]

If the salt deposit density of pre-contamination for each insulator surface is \( SDD_d \), then the total equivalent salt deposit density (\( SDD_t \)), which reflects the combined effect of the fog water and polluting salt deposits, can be approximated as:

\[
SDD_t = SDD_w + SDD_d
\]

\[
= \frac{0.42 \times W}{\rho \times A_s} \left[ \frac{\gamma}{1 + C_t (T_W - 20)} \right]^{1.039} \times 10^{-3} + SDD_d \tag{8}
\]

In this paper, FWC has been corrected to 20°C, and it is assumed that \( \rho = 1 \) kg/L. Thus, \( SDD_d \) is

\[
SDD_d = SDD_w + SDD_d = \frac{4.2 \times W}{\rho \times A_s} \gamma^{1.039} \times 10^{-4} + SDD_d \tag{9}
\]

Therefore, the relation between the critical flashover voltage (\( U_f \)) and \( SDD_t \) can be approximated as follows:

\[
U_f = A_d (SDD_d)^{-a_d}
\]

\[
= A_d \left( \frac{4.2 \times W}{\rho \times A_s} \gamma^{1.039} \times 10^{-4} + SDD_d \right)^{-a_d} \tag{10}
\]

### E. TEST VALIDATION

\( U_{50} \) of three types of insulators is presented in Table 5 for SDD values from 0.03-0.30 mg/cm² and values from 0.5-3.0 mS/cm.

Based on Table 5 and (10), it can be seen that the maximum relative error in the critical flashover voltage between the

### Table 5. Results of flashover voltage for specimens.

| Type | SDD, mg/cm² | \( \gamma \), mS/cm | \( U_{sd}(t) \), kV | \( U_{sd}(c) \), kV | \( \Delta \% \) |
|------|-------------|---------------------|-------------------|-------------------|----------|
| A    | 0.03        | 1.0                 | 101.7             | 101.0             | 6.8      |
|      | 0.05        | 2.0                 | 84.1              | 87.2              | 3.7      |
|      | 0.08        | 3.0                 | 74.7              | 77.3              | 3.5      |
|      | 0.10        | 0.5                 | 75.6              | 77.5              | 2.5      |
|      | 0.15        | 3.0                 | 65.8              | 67.6              | 2.7      |
|      | 0.20        | 2.0                 | 62.3              | 63.9              | 2.6      |
|      | 0.25        | 0.5                 | 60.9              | 61.3              | 0.7      |
|      | 0.30        | 2.0                 | 56.1              | 57.8              | 3.0      |
| B    | 0.03        | 2.0                 | 123.9             | 120.7             | 2.6      |
|      | 0.08        | 1.0                 | 89.8              | 92.6              | 3.1      |
|      | 0.10        | 0.5                 | 85.7              | 86.6              | 1.1      |
|      | 0.15        | 2.0                 | 68.5              | 72.7              | 6.1      |
|      | 0.20        | 3.0                 | 61.7              | 64.9              | 5.2      |
|      | 0.25        | 0.5                 | 60.7              | 61.5              | 1.3      |
|      | 0.30        | 1.0                 | 56.5              | 57.2              | 1.2      |
| C    | 0.30        | 3.0                 | 45.2              | 46.1              | 2.0      |
|      | 0.03        | 2.0                 | 106.4             | 103.6             | 2.6      |
|      | 0.08        | 0.5                 | 82.0              | 80.0              | 2.4      |
|      | 0.15        | 2.0                 | 65.6              | 60.3              | 6.7      |
|      | 0.25        | 1.0                 | 49.1              | 50.5              | 2.9      |
|      | 0.05        | 3.0                 | 83                | 84.9              | 2.3      |

Note: \( \Delta \% = \frac{[U_{sd}(c)-U_{sd}(t)]/U_{sd}(t)}{100\%} \)

where \( U_{sd}(t) \), \( U_{sd}(c) \) is the test results, calculated results, respectively.
calculated results and the test results is only 6.8%. Therefore, the relations between \( U_{50} \) and \( SDD_d \) represented by Equation (10) is acceptable, so the assumptions in the total equivalence model on Section III is proved to be reasonable and can be provided reference for design stage of power lines.

