

## TRANSMISSION SYSTEM FOR SERIES-SHUNT COMPENSATED NETWORK USING MATLAB/SIMULINK

By

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Email: [eyenubo63@yahoo.com](mailto:eyenubo63@yahoo.com)**ABSTRACT**

*This paper presents an analysis of the effects of shunt and series line compensation levels on the transmission line voltage profile, transferred power and transmission losses for different static load models. For this purpose, a simple model is developed to calculate the series and/or shunt compensated transmission line load voltage. Principle of superposition of modal transformation matrices for calculating relaying discriminants was used. Consequently, different shunt and series compensation levels are used with several voltage sensitive load models for two different line models. It is observed that the compensation level is significantly affected by the voltage sensitivities of loads. Moreover, the voltage level of the transmission is an important issue for the selection of the shunt and series capacitor sizes when load voltage dependency is used.*

**Keywords:** series compensation transmission system, metal oxide varistor, relaying discriminants.

**INTRODUCTION**

Series compensation has been employed to improve power transfer in long-distance transmission systems worldwide. However, this in turn introduces problems in conventional distance protection. The complex variation of line impedance is accentuated as the capacitor's own protection equipment operates randomly under fault conditions. A 735 kV, 300 km line is used to transmit power from bus B1 (735 kV equivalent system) to bus B2 (315 kV equivalent). In order to simplify, only one phase of the system has been represented. In order to increase the transmission capacity, the line is series compensated at its center by a capacitor representing 40% of the line reactance. The line is also shunt compensated at both ends by a 330 Mvar shunt reactance (110 Mvar /phase). The series capacitor is protected by a metal oxide varistor (MOV) simulated by the Surge Arrester block. The 250 MVA, 735 kV / 315 kV transformer

is a Saturable Transformer block simulating one phase of the three-phase 750 MVA transformer. A modal transformation technique, which decomposes the three-phase line into three single-phase lines, is used for this purpose (Xiao-Ping and Christian, 2012; Edris *et al*, 1997).

The addition of series capacitors in the transmission circuit makes the design of the protection more complex. The degree of complexity depends on the size of the series capacitor, its location along the transmission line and method of series capacitor bypass. Series capacitors introduce more difficulties; this is because the fundamental voltage and current phasors are functions of distance to fault, the amount of series capacitors and the placements of series capacitors. In addition, operation of the overvoltage protection scheme of the series capacitors introduces different frequency components and affects the steady-state fault signals (Abdelaziz *et al*, 2003). Furthermore, during faults on

series compensated transmission lines the series capacitors form resonant circuits with the system inductance. The frequencies of these circuits are in the vicinity of the fundamental frequency. Consequently, these extraneous frequencies cause considerable difficulties if not accounted for in series compensation schemes (Bachmann *et al*, 1996).

**Fault Detection Principles and Relaying Discriminant Using Traveling Wave Theory Relaying Signals for Single-Phase Line**

Figure 1 shows series and shunt compensated transmission system. The inception of a fault in a

transmission line will cause the post fault voltage  $v_R$  and current  $i_R$  at the relaying point to deviate from the steady-state prefault voltage  $v_R'$  and current  $i_R'$  respectively, where  $\Delta v_R$  and  $\Delta i_R$  as shown in Figure 2; denote the fault generated voltage and current deviation from pre-fault steady-state values as functions of time. The approach described in this paper, like others utilizes these superimposed quantities of voltage and current at the relaying point for making its decisions (Johns, 1980; Crossley and McLaren, 1983; Wedepohl, 1963)

