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Power Quality Problems Due to Transformer Inrush Current

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SUMMARY

Transformer energization can produce a large nonsinuoidal inrush current which contains both odd and higher order harmonic components that can put transformer winding under mechanical stress. Additionally, they can cause irregular tripping of harmonic protection relays. Furthermore, in relatively weak power systems, such as is the Bosnian system, the superposition of harmonic components with system resonance frequencies may produce temporary overvoltages (TOV). Transformer winding failures and metal oxide surge arrester (MOA) energy stresses can occur due to TOV. The paper demonstrates a case study of an energization of a 220/110 kV transformer and power quality problems that can appear due to higher harmonics. Energy stresses of MOA provoked by transformer energization are considered in the paper.

KEY WORDS

Power quality, transformer, inrush current, temporary overvoltage, surge arrester

1. INTRODUCTION

Transformer energization is a regular operation in an electric power system which can lead to large transformer inrush current. The basic characteristic of inrush current is relatively slow decay time to reach its steady state value, determined by transformer and power system parameters. The magnitude and duration of inrush current have a strong dependence from transformer saturation curve. Since the magnetizing inductance in unsaturated region of this curve is high, the inrush current can take a long time to reach its steady state. On the other way, the magnetizing inductance in saturated region is dominant parameter in determination of inrush current magnitude. In addition, inrush current characteristics are depended on the switching breaker time, magnitude and polarity of residual flux [1]. These currents can provoke false operation of protective relays and fuses [2] and mechanical damage to the transformer windings due to magnetic forces [3], cause voltage sags [4], establish temporary harmonic overvoltages [5] and generally reduce power quality on the system. This paper is focused on the analysis and consequences of temporary overvoltages that result from transformer inrush current.

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2. TEMPORARY OVERVOLTAGES DUE TO TRANSFORMER INRUSH CURRENTS

During transformer energization, the inrush current is asymmetrical and contains DC and fundamental components as well as all odd and even harmonics of the fundamental power frequency. In weak systems, i.e. in systems with relatively low short circuit power, transformer energization through an overhead line can produce resonance with a low frequency. If this resonance occurs and coincides with one of the harmonics produced during transformer energization, overvoltages can be provoked. The most important characteristics of these overvoltages are their relatively long duration, usually 0.1 to 1 sec, extremely 10 sec [6]. Namely, during energization, transformer behaves like a harmonic current source and flows through the lowest impedance point in the power system. Harmonic voltage at a certain point of the system can be expressed as:

$$U(n) = I(n) \cdot Z(n) \qquad (1)$$

where n is order of the harmonic component, $Z(n)$ is the impedance seen from the given system point at the harmonic frequency of order n, and $I(n)$ is the injected harmonic current to the system of order n. Based on the relation (1), during resonant conditions, when resonant frequency of system impedance $f_r = n \cdot f_0$, $f_0 = 50\,Hz$, coincide with corresponding harmonic current source, temporary overvoltages which contain high voltage harmonic will be established. Magnitude of harmonic voltage has a strong dependence on the corresponding magnitude of the harmonic current. If a magnitude of harmonic current at the resonant frequency of impedance has a relatively low value, then temporary harmonic overvoltage will no appear. Mentioned temporary harmonic overvoltages may considerably energy stress metal-oxide arresters which are located close to the transformers [7]. Energy stresses depended on the network configuration, transformer and arreseter parameters and initial conditions (breaker switching time and residual transformer flux). Magnitude and duration of these temporary overvoltages as well as energy stresses of surge arrester are sustained significantly in weak power systems.

3. CASE STUDY

Temporary harmonic overvoltages generated during transformer energization via an overhead line (Figure 1) will be analyzed in this paragraph.

