A Common-leg Power Electronics Converter for Multi-axis Active Magnetic Bearing Drive

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***Abstract*— This paper has proposed a common-leg structure power electronics converter to drive the multi-axis active magnetic bearing(AMB) system. With this new structure, the number of devices is obviously reduced compared to existing topologies so that the cost can be decreased. Simulation and experiment are carried out to validate the feasibility of this converter. The results show that the current in either coil can be controlled independently and will not be influenced by the variation of other coil current. It also shows the performance of common-leg converter in the 4-DOF AMB system. The position of the rotor can be well controlled with this converter while the cost of the control system is greatly reduced.**

I. INTRODUCTION

Active magnetic bearing (AMB) can produce magnetic suspension force which suspend the rotor without mechanical friction. It has been developed in recent decades to solve the problem of mechanical bearing, it is applied in high speed rotational machinery.

Generally, as shown in Fig.1, an AMB system consists of the electromagnet, displacement sensors, controller and the power electronics converter [1]. As for the electromagnet, it can be with or without the permanent magnet. In this paper, the permanent magnet is not applied and the magnetic field is excited by the unidirectional bias winding current i_b.

The linear model of magnetic bearing is[1]:

$$F_{mag} = k_i i_c - k_x x \quad (1)$$

In (1), ki is the current stiffness coefficient, k_x is the displacement stiffness coefficient, i_c is the differential control current and x is the position of the rotor. From the principle, the magnetic force is influenced by i_c and x, and actually i_c is what we can actively control. As the current is directly controlled by the power electronics converter, the power electronics drive is the key technology for AMB system.

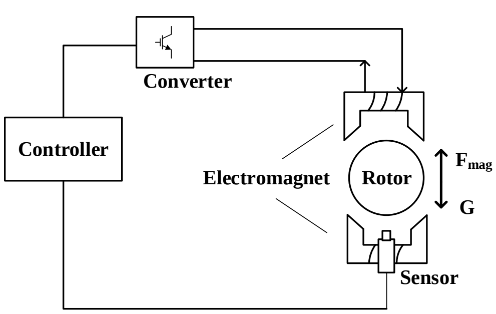

Figure 1. A single axis AMB system

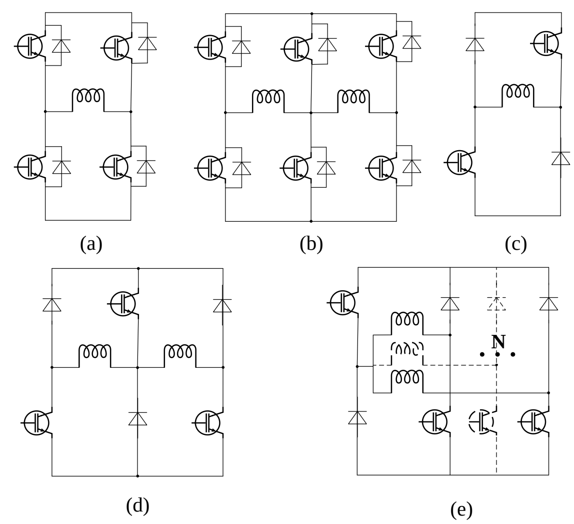

Figure 2. Power electronic converters for AMB system:(a) Full bridge. (b) There-phase full bridge. (c) Half H-bridge. (d) Three-half-phase-legs. (e) Common-leg converter.

There are some researches paying attention to converter structure. The first generation of the magnetic bearing drive is the linear power amplifier[2]. However, due to its high power losses, switching power electronics converter has been developed and replaced it[3]. Initially, as shown in Fig.2(a) and (b), full bridge converter and the three-phase full bridge converter has been used for the current control[4][5]. Generally, the control current i_c is much smaller than the bias current i_b, so the current in each winding is unidirectional. Due to this characteristic, some devices of full bridge converter are redundant and can be removed. The half H-bridge in Fig.2(c) can be used for unidirectional current control. In [6], a three-half-phase-legs converter for AMB system has been put forward. As it shown in Fig.2(d), the requirement of the devices can be reduced effectively by sharing one phase-leg for two windings of one axis. Based on this structure, in this paper, it is found that when the three-half-phase-legs converter is used in multi-axis AMB system, the quantity of the devices can be further reduced by sharing the common phase-leg. The topology of common-leg converter is shown in Fig.2(e). With this topology, the requirement of devices, PWM signals and gate drivers can be greatly reduced. Therefore, the cost and size of the control system can be reduced, which is beneficial to promote the application of the magnetic bearing. The comparison of requirements of different topologies will be provided in part II.

