Design and Implementation of 3-Phase 2-Stage Grid-Connected Solar PV System

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Abstract: **Solar Photo Voltaic (SPV) system is categorized under Distributed generation to meet the demand of power for load variations, as it also helps in assisting the existing power system. In this paper, Standalone PV system is interfaced to three phase grid which includes PV array, Perturb and Observe (P and O) Maximum Power Point Tracking (MPPT) technique used to track maximum power from PV array and also for the adjustment of Duty Cycle for giving switching pulses to High level switch of Boost Converter. 2-level Inverter is used for DC to AC conversion with Pulse-Width Modulation (PWM) control. Phase-Lock-Loop (PLL) technique is implemented to synchronize the Standalone PV system with grid at certain phase angle and frequency. Control circuit is designed to supply active and reactive power to load by standalone PV system and grid according to load variations. The overall system is simulated in Matlab software for outputs.**

Index Terms: **MPPT, Boost Converter, 2-Level Inverter, PWM, PLL.**

I. Introduction

Renewable energy sources like solar photovoltaic cells, wind, biogas are mainly employed for generation of power locally at a distribution level of voltage known as Distributed Generation (DG). Commonly solar photovoltaic (SPV) systems are utilized as Distributed Generation (DG) source due to abundant solar energy availability, long life of the solar photovoltaic (SPV) system with less maintenance [1]. Earlier standalone photovoltaic (PV) systems were in use which involves battery usage for storage of energy to meet the peak power demand associated with system complexity, reliability and maintenance [2]. To avoid such problems Grid interface PV system came into existence to improve the efficiency as the generated power can be supplied to the grid without any storage.

At present scenario photovoltaic array are extremely safe and reliable with minimum power loss. Usage of solar array for power generation reduces fossil fuel deposits to the great extent. As photovoltaic array is the combination of modules, includes a group of individual solar cell which outputs the voltage and current according to the inputs (Temperature & Irradiance) having non linear characteristics [15]. Solar cell is the basic functional block in the entire solar photovoltaic system with low efficiency output, to increase the output solar cells are connected series or parallel forming PV module [16].

PV module applications may be on the field installation or on building top roofs, based on the locality PV module design depends on the properties such as resistance to bad weather conditions, ability of solar capture, shade conditions for adaptability working of the module under any circumstances [17]. However PV array is connected to grid involves certain impacts of phase unbalance, reactive power, stability and power quality [18].

To interface grid tracking maximum power from the array is essential due to non linear characteristics of array Maximum power point Techniques (MPPT) are used. A review of different MPPT techniques are listed below based on control and operation [3].

1. Incremental Conductance MPPT
2. Perturb and Observe
3. Fractional open circuit voltage
4. Fractional short circuit current

In this paper perturb and observe technique is discussed to track maximum power and for the Duty Cycle adjustment. From PV to grid connected PV system HAS 2 stages of conversion.

1. DC-DC Conversion
2. DC-AC Conversion

First stage of conversion is done by boost converter to boost the input dc voltage level. Second stage of conversion is done by 2-level inverter to convert into 3-phase AC supply by pulse width modulation (PWM) control.

For load sharing between standalone system and grid a control strategy is required, so PLL technique is considered. It plays a vital role in synchronization of standalone system with grid as it gives the information of phase values and frequency. As the phase of inverter and grid outputs are same then the load is connected to the system for active and reactive power flow supply to the load. Based on control procedure adapted to handle both the power flow important techniques are available

1. P-V Controlled inverter strategy
2. P-Q Control strategy
3. Current control scheme

In this paper active power control is done by adapting current control scheme. The block diagram of overall system is shown in Fig 1.

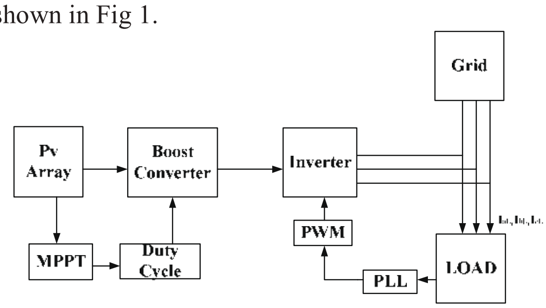

Figure 1. Block Diagram of grid connected SPV system

II. SPV SYSTEM DESIGN

A. PV Array

PV Array has number of solar cells connected in series and parallel for required voltage and current to obtain characteristic curves [4]. Equivalent circuit of single diode model of solar cell shown in Fig 2.

