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DESIGN AND ANALYSIS OF POWER SWITCHED CAPACITOR FOR POWER QUALITY AND POWER SYSTEM STABILITY

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I. INTRODUCTION

The electric utility industry and consumers of electrical energy are facing new challenges for cutting the electric energy cost, improving energy utilization, enhancing electric energy efficiency, improving supply waveform power quality, reducing any safety hazards to personnel and protecting electronic sensitive computer and automatic data processing networks. The global need for electrical energy sources, energy conservation measures, and rising world energy demand drive exiting power systems and transmission lines toward their crucial stability and thermal limits and grid security, reliability, and voltage stability. The growing use of nonlinear type electric loads causes a real challenge to power quality for electric utilities. The deregulated electricity market where: competition, supply quality, security and reliability are now key issues for any economic survival. Electrical power network pollution is characterized by the nonlinear electric load ability to distortion modify and change the voltage and current wave form Root Mean Square (RMS) due to its inherent nonlinearity.

All these devices will cause harmonic currents to flow and some devices, actually, directly produce voltage harmonics. Any ac current flow through any circuit at any frequency will produce a voltage drop at that same frequency. Other option is using the switched/modulated family of passive filters and capacitive compensators developed. Advent of Flexible A. C. Transmission System (FACTS) based Switched Capacitor Compensation (SCC) utilized with dynamic control systems for compensation of reactive power and harmonics to system [2]. Nonlinear loads are sources of dynamic and quasistatic type harmonics, of integral, sub- and super hanmnic content. Other non-integer modulating type peculiar frequency signals: are introduced by load temporal nonlinearities. Their peculiar frequencies are generated by periodic and cyclical load variations along with the nonlinearity in the load. The nonlinearity is either analog or of the switching-type. Voltage drop calculations, reactive power compensation and power factor correction become &icky and complex issues in the presence of these non-common, non-sinusoidal feeder voltage and current waveforms.

The use of distribution capacitor banks alone or as part of a low pass tuned arm, C-type, or a high pass damped type filter may not be either adequate or effective in providing the required reactive- compensation, voltage stabilization or targeted power factor correction level. This is caused by the generated uncommon' voltage and current harmonics that require new definitions of residual and generated type currents. The validation results using the MATLAB/Simulink/ Power System Blockset (PSB) indicated the effectiveness and simplicity of this low cost (USCS) solution to harmonic reduction. Total voltage and current distortions (THD)v, (THD)i indices were utilized to select the (USCS) compensator parameters using an off-line performance criterion "J" based on (THD) magnitude of offending harmonic and RMS value of source current:
J= Minimum {a, (THD)i+ a2 (THD), + a3 (Is0tla / IS"W) + a 4 II"/ Where all a are specified weighting factors and II,I is any offending dominant low order neutral (triplen or odd) .
harmonic intensified by any near-parallel resonance condition on the utilization grid network.

II. MULTI-LOOP DYNAMIC ERROR DRIVEN CONTROLLER

The multi-loop dynamic error driven decoupled and coordinated controller is a dual action controller to modulate two operating modes of the SCC. It comprises two main controller blocks which their outputs are indicated by e(A) and e(B) in Fig.2. The first controller block is a dynamic tracking regulator and includes three loops. The first loop is a voltage regulator that tracks reference voltage (Vg-ref). The second and third loops are dynamic tracking ones to stabilize current excursions and limit generator power excursions, respectively. The second controller block is a minimal ripple content regulator which minimizes ripple and sudden change contents caused by prime mover variations. This block does its responsibility by limiting the changes in Vg, Ig, and Pg loops.

It is worthy to mention that the two blocks are time-decoupled weighted to ensure coordinated regulation action. The global output signal of the dynamic error driven controller is followed by a Weighted-Modified PID controller (WMPID) displayed in Fig. 3. WMPID includes an error sequential activation supplementary loop to ensure fastdynamic response and effective damping of large excursions, in addition to conventional PID structure. The output signal of the Weighted-Modified PID controller enters a PWM signal generator. On-off switching sequences produced by PWM define two operating modes of the FACTS device.