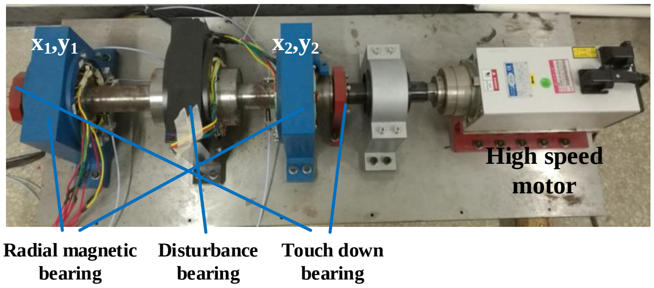

Figure 3. Photograph of the 4-axis AMB experiment platform

In order to verify the feasibility of common-leg converter, simulation has been down and a prototype of the common-leg converter has been designed and manufactured. Experiments has been carried out on a 4-axis AMB experiment platform which is shown in Fig.3. A high speed induction machine is used to rotate the shaft. Two 8-pole radial magnetic bearings with 500 µm air gap g_1 are set to control the position of the shaft. Besides, two touch-down bearings with 250 µm air gap g_0 are set at the ends of the shaft to protect the magnetic bearing in case of the control failure. The details of dimensions of magnetic bearing are shown in Fig.4. The inner diameter of the stator R_0=87mm, the outside diameter of the stator R_2=180mm, the stator teeth t=18mm which equals the stator yoke, and the thickness of the stator h=60mm. The number of turns of winding on each pole N=46. In this paper, experiment results for current control and rotor suspension by common-leg converter are shown in part IV.

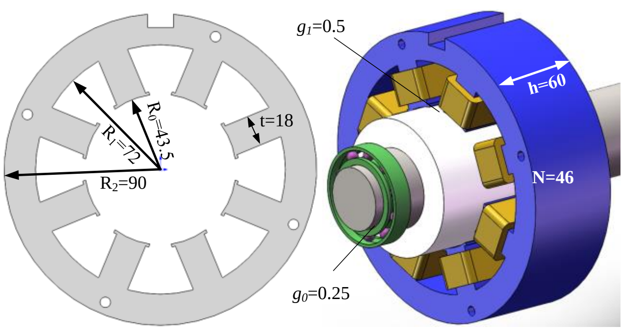

Figure 4. Dimensions of magnetic bearing (Unit: mm)

II. COMMON-LEG CONVERTER

A. Comparison of Different Topologies

As for the full bridge converter, 4 switches and 4 diodes are used for each coil. And for each axis, two coils are required. Therefore, 8N switches and 8N diodes are required for a N-axis AMB system. The three-phase full bridge converter can reduce the number of devices by share one phase leg. And 6N switches and 6N diodes are required in total.

However, as the current in AMB system is always unidirectional, half of the devices in full bridge converter are redundant. Therefore, Half-H bridge converter and three-half-phase leg converter need half of devices.

In the three-half-phase-legs converter, two windings share the center phase-leg. With this method, when the circuit is used in multi-axis AMB system, one phase-leg can be used as a common leg, and two coil bridge-legs will be added for each additional axis. For N-axis system, there is one common bridge and 2N coil bridges in the control circuit. Accordingly, 2N+1 switches and 2N+1 diodes are used in total, while 3N switches and 3N diodes are needed in the three-half-phase-legs converter. As the requirement of number of devices is reduced, the requirement of number of PWM signals is also reduced. Moreover, in common-leg converter, only the common-leg switch is with floating ground and others are with the same ground. It means 2N switches can share one common gate drive power supplier, and only another isolated gate drive power supplier is needed for the common leg switch. The comparison of requirements with different topologies for a N-axis AMB system is shown in Table 1.

