A Plate Moving-Magnet Linear Generator Designed for Free-Piston Engines

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ABSTRACT Free-piston engine coupled with linear generator is a research hotspot in the field of novel vehicle mounted power generation devices. A plate moving-magnet linear generator (PMMLG) is proposed and designed for free-piston engines in this paper. Magnetic circuit of the novel linear generator is analyzed and modeled in detail. The dimensions of a 2 kW prototype with the max stroke of 40 mm and the max electromagnetic force of 800 N is designed by using the derived magnetic circuit model. Static and transient electromagnetic field finite element models with motion solvers are created. Magnetic field distribution, electromagnetic force characteristics, EMF characteristics, coil inductance, generating power and losses of the linear generator are analyzed and compared with two reported prototypes. Computational fluid dynamics model of the PMMLG is established, and the temperature field is analyzed to verify that the air-cooling conditions can ensure long-term stable running of the linear generator without demagnetization. The research results show that the linear generator has the characteristics of low moving mass, low cogging force, high generating efficiency and high response speed.

INDEX TERMS Linear generator, electromagnetic analysis, thermal analysis, free-piston.

I. INTRODUCTION

Energy crisis and environmental pollution nowadays are of great concern, which drive the transformation of the automotive industry. Research and development of new energy vehicles and extreme power units has become a hot topic in the automotive industry. As a novel vehicle-mounted power generation system, free-piston engine generator (FPEG) has received high attention in recent years [1]–[3]. Fig.1 shows the structure of the FPEG. This system is a direct combination of a free piston and a linear generator, eliminating the crankshaft and connecting rod mechanisms in traditional internal combustion engines. Under different operating conditions and loads, the compression ratio of the in-cylinder work can be improved by changing the stroke length of the piston, and the thermal efficiency of the internal combustion engine can be improved [4]. The variable compression ratio also enables FPEG to achieve different combustion modes and good fuel universality, which lays the foundation for more clean energy applications [5].

The free piston includes a compression stroke and a power stroke in the combustion cycle. In the compression stroke, an air spring pushes the piston to move from the bottom to the top. After reaching the top dead center, it enters the power stroke. The fuel in the combustion chamber expands and works, pushing the piston to the opposite direction.
The piston and the mover of linear generator are connected through a piston rod. The piston movement drives the mover to produce a changing magnetic field in the linear generator to generate electricity.

As an important part of FPEG, the linear generator needs to meet the requirements of low moving mass, low cogging force, high generating efficiency, fast response and high controllability. This is because an increased moving mass will increase the inertia, reduce the operating frequency and increase the response. Low cogging force can make the generator run smoothly. Generating efficiency is an important performance indicator of generators. Nowadays, these strict requirements are the main problems for a suitable linear generator for FPEG to be developed [6], [7].

Many scholars around the world have done a lot of researches on linear generators for energy converters. A new dual-port linear electrical generator topology was proposed in [8], improving the generation performance of linear generators by optimizing the shape of stator teeth, which is capable to transfer electrical power with an adequate voltage even at zero vertical velocity of the oceanic wave. Xu designed a tubular permanent magnet linear generator using I-shaped and rectangular designs, and the output power and efficiency of the I-shaped PMLG are higher than that of rectangular one [9]. A linear generator for the wave energy conversion system was proposed in [10], which improves system stability by reducing the cogging force. A permanent magnet planar translational generator which increases the magnetic flux in the coil by optimizing the shape of the coils and reducing the distance between the coils and the permanent magnet was proposed in [11]. High grade ferromagnetic cores were used in [12] to reduce the core loss of the linear generator and reduce the heat generation. A primary excitation fully superconducting linear generator with a plate structure which has larger output power than two other traditional primary excitation linear generators was proposed in [13].

In the course of theoretical research, some scholars produced prototypes of linear generators and carried out experimental research. Yang [14] proposed a moving coil linear generator (MCLG) with the characteristics of low moving mass, fast response, high efficiency, and easy to control, but the power density of the MCLG is low. A tubular permanent-magnet linear machine (TMLM) was manufactured in [15], and back electromotive force (EMF) and thrust were taken as the main concerned aims. The efficiency of the TMLM is not high. It can be seen that low cogging force and low heat caused by low loss are important factors to maintain stable operation of linear generators. At the same time, the power density of these existing linear generators needs to be improved.

The moving-coil linear generator is a major research hotspot worldwide because of the characteristics of low moving mass, fast response, high efficiency and so on [16]. However, copper loss as the main loss of the generator will cause the temperature of the coil to rise sharply. At the same time, the coil as a moving part cannot be effectively cooled. This will lead to high temperature in the generator cavity, which will cause that the generator cannot operate for a long time. However, many tubular moving-magnets linear generators, although they can actively cool the coils, cannot solve the problems of large moving mass, low operating frequency, and slow response [17].

This paper will propose a plate moving-magnet linear generator (PMMLG) for FPEG. First, the 3D model of the PMMLG will be introduced, a prototype will be manufactured based on the dimensions calculated by the equivalent magnetic circuit model. The electromagnetic characteristics and the generating performance of the prototype will be analyzed by FE method. Since the main failure form of PM generators is demagnetization of the PM, a computational fluid dynamics (CFD) model of the moving-magnet temperature field will be established, the temperature rise characteristics of the moving-magnet will be studied to verify whether the linear generator can run continuously.

