Reduced-Rating DVR Control with BESS for Voltage Sag, Swell and Harmonic Compensation

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Abstract: *In this paper, the compensation of the voltage sag, swell, and harmonics in three phase system is analyzed using a reduced-rating DVR. For reducing the rating of DVR, different voltage injection scheme are analyzed to minimize the rating of VSC used in DVR. The voltage rating of VSC can be reduced then the DVR rating can also be reduced. By using unit vectors we can determine the load voltage references. The voltages from rotating axis to stationary axis can be converted by using synchronous reference frame (SRF) theory. The remuneration of power quality problem such as voltage lists, swell, and harmonics is shown by utilizing a diminished rating DVR.*

Keywords: Dynamic Voltage restorer (DVR), power Quality, unit vector, Synchronous Reference Frame (SRF) theory, voltage source converter (VSC)

1. Introduction

Now days in the distribution system, power quality problems are identified due to most use of sensitive and basic hardware pieces [1]-[6]. Performance of these hardware pieces are affected when the power quality problems to the supply voltage of the sinusoidal waveform. For providing protection against power quality problems a custom power devices technologies are used. Unified power quality conditioner, distribution static compensators, dynamic voltage restorers are three important categories of custom power devices. The power quality problems in the supply voltages then the load voltage can be control by DVR. Thus, the tripping and consequent losses of critical consumer loads can protect it. For meeting the power quality norms at consumer point the custom power devices are installed and developed [7].

Voltage sags is always not feasible to evade in an electrical grid due to finite clearing time of faults. Due to this the spread of sags and voltage sags to the low-voltage loads from the transmission and distribution system. Disturbance in production and for end-client equipment are the common reasons in voltage sags. Specifically, production line can cause production disturbance by tripping the equipment and also more cost due to production loss. The first solution for this voltage sags is to make the apparatus itself more tolerant, it can be done by smart regulate or storing energy in apparatus through ride-through. Another solution is mitigation of voltage sags for short period a DVR can install on the incoming supply, instead of each component modifying [8]-[12]. DVR can erase almost all sags and reduce the risk of tripping load for short duration sags, but their disadvantage is more losses, cost of equipment and for downstream short circuit protection scheme is required.

2. Operation of DVR

Figure 1 (a) shows a basic circuit diagram of DVR system and figure 1 (b) shows the various voltage insertion schemes of DVR phasor diagram.
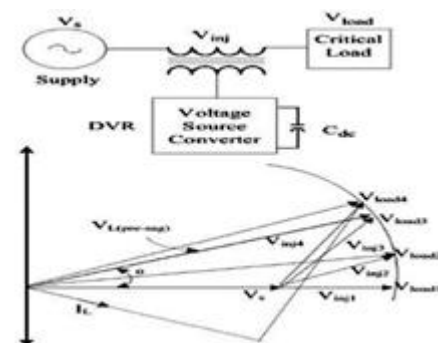
Figure 1(a) DVR basic circuit and **Figure 1(b)** DVR pahsor diagram for different voltage injection schemes

The voltage at the load side is uninterrupted and constant in magnitude and supply side voltage is interrupted and not constant in magnitude at the time of voltage insertion. For voltage sag condition voltage across the critical load is V_L (pre−sag). With a lag phase angle θ the voltage is decreased to V_S in the time of voltage sag. Before the sag condition the load voltage is maintained magnitude when DVR injects voltage. The insertion of voltages can be understood into four ways according to the load voltage phase angle. For the voltage Vinj1, the insertion voltage in-phase with the source voltage. In case of Vinj2, the magnitude of heap voltage is same however it leads by a little angle V_S. The phase angle of load voltage is same as that of pre-sag condition for Vinj3. In the case of Vinj4, the insertion voltage and current are in quadrature, a capacitor-supported DVR is used. But, Vinj1 is achieved a minimum possible rating. In this case, the operation of can be done with battery energy storage system (BESS).