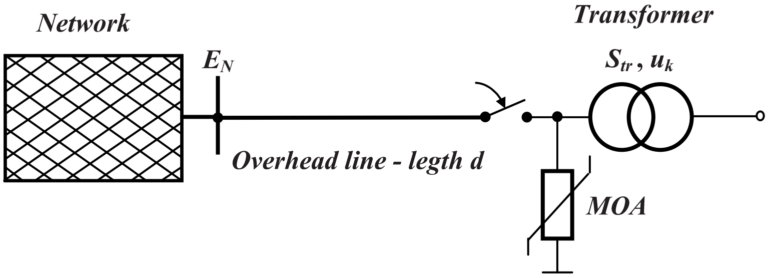

Figure 1. Transformer energization via overhead line, with MOA

In the first step the analyses will be conducted without connected surge arrester. The simplified model, while the transformer energizes through the overhead line, is shown in Figure 2. The network is represented by the ideal voltage source $e(t) = E_N \cos \omega t$, with corresponding network impedance $\bar{z}_N = R_N + j\omega L_N$. The equivalent network inductance L_N is evaluated from the 3-phase short circuit power S_{SC} $\omega L_N = \left(E_N \sqrt{3} / \sqrt{2}\right)^2 / S_{SC}$, while the resistance R_N is determined on the recommended short-circuit relationship X_N / R_N. The overhead line is represented with distributed parameters $R_L^{'}, L_L^{'}, C_L^{'}$ and its length d. The transformer model comprises the constant parameters: R_p, L_p, R_m and magnetizing inductance L_m, defined by nonlinear saturation curve. The transformer energization starts at the moment $t = T_0$.

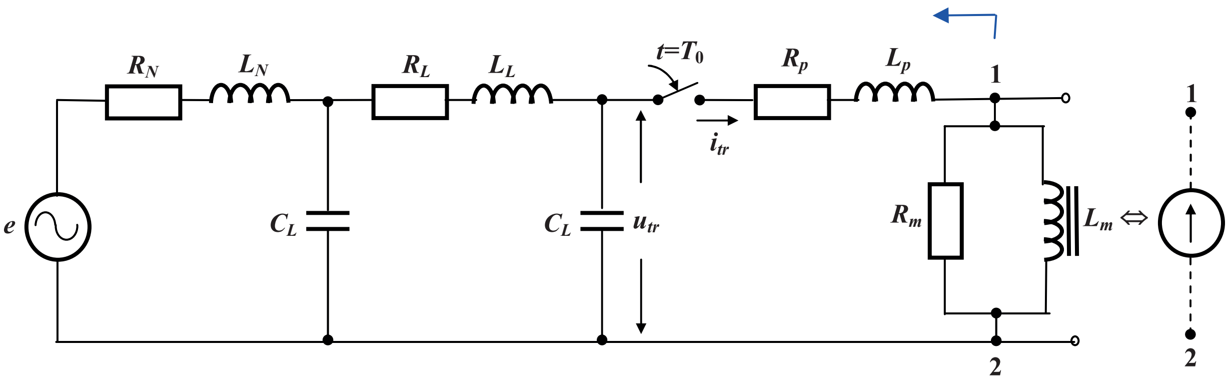

Figure 2. Transformer energization – simplified equivalent model, without MOA

Real data from the Power Utility of Bosnia and Herzegovina ($220\ kV$ voltage level) were used in order to investigate the possibility of generation of temporary overvoltages:

Transformer parameters of the Gradacac substation are:

- nominal power $S_{tr} = 150\, MVA$,
- short circuit voltage $u_{k\%} = 11\,\%$,
- resistance per winding phase $R_p = 0.292\,\Omega$,
- leakage inductance $L_p 0.113\, H$,
- iron core losses $R_m = 1.124\, M\Omega$.

Table I: Magnetization curve of 150 MVA transformer

i_m [$p.u.$]	0	0.00102	0.00187	0.0035	0.00683	1.0
Φ [$p.u.$]	0	0.95	1.0	1.05	1.1	1.3185

Network parameters (Tuzla):

$E_N = 220\sqrt{2}/\sqrt{3}\ kV$, $X_N / R_N = 15$, $S_{SC} = k \cdot S_{tr}\ MVA$, k is natural number

Parameters of the Tuzla - Gradacac overhead transmission line, per phase, per km are:

- resistance $R_L^{'} = 0.022\,\Omega / km$,

- inductance $L_L^{'} = 1.067\ mH / km$,
- capacitance $C_L^{'} = 0.03032\ \mu F / km$,
- line length $d = 52\ km$.

3.1 SIMULATIONS OF TEMPORARY OVERVOLTAGES

All simulation results are obtained by the software MATLAB/SimPowerSystem. The simulation tool has been developed using state-variable approach and the simulation runs in the MATLAB/Simulink environment. The worst case of the switching condition is presumed in all performed simulations and it implies that the breaker switching-in occurs at the same moment as the source voltage crosses the zero.