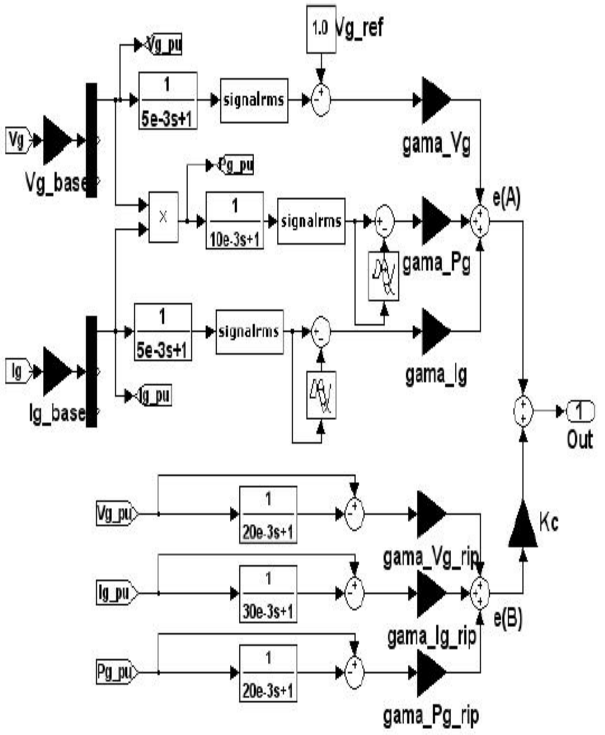
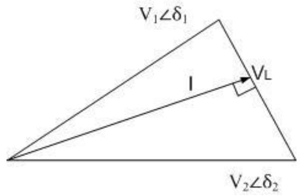


Fig. 1 Multi-loop dynamic error driven

III. BASIC PRINCIPAL OF POWER COMPENSATION IN TRANSMISSION SYSTEM

Figure 2.1(a) shows the simplified model of a power transmission system. Two power grids are connected by a transmission line which is assumed lossless and represented by the reactance X_L, $V_1\angle\delta_1$ and $V_2\angle\delta_2$represent the voltage phasor of the two power grid buses with angle δ= δ1 - δ2between the two. The corresponding phasor diagram is shown in Figure 2.1(b).

(a)



(b)

Figure 2.1 Power Transmission System: (a) Simplified Model (b) Phase Diagram

The magnitude of the current in the transmission line is given by,

$$I = \frac{V_L}{X_L} = \frac{|V_1\angle\delta_1 - V_2\angle\delta_2|}{X_L} \tag{2.1}$$

The active and reactive components of the current flow at bus 1 are given by,

$$I_{d1} = \frac{V_2 \sin\delta}{X_L}, \quad V_{q1} = \frac{V_1 - V_2 \cos\delta}{X_L} \tag{2.2}$$

The active power and reactive power at bus 1 are given by,

$$P_1 = \frac{V_1 V_2 \sin\delta}{X_L}, \quad Q_1 = \frac{V_1(V_1 - V_2 \cos\delta)}{X_L} \tag{2.3}$$

Similarly, the active and reactive components of the current flow at bus 2 can be given by,

$$I_{d2} = \frac{V_1 \sin\delta}{X_L}, \quad I_{q2} = \frac{V_2 - V_1 \cos\delta}{X_L} \tag{2.4}$$

The active power and reactive power at bus 2 are given by,

$$P_2 = \frac{V_1 V_2 \sin\delta}{X_L}, \quad Q_2 = \frac{V_2(V_2 - V_1 \cos\delta)}{X_L} \tag{2.5}$$

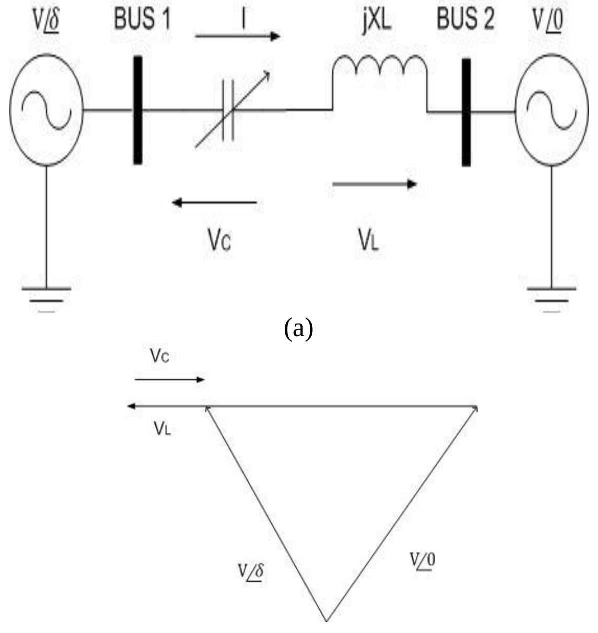
Equations (2-1) through (2-5) indicate that the active and reactive power/current flow can be regulated by controlling the voltages, phase angles and line impedance of the transmission system. The active power flow will reach the maximum when the phase angle δ is 90º. In practice, a small angle is used to keep the system stable from the transient and dynamic oscillations [26]. Generally, the compensation of transmission systems can be divided into two main groups: shunt and series compensation.

