A Simple Simulation Model for Analyzing Very Fast Transient Overvoltage in Gas Insulated Switchgear

Nguyen Nhat Nam

Abstract— *The paper presents an simple model based on ATP-EMTP software to analyze very fast transient overvoltage (VFTO) phenomenon in Gas-Insulated Switchgear or Substation (GIS). The accuracy of this model is confirmed in a simple benchmark case study. The presented model is then applied to compute VFTOs in Binh Tan 220kV GIS in Vietnam. The computation results show that VFTOs generated by switching operations can be high enough to decrease the reliability in normal operations of the GIS. In addition, some VFTO-mitigating methods are introduced, and a feasible one is selected to apply to the GIS. The effectiveness of the chosen method is then validated by the simulation model. The obtained results in this research demonstrate that ATP-EMTP is a useful tool for transient analysis in high voltage engineering.*

Keywords— **Very fast transient overvoltage, gas-insulated substation, VFTO mitigation, ATP-EMTP.**

1. INTRODUCTION

Gas-insulated substations with main insulation of SF6 are more and more popular because of their ability to fulfill high energy demands with small space allocation and high reliability [1]. In GIS, during the operation of disconnecting switches (DS), flashovers in forms of pre-strikes and re-strikes occur in SF6 and lead to the appearance of VFTOs [2]. For the rated voltage up to 550kV, design of GIS is mainly based on the impulse withstand voltage [3]. Hence, VFTO level is not concerned in the design stage of GISs. However, this phenomenon can have negative impacts on the insulation of equipment in GISs [3].

The need for VFTO analysis in GISs is inevitable. There are two popular approaches proposed to solve this requirement as in [2-11]. The first one is based on the circuit model, in which all components of GIS are presented in forms of electrical elements and distributed transmission lines (TLs). This circuit based method is very convenient and can be applied to analyze a whole system of GIS, as in [4, 7-10]. The second approach is developed using Finite Element Method (FEM), hence it can solve full-wave Maxwell's equations. Although this method is able to provide a high level of accuracy, it can only be used to analyze a single module of GIS because of its high requirement of computation. A typical application of this approach can be seen in [5].

In this study, a simple but effective circuit model is presented, and then applied on the platform of ATP-EMTP for analyzing VFTO phenomenon in Binh Tan 220kV GIS. The simulation results show that the generation of VFTOs can become a hazard to the substation. Therefore, a suitable mitigation method is introduced to attenuate VFTOs in this substation. Then, the ATP-EMTP model is used to verify the effectiveness of the suggested mitigation solution.

The structure of this article consists of 4 sections. The first one is the introduction while the second one presents the circuit model of ATP-EMTP for VFTO analysis. The next section is written for discussion about the obtained simulation results and a reasonable solution to mitigate VFTOs. Finally, some conclusions are presented at the end of the paper.

2. CIRCUIT MODEL OF ATP-EMTP FOR VFTO ANALYSIS

2.1 Model of GIS components

Fig. 1 is the cross-section view of a single-phase encapsulated GIS. This configuration is popular in GISs in Vietnam. Binh Tan 220kV GIS, which is the substation under VFTO analyzing in this paper, was also built with this structure and has been in operation since 2012.

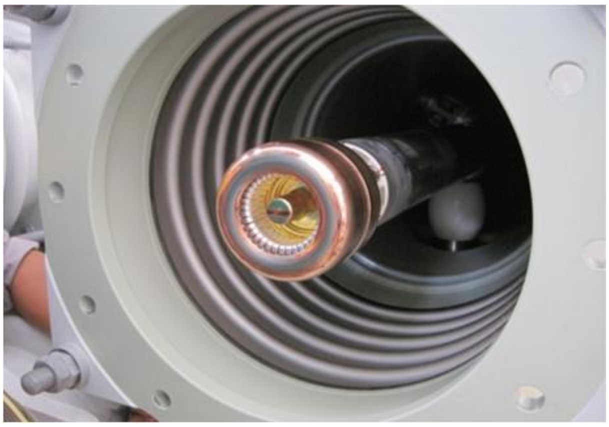

Fig.1. Cross-section view of single phase enclosure type.

Under VFTO analysis based on circuit model, each bus duct section of GIS can be presented by a distributed TL as in Fi.2 with the parameters as follows.