In Figure 3 are shown system impedances as seen from magnetizing inductance terminals 1 and 2, for different values of the ratio between the transformer nominal power S_{tr} and the short circuit power of the system S_{SC} (i.e. rate S_{tr} / S_{SC}).

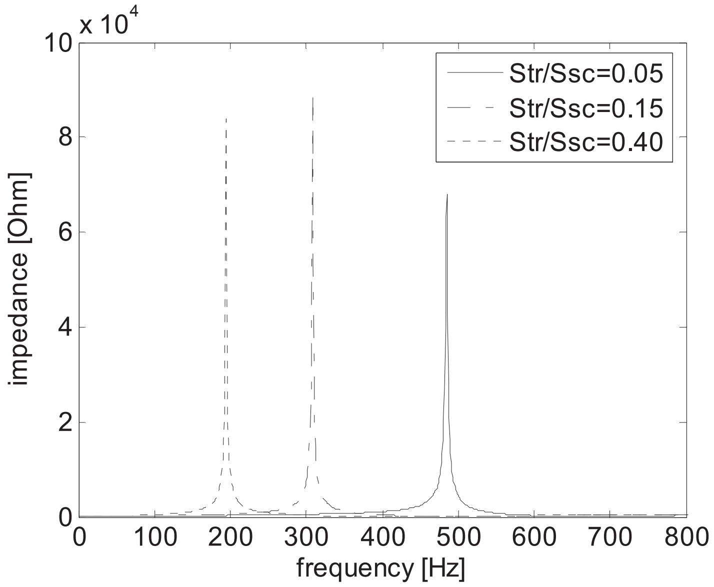

Figure 3. Impedance at magnetizing inductance terminals *Zeq*. Resonant frequency are: 194 Hz for S_{tr}/S_{SC}=0.40, 308 Hz for S_{tr}/S_{SC}=0.15, 485 Hz for S_{tr}/S_{SC}=0.05

It is obvious that resonant frequency is lower for larger ratio S_{tr} / S_{SC} i.e. for lower short circuit power of the system (weaker system). Figure 4 depicts the waveform of the typical transformer inrush current obtained for the rate $S_{tr} / S_{SC} = 0.15$. Furthermore, Figure 5 shows corresponding harmonic content of this inrush current. Resonant frequency for this case is 308 Hz, i.e. close to 6th harmonic component. However, inrush current harmonic level of order 6th as well as near harmonics order 5th and 7th are very low and sustained temporary harmonic overvoltages are not expected in this case of transformer energization. This is clearly shown in Figure 6, where transformer overvoltage has relatively low magnitude and relatively short duration.