A three-phase critical load voltage is restored by connecting three-phase DVR as shown in figure (2). Through three-phase injection transformer a three-phase source is connected to sensitive and critical load. Through short circuit impedance Z_{sa} the phase A voltage V_{Ma} is connected to V_{Sa} (point of prevalent coupling that is PCC). The load voltage V_{La} is uninterrupted and magnitude when the DVR inserts a voltage in phase A V_{Ca} . By utilizing three single-stage transformers Tr a three-phase DVR is connected in series to the line for injecting the voltage. To eliminate the ripples in insertion voltage, the filter components are used. Here, Lr and Cr are used as filters. In a DVR, insulated-gate bipolar transistors (IGBTs) are used in VSC, and at the DC side a battery is connected.
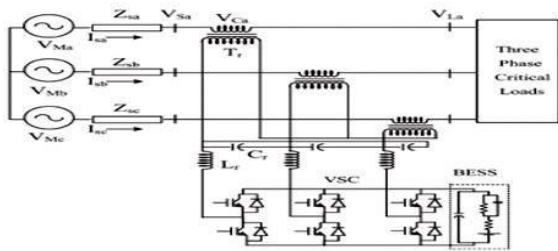
Figure 2: Three-phase DVR connected system

3. Control of DVR

By using DVR the compensation of voltage sags can be done and the performance of DVR can be done by inserting the reactive power or absorbing the actual power. The compensation is done by inserting reactive power when the insertion voltage and current are in quadrature at fundamental frequency. In this case, a DVR is operated with self-supported DC bus. But, DVR inserts real power when current and insertion voltage are in phase. In this case, DVR operated with battery at DC side. The control strategy received ought to think the inhabitations, where as the voltage insertion capacity and minimization of energy storage size.

3.1 DVR control with BESS for voltage sag, swell, and harmonics compensation

The control block of DVR is shown in Figure 3. Reference signal can be estimated by using SRF theory.
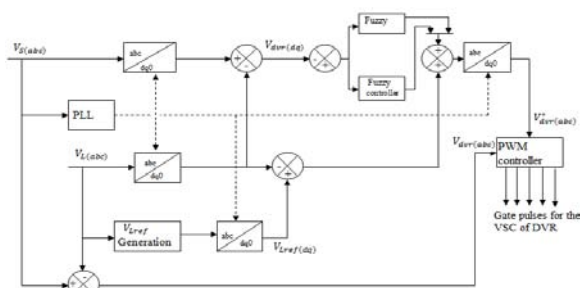
Figure 3: Control block of DVR when injected voltage in-phase with current

The IGBTs' gate signals can be derived by sensing the PCC voltage V_S and load voltage V_L. By using unit vectors the load voltage references V_L^* is separated. Convert the load voltages (V_{La}, V_{Lb}, V_{Lc}) from abc$-$dqo by utilizing Park's

transformation with derived unit vectors using a phase-locked loop as

$$\begin{bmatrix} V_{Lq} \\ V_{Ld} \\ V_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_{Laref} \\ V_{Lbref} \\ V_{Lcref} \end{bmatrix} \quad (1)$$

According to equation (1) convert the load voltage references ($V_{La}^*, V_{Lb}^*, V_{Lc}^*$) and PCC voltages V_S into d-q-0. The d and q axes of DVR voltages are obtained as

$$V_{Dd} = V_{Sd} - V_{Ld} \quad (2)$$
$$V_{Dq} = V_{Sq} - V_{Lq} \quad (3)$$

Similarly, the d and q axes of reference DVR voltages are obtained as

$$V_{Dd}^* = V_{Sd}^* - V_{Ld} \quad (4)$$
$$V_{Dq}^* = V_{Sq}^* - V_{Lq} \quad (5)$$

By using two Fuzzy controllers in rotating frame we can control the error between reference DVR and actual DVR voltages. From eq (4) and (5) convert the Reference DVR voltages into abc by using converse Park's change taking from V_{D0}^* as zero as

$$\begin{bmatrix} V_{dvra}^* \\ V_{dvrb}^* \\ V_{dvrc}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_{Dq}^* \\ V_{Dd}^* \\ V_{D0}^* \end{bmatrix} \quad (6)$$

For generating gating pulses to a VSC the reference DVR voltages ($V_{dvra}^*, V_{dvrb}^*, V_{dvrc}^*$) and real DVR voltages ($V_{dvra}, V_{dvrb}, V_{dvrc}$) are utilized in (PWM) controller. The operating frequency is 10 kHz for PWM controller.

