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Investigations on Capacitor Compensation Topologies Effects of Different Inductive Coupling Links Configurations

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ABSTRACT

This paper presents investigations on capacitor compensation topologies with different inductive coupling links for loosely coupled inductive power transfer (IPT) system. In general, the main constraint of the loosely coupled IPT system is power losses due to the large leakage inductances. Therefore, to overcome the aforementioned problem, in this work, capacitor compensation is proposed to be used by adding an external capacitor to the system. By using this approach, the resonant inductive coupling can be achieved efficiently and hence the efficiency of the system is also increased significantly. This paper analyzes the performance of two different compensation topologies, which are primary series-secondary series (SS) and primary series- secondary parallel (SP) topology. The performance of such topologies is evaluated through the experimental results at 1MHz operating frequency for different types of inductive coupling. From the results, SS topology produces a high power transfer but SP topology gives better efficiency.

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1. INTRODUCTION

Recently, Wireless Power Transfer (WPT) technologies become a great attention among researchers. WPT system provides transmission power from the source circuit to the load circuit without any cable connection. The most current popular research of WPT system are; 1) Inductive Power Transfer (IPT) system, 2) Capacitive Power Transfer (CPT) system, and 3) Acoustic Energy Transfer (AET) system [1]. Among them, IPT has obtained higher attention because of the highest power transfer can be achieved at several large air gap distance [2]. Therefore, it has been developed and widely used in mobile devices, medical equipment, vehicles and industries [3] [4] [5]. On the other hand, CPT and AET system only can supports the power transfer in mili-Watt (mW) and require high input voltage to produce higher output power.

Figure 1 shows the general block diagram of loosely coupled IPT system [6]. Term “loosely” represents the primary, L1 and secondary coils, L2 are not coupled by common core and move freely between two. An AC source is required to generate a magnetic flux. The voltage will be induced from primary coil, L1 onto the secondary coil, L2. The primary and secondary capacitor compensation is essential in IPT system to obtain a great efficiency for the load, RL by achieving resonant inductive coupling. Despite a lot of works have been done in the framework of IPT system, it is still quite less efficient and needs to be improved because of the large leakage magnetic flux, $L_{leakage}$. [7]. At present, there are several studies to improve the behavior of the resonant inductive coupling by using capacitor compensation [8] [9] [10] [11]

[12] [13] [14]. Capacitor compensation is a method where an external capacitor is connected either in series or parallel with the respective coils to achieve resonance coupling.