The correction coefficient indicating the effect of FWC on the critical flashover voltage \( U_{50} \) for each insulator can be approximated as follows

\[
K_x = \frac{U_{fd}}{U_{fg}} = \frac{A_d(SDD_d)^{-a}}{A_g(SDD_g)^{-a}} = \left(\frac{4.2 \times W \times 1.039 \times 10^{-4}}{SDD_g \times 1 + 1}\right)^{-a} 
\]

(11)

where \( U_{fd} \) is the flashover voltage of insulators with FWC \( (\gamma_20, \mu S/cm) \), \( U_{fg} \) is the flashover voltage of insulators with \( \gamma_20 = 10\mu S/cm \).

For \( SDD <0.15 \, \text{mg/cm}^2 \), FWC has a strong effect on the flashover voltage. Therefore, the combined effect of increases in both the pollution level and FWC is to substantially reduce the flashover voltage for each insulator. For each sample, the correction coefficient \( (K_x) \) with \( SDD_g = 0.03 \, \text{mg/cm}^2 \) is

\[
K_A = \left(2.00 \times 10^{-4} \times \gamma_20^{1.039} + 1\right)^{-a_A} \\
K_B = \left(1.73 \times 10^{-4} \times \gamma_20^{1.039} + 1\right)^{-a_B} \\
K_C = \left(1.61 \times 10^{-4} \times \gamma_20^{1.039} + 1\right)^{-a_C} 
\]

(12)

The relationship between the correction coefficient \( K_x \) and FWC is shown in Fig. 5. As FWC increases, \( K_x \) decreases. Thus, a higher value of FWC gives a lower value of \( U_{50} \). Moreover, for the same fog water conductivity, \( K_A > K_C > K_B \), which means that FWC has a greater influence on the critical flashover voltage of the ceramic insulator than on that of silicone rubber insulator.

IV. CONCLUSION

(1) For the same fog water conductivity (FWC), the AC critical flashover voltage \( (U_{50}) \) decreases nonlinearly as \( SDD \) increases. Moreover, the relationship between \( U_{50} \) and \( SDD \) can be expressed as a power curve, and the power curve exponent \( a \) relating \( SDD \) and \( U_{50} \) varies fit the data well. The exponent \( a \) relating \( SDD \) and \( U_{50} \) decreases as FWC increases.

(2) For the same \( SDD \), \( U_{50} \) decreases as FWC increases. This study measured a reduction in \( U_{50} \) ranging from 2.6–18.9 kV for Type A, 2.3–21.5 kV for Type B, and 2.3–28.3 kV for Type C with FWC up to 3 mS/cm. For \( \gamma <3.0 \, \text{mS/cm} \), the average value of the exponent \( a \) can be used to relate the pollution level and the flashover voltage.

(3) As \( SDD \) increases, the relative variation in the flashover voltage \( \Delta U_{50} \% \) fluctuates. The effect of FWC on \( U_{50} \) decreases as \( SDD \) increases. For samples A, B and C, as \( SDD \) varies from 0.03-0.30 mg/cm\(^2\), \( \Delta U_{50} \% \) decreases by 4.7–20.0%, 5.1–21.8%, and 4.1–25.6%, respectively. The results at higher pollution levels do not show as much dependence on FWC as at lower pollution levels. That is, \( U_{50} \) does not vary at all with respect to \( \gamma \) when \( SDD >0.15 \, \text{mg/cm}^2 \); however, FWC has a strong influence on the flashover voltage of insulators for \( SDD <0.15 \, \text{mg/cm}^2 \). Therefore, the combined effect of increases in both the pollution level and FWC on the insulator surface is to substantially reduce the flashover voltage.

(4) A model for calculating the total equivalent salt deposit density given FWC and pre-polluting salt density has been established. Using this model, a formula for \( U_{50} \) of insulators in salt fog was proposed by considering the effect of FWC and pre-polluting SDD. The calculation results are in good agreement with the test results, with a relative deviation of less than 6.8%. The influence of FWC on the \( U_{50} \) is greater for ceramic insulators than for silicone rubber insulators.

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