TABLE I. COMPARISON OF REQUIREMENTS WITH DIFFERENT TOPOLOGIES

	Switches	Diodes	PWM signals	Gate drive power suppliers
Full bridge	8N	8N	8N	4N+1
Three phase full bridge	6N	6N	6N	3N+1
Unidirectional H-bridge	4N	4N	4N	2N+1
Three-half-phase-legs	3N	3N	3N	N+1
Common-leg	2N+1	2N+1	2N+1	2

However, there is also a penalty getting by reducing the device: the current across the common leg is the sum of all the coils. This will bring challenges on the current carrying capacity of common-leg devices. And at the same time, as the losses are concentrated on these devices, the cooling of these devices needs to be fully considered.

B. Control of Common-leg Converter

The topology of common-leg converter for 5-axis AMB system is shown in Fig.5. The currents in opposite-placed coils L_1 and L_2 are respectively controlled by switch A_1 and A_2 to generate electromagnetic force in radial direction X_1. Similarly, Switch B_1 and B_2, C_1 and C_2, D_1 and D_2 control the radial force in direction X_2, Y_1, Y_2 respectively. The axial force is generated by the current in coil L_9 and L_{10}.

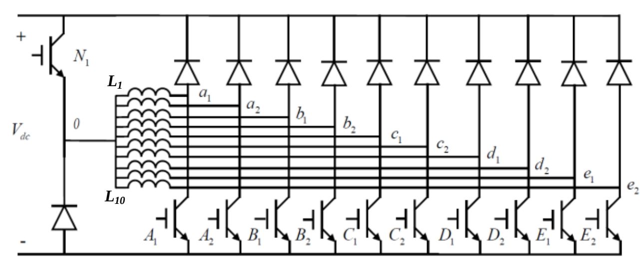

Figure 5. Topology of 5-axis common-leg converter.

In the three-half-phase-leg converter, one of the control methods is that the duty cycle in the central leg is fixed, and changing the duty cycle in phase A or C to vary the unidirectional current in either coil[7]. Similarly, in common-leg converter, the modulation of common-leg switch N_1 can be kept constant duty cycle, and the amplitude of the current in each coil is decoupled and can be varied independently by modulating the corresponding switch. The four modes of operation in one coil is shown in Fig.6. The current moving path is marked in the picture. The current can be rapidly increased or decreased by mode I or IV. Mode II and III are freewheeling modes. The current will be slowly decreased at these modes.

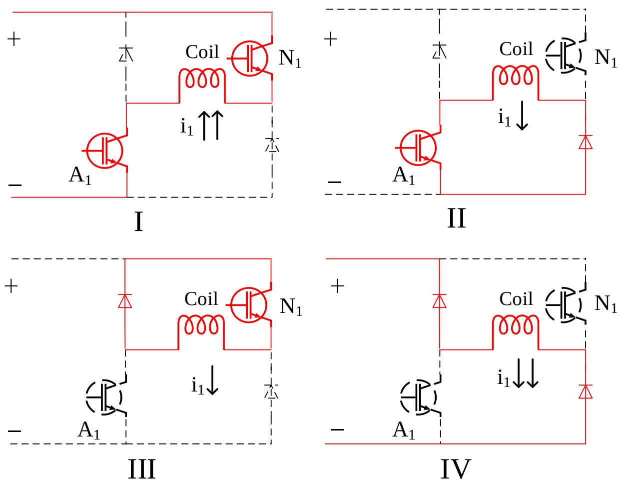

Figure 6. Operation modes of each coil: (I)increase mode, (II)(III) freewheeling mode, (IV)decrease mode.

The operating modes of each coil leg are the same, and the coil current can be controlled with these modes.

The voltage across each coil v_L can be expressed as:

$$v_L = s_N V_{dc} - s_p V_{dc} = (s_N - s_p) V_{dc} \tag{2}$$

where s_N and s_p are respectively the switch function of the common-leg switch and the phase-leg switch. Then, replacing the switch function by duty cycle d_N and d_p, and we can get the average model:

$$v_L = (d_N - d_p) V_{dc} \tag{3}$$

The duty cycle d_N is fixed, and d_p can be verified from 0 to 1, so the variation range of v_L is $(d_N-1)V_{dc}$ to $d_N V_{dc}$. Generally, d_N is fixed at 0.5 to balance the maximum and the minimal voltage across the coil.