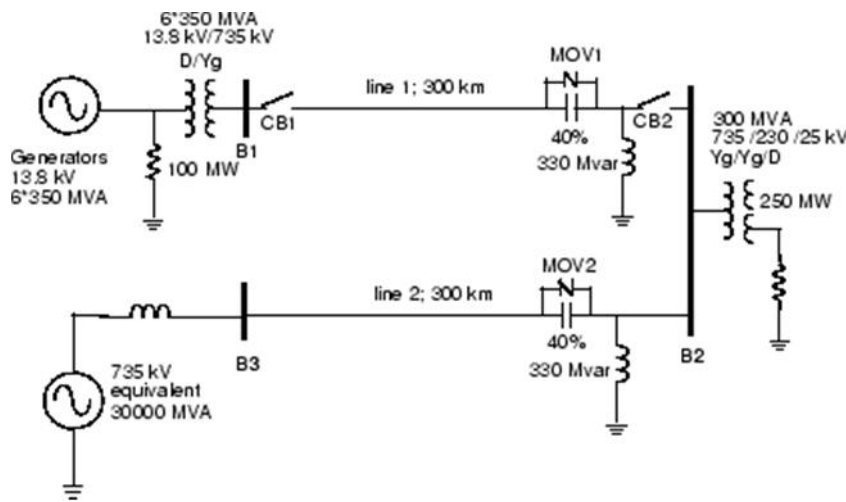
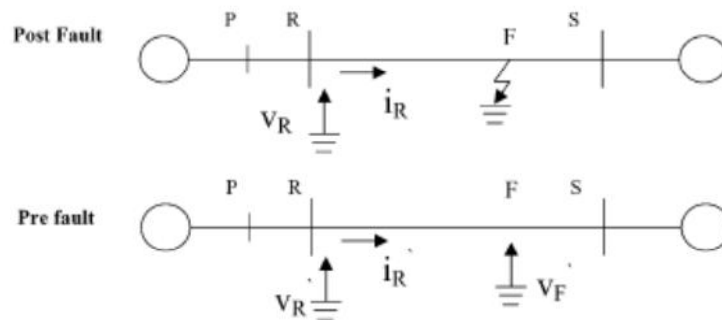


Figure 1: Series and shunt compensated transmission system



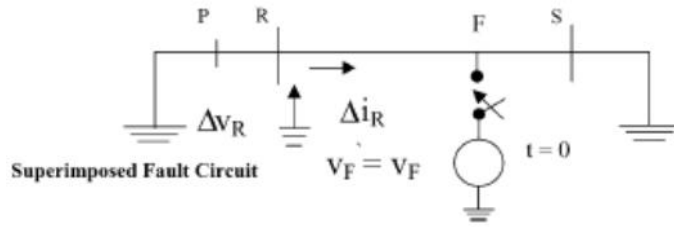


Figure. 2. Principle of superposition

**- Forward relaying signal:**

$$S_F = (\Delta v_R - z\Delta i_R) = -2V_{max} * \sin(\check{S}t + \{ ) \text{ for internal fault} \tag{1}$$

$$= 0 \text{ for no/or external fault}$$

**- Backward relaying signal:**

$$S_B = (\Delta v_R + z\Delta i_R) = -2V_{max} * \sin(\check{S}t + \{ ) \text{ for internal fault} \tag{2}$$

$$= 0 \text{ for no/or external fault}$$

**Single-Phase Line Relaying Discriminants**

The characteristic magnitude becomes a ramp function:

$2\sqrt{2V_{rms}}$  Which would be difficult to detect. This problem is avoided by using the wave characteristic in combination with its derivative to define a "forward fault traveling wave discriminant" (Mansour, 1984; Swift, 1979):

**- Forward discriminant function:**

$$D_F = S_F^2 + \frac{(dS_F/dt)^2}{\check{S}^2} = 8V_{rms}^2 \text{ for internal fault} \tag{3}$$

$$= 0 \text{ for no/or external fault}$$

Following the same procedures used in deriving the forward wave discriminant, a backward discriminant  $D_B$  can be established in the following form:

**- Backward discriminant function:**

$$D_B = S_B^2 + \frac{(dS_B/dt)^2}{\check{S}^2} = 8V_{rms}^2 \text{ for internal fault} \tag{4}$$

$$= 0 \text{ for no/or external fault}$$

The direction discrimination on calculating both  $D_F$  and  $D_B$  can be summarized as follows:

If  $D_B$  converges (exceeds a certain threshold) before  $D_F$  it means that it is a backward fault, otherwise it is a forward

fault. The discrimination is seen to be quite reliable with this procedure.