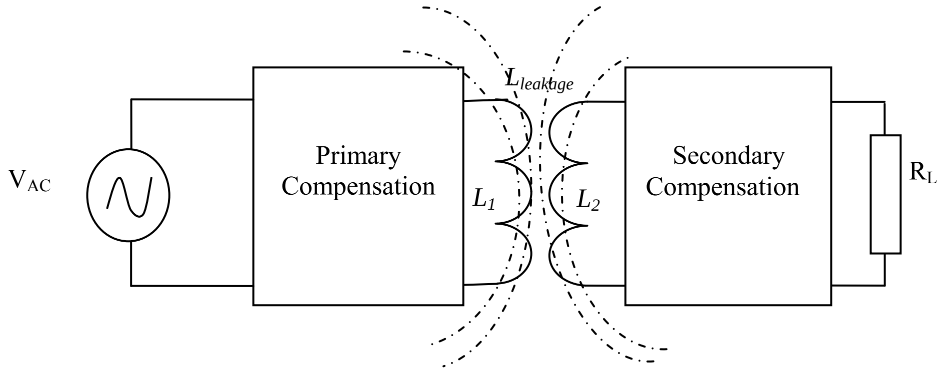


Figure 1. General Block Diagram of IPT System

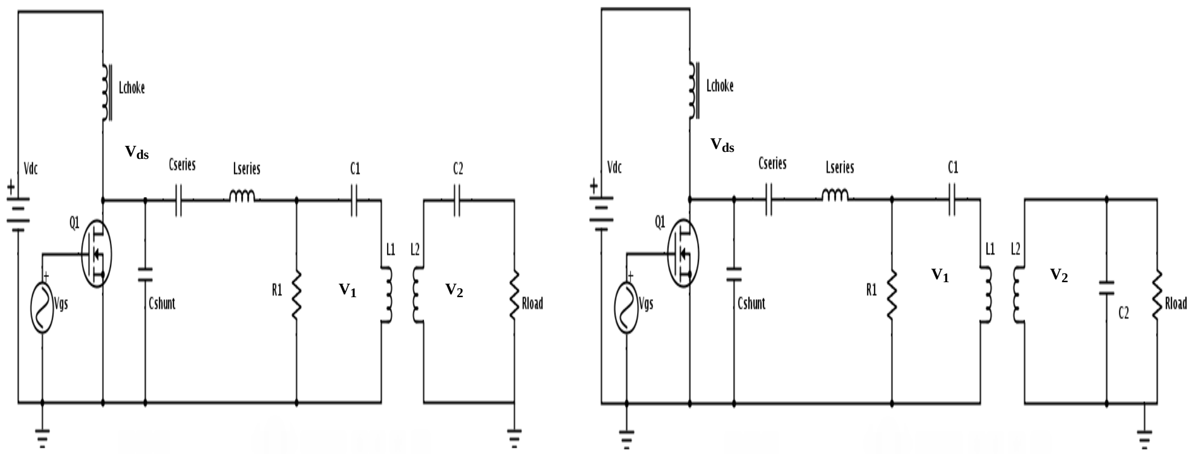
Normally, primary capacitor compensation is required to minimize the voltage-ampere (VA) rating of supply while secondary capacitor compensation is needed to enhance maximum power transfer [8] [9]. Authors in [10] present that higher power transfer and higher efficiency are caused by higher coupling coefficient of SS compensated IPT system. In [11], four capacitors are used in IPT system for compensation purpose at 50 kHz of operating frequency. The output power produced in between nW and mW with the input voltage of 5V. Moreover, [12] presents Series-Series (SS) and Series-Parallel (SP) compensation topologies in IPT system. Based on their results, the SS topology gives a better performance among the two. Next, secondary series and parallel compensated IPT system have also been studied by varying the operating frequency in [13]. While in [14], capacitor compensation technique has been studied with the different geometry coil between circular and square coils. So, the circular coil gives better coupling during perfect alignment.

In this paper, the capacitor compensation method is studied to solve the problem of large leakage inductances by achieving the resonance inductive coupling. The contribution of this paper is to facilitate the designers to make a decision in choosing types of inductive coupling that most effective either coupled the coil with SS or SP topology. So, the analysis of the coupling coefficient of different types of coupling and compensation topologies for loosely coupled IPT system is done at 1MHz operating frequency. The efficiency of different type of compensations is studied by varying air gap distance and use the different type of inductive coupling also is implemented.

In this work, the paper is structured as follows; Section 1 consists of literature review of SS and SP topologies. Design example is proposed and verified via experimental work in section 2. Section 3 contains the main results and a brief discussion on SS and SP topologies performances for different type of inductive coupling configurations when varying the air gap distance. Lastly, section 4 provides the conclusion of this work.

2. RESEARCH METHOD

Class E converter circuit with thematching resonance circuit is developed as shown in Figure 2(a) and (b) to determine their performance. Since the load resistance may vary during the experimental works, the matching circuit is required to provide the impedance transformation [15]. So, the impedance transformation is accomplished by tapping the inductor and capacitor (L-C) circuit. Next, Class E converter circuit is a DC resonance supply that offers a great efficiency in wireless power transfer due to its theoretical has zero switching losses [6] [16]. It is used to convert DC electrical energy into electromagnetic field energy [17]. Based on the Figure 2, IRF510 MOSFET is used as a switching device of Class E converter. This type of MOSFET is preferred due to low on-resistance, low cost and suitable for fast switching. 9V DC supply and 1MHz operating frequency are applied in this work.