Necessity of reactive power compensation:-

“Reactive power (vars) is required to maintain the voltage to deliver active power(watts) through transmission lines. Motor loads and other loads require reactive power to convert the flow of electrons into useful work. When there is not enough reactive power, the voltage sags down and it is not possible to push the power demanded by loads through the lines”. Transformers, transmission lines, and motors require reactive power. Transformers and transmission lines introduce inductance as well as resistance; both oppose the flow of current. It must raise the voltage higher to push the power through the inductance of the lines, unless capacitance has introduced to offset of inductance. The reactive power is require when one waveform leads to other , Phase angle not equal to 0° and Power factor less than unity. The reactive power produced when the current waveform leads voltage waveform (Leading power factor), and consumed when the current waveform lags voltage (lagging power factor).

A. Series compensation:-

Series compensation aims to directly control the overall series line impedance of the transmission line. Tracking back to Equations (2-1) through (2-5), the AC power transmission is primarily limited by the series reactive impedance of the transmission line. A series-connected can add a voltage in opposition to the transmission line voltage drop, therefore reducing the series line impedance. A simplified model of a transmission system with series compensation is shown in Figure 2.2(a). The voltage magnitudes of the two buses are assumed equal as V, and the phase angle between them is δ. The transmission line is assumed lossless and represented by the reactanceX_L. A controlled capacitor is series-connected in the transmission line with voltage additionV_{inj}. The phase diagram is shown in Figure 2.2(b).



(a)

(b)

Figure 2.2 Transmission systems with series compensation (a) Simplified Model (b) Phasor diagram [24]

Defining the capacitance of C as a portion of the line reactance,

$$X_C = k\,X_L \tag{2.6}$$

The overall series inductance of the transmission line is,

$$X = X_L - X_C = (1-k)X_L \tag{2.7}$$

The active power transmitted is,

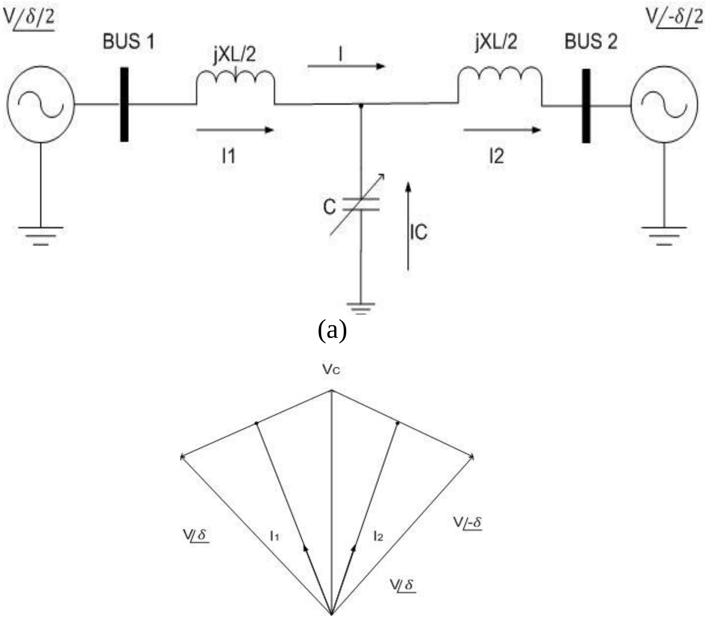
$$P = \frac{V^2}{(1-k)X_L}\sin\delta \tag{2.8}$$

