

# Calculation of AC and Transient Potential Distribution along HV Insulator String under Polluted Condition based on FEM

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**Abstract** – Porcelain insulators are extensively used in overhead high voltage transmission lines. Uninterrupted reliable operation of a power system depends on a satisfactory performance of insulators under different environmental conditions. This paper presents the results of a study of the transient and power frequency voltage distribution along a 230kV cap and pin type porcelain insulator string in both clean and pollution conditions. Finite element method based software, MAXWELL v.14, is used for some 3-D simulations to investigate the effects of tower, conductor and four different types of corona ring on voltage distribution along the insulator string. Also, by choosing the optimal corona ring type, the equivalent circuit for a suspended insulator string in pollution condition is represented. The voltage distribution along HV insulator string for different severities of surface pollution is calculated by ATP-EMTP software, by using the optimal corona ring and presented equivalent circuit. The capacitive-resistive voltage distribution along the polluted string under both AC and transient voltages are also calculated to show the disadvantages of pollution on performance of the string.

**Keywords** – Finite Element Method, Lightning Impulse, Pollution, Porcelain Insulator, Potential Distribution.

## I. INTRODUCTION

Porcelain insulators strings are widely applied in outdoor high voltage insulation systems, this is due to their high mechanical strength, easy insulation and operation and cost. High voltage insulators are exposed to various climates. Severe environmental conditions and pollution degree have a strong influence on insulator performance [1]. It is known that, deposited pollution on insulator surface combined with humidity, reduces the superficial resistance of insulators and provides a conductive layer for leakage current [2]. Calculations or measurements of electric field distribution around high voltage equipments such as insulators, under different conditions are very important to improve the design of such devices [3,4]. Several numerical methods were used to compute the electric field and potential distribution along high voltage insulators [5,6,7]. Most of the studies were performed for power frequency excitations, in dry and clean condition

[8,9,10]. In some research has been done to calculate pollution effects on potential distribution along HV insulator strings, a parallel resistance is considered between each insulators [1,11]. The effects of uniform and nonuniform surface pollution on the electric field and potential distribution along insulators were investigated in [2,12]. Many numerical studies were performed to analyze the electric field and potential distribution around insulator under transient voltages [3,13]. In [14], impulse voltages were approximated by equivalent sinusoidal voltages to investigate field distribution around a semi conducting glazed insulator under icing conditions. Double exponential functions were employed to simulate the lightning and switching impulse voltages to investigate the effects of frequency and waveform of applied voltage on capacitive-resistive field distribution around a post type insulator string, in [12].

In this paper, AC and transient (lightning impulse) electric potential distribution along a 230kV cap and pin type insulator strings are investigated for clean and polluted insulator surfaces. MAXWELL v.14 Finite Element Method based software is used to investigate the effects of transmission tower, conductor and four different types of corona rings on potential distribution along the string under lightning impulse and power frequency excitations. In present work, by using proposed equivalent circuit of suspended insulator string, the capacitive-resistive voltage distribution along polluted string is calculated. ATP-EMTP software is employed to calculate the AC and transient voltage distribution along the string under various pollution levels.

## II. SIMULATION METHOD AND DETAILS

This paper employs a commercially available program, version 14 of Maxwell 3-D (Ansoft corporation), which is a finite element method based software. According to finite element method, the calculation model is divided to many elements and nodes. All the elements connected together by nodes. Based on characteristics of different materials, which are used in simulated model, corresponding parameters of electric characteristics will be defined to each element. Depending on the specific feature, proper calculation method is chosen to solve the field physical quantity of unknown nodes. In dry and clean conditions, all the transient simulations are done by electric transient solution and all the ac simulations are

done by electrostatic solution and about 700,000 and 1,500,000 elements have been used for simulated model of a suspension insulator string with 13 units, respectively.

A Pentium 3.46GHz computer with 16GB RAM was used for the calculations. The CPU time for each transient and power frequency simulation is about 4 hr and 2 hr, respectively.

Also, in pollution condition, ATP-EMTP (The Electromagnetic Transient Program) is used to calculate the effects of various pollution levels on voltage distribution along the string under lightning impulse and power frequency excitations.