(a) SS Topology (b) SP Topology

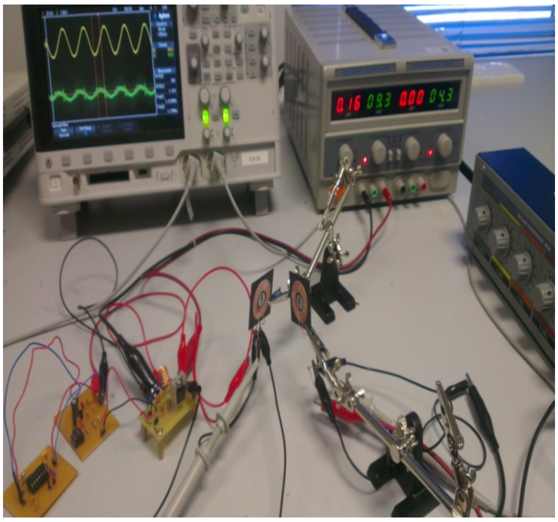
Figure 2. Circuit Diagrams for Experimental Works

Then, the values of passive elements for Class E converter circuit are determined in this work based on the exact analysis[18]. Class E resistance, $R_1 = 0.5514(V_{DD})^2/P_o$. Next, the value of shunt capacitor can be determined as $C_{shunt} = 0.1971/(\omega R_L)$ while the series capacitor, $C_{series} = 0.1062/(\omega RL)$. If the operating frequency is greater than the resonant frequency, resonant series circuit represents an inductive load at the operating frequency, *f*. Therefore, the series inductance, L_{series} can be divided into two inductances, L_{ext} and L_{res}, connected in series such that $L_{series} = L_{ext} + L_{res}$ and L_{res} where $L_{ext} = 1.153R_L/\omega$ and $L_{res} = 10.62R_L/\omega$. RF Choke Inductor, L_{choke} is chosen to be high enough so that an AC ripple can be neglected [6]. The primary and secondary side circuit of loosely coupled IPT system has an identical resonant frequency at 1MHz. So, the capacitor that is compensated with the coil for both sides can be determined as $C_1 = C_2 = (\omega^{-1})^2/L_{1/2}$.

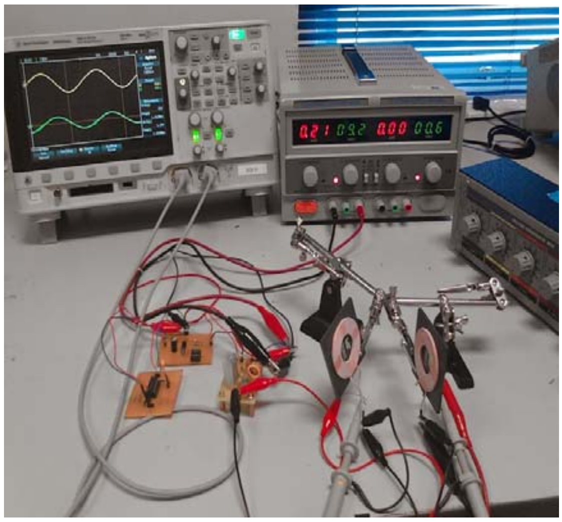
Table I. Components and Parameters Used in IPT System

Circuit Components and Parameters	**Values**
Power MOSFET, NMOS	IRF510
Operating Frequency, f_o	1MHz
Input DC supply, V_{dc}	9.0V
Rated Power, P_o	3.0W
Choke Inductor, L_{choke}	5.0mH
Shunt Capacitor, C_{shunt}	2.2nF
Series Capacitor, C_{series}	1.0nF
Series Inductance, L_{series}	22.0µH
Primary and Secondary Coil, L_1 and L_2	10µH, 24µH
Primary and Secondary Capacitor Compensation, C_1 and C_2	2.2nF, 1.0nF
Internal Primary Resistance Coil, R_1	0.3Ω
Internal Secondary Resistance Coil, R_2	0.2Ω
Load Resistance, R_L	100Ω