The reactive power supplied by the capacitor is calculated as,

$$Q_C = 2\,\frac{V^2 k}{(1-k)^2 X_L}(1-\cos\,\delta) \tag{2.9}$$

B. Shunt compensation:-

Shunt compensation, especially shunt reactive compensation has been widely used in transmission system to regulate the voltage magnitude, improve the voltage quality, and enhance the system stability [27]. Shunt-connected reactors are used to reduce the line over-voltages by consuming the reactive power, while shunt-connected capacitors are used to maintain the voltage levels by compensating the reactive power to transmission line.A simplified model of a transmission system with shunt compensation is shown in Figure 2.3(a). The voltage magnitudes of the two buses are assumed equal as V, and the phase angle between them is δ. The transmission line is assumed lossless and represented by the reactance X_L. At the midpoint of the transmission line, a controlled capacitor C is shunt-connected. The voltage magnitude at the connection point is maintained as V.



(a)

(b)

Figure 2.3 Transmission System with Shunt Compensation: (a) Simplified Model (b) Phase diagram [24]

As discussed previously, the active powers at bus 1 and bus 2 are equal.

$$P_1 = P_2 = 2\,\frac{V^2}{X_L}\sin\frac{\delta}{2} \tag{2.10}$$

The injected reactive power by the capacitor to regulate the voltage at the mid-point of the transmission line is calculated as:

$$Q_C = 4\,\frac{V^2}{X_L}\left(1-\cos\frac{\delta}{2}\right) \tag{2.11}$$

IV. SWITCHED CAPACITOR COMPENSATION FOR HARMONIC REDUCTION

A variable capacitor can be brought about by switch controlled capacitance which can control the fundamental component of current from zero to maximum amount. Therefore the injected reactive power to the AC bus can be controlled continuously by Switched Capacitor Compensation (SCC) [32]. Active filters are slightly inferior in cost and operating loss, are compared to the passive filters, even at present. Electrical loads have a combination of both active and reactive power. Active power is supplied by the generating stations while reactive power can either be

supplied from the generating stations or by making use of shunt capacitor banks strategically located on the power system (or other, generally more expensive, reactive power compensation schemes).
Reactive power compensation with capacitors is by far the most cost effective way to meet reactive power requirements of consumer loads. The addition of shunt capacitors releases thermal capacity in the distribution networks by reducing current flowing through the networks, which is required to supply the loads.

$$Q_{C=}P(\tan\varphi-\tan\varphi_1)$$

Saving of $S-S_1$

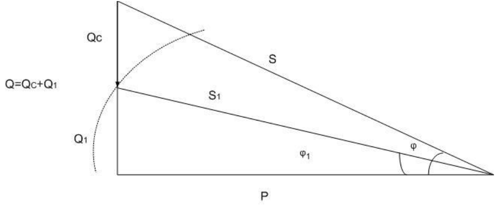


Figure 3.1 Effect of capacitor on reactive power

Traditionally, rotating synchronous condensers and fixed or mechanically switched capacitors or inductors have been used for reactive power compensation. The reactive power generated by the ac power source is stored in a capacitor or a reactor during a quarter of a cycle, and in the next quarter cycle is sent back to the power source.

A. Switched capacitor compensation for harmonic mitigation: -

As shown in Figure 3.2 switch capacitor compensation has a meaning of reactive power compensation and harmonic compensation [28]. Switched capacitor compensation to provide or absorb the required reactive power and harmonic mitigation from power supply system. The capacitors store energy in an electric field, Inductors store energy in a magnetic field.

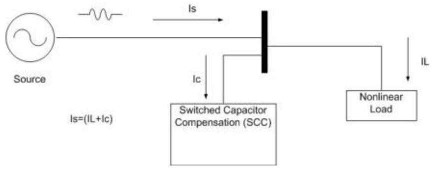


Figure 3.2 Circuit diagram for single-phase supply system to nonlinear load

As shown in Figure 3.3 to mitigate harmonics from distribution networks switched line capacitor bank is used, i.e. Transformer tap changers, substation capacitor banks, fixed feeder capacitor banks, switched feeder capacitor banks and voltage regulators are used in case of three-phase line. The key difference between capacitor banks and voltage regulators is that capacitor banks reduce the losses across the length of the feeder and voltage regulators only improve the voltage at a particular point. Use switched capacitor banks to compensate for source current distortion of waveform. The passive filter with switched capacitor filter is quite economical, simple, and reliable.