**Three-Phase Line Relaying Discriminants**

According to the theory of natural modes, a three phase coupled line can be decomposed into three

$$D_F^{(k)} = \left( \Delta v_R^{(k)} - z^{(k)} \Delta i_R^{(k)} \right)^2 + \frac{1}{\xi^2} \left\{ \frac{d}{dt} \left( \Delta v_R^{(k)} - z^{(k)} \Delta i_R^{(k)} \right) \right\}^2 \tag{5}$$

for the mode (k) forward discriminants;

$$D_B^{(k)} = \left( \Delta v_R^{(k)} - z^{(k)} \Delta i_R^{(k)} \right)^2 + \frac{1}{\xi^2} \left\{ \frac{d}{dt} \left( \Delta v_R^{(k)} - z^{(k)} \Delta i_R^{(k)} \right) \right\}^2 \tag{6}$$

For the mode (k) backward discriminant, where  $z^{(k)}$  is the mode (k) surge impedance,  $\Delta v_R^{(k)}$  and  $\Delta i_R^{(k)}$  superimposing voltage and current, respectively, at relay

$$[v(t)] = [S] * [v^{(mode)} * (t)] \tag{7}$$

$$[i(t)] = [S] * [i^{(mode)} * (t)] \tag{8}$$

Where [S] and [Q] are the modal transformation matrices. For an ideally transposed single circuit line [Q] will be equal to [S] and both will be constant, but except for the zero sequence mode, they will not be uniquely defined (Chamia and Liberman, 1978; IEEE Tutorial Course, 1979).

Discrete transposition of transmission lines is relatively rare. However, conventional practice involves

$$[Q] = [S] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & -2 \\ 1 & -1 & 1 \end{bmatrix} \tag{9}$$

independent single-phase lines (modes). The discriminants for fault detection in a three-phase line are defined by utilizing the superimposed modal voltages and currents at the relaying point as follows (Dommel, 1969):

point "R". These modal voltages and currents can be transformed from the corresponding phase quantities by the following equations:

setting the protective relays assuming that the line is ideally transposed. Therefore, in the present study, like some others, the developed algorithm will be based on the assumption of perfectly transposed transmission lines (Mansourm and Swift, 1985). Two of these constant modal transformation matrices for perfectly transposed lines are considered, namely Wedepohl transformation (Ibrahim, 2003):

Karrenbauer transformation [15, 18]:

$$[Q] = [S] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & -1 & -2 \end{bmatrix} \tag{10}$$

**Series Compensated Lines**

Basic modelling of the standard transition line discussed in the previous chapter can be used for developing a fault location algorithm. However, in the recent past new FACTS technology has been used in many transmission networks to control the power transfer in the line, with many other advantages such as higher power transferability, damping of oscillations and improvements to stability etc. The next section describes

the detail modelling of series line compensation which is a cornerstone of FACTS technology (Hingoraani, 2000).

**Series Compensation Unit**

Figure 3 shows the typical configuration of the series compensation device, with its basic protection mechanism. During normal operations, the series capacitor (C) generates leading Vars to compensate for some of the Var consumed by the network.

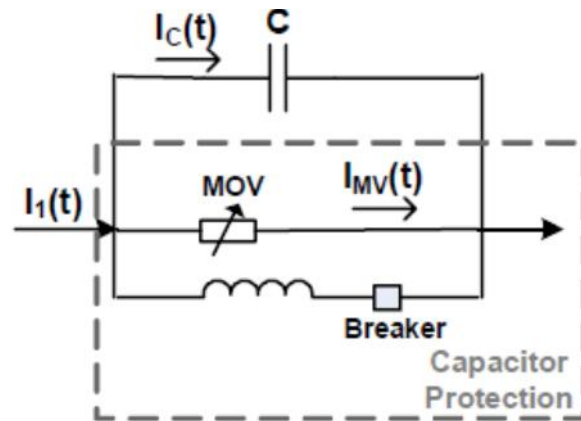


Figure 3: Basic series compensation unit

**Faulted Phase Selection and Fault Classification**

Faulted phase selection and selective pole tripping is an important relaying capability because it increases the system stability as well as its availability. Fault classification is a relaying feature that enhances the protection scheme. This section of a phase selection and fault classification relaying principle based on the foregoing discussion is developed through modal transformation theory. Consider, for example, the

Karrenbauer transformation (Eq. (10)), the forward modal discriminant functions for different fault types and different faulted phase(s) combinations can be considered. The transformation to the modal domain is based on phase 'A'. The contents are normalized with respect to  $V_{rms}^2$ , i.e., the square of the operating voltage (Moore, 1960).