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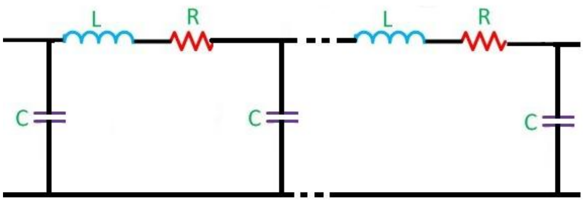


Fig.2. Distributed TL

$$C = \frac{2\pi\varepsilon}{ln\frac{b}{a}} \quad (1)$$

$$L = \frac{\mu ln\frac{b}{a}}{2\pi} \quad (2)$$

$$Z = \sqrt{\frac{L}{C}} \quad (3)$$

$$v = \frac{1}{\sqrt{LC}} \quad (4)$$

In the above equations, C(F/m) and L(H/m) are the per-unit length capacitance and inductance, respectively; $Z(\Omega)$ is the surge impedance; v(m/s) is the the surge travelling velocity; a(m) and b(m) are the outer radius of the bus duct and the inner one of the enclosure; ε and μ are the permittivity and the permeability of gas FS6, respectively.

In GIS, surges travel along many connected modules with the average velocity lower than the one in Eq. 4 due to the presence of spacers, elbow joints, T-shaped joints, etc. Hence, the average velocity can be calculated by Eq. 5 suggested by IEC 60071-4.

$$v_{ave} = \frac{0.95}{\sqrt{LC}} \quad (5)$$

In addition, the series per-unit length resistance of the bus duct R can be extracted from data provided by the GIS manufacture of the substation under study.

The equivalent circuits of GIS components are based on distributed TLs and lumped electrical elements. In addition, these circuits are dependent on the component status, and are summarized in Table 1.

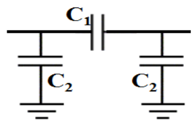
2.2 Model of DS switching operation

To model the DS switching operation, the exponential spark resistance of arc is proposed by Povh D., et al. in [6] as follows.

$$R(t) = r + R_0 e^{-\frac{t}{\tau}} \quad (6)$$

In Eq. (6), r is the arc resistance, R_0 is the opening DS resistance, and τ is the time constant of SF6 breakdown duration. In the above model, only the highest-amplitude spark is included in the VFTO analysis and trapped charge (TC) on the load side of the operated DS is not mentioned in the computation.

Table 1. The equivalent circuits of GIS components

No.	Component	Description
1	Disconnected Switch (DS)	+ *Closing:* distributed TL + *Opening:* 1 series capacitance
2	Circuit Breaker (CB)	+ *Closing:* distributed TL + *Opening*: 1 series Capacitance C_1 and 2 shunt capacitances C_2 
3	Spacer T-joint	Shunt capacitance
4	Current Transformer	Distributed TL and shunt capacitance
5	Potential Transformer	Shunt capacitance
6	Earthing Switch	Shunt capacitance
7	Gas to Air Bushing	Distributed TL and shunt capacitance on the side of air
8	Lightning Arrester (ZnO)	Shunt capacitance – resistance
9	Power Transformer	Shunt capacitance
10	Cable	Lumped TL with LCC module consisting of π-equivalent circuits
11	Overhead TL	Distributed TL

To take the whole procedure consisting of many re-strikes, pre-strikes, and trapped charge into account during opening or closing DS, a new model is developed by Szewczyk M., et al. in [7-8]. In this model, the nonlinear resistance *R(t)* which is based on the suggestion in [6] is controlled by the ATP-EMTP MODEL tool based on the voltage difference between the two DS contacts and the breakdown voltage of SF6 across the DS moving gap. Besides, a controlled switch is used to include an additional energized capacitance with an initial voltage into the circuit [8]. The supplement of this capacitance allows for including the presence of TC on the floating side of the DS in this model. It is demonstrated in [7-8] that this model can analyze the entire VFTO process including many arc sparks and TC in GIS during a very long interval with a reasonable precision. However, this model requires complex data of GIS such as the breakdown characteristics of FS6 between the changing gap of DS during operation.

