Analysis of Voltage-output LLC Resonant Converter

JINGYI SHAO, YING LUO
Faculty of Civil Engineering and Mechanics
University of Jiangsu
301 Xuefu Road, Zhenjiang, Jiangsu
CHINA
sjy2028@126.com http://cm.ujs.edu.cn/info/1074/3378.htm

Abstract: The optimal LLC resonant converter with the great performance in wide range of load and frequency is described in this paper. The output voltage can be remained stable by changing the frequency in different input/load conditions. It can realize the high efficiency and high density. The LLC resonant converter is simplified as the FMA model firstly to analyse its operating characteristics. These characteristics then can be verified by simulation results. The practical circuit is also built on PCB to prove it work properly.

Key-Words: LLC resonant converter, FMA model, output voltage, frequency, high efficiency

1 Introduction

With the rapid development of power electronics, the power supply has been a popular researching field. The common converter, however, may account for some problems, such as much power loss at high frequency or additional electromagnetic interference. Therefore, the resonant converter comes forth. It can create the resonant effect so that the voltage or the current will reach the zero point periodically. This so-called soft switching technology can help reduce the switching loss in the power supply [1].

It is known that there are three main topologies of half-bridge resonant converter: the series-resonant converter (SRC), the parallel-resonant converter (PRC) and the combination series-parallel resonant converter (SPRC). All of these three types of resonant converter can regulate the output voltage by changing the frequency. Nevertheless, there are some limitations on the former two types. The frequency is required to be relatively high in SRC, which will lead to the bad performance when the light load is connected. For PRC, the load is parallel-connected with the resonant capacitor, and the circulating current will go up to a high value [2]. Therefore, SPRC is the best with advantages that both SRC and PRC have. It can operate properly at the wide range of frequency and load. The efficiency is also improved due to the less power loss. Compared to the LCC resonant converter, LLC topology uses one capacitor only, making great contributions to the smaller volume and the cheaper cost [3]. It can be used in various applications such as portable electronic devices, battery chargers, electrical vehicles, etc. [4]

2 Designed LLC Resonant Converter

The schematic diagram (Fig.1) and relevant specifications (Table 1) of the LLC resonant converter are given below.

Table 1
Specifications and component values of the LLC resonant converter

Parameter	**Value**
Input voltage Vdc	45V~55V
Output voltage Vo	5V
Maximum load Imax	5A
Operating frequency f	180kHz~350kHz
Resonant inductor Ls	5.1μH
Leakage inductance Lp of transformer	23.2μH
Resonant capacitor Cs	66nF (2*33nF)
Transformer turn ratio n	5.5 (11:2)