### III. MODEL PARAMETERS

Fig. 1 shows the basic dimensions of a porcelain insulator unit and a simplified model of a transmission tower used in 230kV transmission system. Relative permittivity of porcelain and cement are assumed to be 6 and 14, respectively.

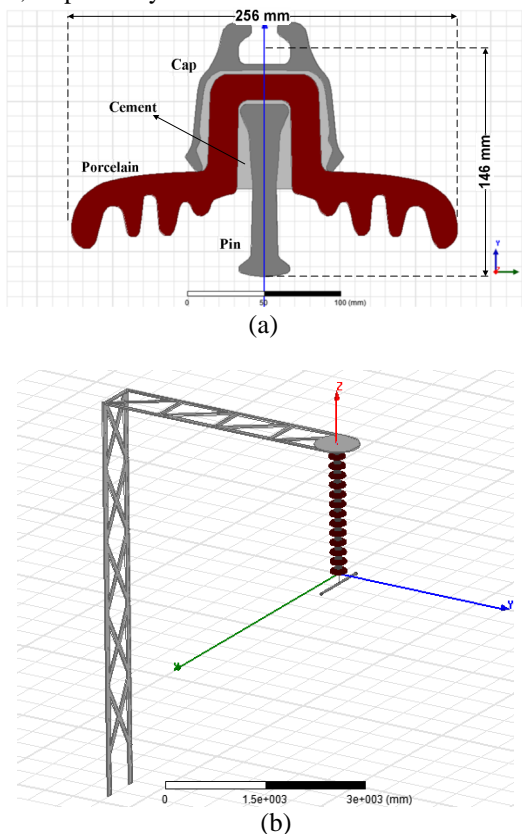


Fig.1. (a) Basic dimensions of cap and pin type porcelain insulator unit, (b) Simplified 3-dimensional simulation model of tower

The vertical suspended string contains 13 insulator units and the units are numbered from energized end to grounded end of the string. Fig. 2 shows the basic design of corona ring, such as corona ring tube diameter (R), corona ring diameter (D) and corona ring mounting height from energized end fitting (H). Table 1 shows the basic design parameters of 4 types of commonly used corona rings in 230kV transmission lines.

In transient simulations, the  $1.2/50\mu\text{s}$ ,  $950 \text{ kV}_{\text{peak}}$  lightning impulse voltages are represented by a double exponential wave-form as given below:

$$V(t) = A[\exp(-at) - \exp(-\beta t)] \quad (1)$$

The constants A,  $a$ , and  $\beta$  are 1.0371, 0.01426 and 4.8762, respectively. The voltage is applied to corona ring, line conductor and pin of the first line-side insulator unit, while tower, cap of the last insulator and additional metal link between last insulator units and tower are grounded. All the transient simulation results are expressed in peak values of the time dependent voltages ( $t=1.2\mu\text{s}$ ). In power frequency simulations, the instant voltages  $230 \times (\sqrt{2}/\sqrt{3})=187.79 \text{ kV}_{\text{peak}}$  (peak values of line-to-ground voltage) of 50 Hz were applied to live parts of transmission system (as mentioned before). In all simulations, for better studying of distributed voltages, all values of voltages were normalized as follows:

$$\%U_i = (U_i/U_{\text{max}}) \times 100 \quad (2)$$

Where  $U_i$  is the voltage of  $i$ -th unit in kV and  $U_{\text{max}}$  is the peak values of applied voltage (depends on transient or power frequency excitations) and  $U_i$  is the normalized voltage of the same unit.

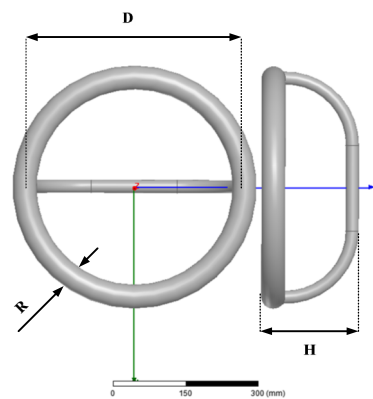


Fig.2. Dimensions of corona ring

Table 1: Corona ring design parameters

Model Name	Model Parameter (cm)		
	R	D	H
Type I	6	50	10
Type II	4	60	10
Type III	4	50	20
Type IV	4	50	10