In the state-of-the-art viewpoint, the main concern is to compute VFTOs generated by the highest-amplitude spark in a very short duration. Therefore, it is not necessary to take into account the entire process of many arc-sparking events. In this study, a simple model of DS switching operation is presented. This model is based on the basic ideals of the two above researches proposed in [6-8]. Its description is outlined in Fig. 3.

In Fig. 3, before DS operation, the load side of DS is neither connected to the source nor to the ground, hence it has an electrical role as the potential-floating part. A voltage source U_{c0} is used to charge this floating circuit up to a trapped charge voltage (TCV). This TCV can be determined based on the voltage source amplitude, the charging resistance R_{c0}, and the opening time t_1 of switch K_1. Then, switch K_2 will be closed at the time t_2 to start an arc-sparking event by including the resistance $R(t)$ between the two DS contacts. The resistance $R(t)$ is calculated by Eq. 6 with the arc resistance, the opening DS resistance and the time constant of 0.5Ω, 10^{12}Ω and 1ns, respectively [6]. It is noted that K_2 is closed after opening K_1 (i.e. $t_2 > t_1$) to make sure that the charging source will not have any impacts on arc-sparking and surge travelling. The proposed procedure ensures that the physical basics of these two processes are preserved perfectly.

2.3 Validation

A simple case study is considered in Fig. 4 for verifying the accuracy of the presented circuit model. The load side of the DS is a π-equivalent circuit which consists of one inductance 1.5 µH and two capacitances 250 pF. The charging voltage source $U_{C0}=1cos(\omega t+\pi)$ pu is closed at -1s and opened at -0.2 s by switch K_1. As a result, the DS load side is charged up to -1 pu at -0.2 s, and it has this floating potential until K_2 is closed at 0 s. Then K_2 connects the voltage source $U_s=1cos(\omega t)$ pu to the load side of DS through the arc resistance of 2Ω. The reason of using this linear resistance instead of the nonlinear one in Eq. 6 is that the analytical solution of potential $u(t)$ at the DS load side can be obtained by Laplace transform method. The comparision between this analytical solution and the one of ATP is displayed in Fig. 5. The two solutions are well comparable, and this result demonstrates that the presented model of DS operation can provide a very reasonable solution in VFTO analysis.

3. SIMULATION RESULTS AND MITIGATION METHODS

3.1 Introduction of GIS under VFTO analysis

Binh Tan 220kV GIS is designed using the configuration of double bus and single breaker to connect six circuits of TLs and two circuits of transformers. Fig. 6 is the arrangement of a transmission circuit in this GIS. At the time of this research, there are two 220kV/110kV transformers rated 250 MVA in service. The third one of 250 MVA will be installed in the future. This substation was built with the single-phase encapsulated technology as in Fig. 1.

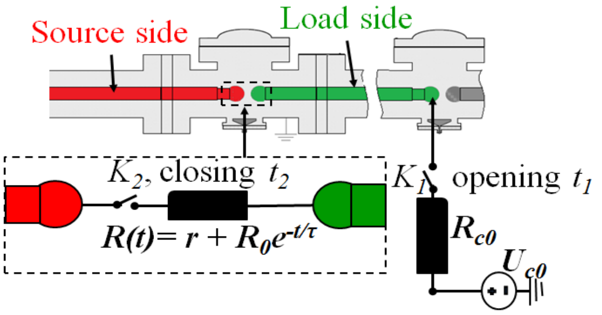


Fig.3. Model of DS switching operation.

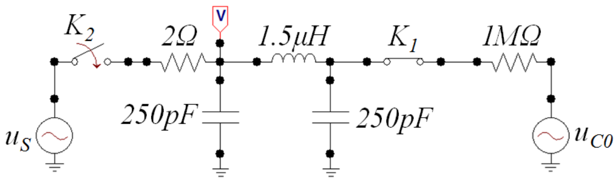


Fig.4. ATP circuit of simple case study for validation.

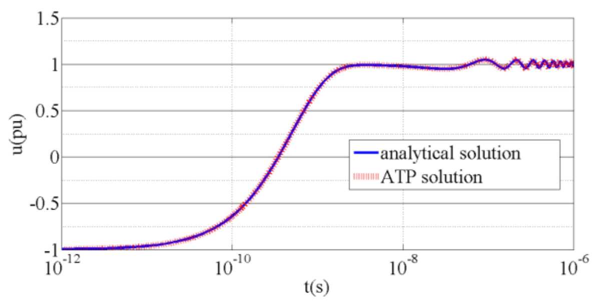


Fig.5. Comparison between analytical and ATP solutions of the simple case study.