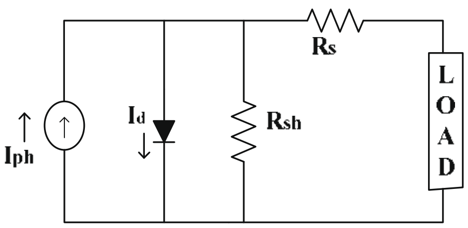

Figure 2. Single diode Circuit of solar cell

Output current of PV module is given by:

$$I_{pv} = N_p I_{ph} - N_p I_d \left[\exp\left\{ \frac{q \times \left(V_{pv} + I_{pv} R_s\right)}{N_S AKT} \right\} - 1 \right] \quad (1)$$

Where,

I_{ph} = Photo current

I_d = Module Saturation Current

N_p , N_S = Series and Parallel Cells Number

T = Temperature (Kelvin)

K = Boltzmen Constant (1.381×10^{-23})

A = Ideality Factor

q = Charge of e^- (1.602×10^{-19})

R_s = Series Resistance Ω

Another model is Two-Diode which as 2 diodes with better accuracy but complexity in modeling [5].

B. MPPT

In Perturb and Observe (P and O) MPPT Power and Voltage values are used for perturbation. P and O Control algorithm is designed in such a way that change in voltage measures the maximum power in forward direction, if power decreases for voltage change adjustment is done in backward direction for maximum Power [6]. The governing equations of ΔP and ΔV are

$$\Delta P = P_k - P_{k-1} \quad (2)$$

$$\Delta V = V_K - V_{K-1} \quad (3)$$

The conditions for perturb and observe MPPT are as follows [7].

$\frac{dp}{dv} > 0$ (+ve slope, left side of curve)

$\frac{dp}{dv} < 0$ (-ve slope, right side of curve)

$\frac{dp}{dv} = 0$ (At Maximum power point MPP)

The Perturbation Process shown in Fig 3.

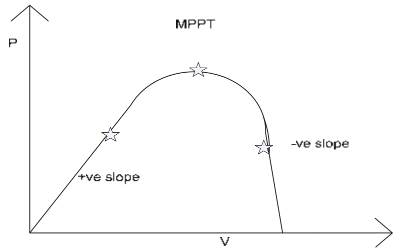

Figure 3. MPPT process

Due to perturbation it decides the Duty ratio to increase or decrease [7].

C. Boost Converter

PV Array DC voltage is necessary to step up for required RMS AC Voltage using Boost Converter [8]. The Boost Converter consists of Voltage Source, Inductor, Switch (IGBT), Diode, Capacitor, Load. It involves two modes of operation [9].

Mode1: Switch is ON state, current flows through Inductor (L), Switch.

Mode2: Switch is OFF state, current flows through Inductor, Diode, Capacitor, Load.

Here energy storage of Inductor flows through the circuit in mode2 operation. The general circuit diagram of Boost Converter shown in Fig 4.

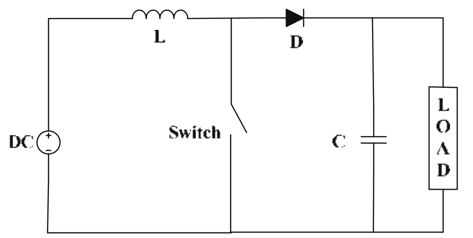

Figure 4. Boost Converter

The output of Boost Converter voltage is

$$V_{out} = \frac{V_{in}}{1 - D} \quad (4)$$

Where,

V_{out} = Output voltage

V_{in} = Input voltage

D = Duty cycle ratio

Duty cycle is extracted from MPPT and given to switch (IGBT) through PWM generator.

D. INVERTER

Two Level Voltage Source Inverter (VSI) is applied which converts fixed DC voltage to 3-Phase AC voltage. Mostly these type of inverters are employed in machines and converter control. The VSI consists of three legs with two

IGBT switches on each leg, DC Source and Load. General diagram of VSI is shown in Fig 5.