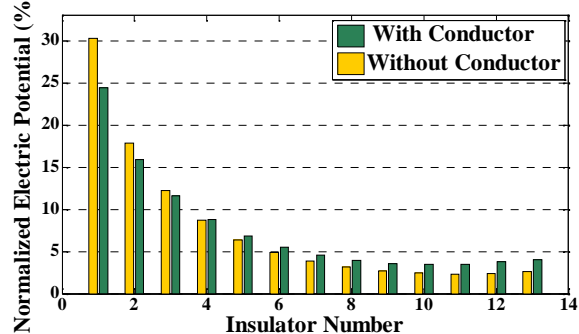
### IV. SIMULATION RESULTS

In order to investigate the effects of pollution on voltage distribution under transient and power frequency excitations, several simulations were done to inspect other important factors on string performance. Different simulations of the insulator string in clean and dry condition have been carried out by FEM based software and results were presented.

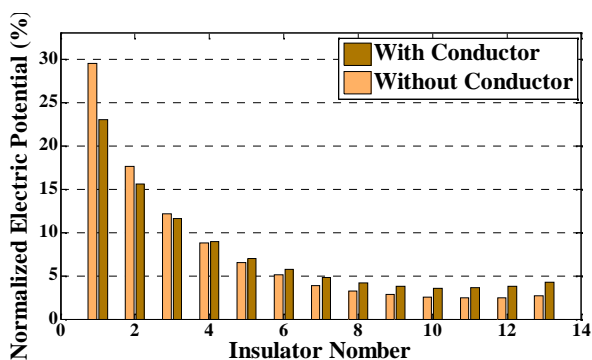
#### A. Effects of Conductor

In order to investigate conductor effects on voltage distribution along insulator string, results of transient and power frequency simulations are presented in figure 3. As

can be seen from both Fig. 3(a) and 3(b), the effects of stray capacitances between transmission line and different parts of the string to uniform the voltage distribution, cannot be omitted. The effects of conductor on maximum electric field magnitude along the insulator string under transient and AC excitations are shown in table 2. The results indicate that the significant overestimation of maximum electric field would occur if conductor neglected in representation of overall geometry.



(a)



(b)

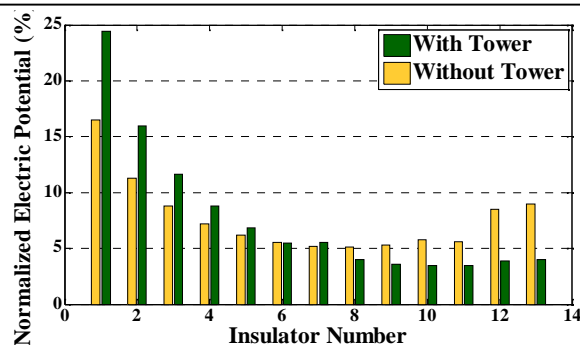
Fig.3. Effects of conductor on potential distribution along insulator string (a): under lightning impulse voltage (b): under power frequency voltage

Table 2: Effects of conductor on maximum E-field magnitude along insulator string

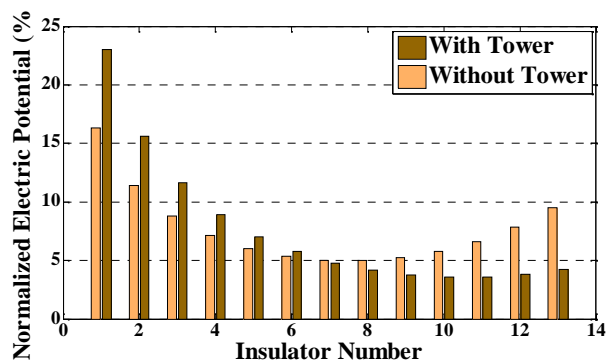
$E_{MAX}$ (% of applied voltage per unit length)	With Conductor	Without Conductor
Transient	14.8	19.03
Power Frequency	14.21	18.5

### B. Effects of Tower

The effect of tower on voltage distribution was investigated, using the simplified tower configuration shown in Fig. 1(b). The cross-arm length and tower height are assumed to be 4m and 6m, respectively. The normalized voltage distribution under lightning impulse and power frequency excitations were presented Fig. 4(a) and 4(b), respectively. Table 3 shows the effects of tower on maximum E-field magnitude along insulator string. As shown in Fig. 4 and table 3, under both kinds of excitations, the differences between results (with and without tower) are not negligible.