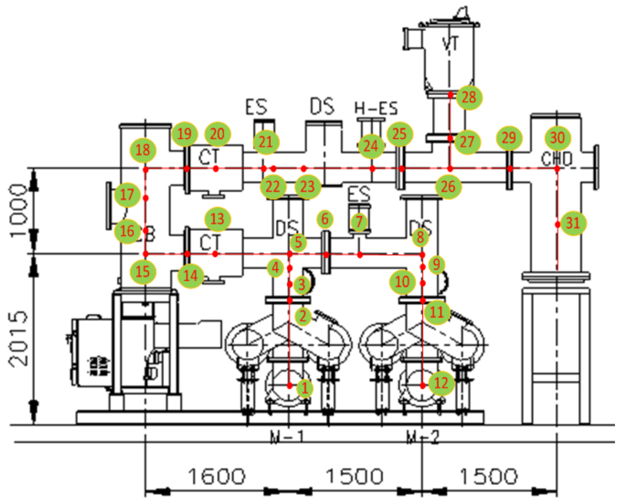


Fig.6. Transmission line module of Binh Tan 220kV GIS.

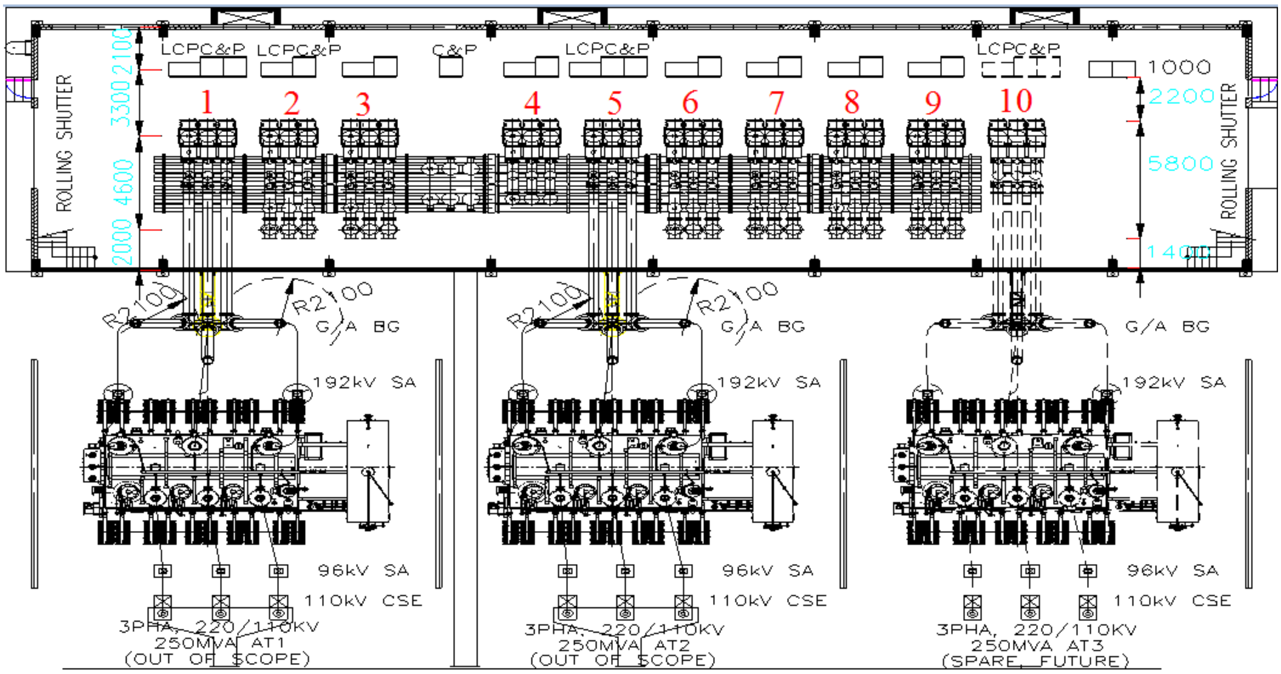


Fig.7. Full layout of Binh Tan 220kV GIS

Fig. 7 presents the full layout of Binh Tan 220kV GIS. Modules 1 and 5 are transformer circuits connected to transformer 1 and 2, respectively while module 10 is a transformer circuit installed in the future. Besides, modules 2, 3, 6, 7, 8, and 9 are transmission line circuits, which are named Binh Tan – Cau Bong 1 (BT – CB1), Binh Tan – Cau Bong 2, Binh Tan – Phu Lam 1, Binh Tan – Phu Lam 2, Binh Tan – Hoc Mon 1, and Binh Tan – Hoc Mon 2, respectively. Module 4 is the bus coupler circuit connecting the two main buses in operation.