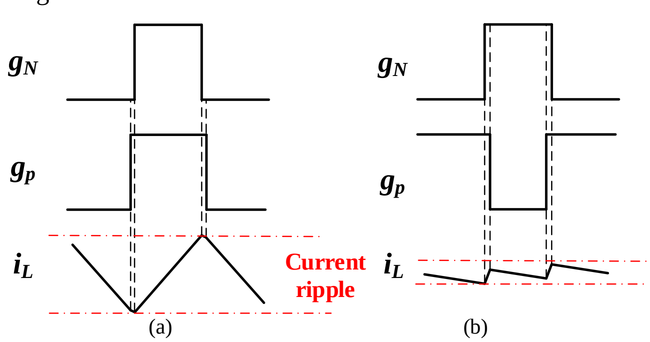

Figure 7. Modulation methods:(a)in phase (b)inverse.

Fig.7 shows two kinds of modulation method[6]. In method 1 shown in Fig.6(a), the gate signal of phase leg g_p is in phase with the gate signal of the common leg g_N, while in method 2 shown in Fig.6(b), g_p is inversed from g_N. It is obviously that in method 2, the coil is always at freewheeling mode while the coil in method 1 is always at increase or decrease mode. Therefore, the current ripple by method 2 can be much smaller than the other. So in this paper, method 2 is used in modulation for analysis. Fig.8 shows the principle of current control with method 2. If d_p is bigger than 0.5, the coil current i_L will be increased, otherwise, i_L will be decreased.

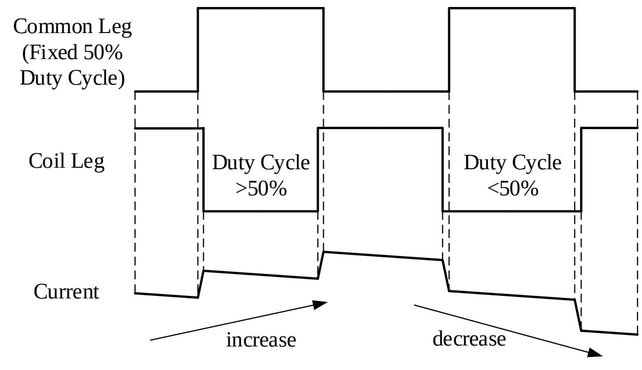

Figure 8. Principle of current control

With the current control method above, the control block diagram for each axis of AMB system is shown in Fig.9. The outer loop is the position loop and the inner loop is the current loop. The position of the rotor x is captured by the sensor and sent to a microcontroller. Comparing with the reference position x_{ref}, and with a PID controller, the command signal of control current i_c* is generated. In AMB system, two opposite-displacement coils are required to control one axis of the rotor, and the reference current command for each coil is the bias current i_b plus or minus half of i_c*. The duty cycle d_p is generated by a PI controller. And modulating by triangle wave, the gate signal for each phase-leg is generated. The control of the common-leg switch is not shown in Fig.9, and the duty cycle d_n is fixed at 0.5.

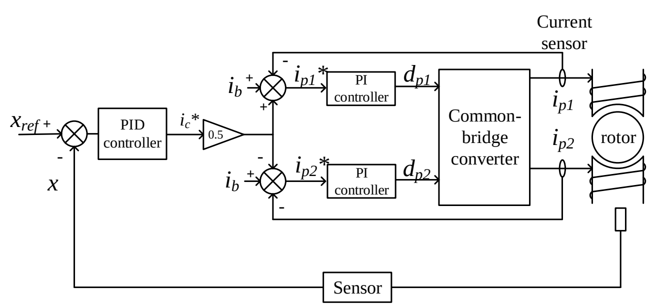

Figure 9. Control block diagram for each axis of AMB system

III. Simulation and Experiment

A. Simulations and experiments for current control

To verify the feasibility of this common-leg topology, simulation is carried out under the condition of V_{dc}=150V, L=10mH, R=1Ω and N=4. The reference signals are given differently for each coil, and a tuned PI controller is used. The reference signals of these coils are different: all the reference signals are 5A at the beginning, and then step to different values at different points. As the results shows in Fig.10, the current in each coil can track the respective reference signal, and will not be influenced by the currents in other coils.