(a)



(b)

Fig.4. Effects of tower on potential distribution along insulator string (a): under lightning impulse voltage (b): under power frequency voltage

Table 3: Effects of tower on maximum E-field magnitude along insulator string

$E_{MAX}$ (% of applied voltage per unit length)	With Tower	Without Tower
Transient	14.8	10.07
Power Frequency	14.2	10.03

### C. Effects of Corona Ring

Corona rings play an important role in making the voltage distribution across the insulator string more uniform and preventing insulators and end fittings from developing corona [6]. There are no standards for design and placement of corona rings. Several studies are done to find the appropriate ring configuration [6,5]. In this section, in order to investigate the effects of corona ring on voltage distribution, four different types of corona ring, as introduced before are assumed to install at the energized end of the string. Normalized voltage distributions and maximum E-field magnitude along insulator string without and with four different types of corona ring under lightning impulse and power frequency excitations are shown in Fig 5 and table 4, respectively. As can be seen from Fig. 5 and table 4, corona ring type III is the most effective ring to improve electric field and potential distribution along insulator string under both transient and power frequency excitations.

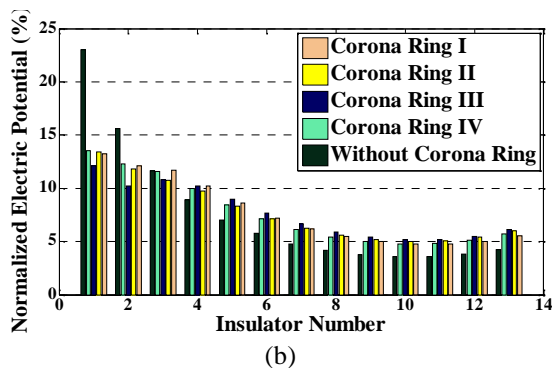
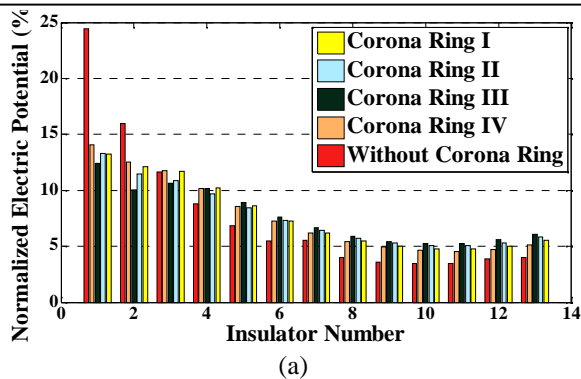


Fig.5. Effects of four different types of corona ring on potential distribution along insulator string (a): under lightning impulse voltage (b): under power frequency voltage

Table 4: Effects of four different types of corona ring on maximum E-field magnitude along insulator string

$E_{MAX}$ (% of applied voltage per unit length)	Ring Type I	Ring Type II	Ring Type III	Ring Type IV	Without Ring
Transient	7.85	7.91	7.25	8.072	14.8
Power Frequency	8.19	8.23	7.48	8.34	14.2

#### D. Effects of Pollution

Pollution severity on naturally polluted insulators is expressed in terms of; ESDD and NSDD [15]. As mentioned before, to calculate pollution effect on insulation considering superficial resistance reduction by pollution, a resistance is considered parallel to each unit of the string.

The values of  $R_p$  equal to different contamination levels are presented in table 5 [16].

Table 5. Values of superficial resistance for different pollution levels

Pollution Level	ESDD ( $mg/cm^2$ )	$R_p$ (M $\Omega$ )
Light	0.03-0.06	4000
Moderate	0.1-0.2	2000
Heavy	0.3-0.6	720

Via FEM based software, the equivalent circuit parameters of vertical suspended strings contains 13 insulator units are achieved. The mentioned parameters are shown in Fig6. According to the figure:

- $C_{ij}$  = Capacitance between insulator unit number i and j
- $C_{ig}$  = Capacitance between each unit and the grounded tower
- $C_{il}$  = Capacitance between each unit and transmission line
- $R_p$  = Pollution resistance of each insulator