3.2 Simulation results

The typical case study for VFTO analysis in Binh Tan 220kV is chosen from a practical operation of the substation. In this situation, BT – CB1 transmission line is out of service, and other transmission lines together with the two transformers are in operation. The two substation buses are connected through the bus coupler. BT – CB1 transmission line is required to be back in operation in order to connect two substations Binh Tan and Cau Bong. The procedure is to establish the connection of the line to Binh Tan substation before to Cau Bong. On the GIS module of this line, as illustrated in Fig. 8, DS1, DS7 and CB will be closed in the chronological order while DS2 is kept open. Hence, VFTO analysis is conducted during closing DS1 while DS7 and CB are still open. It is noted that the load side of DS1, which is the green part in Fig. 8, is the floating potential circuit.

VFTOs at the two sides of DS1 are presented in Fig. 9a with TCV of -1 pu and in Fig. 9b without TCV. The peak values of voltages at DS1 contacts are 1.824 pu in the analysis with TCV of -1 pu and 1.423 pu in the one without TCV. These results demonstrate the significant impact of TCV on VFTOs generated during switching operations in GISs.

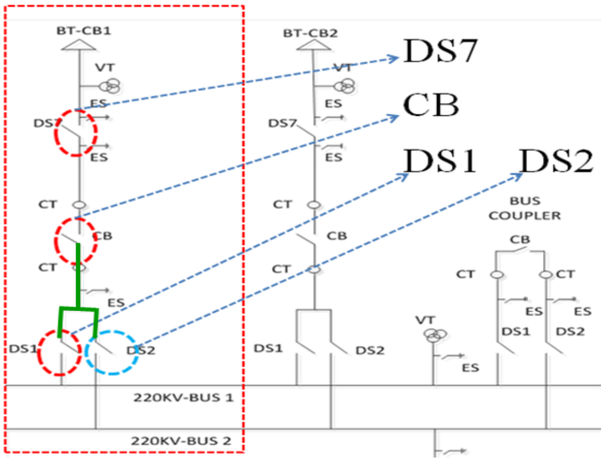


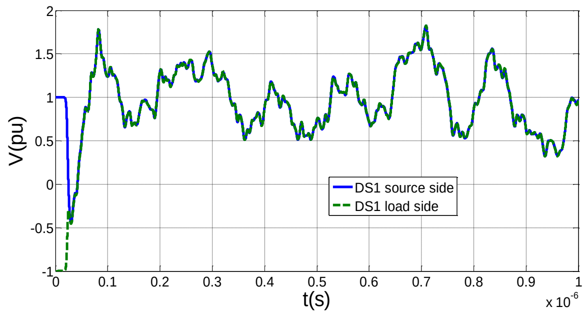
Fig.8. One-line diagram of BT – CB1 GIS module.

VFTOs at the two contacts of DS1 and the two transformers are presented in Fig. 10 for the case with TCV -1 pu. It is noted that the VFTO at the transformer 1 which is near the module BT – CT1 is very high with a peak of 2.417 pu. This can cause negative effects on the transformer and can significantly shorten the lifetime of this electrical machine.

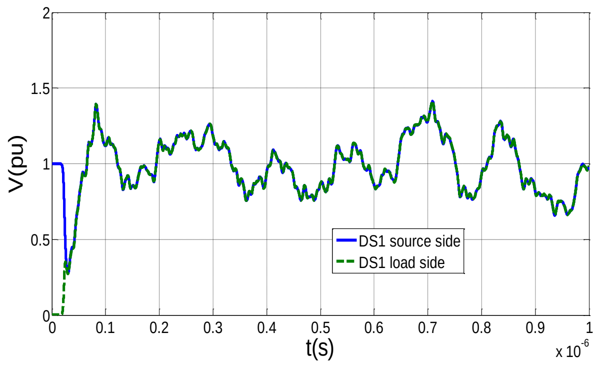
3.3 Mitigation methods

From the obtained results in the previous sub-section, the need to reduce VFTOs in the GIS is inevitable. Many mitigation methods have been studied to solve this problem.