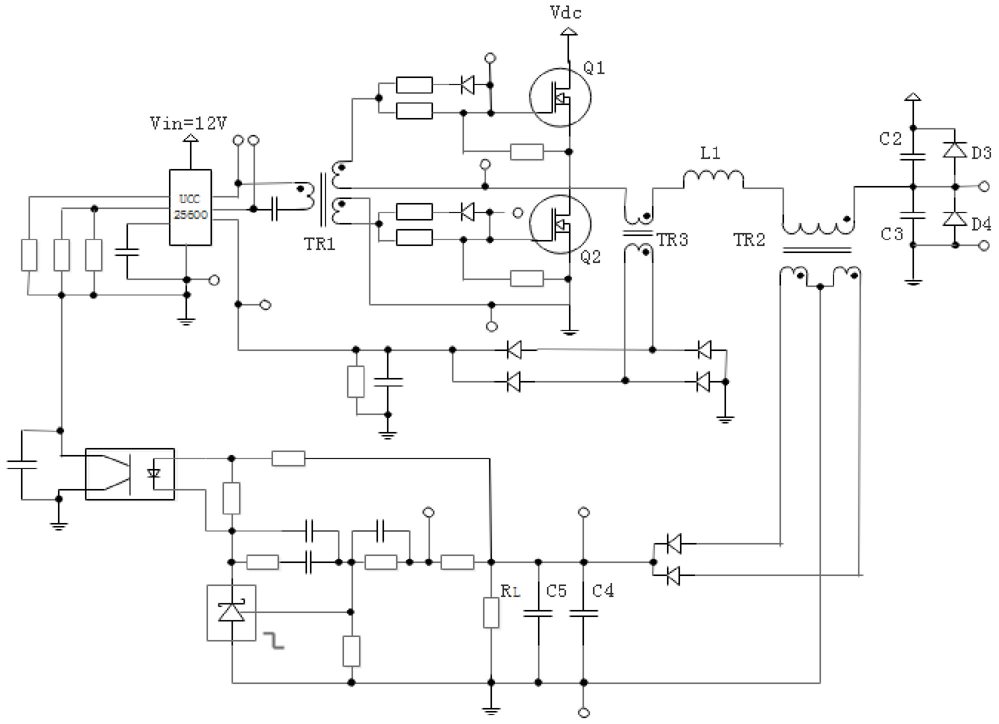


Fig.1 Schematic diagram of the LLC resonant converter

As is seen in the circuit (Fig. 1), the input voltage Vdc is applied to the two MOSFETs Q1, Q2 with the duty of 50% to produce the square wave. Then it flows through the series-connected inductor Ls, the parallel-connected inductor Lp which is from the leakage inductance of transformer TR2, and the series capacitor (C2+C3). The secondary voltage of the transformer TR2 is added across the output load after being rectified and smoothed. A phase-locked loop (PLL) controller UCC25600 is also put into use so as to generate two signals which are compared in the transformer TR1 to control operating states of two MOSFETs. Besides, the PID control circuit at the bottom is set as the feedback network to obtain the more accurate and steady value of the output voltage.

There exist two operating states of this converter: the static state and the dynamic state. In the static state, the function of LLC resonant converter is to keep the output voltage relatively stable by changing the operating frequency. In the dynamic state, the adjustable load will make the output voltage go ups and downs.

3 Fundamental Mode Approximation

The resonant tank of LLC resonant converter can be simplified as the equivalent model in Fig. 2, which is called the fundamental mode approximation (FMA), or the fundamental harmonic approximation (FHA) [5]. This model is based on the assumption that the power transferred from input to output is associated with the fundamental harmonic of the relevant voltages and currents only, due to the selective nature of the resonant circuit. Both the voltage and the current of the rectifier branch are considered as the ideal sinusoidal wave. All other harmonic components are neglected except the fundamental one.

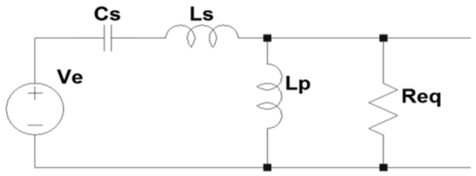


Fig.2 The equivalent model of LLC resonant converter

In this case, the equivalent input voltage Ve is the square wave, whose value is equal to the fundamental harmonic of the practical input voltage Vdc. According to the Fourier transform:

$$V_e = \frac{2}{\pi} V_{dc} \tag{1}$$

Then comes the resonant LLC tank, where Cs is the series-connected capacitor, equal to the sum of C2 and C3. Ls is the series-connected inductor, which is actually L1. Lp, coming from the leakage inductance of the transformer TR2, acts as the parallel-connected inductor. Then the transformer TR2 can be considered as the ideal transformer. The turn ratio is 11:2. At the secondary side of the transformer, the equivalent resistor is connected. All the rectifiers and filtering capacitors are neglected in this model.

Thus, the equivalent load resisitance is:

$$R_{eq}=n^2\frac{V_{R(rms)}}{I_{R(rms)}}=n^2\frac{\frac{2\sqrt{2}}{\pi}V_o}{\frac{\pi}{2\sqrt{2}}I_o}=n^2\frac{8}{\pi^2}R_{Load} \qquad (2)$$

In which R_{Load} is the output load resistor, n is the turn ratio of the ideal transformer.