By investigating any of Karrenbauer or Wedepohl tables it should be noted that some discriminant

components vary with respect to the faulted phase(s). Thus, by calculating the discriminant components for the same faults with the transformation base phase changed from "a" to "b" and then to "c", in Table I to each of the corresponding transformations (Xiao-Ping, 2006).

### ***The System under Study***

*Phase mode :*

$$Z_1 = 0.041 + j0.528(\Omega / \text{mile})$$

$$Y_1 = 7.86(\sim S / \text{mile})$$

*Ground mode :*

$$Y_0 = 4.25(\sim S / \text{mile})$$

The system is completely transposed and has communication channels between phases. All the components are modeled by the modified version of the Electromagnetic Transient Program (Schweitzer and Flechsig, 1977).

### ***Frequency Analysis***

From Figure 1, in order to understand the transient behaviour of this series-compensated network, a frequency analysis is first performed by measuring the Impedance at node B2. This measurement is performed by the Impedance Measurement block connected at node B2. Opening the Powergui and the Tools menu to select 'Impedance vs Frequency Measurement'. Then clicking on Display menu to compute and display the impedance for the 0 - 500 Hz range. The impedance curves will show two main parallel resonances (impedance maxima and phase inversion), corresponding to 15 Hz and 300 Hz modes. The 15 Hz mode is due to a parallel resonance of the series

The system studied is composed of two generators, two series capacitors that provide 80% compensation and their protection equipment (MOV) in the 100 miles, 500 kV transmission line. The volt-ampere characteristics of the MOV protection is calculated. The characteristics of the line:

capacitance and the two shunt reactances. The 300 Hz mode is mainly due to resonance of shunt line capacitance and series reactance of the transmission system. These two modes are likely to be excited at fault clearing (Song *et al.* 1996).

### ***Fault Phase Selection Component***

Based on the travelling wave signal generated by fault and its related theory, the fault phase selection principle can be obtained. According to the differences in the information of all fault types, the travelling wave based fault phase selection is achieved. Since the electromagnetic coupling relationship exists among three phase current, it will be difficult to select fault phase if only the phase current is used. So the selection phase component will use the mode current component. Through Karrenbauer transformation of three phase current, mode current component can be obtained (Caudill and Butler, 1992; Mansour and Swift, 1986).

$$\begin{aligned} I_0 &= (I_A + I_B + I_C) / 3 \\ I_r &= (I_A - I_B) / 3 \\ I_s &= (I_A - I_C) / 3 \end{aligned} \tag{II}$$

In order to select the fault type easily a virtual mode component  $\gamma$  is introduced here.

$$I_x = (I_B - I_C) / 3 = I_s - I_r \tag{12}$$

According to fault border conditions and equations (3) and (4), the criterions for selecting fault phase can be constructed based on mode current component 0,  $\alpha$ ,  $\beta$ ,  $\gamma$ .

**Criteria for Selecting Fault Phase** (Narain *et al.*, 1999)

1.  $I_0 \neq 0$

If  $|I_0| = |I_r| = |I_s|$ , then it is phase A to ground fault;

If  $|I_0| = |I_r| = |I_x|$ , then it is phase B to ground fault;

If  $|I_0| = |I_s| = |I_x|$ , then it is phase C to ground fault

} (13)

2.  $I_0 = 0$

If  $|I_r| = 2|I_s| = 2|I_x|$ , then it is phase A to phase B fault

If  $|I_x| = 2|I_r| = 2|I_s|$ , then it is phase B to phase C fault

If  $|I_s| = 2|I_r| = 2|I_x|$ , then it is phase A to phase C fault

} (14)

3.  $I_0 \neq 0$

If  $I_0 = I_s + I_x$ , then it is phase A and B to ground fault.