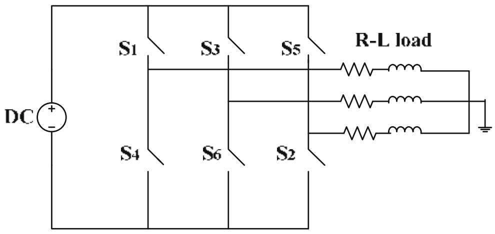

Figure 5. VSI

For controlling 2- Techniques are categorized [10]

A. Pulse Width Modulation (PWM)
B. Space Vector PWM (SVPWM)

In this paper switching purpose pulses of IGBT are driven by Pulse Width Modulation (PWM) Technique. In PWM Triangular carrier Wave (f_c) is compared with Sinusoidal Reference wave (f_r) of desired frequency. According to the condition ($f_r > f_c$) provides Switching instant pulses to IGBT. VSI is equipped with DC link of Capacitance bank which is used for grid synchronization purpose.

III. Control Design

A. Phase Lock Loop

To interface the voltage source inverter with the grid phase angle information is necessary. For obtaining accurate results of phase angle Phase Lock Loop (PLL) technique has been used. It estimates the phase and frequency values [11]. Besides interfacing phase angle parameter is necessary for active and reactive power flow control [12]. The block diagram of PLL is shown in fig 6.

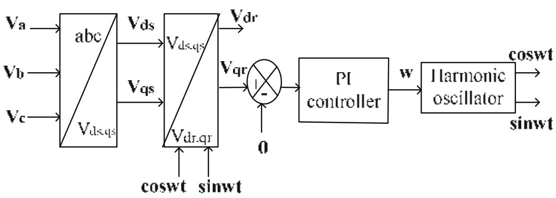

Figure 6. Phase Lock Loop

In PLL, Three-phase AC voltage (V_a, V_b, V_c) are transformed to 2-phase stationary frame (V_{ds}, V_{qs}) using equation (5) and again two-phase voltage are transformed to rotating frame of d, q axis (V_{dr}, V_{qr}) using equation (6). To transform from rotating frame to synchronous frame PI Controller and Integrator are used to estimate angular frequency and phase angle.

$$\begin{pmatrix} V_{ds} \\ V_{qs} \\ V_o \end{pmatrix} = \frac{2}{3} \begin{pmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (5)$$

$$\begin{pmatrix} V_{dr} \\ V_{qr} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} V_{ds} \\ V_{qs} \\ V_o \end{pmatrix} \quad (6)$$

If estimated frequency (w^*) equals to actual frequency (w) at the estimated phase angle (θ^*) which is integral of (w^*), then rotating frame voltages (V_{dr}, V_{qr}) appear as DC Value [12]. These estimated values are feed backed as Cos (wt), Sin (wt) to determine rotating frame voltages and PLL gets locked at ($\theta^* = \theta$).

B. Standalone PV System

Standalone PV System includes PV array, MPPT, Boost converter, Inverter, PWM, 3 phase load. Voltage (V) and currents (I) are sensed from PV array by MPPT for duty cycle adjustment in order to provide gate pulses to IGBT switch of Boost converter which boost up the DC voltage. Obtained DC voltage is supplied to dc link (capacitor) which acts as a source to the inverter (2-level) converting Dc to Ac. For conversion process in inverter switching pulses to IGBT switches are given by Pulse Width Modulation (PWM) technique. Three phase voltage and currents from inverter are provided to 3-phase load. The general block diagram of standalone PV system is shown in Fig 7.

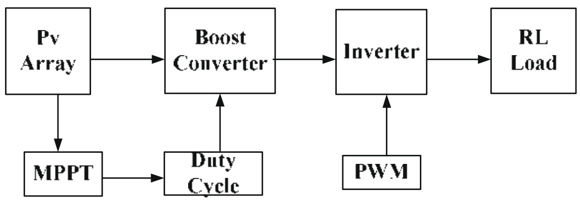

Figure 7. Standalone PV

C. Grid Connected PV System

In grid connected, standalone system and grid are connected to load as shown in Fig 8. For interfacing the both PLL technique is used to maintain at same phase angle and frequency at inverter and grid side [13]. According to the load standalone pv and grid supplies required voltage and current.