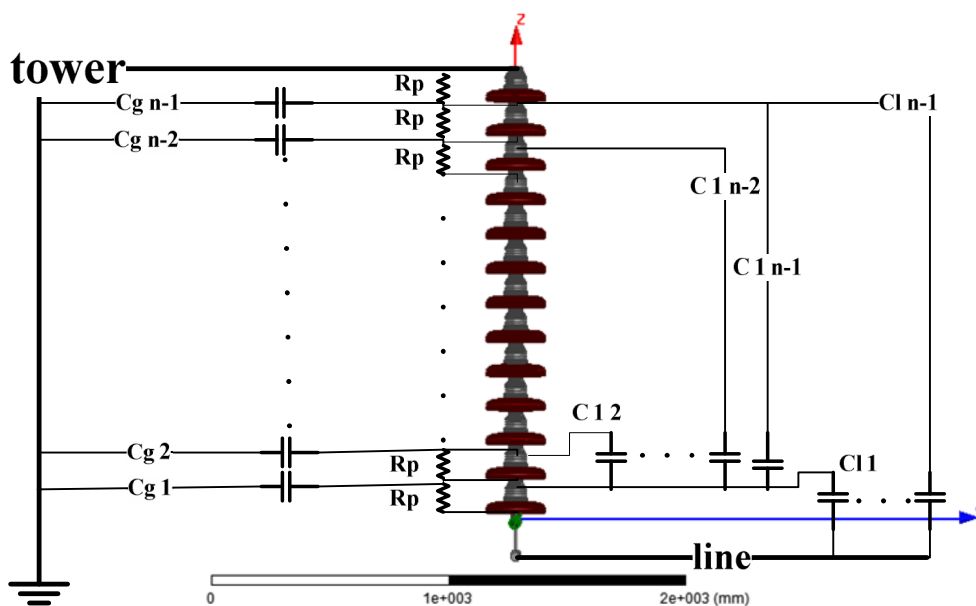


Fig.6. Schematic of the equivalent circuit of a parallel insulator string

Voltage distribution of insulator string in different pollution levels under lightning impulse and power frequency voltages are shown in Fig. 7(a) and 7(b), respectively. It can be depicted from the figures that, by varying superficial resistance equal to light to heavy pollution levels, voltage distribution along the insulator string under both AC and transient excitations has not changed significantly. In other words, since the paralleled resistances do not significant effect on equivalent impedance of the insulator string, the potential distribution along the insulator string is capacitive.

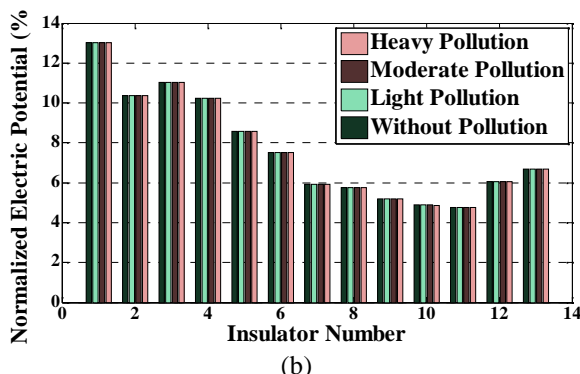
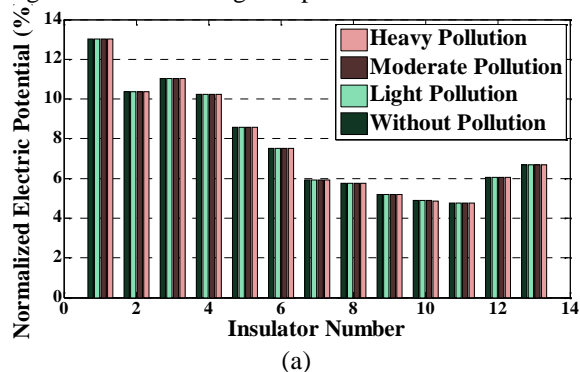


Fig7. Voltage distribution along insulator string with different pollution levels (a): under lightning impulse voltage (b): under power frequency voltage

In order to identify the range of  $R_p$  within which the voltage distribution changes from capacitive to capacitive-resistive and from capacitive-resistive to resistive under lightning impulse and power frequency excitations, several simulations are done. Simulations are performed for wide ranging values of  $R_p$  under both lightning impulse and power frequency voltages. For lightning impulse it has been found that the field is capacitive for  $R_p = 2M$ , while the field is resistive for  $R_p = 0.05M$ . For intermediate values of  $R_p$  the field is capacitive-resistive. Fig. 8(a) shows the capacitive, capacitive-resistive and resistive potential distribution along the insulator string at  $1.2\mu s$  under lightning impulse voltage, similar potential distribution under power frequency voltage are shown in Fig. 8(b). As can be seen from Fig. 8(b), the voltage distribution changes from capacitive to resistive for  $R_p=720M$  to  $R_p=10M$  under power frequency voltages.