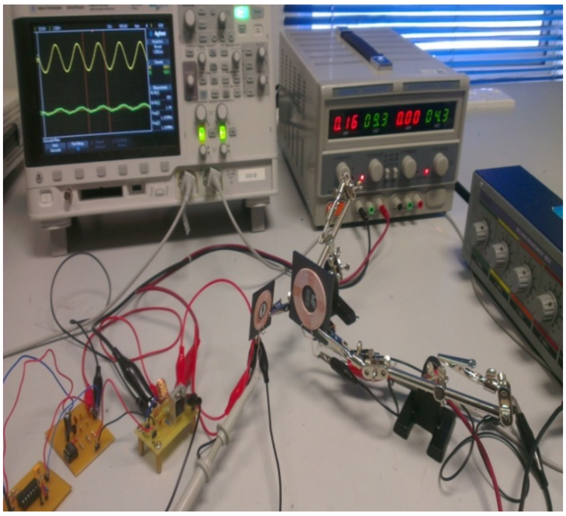
The prototype of IPT system is developed with the components and parameters given in Table I. The coupling coefficient, output power and efficiency of loosely coupled IPT system are evaluated for different compensation topologies and types of inductive coupling in this experimental works. The size of two types of ready-made Litz wire coil is 37.0mm x 37.0mm x 1.8mm for 10µH and 53.3mm x 53.3mm x 6.0mm for 24µH respectively are used. The reason of choosing Litz wire coil is because of its capability to minimize the losses at high frequency [3].



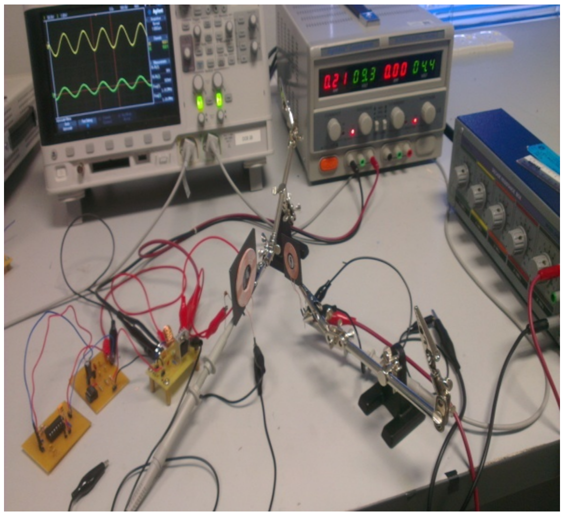
a) 10uH-10uH



b) 24uH-24uH



c) 10uH-24uH



d) 24uH-10uH

Figure 3. Types of Different Inductive Coupling Configurations

The different size of coils is used to evaluate the performances of different topologies of inductive coupling when varying the air gap. The placement of external capacitor compensation either in series or parallel is implemented to study the performance of the different type of capacitor compensation topologies. The air gap distance between two separation coils is varied from 5mm to 45mm. The experimental works are shown in Figure 3.

3. RESULTS AND ANALYSIS

In this section, the results of the work are explained and at the same time the concise of discussion is given. Figure 4 shows the coupling coefficient of inductive power transfer is slightly decreases as air gap distance increases from 5mm to 50mm for different topologies of inductive coupling. It can be observed that the best resonant inductive coupling is the big isolation configuration as shown in Figure 4(d) with dimension of 53.3 x 6 x 53.3 mm among others. This is because the slope of that configuration is the highest with 18.0 values. So, the primary coil produced more magnetic fluxes to induce onto the secondary coil. This result on more fluxes will be received by the secondary coil. As the coupling coefficient increase, mutual inductance of loosely coupled IPT system will increase too at the alignment position [19].