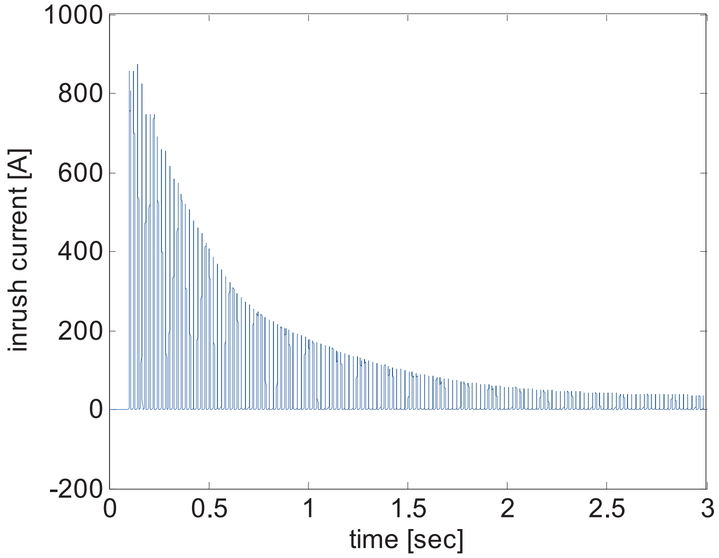

Figure 4. Transformer inrush current, case S_{tr}/S_{SC}=0.15

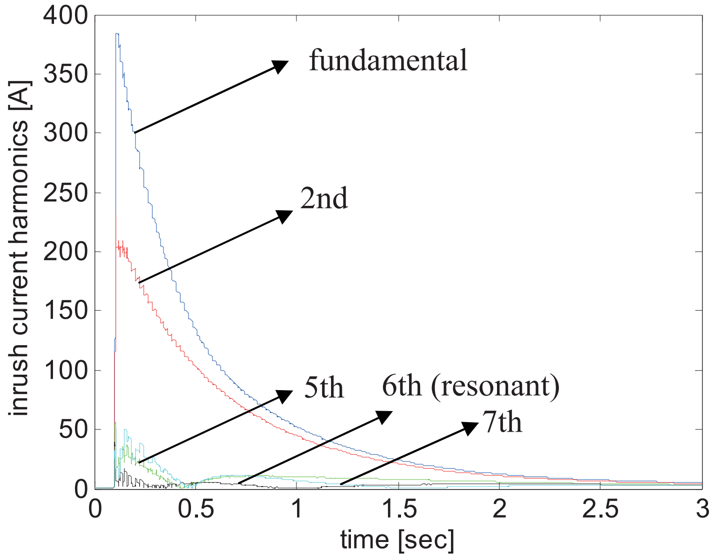

Figure 5. Harmonic content of inrush current, case S_{tr}/S_{SC}=0.15

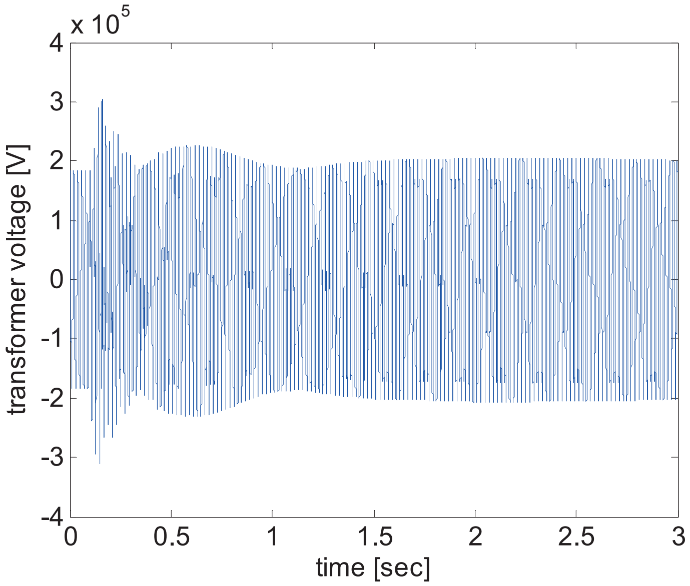

Figure 6. Temporary transformer harmonic overvoltages, case S_{tr}/S_{SC}=0.15

On the other hand, different simulation results are obtained for the rate case $S_{tr} / S_{SC} = 0.40$. Figure 7 shows harmonic content of transformer inrush current for this case. Now, resonant frequency is 194 Hz, i.e. close to 4th harmonic component. It is interesting to note relatively large level of corresponding 4th harmonic compared to others harmonics. This harmonic is close to fundamental inrush current component. Sustained temporary harmonic overvoltages are expected in this case of transformer energization. This is clearly shown in Figure 8, where transformer overvoltage has relatively large magnitude and relatively long duration.