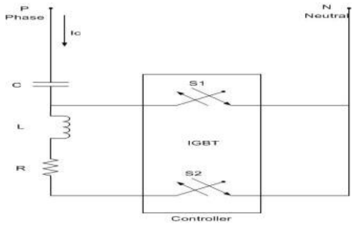


Figure 3.3 Circuit diagram for switched capacitor compensation (SCC)

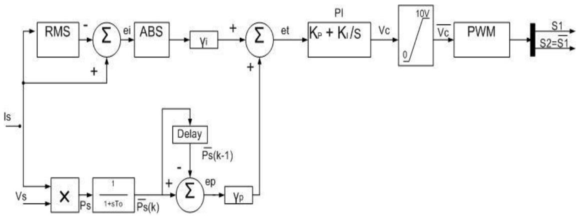


Figure 3.4 Control scheme for switched capacitor compensation (SCC)

A design of Switched capacitor compensation is shown in Figure 3.4. It is based on measurement of the current I_{rms} at the source point. The current error signal is obtained by comparing the measured I_{rms} current against a reference current, I_{rms_ref} . The difference between these two signals is processed by a PI controller in order to obtain the phase angle delta required to drive the error to zero. The angle delta is used in the PWM generator as the phase angle of the sinusoidal control signal. The switching frequency used in the sinusoidal PWM generator is $f_{s/w}$ - 900 Hz. The control Mechanism for Switched Capacitor Compensation is described here. The major parts of controlling mechanism are PI Controller, PWM, IGBT, Low Pass Filter (LPF) as transfer function and the other controlling parameters like Absolute (ABS), RMS, Weighting Factor, and Limiter are describe in chapter no. 4. The whole control mechanism is based on feedback control mechanism. Source current and source voltage are given to controlling mechanism. After collecting source current in feedback Harmonic error are generated, and on other side power error is also generated. Overall Total error is generated on the basis of PI controller, it is operated by feedback dual loop system and compensation is provided to system.

B. Necessity of SCC placed near to the load: -

- Keeping voltage within required limit
- Advantage: much lower cost compared to Static VAR Compensator (SVC)
- Switching speeds can be quite fast with current limiting reactors to minimize switching transients.

C. Power supply with charging resistor: -

In this technique, the energy storage capacitor is charged by a high voltage dc power supply through a charging resistor as illustrated in Figure. 3.5. The charging mode ends when the capacitor voltage equals the output voltage of the power supply. The capacitor is continually refreshed by the power supply.

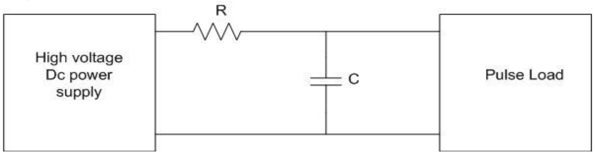


Figure 3.5 High voltage dc power supply and charging resistor

During the discharge mode, the charging resistor isolates the power supply from the pulse load. The advantages of this technique are its simplicity, reliability, and low cost. The major disadvantage of this technique is its poor efficiency. In the charging mode, the energy dissipated in the charging resistor is equal to the energy stored in the capacitor in the ideal case; therefore the maximum efficiency is 50%. As a result, this technique is utilized only in applications where the charge rate is low, i.e. 200 J/s. Another disadvantage of this technique is related to the charging time, which is determined by the RC time constant. Some laser applications require that the output voltage be within 0.1% of a target voltage. For this technique, more than five time constants are required for the capacitor voltage to meet this voltage specification [1].

V. SIMULATION AND RESULTS

The system used for simulation is comprises of a simple single-phase system where AC source is supplying Nonlinear load. Switched capacitor compensation is connected in shunt between source and nonlinear load. The system circuit values are given in Appendix. The simulations were carried out for with and without SCC. In this simulation high frequency based switching of IGBT are done and current harmonic mitigation results are analyzed. The simulations were run for a long period of time but only a few cycles are presented for clarity. The 5th order harmonics are also reduced that can be easily analyze from results. All simulations and there results are run in MATLAB 2010a/Simulink software.