3.2. DVR control with capacitor-supported for voltage sag, swell, and harmonics compensation

A capacitor-upheld DVR and its control block diagram as shown in figure 4(a) and figure 4(b)
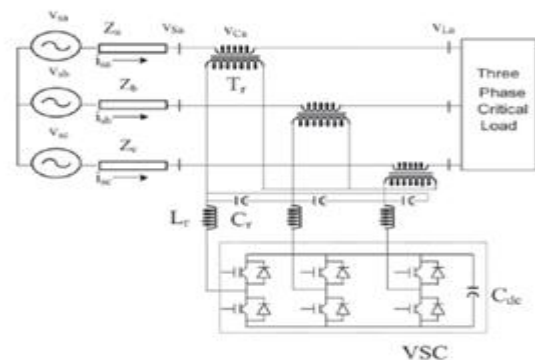
Figure 4(a): Capacitor-supported DVR
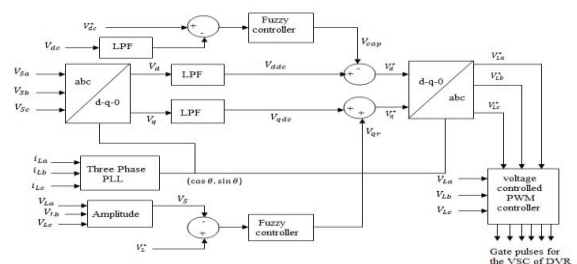
Figure 4(b): control block of self-supported DVR

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Convert the voltages at the PCC V_s from abc-dq0 by using parks transformation. By using low pass filters (LPFs) eliminate the harmonics and wave components. The d-axis and q-axis voltage element are

$$V_d = V_{ddc} + V_{dac} \qquad (7)$$
$$V_q = V_{qdc} + V_{qac} \qquad (8)$$

At the time of compensation taking load voltage as undistorted and rated magnitude.

A Fuzzy controller is used for maintain the DC voltage self-fortified capacitor and output is taken as V_{cap} for accumulating its losses.

$$V_{cap\,(n)} = V_{cap\,(n-1)} + K_{p1}\big(V_{dc\,(n)} - V_{dc\,(n-1)}\big) + K_{i1}V_{dc\,(n)} \qquad (9)$$

Whereas the mistake among the reference V_{dc}^* and detected dc voltages at the nth inspecting moment is $V_{dc\,(n)} = V_{dc}^* - V_{dc\,(n)}$. The expression of d-axis load voltage reference as:

$$V_d^* = V_{ddc} - V_{cap} \qquad (10)$$

By utilizing another Fuzzy controller the heap voltage terminal of amplitude is regulate to its voltage reference. For voltage control of the load voltage terminal the voltage of reactive component V_{qr} is taken as output of Fuzzy controller. From the alternating current voltages (V_{La}, V_{Lb}, V_{Lc}) the load voltage amplitude V_L is determined at the PCC

$$V_L = \left(\frac{2}{3}\right)^{1/2} (V_{La}^2 + V_{Lb}^2 + V_{Lc}^2)^{1/2} \qquad (11)$$

The reference value can be controlled by using Fuzzy controller as

$$V_{qr\,(n)} = V_{qr\,(n-1)} + K_{p2}\big(V_{tc\,(n)} - V_{tc\,(n-1)}\big) + K_{i2}V_{tc\,(n)} \qquad (12)$$

The inaccuracy between the V_L^* and $V_{L(n)}$ at nth sampling point

$$V_{tc\,(n)} = V_L^* - V_{L(n)} \qquad (13)$$

The expression of q-axis reference load voltage as

$$V_q^* = V_{qdc} - V_{qr} \qquad (14)$$

From equation (6) convert the reference load voltages from abc-dqo.