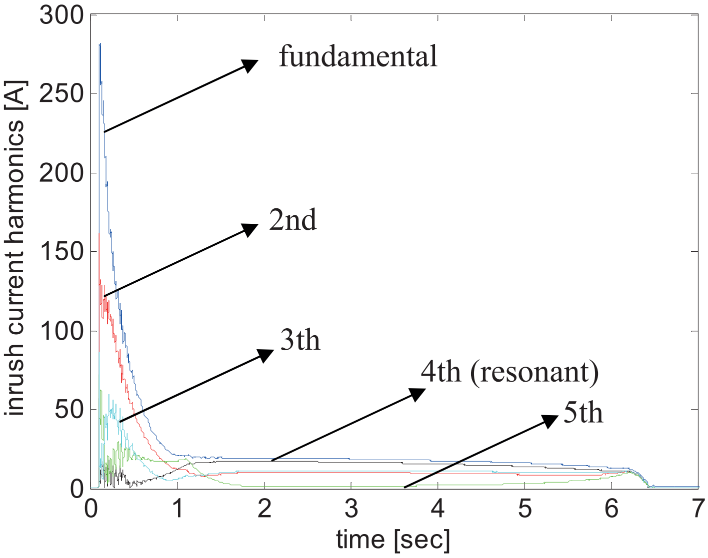

Figure 7. Harmonic content of inrush current, case S_{tr}/S_{SC}=0.40

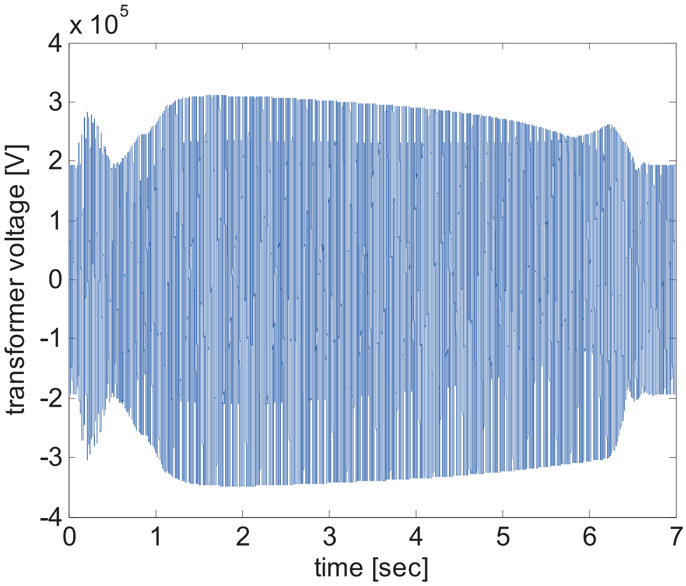

Figure 8. Temporary transformer harmonic overvoltage, case S_{tr}/S_{SC}=0.40

In addition, temporary harmonic overvoltages would have larger values with enlarged length of the line. For example, for the double line length ($d = 104\ km$), the impedance at terminals 1 and 2 has shape shown in Figure 9. In these cases, resonant frequencies are lower than mentioned for the initial line length, and these conditions are critical for the generation of transformer temporary overvoltages. In the other words, overvoltage values rapidly increase with the rise of the line length due to approaching to the resonant state.

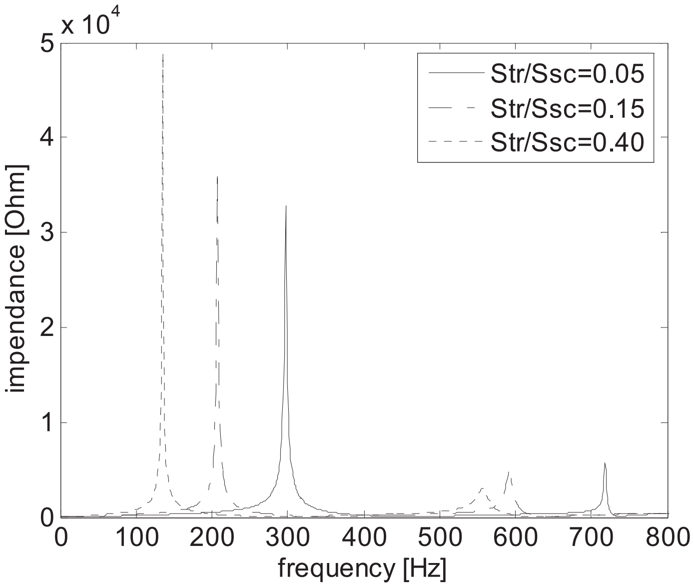

Figure 9. Impedance at magnetizing inductance terminals *Zeq*, line length *d*=104 *km*

3.2 ENERGY STRESSES OF MOA

Temporary harmonic overvoltages may considerably stress metal-oxide arresters located close to the transformers [7]. For the MOA the following residual current-voltage characteristic was assumed:

$i\ [kA]$	0.1	1	10
$u\ [kV]$	356	392	476

Others MOA parameters:

- discharge energy capability $E = 900\ kJ$
- rate voltage $U_{prot} = 180\ kV$

Simulations results are illustrated in Figure 10 which depicts discharge energies of the MOA obtained for different rate values $0.05 \le S_{tr} / S_{SC} \le 1$. Discharge energies of MOA increase when the residual flux Φ_r rises in "direction" to the instantaneous initial transformer current. In addition, discharge energies that MOA has to absorb rapidly increase for the double line length, Figure 11.