Given the n:1 transformer, the equivalent output voltage Vo' is the n times than the practical value, i.e.

$$V_o'=nV_o \qquad (3)$$

In SPRC, there exist two inductors, Ls (5.1uH) and Lp (23.2uH). Therefore, the two different resonant frequencies can be calculated as:

$$f_{r1}=\frac{1}{2\pi\sqrt{L_sC}}=\frac{1}{2\pi\sqrt{5.1\times10^{-6}\times66\times10^{-9}}}=274kHz \qquad (4)$$

$$f_{r2}=\frac{1}{2\pi\sqrt{(L_s+L_p)C}}=\frac{1}{2\pi\sqrt{(5.1+23.2)\times10^{-6}\times66\times10^{-9}}}=117kHz \qquad (5)$$

When the switching frequency $fs<fr_2$, the impedance of the resonant tank is capacitive [6]. In addition, the MOSFETs operate at the state of ZCS, resulting in the lower efficiency compared with the ZVS state at high frequency [7]. If $fr_2<fs<fr_1$, the circuit is set in the series resonant condition (Ls and Cs) and the series-parallel resonant condition (Ls+Lp and Cs) in sequence. In this case, the ZVS state with less power loss can be realized even at the zero current load [8]. In the condition of $fs>fr_1$, the circuit can still operate at the ZVS state. It turns out to be the series resonant circuit with Ls and Cs while Lp makes no sense. Also, the working efficiency will be decreased due to the high switching loss of MOSFETs and the reverse recovery loss of the rectifying diodes [9]. Therefore, the change law of the output gain is illustrated in the Fig. 3. As the switching frequency fs increases, the output gain is supposed to rise at first, up to its top point, and then falls down. Also, the output gain is related with the different load and the input conditions. The load resistance can be represented by the quality factor Q

$$Q=\frac{2\pi f_r L_s}{R_L} \qquad (6)$$

Where fr is the resonant frequency, Ls is the series-connected inductor, R_L is the load resistance [5].

It can be demonstrated that if other parameters are kept same, the output gain increases with the higher input voltage and the larger quality factor [10].

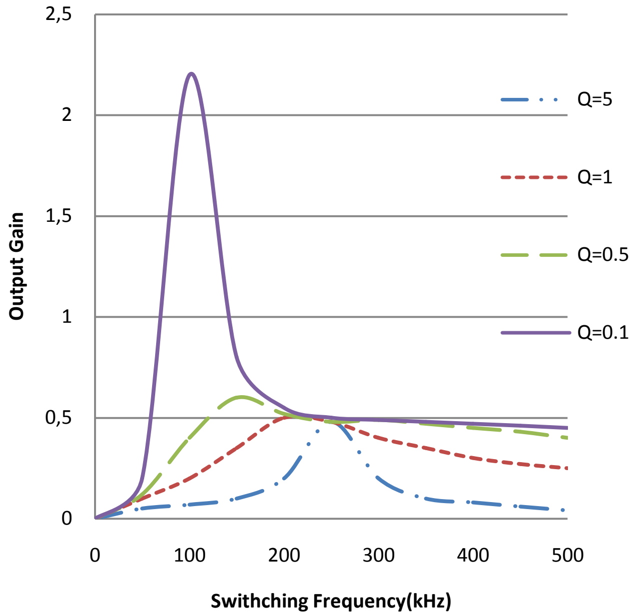
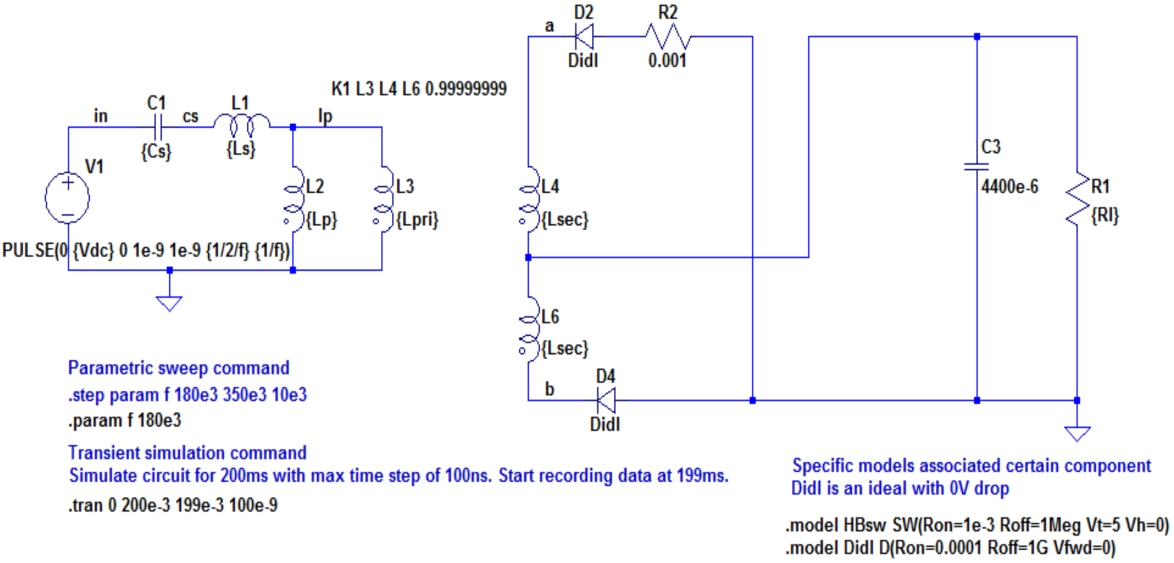