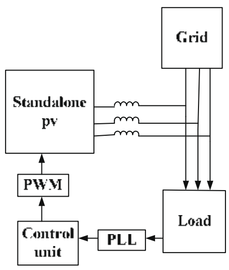

Figure 8. Grid side PV system

For sharing the load between pv system and grid a dq current control scheme is used as shown in Fig. 9.In this control reference signals are estimated according to the load demand. m_d and m_q are estimated voltages given by equation

$$m_d = u_d - \omega L i_q + v_d \tag{7}$$

$$m_q = u_q + \omega L i_d \tag{8}$$

Whereas U_d, $U_q$are specified as

$$U_d = (K_{p1} + \frac{K_{i1}}{s})e_d \tag{9}$$

$$U_q = (K_{p2} + \frac{K_{i2}}{s})e_q \tag{10}$$

e_d and e_q are refered as

$$e_d = i_{dref} - i_d \tag{11}$$

$$e_q = i_{qref} - i_q \tag{12}$$

Here i_{dref} and i_{qref} are reference d and q axis currents. Now estimated values of m_d, m_q are transformed to 3 phase reference values through inverse PLL which serve as switching pulse to the inverter [14].

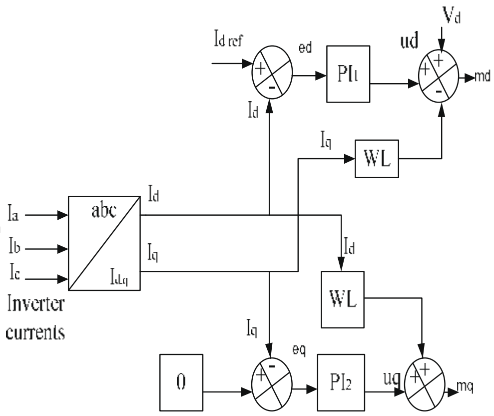

Figure 9. Inverter control circuit

IV. Simulation Results

A. Phase lock loop

In PLL the phase and frequency values are estimated for the input RMS value of voltage or current. At the rms value of voltage of 440 volts V_{dr} is calculated to 359 volts where as V_{qr} is calculated to zero by using the above phase lock loop equations (5, 6) as shown in Fig 10. To find the angular frequency of V_{qr}, it is calculated by 2πf where f is 50 hz which gives ⍰ value as 314 rad/sec as shown in Fig 12. Unit vector of phase values are estimated by harmonic oscillator as shown in Fig 11.

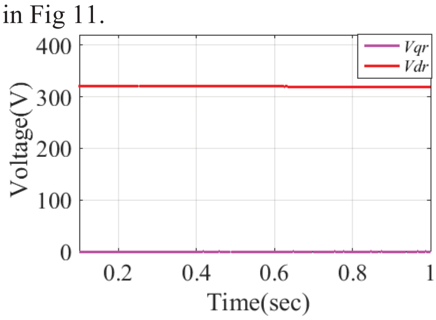

Figure 10. V_{dr} V_{qr} voltages

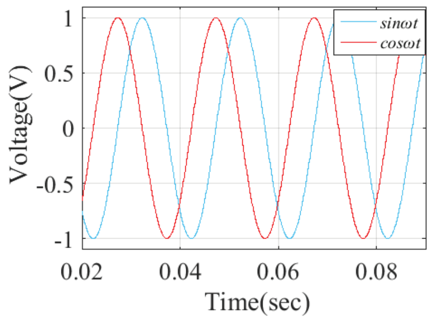

Figure 11. unit vectors

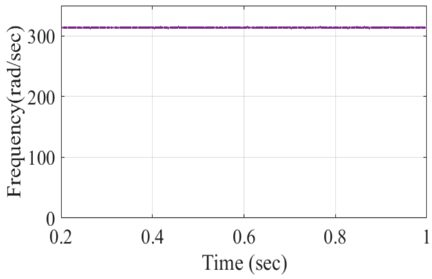

Figure 12. angular frequency

B. Standalone PV System

Standalone PV system simulation study is done based on certain data provided to the system for the block diagram shown in Fig. 7. The simulation data is provided in the table I.