The gating pulses can be generated by using PWM generator by giving the blunder between sensed and reference load voltages.

4. Results

The simulink model of BESS-supported DVR and its control block are modeled in MATLAB and also simulink model of self-supported DVR and its control block are modeled in MATLAB.

For various voltage disturbances such as voltage list, voltage swell is shown for the dynamic performance of DVR. The following figures (5.a to 5.d) shows the transient performance of DVR for voltage sag and swell i.e. is PCC voltage, DVR voltage, load voltage, amplitude of load voltage, source current, load voltage references and dc voltage. The phase A voltages such as PCC voltage and load voltage as shown in figure 6. From figures 5 to 6 shows the in-phase injection of voltage by DVR for voltage sag and swell and also in-phase injection of voltage by DVR for harmonics as shown in figure 7. The total harmonic distortion for PCC voltage, load voltage and supply current
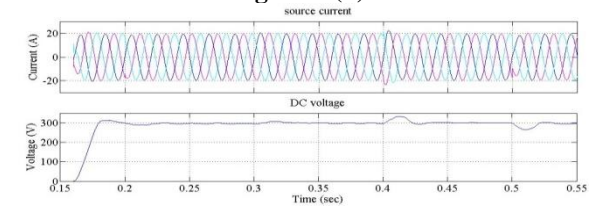
as shown in figure 8 to 10. Similarly for the performance of DVR with capacitor-supported is shown in figure 11 and 12.
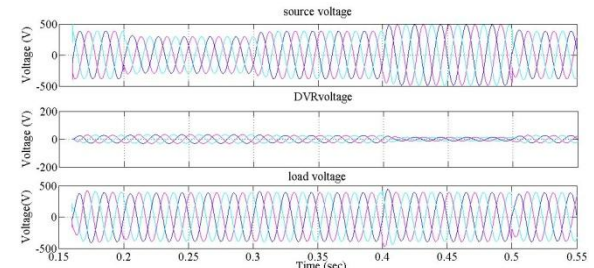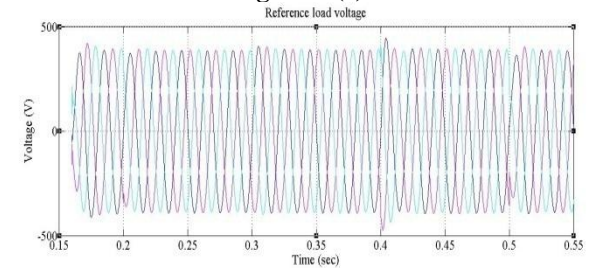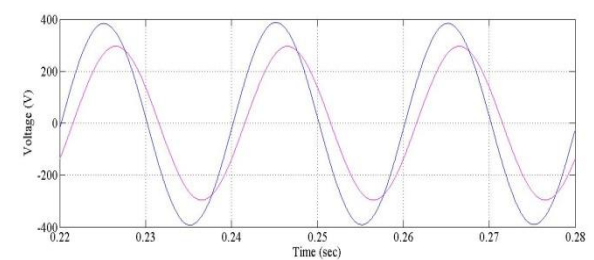

Figure 5 (a)
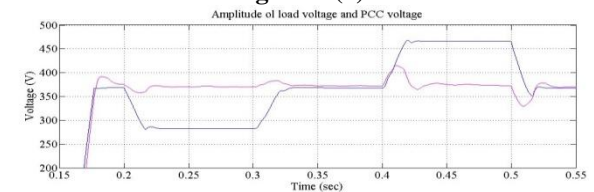
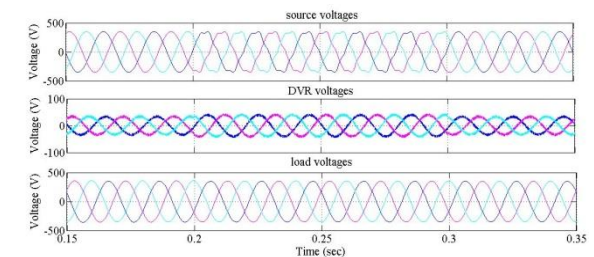