Fig.3 The output gain versus the frequency with different quality factors

4 Simulation Results

The equivalent LLC resonant circuit is drawn in the LTspice, as shown in Fig. 4. The input voltage V_1 is set as 45V square wave at first, with the duty cycle of 50%. The input current passes through the resonant tank, and is transferred to the secondary side of the tranformer.

It is found from Fig. 5 that voltages at the secondary side of the transformer V_{L4} and V_{L6} are both 6.5V around, equal to the primary voltage divided by the turn ratio. They have the phase shift of 180 degrees as one rectifying diode is on while the other is off. The duty cycle is about 50%.



Parametric sweep command
.step param f 180e3 350e3 10e3
.param f 180e3

Transient simulation command
Simulate circuit for 200ms with max time step of 100ns. Start recording data at 199ms.
.tran 0 200e-3 199e-3 100e-9

Specific models associated certain component
Didl is an ideal with 0V drop

.model HBsw SW(Ron=1e-3 Roff=1Meg Vt=5 Vh=0)
.model Didl D(Ron=0.0001 Roff=1G Vfwd=0)

Fig.4 The equivalent LLC resonant circuit in LTspice

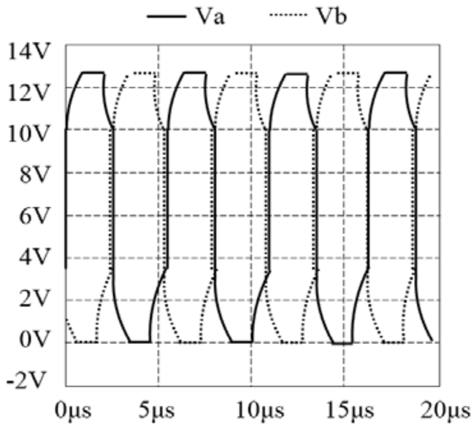


Fig.5 The voltage across L_4 (Va) and the voltage acorss L_6 (Vb)

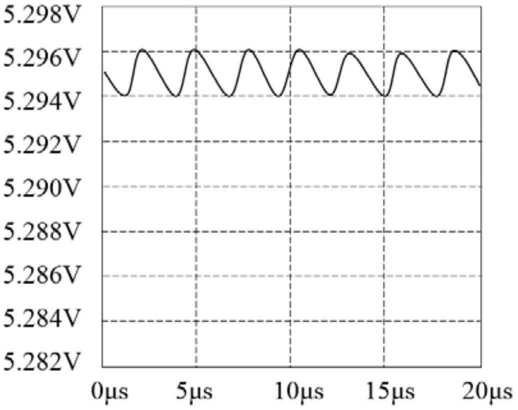


Fig.6 The output voltage when Vin=45V and R_L=20Ω

Fig.7 The curve of the output voltage versus the operating frequency at different load conditions when the input voltage is 45V

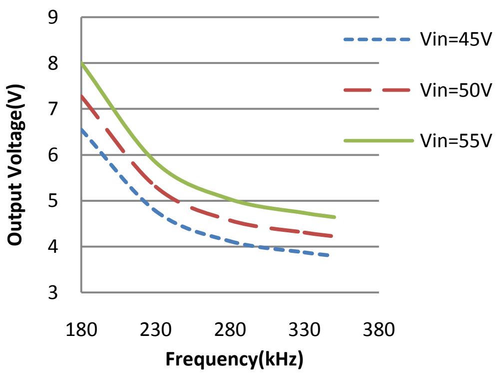


Fig.8 The curve of the output voltage versus the operating frequency at different input conditions when the load resistance is 20Ω

The curves can be drawn based on the data when changing the conditions. The frequency ranges from 200kHz to 350kHz in this simulation, which is located in the region of fs>fs2. If the load and the input are kept unchanged, the output voltage will be decreased as the working frequency goes up. From the diagram, it can be found that the output voltage can be maintained as 5V approximately by changing the frequency. It will be higher with the larger load resistance or the higher input voltage if other values remain unchanged. It is obvious that the simulation result is correspond to the mathematical analysis.