TABLE I.
SIMULATION DATA OF STANDALONE PV SYSTEM

Array Irradiance	1000
Array Temperature	25 deg c
Maximum power(Pmp)	83.2 W
Maximum voltage(Vmp)	10.3 V
Maximum current(Imp)	8.07 A
Boost Inductor L	0.011 H
Capacitance	60 μ F

According to the data, array generates the voltage of 120 (volts). At the point of maximum voltage, maximum power is tracked by(P and O) MPPT maintaining the duty cycle ratio to(D =0.8). Boost converter increases the input voltage fed from array to 600v as calculated from equation (4). The output voltage of boost converter is shown in fig 15. as constant dc voltage.

$$V_{out} = \frac{V_{in}}{1-D}$$

= 120/1-0.8 = 600 V

Here single phase voltage and currents appears to be as step and sinusoidal waveforms are shown in the Fig 13, 14. The peak value of inverter voltage obtained is of dc voltage 600 volts and the sinusoidal currents draw the peak value of current 40 amp for the RL load impedance of 4.6+j0.00146 ohms.

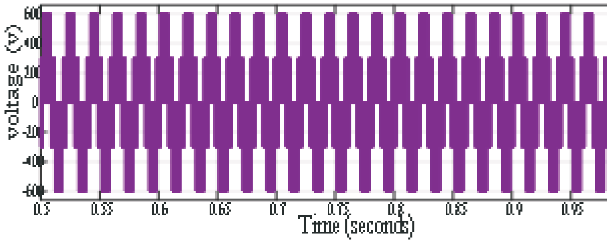

Figure 13. Inverter voltage(Va phase)

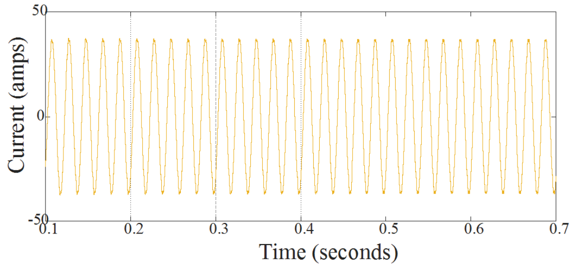

Figure 14. Inverter current (Ia)

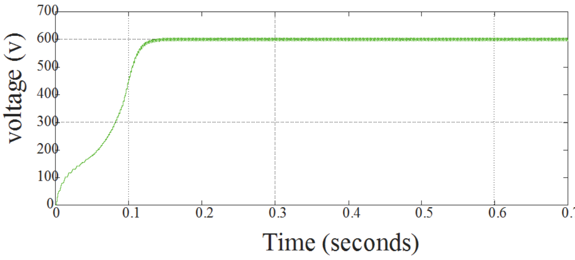

Figure 15. Boost converter voltage(Vdc)

C. Grid connected PV system

The simulation data for simulation study is shown in table II.

TABLE II.
GRID DATA

Parameters	values
Grid voltage	400 v
Grid frequency	50
Load	R=4.6 Ω, L=0.0146H
Pll PI control	P = 50, I= 100
Control PI	P = 0.1, I= 0.2
Filter	$5e^{-3}$

In grid connected PV system impedance of the load is taken as Z= 4.6+j0.0146 ohms, the load currents obtained are (30-j30) amps. To supply active component of current (30 amps) by the inverter, control is designed setting reactive component to zero. For active power control actual current of inverter matches reference current (I_{dinv}=I_{dref}) as shown in fig 16. Inverter supplies peak current of (30 amps) to the load which is active component fed into load as shown in fig 18. but the load demand is more of (50 amps) as shown in fig 19. The remaining power to the load is supplied by grid of current value of (78 amps) as shown in fig 20. as grid is both active and reactive source Here the voltages of grid, inverter and load are not influenced and maintained peak voltage of 330V as shown in fig (21,22,23). The dc voltage obtained (2.3*10^4) volts after interfacing with load and grid is shown in Fig 17.