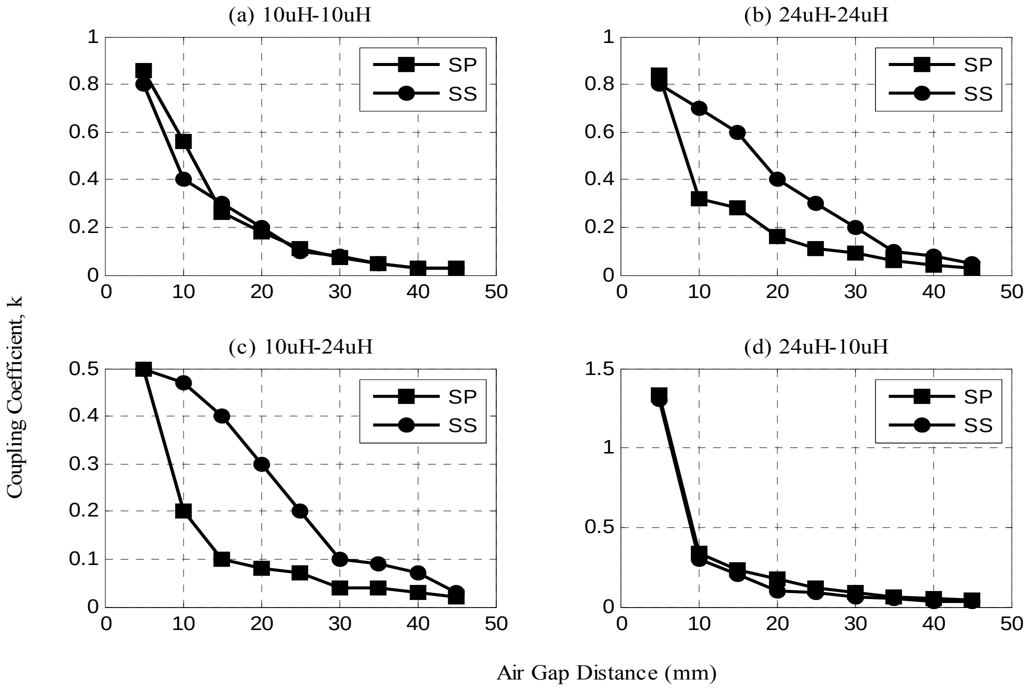


Figure 4. Coupling Coefficient vs. Air Gap Distance

SS topology produces higher coupling coefficient for the big isolation configuration in Figure 4(b) and step up configuration in Figure 4(c). It is because of the secondary coil size is larger to receive more magnetic flux. So, series capacitor compensation secondary acts as a voltage source that supplied a stable voltage [20]. From the measurement of laboratory session, coupling coefficient as in Figure 4 determined from the following equation after the voltage applied to the primary coil, V_1 and secondary coil, V_2 are measured during relative open loop voltage as follows[21]:

$$k = \sqrt{\frac{L_1}{L_2}} \times \frac{V_2}{V_1} \tag{1}$$

where L_1 is transmitter coil and L_2 is receiver coil, are linked together. If the two identical coilshave the same inductance value, the coupling factor, *k* is determined by

$$k = \frac{V_2}{V_1} \tag{2}$$

In short, the main factors that affect the coupling factor, *k* value are the air gap distance between the two coils and their relative size. If the two coils are axially aligned, a displacement of transmitter coil causes a decrease in *k* value. So, the capacitor compensation topology and the type of inductive coupling will not give major impact on coupling coefficient value.

From Figure 5, if air gap distance is small, the highest output power produced for different topologies. To note here that the output power is measured across 100Ω of load resistance, and the air gap is varied. The measured output power of secondary series compensated and secondary parallel compensated at 1MHz frequency are compared and it is shown in Figure 5. At 5 mm air gap distance, SS topology has produced higher output power as compared to SP topology for big isolation in Figure 5(b) which is 1.25 W and for step up is 1.2W respectively as shown in Figure 5(c). These configurations have produced higher output power due to high coupling coefficient as discussed before. So, the output power will be decreased as air gap distance increases.