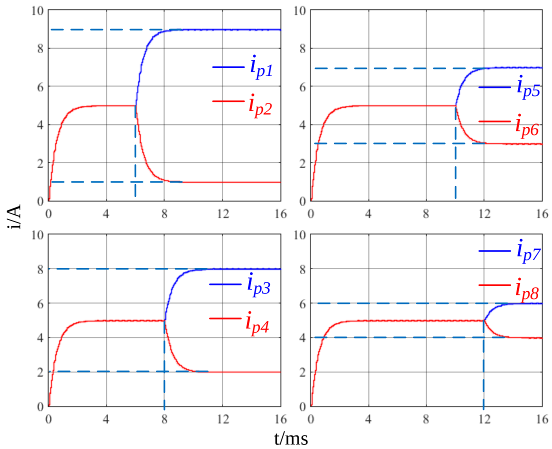

Figure 10. Simulation results for current control

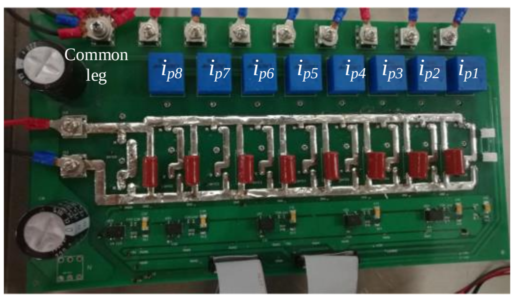

Figure 11. Photograph of the common-leg converter

A prototype was also established based on the 4-axis AMB system platform which is shown in Fig.11. This converter uses only 9 IGBTs and 9 diodes.

The current control experiment for the common-leg converter is carried out at the DC voltage V_{DC}=150V and the switch frequency f=20kHz. The inductance of the coil L_s=11mH, and resistor of coil R_s=1Ω. The current reference signal for each coil is 3A at the beginning, and change into 1A or 5A at some point. To analysis the dynamic process of the prototype, simulation is carried out at the same condition. Fig.12 shows the comparison result of four coil current by experiment and simulation. The experimental results are basically consistent with the simulation results. The difference is that because the rotor is supported by the touch down bearing during the current control experiment, the air gap of coil at bottom side is smaller than the top-side coil's. It means the inductance of bottom-side coil is larger than the inductance of top-side coil. So it can be seen from the figure that the responding time of two coils is different. The experiment results have shown that the current can be well controlled with this converter.

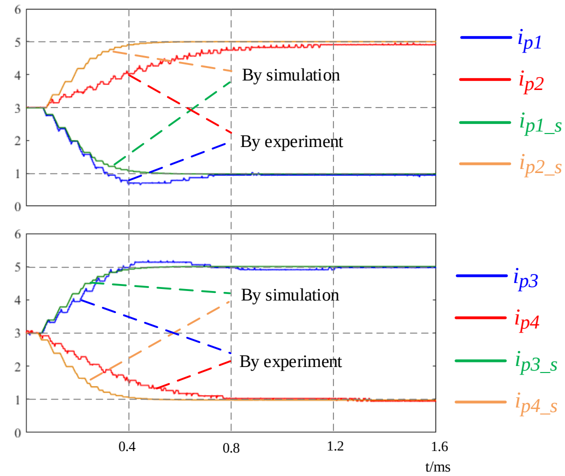

Figure 12. Results for current control simulation and experiment.

B. *Experiments for magnetic bearing control*

Experiment for 4-axis static suspension with common-leg converter is also carried out. Fig.13 shows the arrangement of the 4-axis windings. Each axis is inclined at 45 degrees to share the weight of rotor. The currents of two adjacent coils are reversed to avoid coupling between each pole[1].

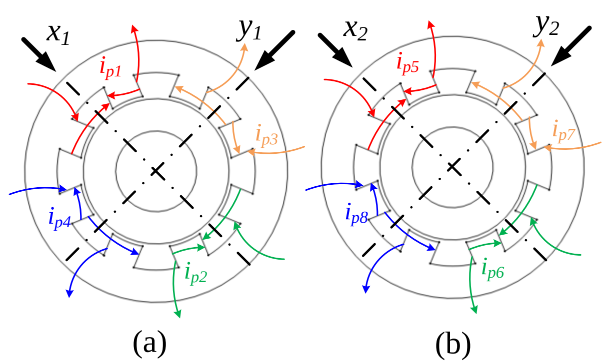

Figure 13. Arrangement of the windings in 4-axis AMB system.