If  $I_0 = -(I_r + I_s)$ , then it is phase B and C to ground fault

If  $I_0 = (I_r - I_x)$ , then it is phase A and C to ground fault

} (15)

4.  $I_0 = 0$

(16)

If the conditions in case 2) are all not met, then it is three-phase to ground fault

**Table:** Simulation results based on modal current values

Fault type	$I_0$	$I_\alpha$	$I_\beta$	$I_\gamma$	Phase Selection
A-G	-1.14593	-1.14577	-1.1462	-0.000437619	A-G
B-G	0.504259	-0.504132	-0.00025473	0.503877	B-G
C-G	0.641671	0.000182888	-0.64189	-0.642073	C-G
AB-G	-0.50137	-2.76032	-1.63118	1.02914	AB-G
AC-G	-0.332003	-1.49339	-2.65535	-1.16196	AC-G
BC-G	0.833373	-0.469218	-0.364243	0.104976	BC-G
ABC-G	0	-2.76024	-2.65535	0.104976	ABC-G
AB	0	-2.76032	-1.38051	1.37928	AB
AC	0	-1.32736	-2.65535	-1.327798	AC
BC	0	-0.0525237	0.05254518	0.104976	BC

**Simulation**

When a 6-cycle fault is applied at node B2. Fault is simulated by the Breaker block. Switching times are defined in the Breaker block menu (closing at  $t = 3$  cycles and opening at  $t = 9$  cycles). Start the simulation and observe waveforms on the two Scopes. At  $t = 3$  cycles, a line-to-ground fault is applied and the fault current reaches 10 kA (trace 1 of Scope2). During the fault, the MDV conducts at every half cycle (trace 2 of Scope1) and

the voltage across the capacitor (trace 1 of Scope1) is limited to 263 kV. At  $t = 9$  cycles, the fault is cleared. The 15 Hz mode is clearly seen on the capacitor voltage (trace 1 of Scope1) and bus B2 voltage (trace 3 of Scope1). During fault the flux in the transformer is trapped to around 1 p.u. At fault clearing the flux offset and 15 Hz component cause transformer saturation (flux > 1.2 p.u, trace 3 of Scope2), producing magnetizing current pulses (trace 2 of Scope2).

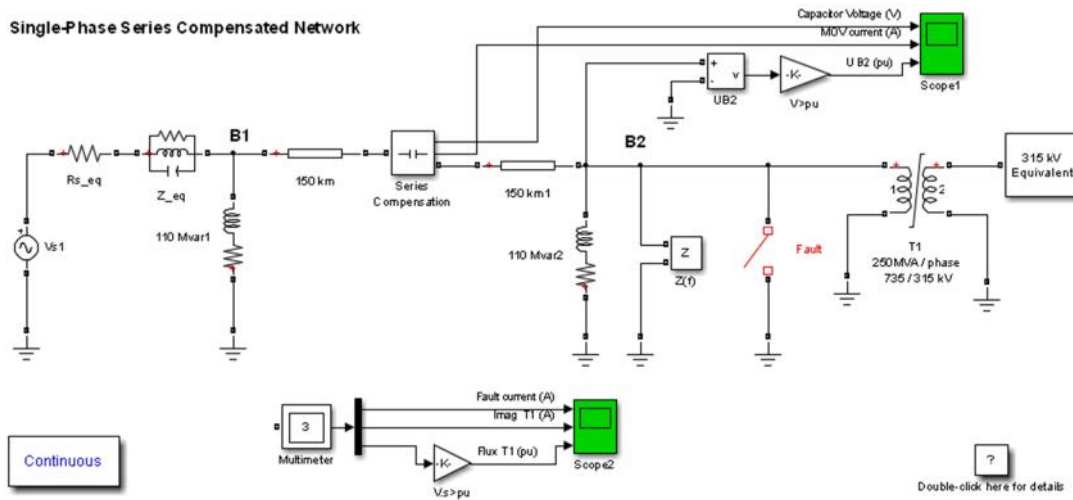


Figure 4: Single Phase Series Compensated Network





Figure 5: MOV conducting at half cycle producing voltage across the capacitor in Scope 1