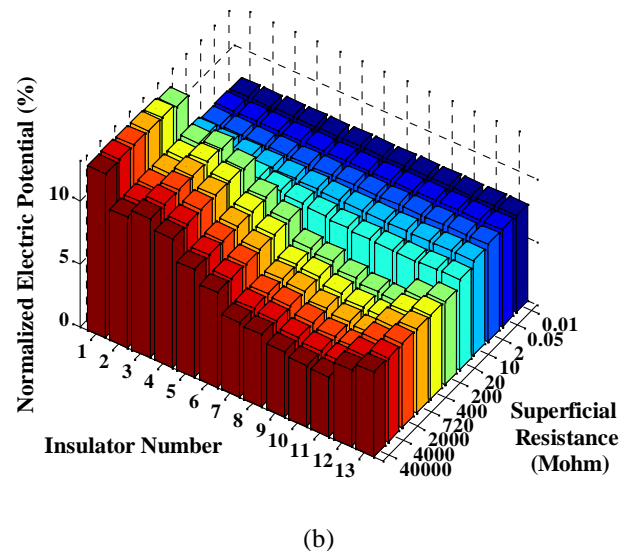
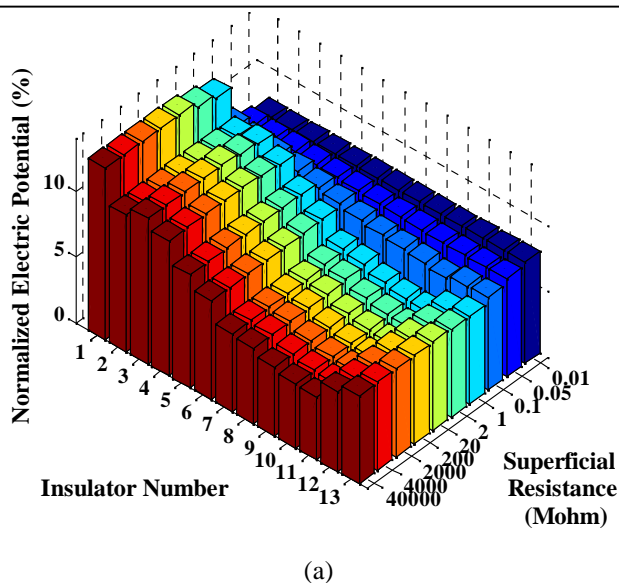


Fig.8. Effects of superficial resistance on potential distribution along insulator string (a): under lightning impulse voltage (b): under power frequency voltage

## V. CONCLUSION

This study has presented some 3-D simulations for 230kV cap and pin type porcelain insulator string under both lightning impulse and power frequency excitations. Finite element method based software, MAXWELL v.14 has been employed to study the influence of transmission line conductor, tower and corona ring on AC and transient electric potential distribution along the insulator string. Modeling the insulator string alone, without taking into account the effect of tower and conductor, leads to extremely inaccurate estimates of electric field and potential distribution under both AC and transient excitations. The simulation results show that using a corona ring reduces the maximum electric field around the energized end of the string and results in a linear voltage distribution along the string. Moreover, the simulation

results in presence of four different types of commonly used corona rings show that ring type III (with maximum mounting height), is the most effective ring to uniform the potential distribution of the insulators. By revealing a full equivalent circuit of insulator string, which takes into account the insulator materials properties and the effects of tower, conductor and corona ring type III, voltage distribution along insulator string in different pollution conditions was investigated. The results show that, the changes of the voltage distribution from capacitive to capacitive-resistive and from capacitive-resistive to resistive occur within a narrow range of surface resistivity under both power frequency and lightning impulse voltages.

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