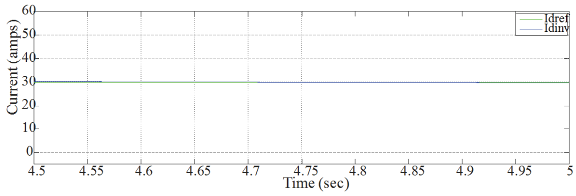

Figure 16. I_{dinv} and I_{dref} currents

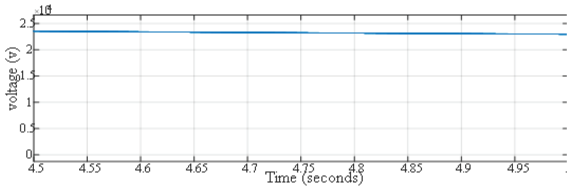

Figure 17. Dc voltage (V_{dc})

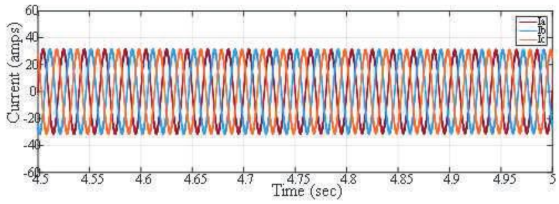

Figure 18. Inverter current

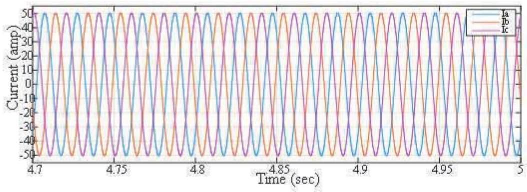

Figure 19. Load current

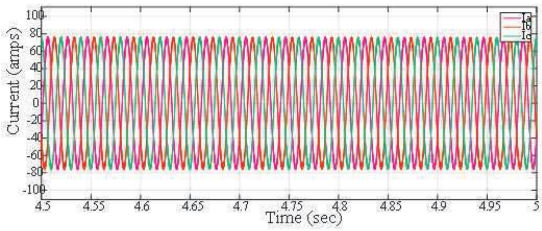

Figure 20. Grid current

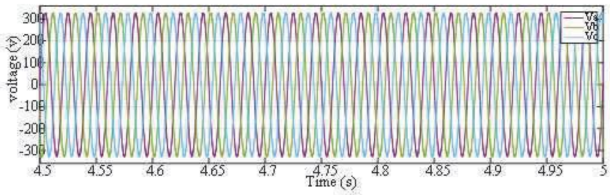

Figure 21. Grid voltage

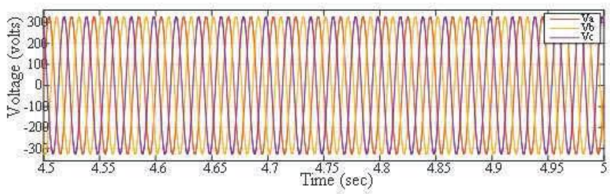

Figure 22. Inverter voltage

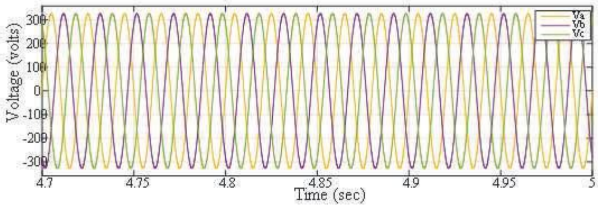

Figure 23.Load voltage

V. CONCLUSIONS

Solar cell is developed with the described equations which operates at an effective voltage and current by the inputs of temperature and irradiance. Standalone system study is done which supply power to the particular load, where it involves the MPPT technique to track maximum power. Phase locked loop plays a significant role in connecting a power electronic converter to the grid. In this paper, PLL is implemented in a grid connected system. The three phase voltages are converted into two phase voltages. The two phase voltages are transformed to synchronous rotating frame. The q-component of source voltage, v_q is made zero using PI controller, which ensures exact frequency information of source at any time.

In this paper power flow control is also implemented using control logic circuit for active power compensation. The control logic generates reference voltages and fed to inverter through PWM technique to supply active component of current for the load connected. The designed system is applicable for the load variations under balanced condition.

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