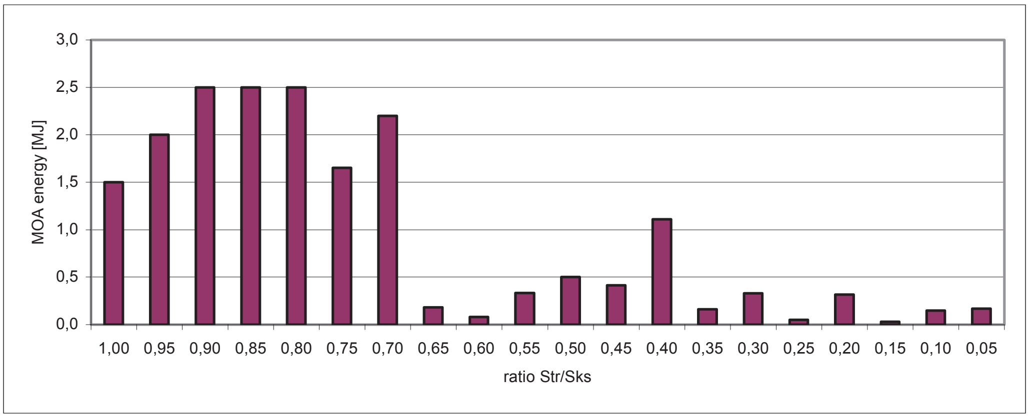

Figure 10. MOA discharge energies for line length *d*=52 *km*, Φ_r=0

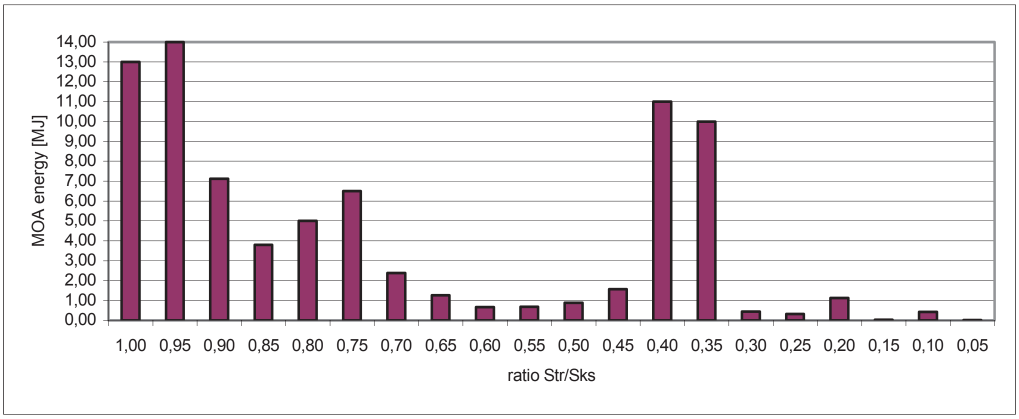

Figure 11. MOA discharge energies for line length d=104 km, Φ_r=0.8Φ_{nom}

4. CONCLUSIONS

The transformer energization may produce a large inrush current that contains high order harmonic components. These currents generally reduce power quality in the system and may have unfavourable effects, as is an irregular tripping of transformer differential protection relays, a deterioration of the insulation and mechanical support structure of transformer windings. Furthermore, in a relatively weak power systems, such as is the Bosnian system, inrush current harmonic components may coincide with system resonance frequencies, producing sustained temporary harmonic overvoltages, whose main characteristics are the relatively long time duration and slowly decreasing magnitude.

The case study is demonstrated and the energization of the 220/110 kV transformer is considered. Different influences on TOV are analyzed for the radial network of Bosnia and Herzegovina, which is divided into three separate subsystems. It is shown that overvoltage magnitudes rapidly grow when approaching to the resonant state. This happens with enlarged length of the line and it increases discharge energies that MOA has to absorb.

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