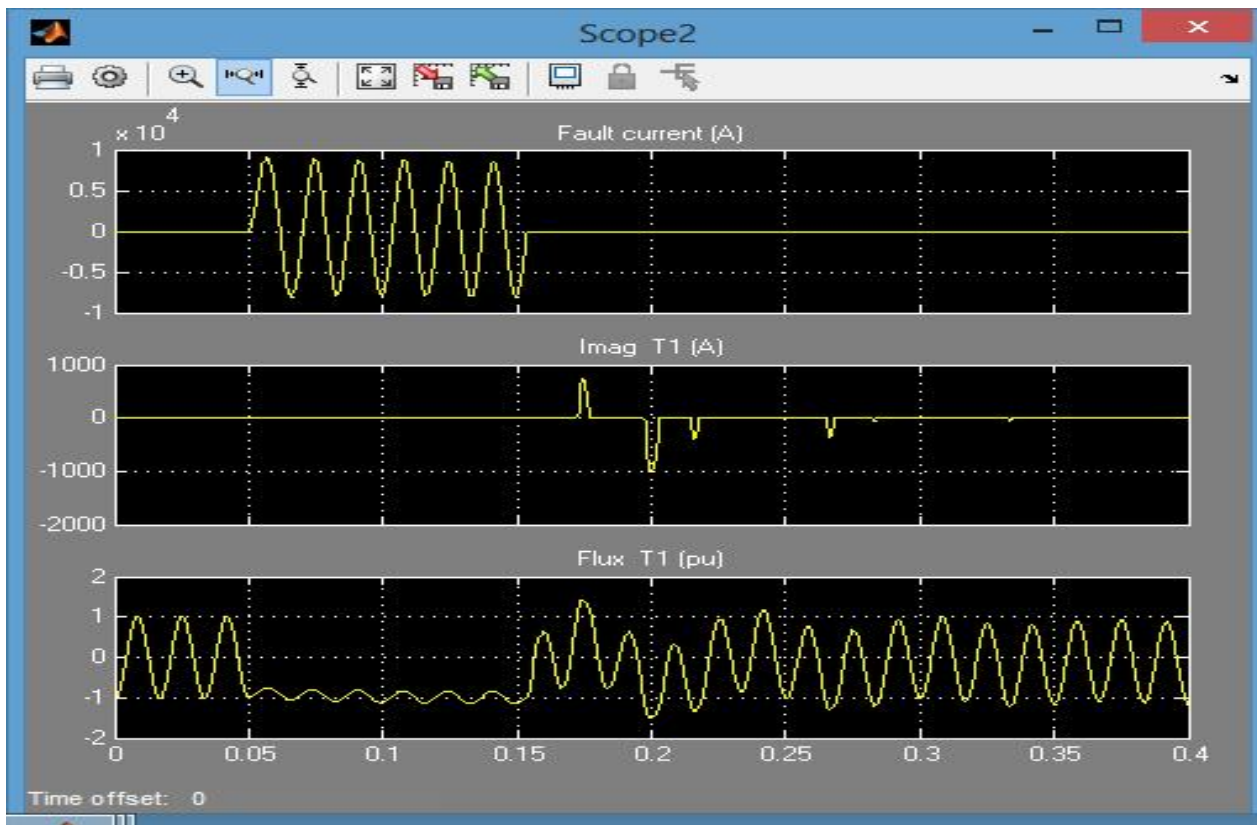


Figure 6: Fault the flux in the transformer is trapped fault clearing the flux producing magnetizing current pulses Scope2.

## DISCUSSION

A new travelling-wave protection principle for digital transmission line relaying has been presented in this paper. This relaying principle features phase selection and fault classification capabilities. The major advantages of the new principle as compared to previous travelling-wave-based relays can be briefly itemized as follows:

1. Faulted phase selection capability for different types of faults, which should then lead to selective pole-tripping and hence enhanced system stability and availability. Meanwhile, fault classification is another inherent special feature of this relay, which has not been realized before in any other travelling-wave-based relaying scheme.
2. The relaying discriminant functions used for fault detection and direction discrimination are quite decisive and insensitive to parameter variation, different system configurations, and fault initiation angle.

## CONCLUSION

The main results regarding MOV protected series compensation, obtained by the fault simulation are summarized as follows:

During a three phase fault, the MOV (metal oxide varistor) protection devices operate immediately, in order to remove the capacitor banks from the system. However, the capacitor is not isolated from the line, so its reinsertion is instantaneous. An important result is that as soon as the bypass switch closes the line current is reduced to a value, as if there were no capacitor banks in the system. During single phase fault, only protection equipment of faulted phase function, while the capacitor banks of the other phases remain in the system to maintain stability. Also, the MOVs' absorption of energy is measured in all phases and the energy is exchanged between the capacitor and the MOV.

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