4 Experimental Results

The finished PCB is shown in Fig. 9.

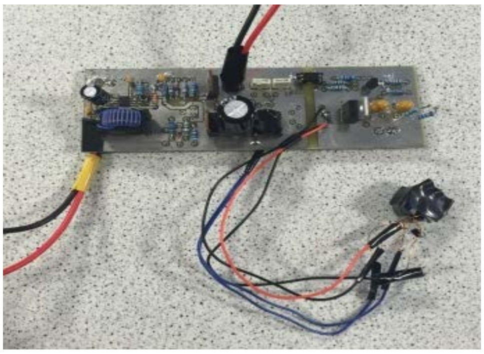


Fig. 9. The LLC resonant converter built on PCB

The first part is the IC controller UCC25600, whose input power is supplied by the 12V dc voltage. The practical voltage is about 11.91V and has some voltage spikes that may account for the error and inaccuracy of other waveforms.

In this experiment, the working frequency of UCC25600 is set as 190kHz approximatly based on the given circuit diagram. The pin 5 and 8 are the low-side and the high-side switch gate driver respectively, which are connected to the transformer's primary side to drive the harf-bridge MOSFETs. The waveforms of the low-side and the high-side gate drives are demonstrated below in Fig. 10. They are square waves with the amplitude of 11V, and have the 184 degrees phase shift with each other based on the equation (7).

$$\alpha_{shift} = \frac{\Delta t}{1/f} = \frac{2.7\mu s}{1/189.36kHz} \times 360^\circ = 184.6^\circ \qquad (7)$$

The duty cycle is about 44.18%.

The 45V power supply is connected to the drain of Q1 to generate MOSFETs Q1 and Q2. It is better to try applying the smaller voltage first, such as 12V, to prevent the explosion or overheating. The Fig. 11 shows the drain-source voltages of two MOSFETs when the input voltage is set as 45V. They have the same amplitude, which is close to the predicted 12V, with the phase shift of 180 degrees around.

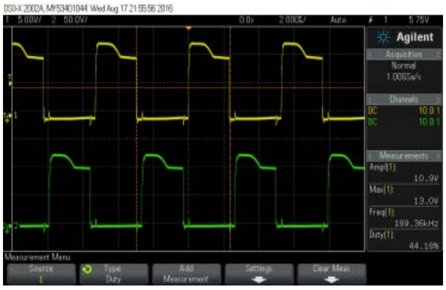


Fig.10 The low-side and the high side gate drivers of UCC25600

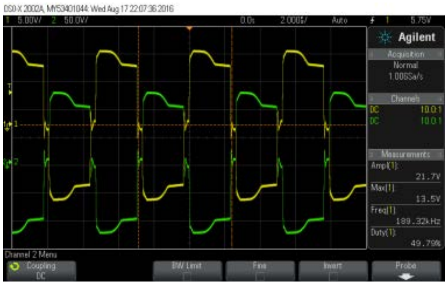


Fig.11 The drain-source voltages of two MOSFETs Q1 and Q2

Next is the core of the LLC converter, the resonant tank. The square wave generated by the half-bridge circuit flows through the series resonant inductor L1, the transformer TR2, and the resonant capacitor C2, C3. The capacitor C1 is short-circuited. The primary side voltage of TR2 is the substraction of these two waveforms, shown in Fig. 13.

Fig.12 The voltage across L1 and the voltage across C2, C3

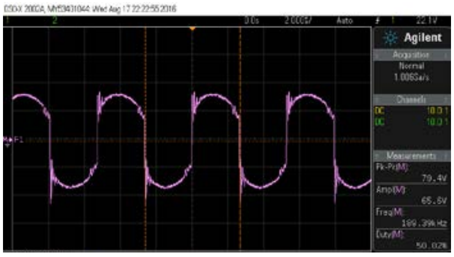


Fig.13 The primary side voltage of the transformer TR2

From the waveform in Fig. 13, it can be illustrated that the amplitude is about 65.6V, which is the peak to peak value, i.e. twice of the primary side voltage. In accordance to the turns ratio 11:2, the secondary side voltage of TR2 should be 5.96V.