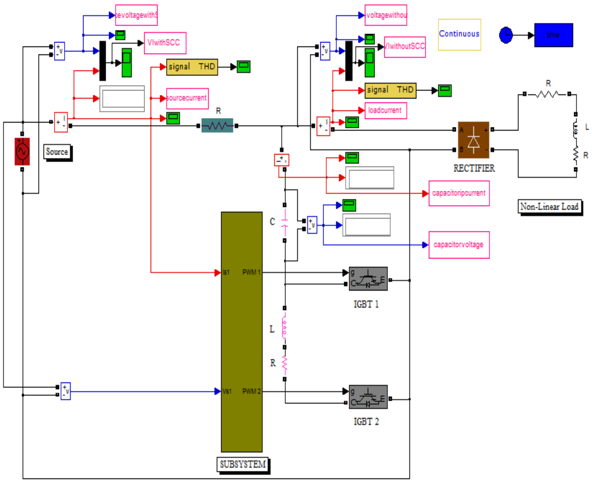


Figure 5.1 Circuit diagram of FACTS based switched capacitor compensation

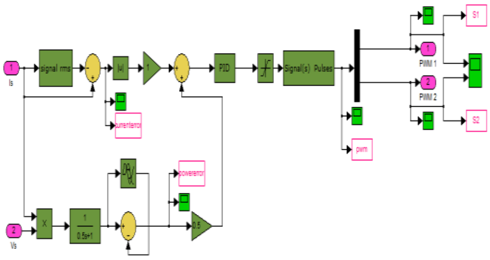


Figure 5.2 Block diagram of dual loop PI controller

As shown in Figure 5.6 switching pulses generated by PWM of switch 2 is shown. The duty cycle of waveform is considered for analysis of switch.

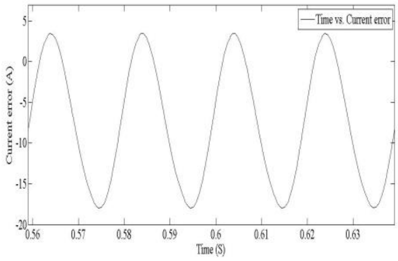


Figure 5.7 Current errors in controller

As shown in Figure 5.7 current error of controller is stable and total error is reduced. It gives smooth waveform and reduced the THDi.

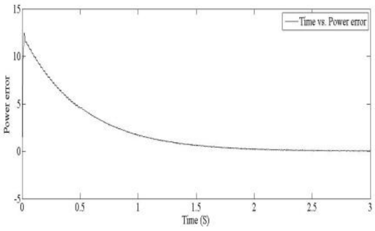


Figure 5.8 Power errors in controller

The simulation of SCC with and without connection to single-phase supply system is implemented. I have got % THD in current (THDi) reduction from 43.20 % to 0.81 %. The 5th order % THDi is also reduced from 18.12 % to 0.25 %. The waveform is distorted for without SCC and it becomes sinusoidal after SCC connection. The Simulation has run for time of 3 second in MATLAB2010a/Simulink software.

VI. CONCLUSION

The increased use of static power converter and static power capacitors can set up system condition to cause power quality problems like harmonics in power system. In the simulation i have present dynamic dual loop current and power error tracking scheme for harmonic mitigation. The proposed dynamic control scheme is now simulated for a single-phase nonlinear load connected power system; it can also be tested for three-phase four-wire system. The main objective is to mitigation harmonics from source current. The 5th order harmonic reduction is also validated with simulation results. The 5th order harmonics creates negative sequence components. Communication line interference can occur due to negative sequence components. It is a low cost novel PWM switched capacitor compensation scheme for either single or 3-phase 4–wire utilization loads including buildings, malls or small industrial loads. These loads are usually nonlinear and temporal in nature. The proposed low cost SCC capacitor scheme ensures both power quality enhancement and RMS current level reduction and effective power utilization. The RMS block includes the total of harmonic distortion of supply system in feedback loop. Low impedance of filter is gives reduction in % THD of source current. The switched capacitor compensation is validated using the MATLAB/Simulink software. The digital simulation results validate the fast response and effectiveness of proposed fast acting as SCC scheme to mitigate harmonics to source side from source current, reactive power compensation and power factor improvement.

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