Figure 5 (b)

Figure 5 (c)

Figure 5 (d)

Figure 5: Dynamic performance of DVR with BESS for voltage sag and swell applied to critical load
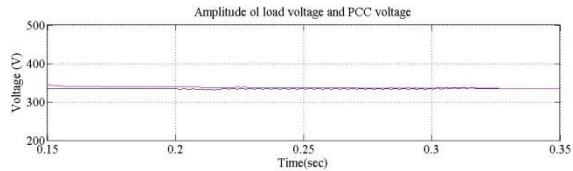

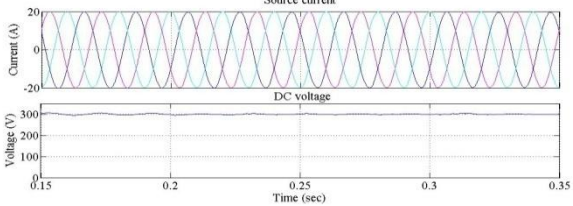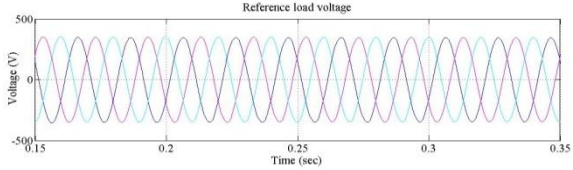**Figure 6:** PCC voltage and load voltage terminal of phase A
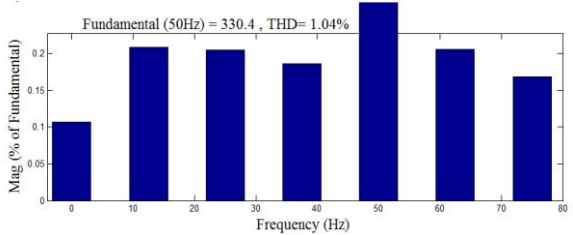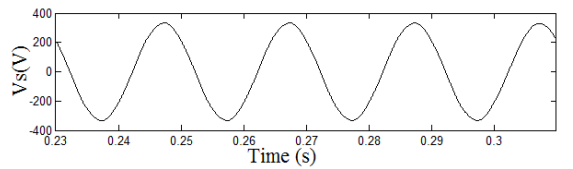

Figure 7(a)

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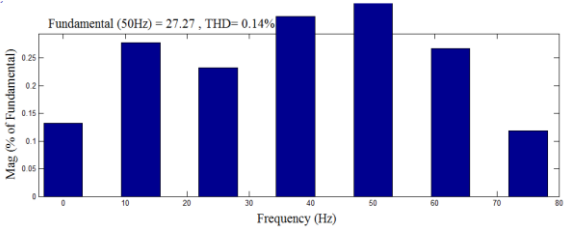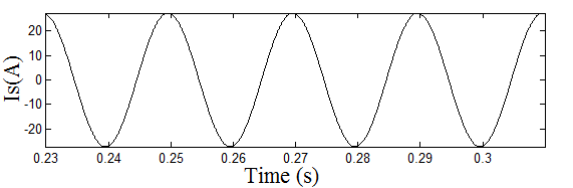
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Figure 7(b)

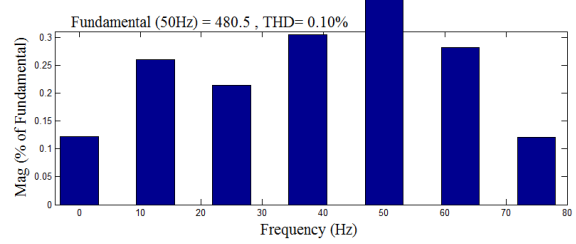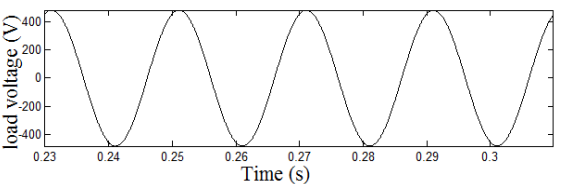**Figure 7(c)**