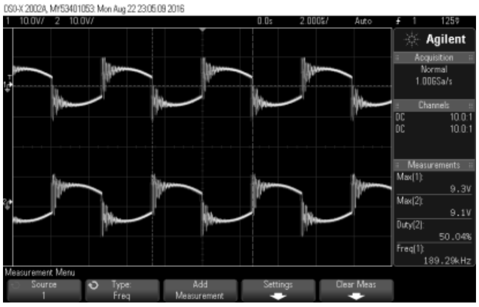


Fig.14 Secondary side voltages of the transformer TR2

When there is no load connected in the circuit, the waveforms of two secondary sides are shown below in Fig. 14. The two voltages has the same amplitude, with the phase shift of 180 degrees, which is corresponding to the previous analysis of the rectifier circuit. The amplitude of the secondary side voltage is about 5.81V, close to the calculated value of 5.96V above.

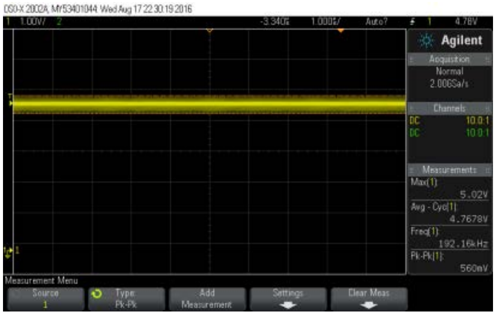


Fig. 15. The output voltage with 20Ω load

When the 20Ω load resistor is connected at the secondary side of TR2, in parallel with the filtering capacitors C4 and C5. The output voltage is around 4.76V with the 560mV sinusoidal ripples shown in Fig. 15. The value meet the requirement of 5V output voltage within the reasonable error range.

Because the maximum load current is limited less than 5A, the load resistor should be more than 1Ω based on the Ohm's Law. In this case, the load is chosen as 20Ω, 30Ω, 40Ω seperatly, to compare the results under different load conditions. Similarly, the output voltages at different frequency and input conditions can be measured to verify characteristics of this LLC resonant converter.

Table 2
Values of input voltage, load resistance and output voltage when the frequency is 192kHz

Vin(V)	RL(Ω)	Vo(V)
45	20	4.78
45	30	4.83
45	40	4.89
50	20	5.30
50	30	5.37
50	40	5.53
55	20	5.87
55	30	6.05
55	40	6.09

Table 3
Values of input voltage, load resistance and output voltage when the frequency is 297kHz

Vin(V)	RL(Ω)	Vo(V)
45	20	3.71
45	30	3.82
45	40	3.93
50	20	4.24
50	30	4.33
50	40	4.41
55	20	4.65
55	30	4.74
55	40	4.86

When changing the working frequency by using different resistance of R12 (R12 is the resistor conntected to the pin RT of IC controller UCC25600), the output voltage will also change.

For example, at the frequency of 297.18kHz (R12=620Ω), the output voltage will become lower compare to that of the 192Hz frequency. Therefore, the output voltage will decrease at the higher frequency when the load and input keep unchanged. It can also be concluded from Table 2 and Table 3 that the ouput voltage will increase with the larger load or the higher input, successfully verifying the simulation results in Fig. 7. and Fig. 8. The values measured in the experimental results are a little smaller than that in the simluation, which results from the power dissapation of wires and other components like diodes or transformers.

5 Conclusion

The operating characteristics of the optimal voltage-output LLC resonant converter are discussed in this paper. It can work properly in the wide range of load and frequency. In order to gain the higher efficiency and smaller volume, the traditional control method is replaced by the IC controller UCC25600 and the leakage inductance of the transformer acts as the paraller-connected inductor of the LLC network. In addition, the PID control in the circuit can improve the accuracy and stability of the output voltage. It is proved by simulation and experiment results that the output voltage will increase with the higher input voltage or the larger load resistance. It can realize the function that the output voltage remain 5V stably in different input/load conditions by changing the operating frequency.

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