A typical solution is using resistor-fitted DSs by Y. Yamagata, et al [9]. The DS modified configuration is suggested as in Fig. 11. During the switching operation of DS, arc-sparks will connect the moving contact with the additional resistor instead of the fixed contact. Hence, a considerable energy of sparks can be dissipated by the resistor and VFTOs can be suppressed.



a) With TCV of -1pu



b) Without TCV

Fig.9. VFTOs at the two sides of DS1.

Another effective method is to install magnetic rings on the bus duct of GIS. This method has been studied in many researches in [2, 4, 8, 12-14].

Beside the two methods above, a modification of bus duct dimmension to form a resonant box, which is suggested in [8], can be a potential solution.

In this research, the solution of using resistor-fitted DSs is verified by the presented simulation model. Fig. 12 shows the VFTOs calculated in the substation with the DS fitted-resistor of 100Ω .

The results in Fig. 12 show the effectiveness of the mitigation method. It is observed that the VFTOs in the GIS are suppressed successfully into smaller oscillations. Besides, a comparison of VFTOs in the original structure and the modified one with resistor-fitted DS is summarized in Table 2. The peak values of VFTOs in this table once again demonstrate the positive impacts of the mitigation method in reducing VFTOs in the GIS.

4. CONCLUSIONS

In this paper, a simple but effective circuit model is presented and applied on the platform of ATP-EMTP for analyzing VFTO phenomenon in Binh Tan 220kV GIS successfully.

The simulation results show that the generation of VFTOs can become a hazard to the substation. Therefore, a typical mitigation method using resistor-fitted DS is proposed to attenuate VFTOs in this substation. The effectiveness of the suggested mitigation solution is then verified by the developed ATP-EMTP model.

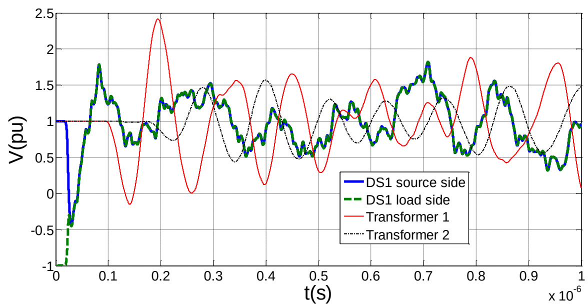


Fig.10. VFTOs in the GIS in the case of -1 pu TCV.

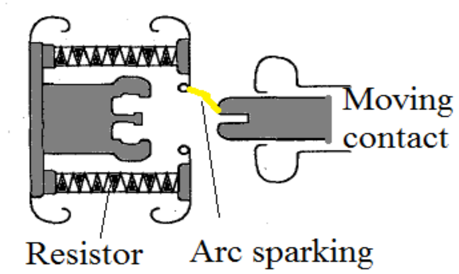


Fig.11. Configuration of resistor-fitted DS suggested in [9].

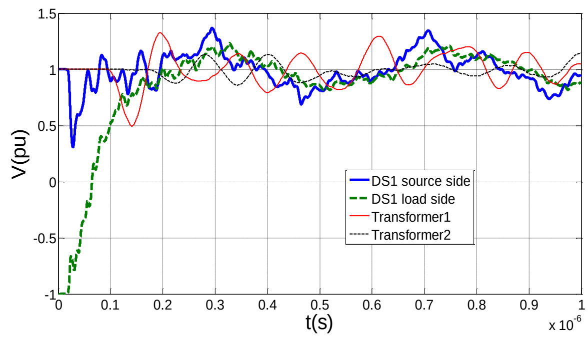


Fig 12. VFTOs in the GIS with 100Ω resistor-fitted DSs in the case of -1 pu TCV.

Table 2. Peak values of VFTOs in the two cases

Case/At	DS1	Transformer 1
Original	1.824	2.417
Resistor-fitted DS	1.369	1.328

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