Figure 7(d)
Figure 7: Dynamic presentation of DVR during harmonics in supply voltage applied to critical load
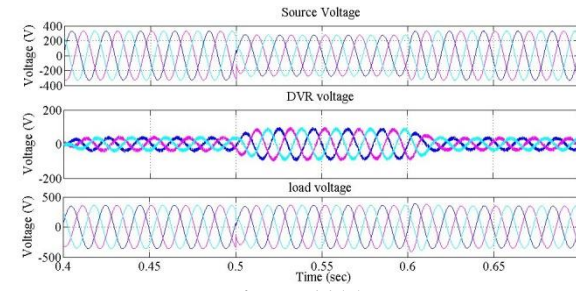

Figure 8: PCC voltage and harmonic spectrum during disturbance
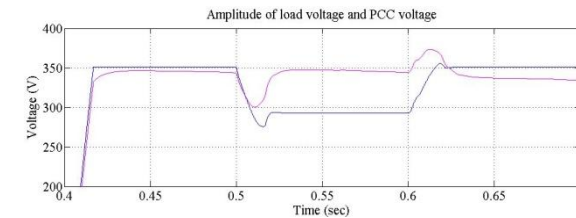

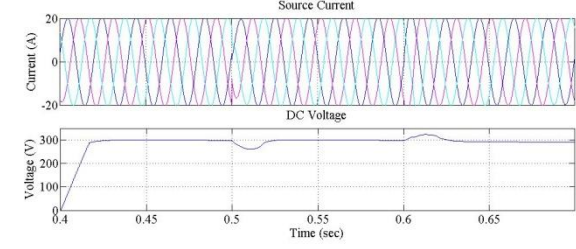**Figure 9:** Supply current and harmonic spectrum during the disturbance

Figure 10: Load voltage and harmonic spectrum during the disturbance
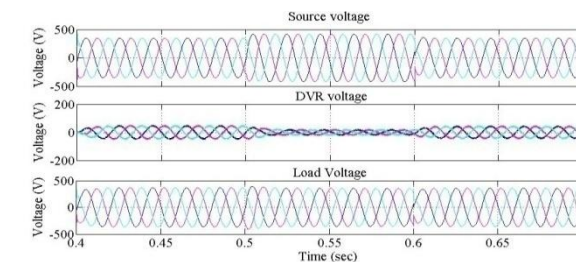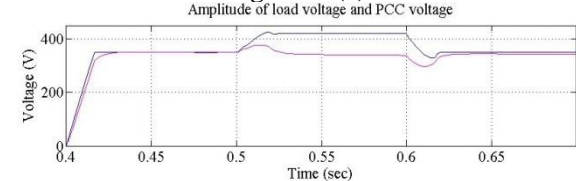

Figure 11(a)
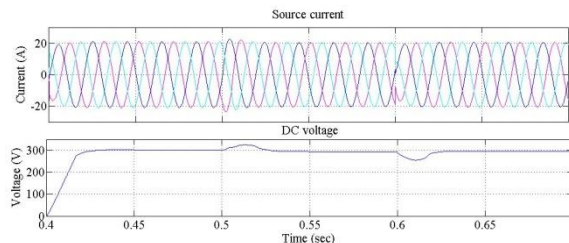

Figure 11(b)

Figure 11(c)
Figure 11: Dynamic performance of capacitor-supported DVR during voltage sag applied to critical load

Figure 12(a)

Figure 12(b)

Figure 12(c)
Figure 12: Dynamic performance of capacitor-supported DVR during voltage swell applied to critical load

5. Conclusion

By applying different voltage injection schemes the role of DVR has been shown with a latest control technique. The presentation of DVR has been balanced with various schemes with a reduced-rating VSC, together with a self-supported DVR. For getting the control of DVR, the reference load voltages have been determined with the help of unit vectors, and the error of voltage insertion is reduced. By using SRF theory the reference DVR voltages have been determined. Finally it is concluded that the voltage insertion in-phase with PCC voltage results in rating of DVR is reduced but at the price of an energy source at its DC bus.

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