The result is shown in Fig.14. At the beginning, the rotor was supported by the touch down bearing. The initial position of the rotor for either axis $x_0=y_0=-g_0/\sqrt{2}=-250\mu m/\sqrt{2}=-177\,\mu m$. Then, the converter started to work, and the rotor is levitated and is controlled at the reference position $x_{ref}=0\,\mu m$ and $y_{ref}=0\,\mu m$ in 5s. The position error for either axis is less than $10\,\mu m$ when static suspension. It has been proved that the proposed drive architecture can be used for multi-axis magnetic bearing suspension well.

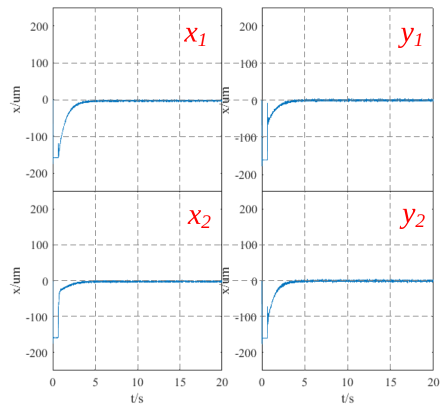

Figure 14. Results for static suspension experiment using common-leg converter.

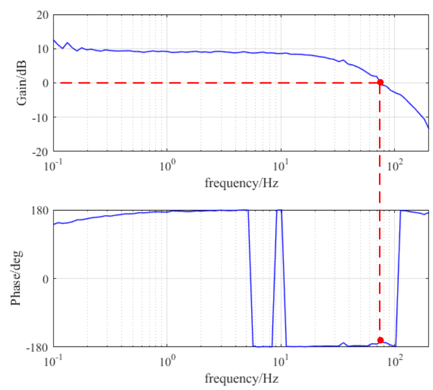

Figure 15. Position open-loop Bode plot

By the method of small signal injection, the position open-loop Bode plot can be derived as shown in Fig.15, which can represent the position control dynamic performance. The zero-crossing frequency is at 70Hz, and the phase-margin is about 20 degree. It indicates that the bandwidth of the position controller is 70Hz, and with the phase-margin. Therefore, the position loop is stable with the tuned controller.

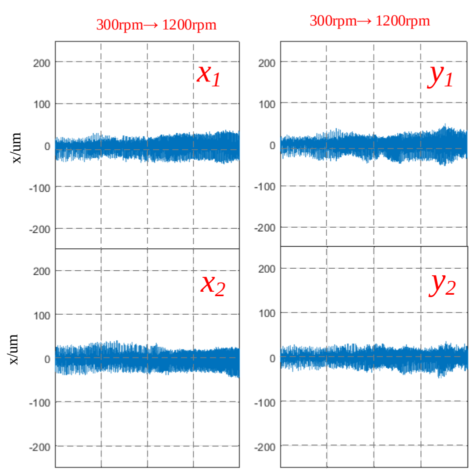

Figure 16. Rotating test with common-leg converter.

Rotating test has also been done with the common-leg converter, and the position errors of four axes are shown in Fig.16. At the beginning, the speed of the rotor is 300rpm, and the peak position errors of the rotor can be controlled into 30 µm. Then, the rotor is accelerated to 1200rpm in 20s. From the result, the position errors are less than 50 µm during the acceleration process, which is less than 20% of the total air-gap of the touch-down bearing. Rotating test has verified the feasibility of common-leg converter in magnetic bearing control. It can achieve the same function with conventional converters while the cost is greatly reduced.

IV. Conclusion

In this paper a common-leg converter for multi-axis active magnetic bearing system is proposed. At the beginning, the significance of the power electronics converter in an AMB system is explained. Then the development of converter and the novel common-leg converter is presented. Comparing with conventional topologies, this converter requires only 9 switches and 9 diodes for a 4-DOF AMB system, which greatly reduces the device number and cost. The operation modes and modulation methods were analyzed to present the principle of this converter. Simulations, suspension experiment and rotating experiments were carried out. Current in either coil can rapidly track the reference signal, and will not be influenced by other coils. As for the position control experiments, the position error is less than 10 µm at static suspension, and 50 µm at rotating. The results successfully verify the feasibility of this topology in magnetic bearing control.

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