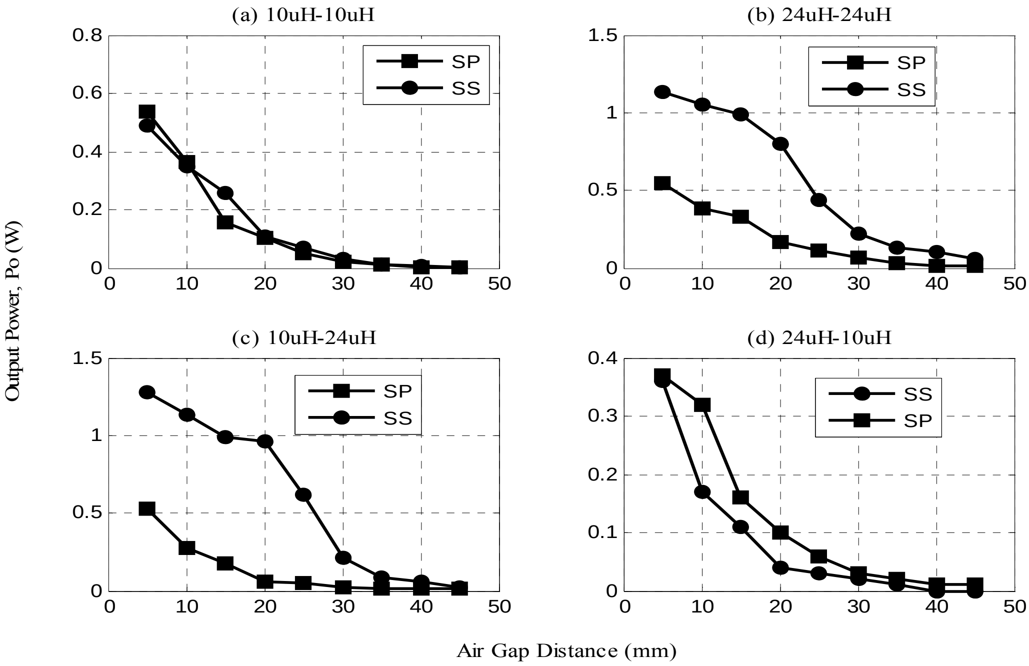


Figure 5. Output Power vs. Air Gap Distance

The measured efficiencies of secondary series compensated and secondary parallel compensated are compared and they are shown in Figure 6. It is observed that the efficiency of IPT system slightly increased with the increasing of the coupling coefficient, k for different types of inductive coupling. From Figure 6, if coupling coefficient, k is large, the maximum efficiency of secondary parallel compensated is generally higher than secondary series compensated at 1 MHz operating frequency. Moreover, there is a ferrite core attached with the coil to shield the magnetic flux that caused high efficiency of inductive coupling occurred.

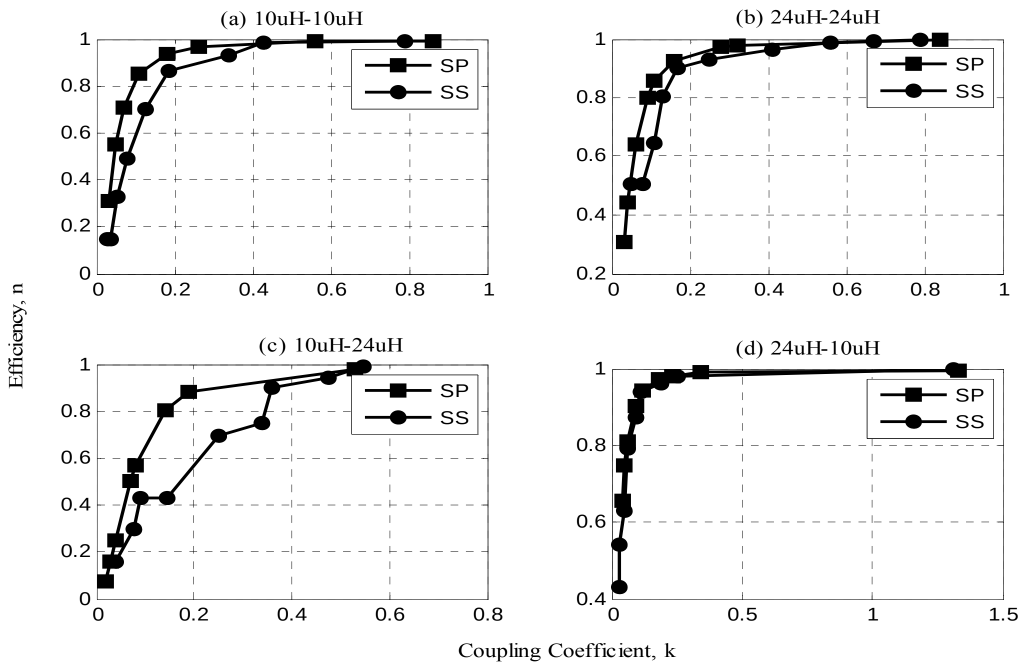


Figure 6. Efficiency vs. Coupling Coefficient

4. CONCLUSION

In this paper, the performance of different capacitor compensation topologies have been studied. A comparison between the different compensation topologies yield that the output power delivered across the load resistance is higher for SS capacitor compensation topology while the inductive link efficiency remains high for SP topology of capacitor compensation. Moreover, the performance of different types of inductive coupling configurations also has been analyzed. Higher inductance of inductive coupling links will deliver the highest output power across the load resistance. Next, the intention future work that should be considered is to study the performance of IPT system with a self-tuning Class E converter circuit and without the self-tuning circuit.

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