II. STRUCTURE DESIGN

The structure of the PMMLG is shown in Fig.2. The PMMLG consists of a base, two stator assemblies and a mover assembly. The mover assembly is composed of two PMs and a mover support. From the picture, the magnetization direction of the two PMs is perpendicular to the shaft, but the directions of them are opposite, and they point to different stator components. Two non-magnetic shafts are fixed on the base, and the whole mover assembly reciprocates on the shaft at a high speed through sliding bearings. Two stator assemblies are
symmetrical about the mover assembly. The stator assembly consists of two coil bobbins, two stator supports, a core and a coil. The bobbin is used to fix the core, and at the same time, it can protect the winding from abrasion of the core. The winding is placed in two slots of the iron core. The stator supports are connected to the base to keep a fixed distance between the stator and the mover. There is an air gap between stator assembly and mover assembly. The magnetic attraction between the stator component and the mover component depends on the PMs and the core.

The stator core is formed by laminating silicon steel sheets in a direction perpendicular to the shafts, which can effectively reduce eddy current loss. Therefore, it is possible to reduce the heat generation of the generator and improve the generating efficiency. As a part of the stator, the coil can be cooled by active cooling [18]. The material selected for the permanent magnet is N42SH, whose maximum working temperature is 423 K.

Fig.3 shows the equivalent circuit model of the proposed PMLMG. A voltage-type H-bridge PWM power rectifier is used to control the current of the generator. The generator is equivalent to a resistor ($R$), an inductor ($L$) and a voltage source ($E$) connected in series. PMLMG is a single-phase generator. The two coils of PMLMG are connected in parallel, so the equivalent resistance value is the resistance value of the two coils connected in parallel. The value of the $L$, $R$ and $E$ will be obtained in the paper.

III. MAGNETIC CIRCUIT ANALYSIS AND PARAMETRIC DESIGN

The equivalent magnetic circuit method can quickly establish a mathematical analysis model of a permanent magnet linear generator, which can quickly determine the main geometric size of the PMLMG and reduce the time required for finite element analysis and optimization. At the same time, it can provide theoretical basis for the design and analysis of the PMLMG.

According to the magnetic resistance calculation formula, the magnetic resistance of each part can be calculated as:

$$R_s = \frac{l_s}{\mu_s S_s}$$  \hspace{1cm} (1)

The permeability of air is $\mu_0$, and the relative permeability of the PM is $\mu_r$. $\mu_s$ represents the magnetic permeability of the silicon steel sheet. Because the magnetic permeability of the silicon steel sheet is excellent, the magnetic resistance can be almost ignored. $S_S$ and $S_m$ represent the cross-sectional areas of the stator teeth and PM respectively. From the formula, a larger magnetic flux can be obtained by reducing the air gap magnetic resistance. The distance between the stator and the PM needs to be as small as possible. Due to the existence of pole shoes, the length of air magnetoresistance is always close to $l_g$. This design also results in low losses and high generating efficiency for PMLMG.

The equivalent magnetic circuit model of PMLMG under no load is shown in Fig.4. Ignoring the effects of the stator pole shoes, it can be roughly considered that the length of each segment of the stator is equal, the magnetic resistance is the same, and the resistance value is $R_S$. Therefore, the equivalent magnetic circuit of the stator part can be composed of 5 equivalent magnetic resistances. $F_{ml}$ and $R_{ml}$ represent the magnet motive force (MMF) and reluctance of the PM-A respectively. $F_{mr}$ and $R_{mr}$ represent the MMF and reluctance of the PM-B. $R_{gul}$ and $R_{gur}$ respectively represent the air gap magnetic resistance between PM-A with PM-B and the upper stator. $R_{gbl}$ and $R_{gbr}$ respectively represent the air gap magnetic resistance between PM-A with PM-B and the bottom stator. When the PM is in the initial position ($x = 0$mm), the left two teeth of the upper and bottom stators form a loop with PM, which is shown in Fig.4 (a). The magnetic flux in the magnetic circuit can be calculated by the loop current method:

$$\Phi_m = \frac{F_{ml} + F_{mr}}{6R_s + R_{gul} + R_{gur} + R_{gbl} + R_{gbr} + R_{ml} + R_{mr}}$$  \hspace{1cm} (4)
When the PM moves to the midpoint \((x = 20 \text{mm})\) of the stroke, the PM forms a loop with the upper and lower teeth at both ends of the stator. The magnetic flux in the magnetic circuit can be calculated by the loop current method:

\[
\Phi_m = \frac{F_{ml} + F_{mr}}{8R_s + R_{gul} + R_{gr} + R_{gbr} + R_{ml} + R_{mr}} \quad (5)
\]

The magnetic circuit of the mover at the starting position is analyzed to simplify the stator part with a small magnetic resistance value. The magnetic flux calculation formula can be simplified as:

\[
\Phi_m = \frac{F_m}{2R_g + R_m} \quad (6)
\]

In the formula, At the starting position, the air gap values of all parts are the same, which are simplified to \(R_g\);
the specifications of the permanent magnets are also the same, and the reluctance and MMF are simplified to \(R_m\) and \(F_m\) respectively.

The relationship between \(\Phi\) and \(H\) can be obtained from the demagnetization curve of the permanent magnet.

\[
\Phi_m = \Phi_r (1 - \frac{F_m}{F_c}) \quad (7)
\]

Among them, \(\Phi_r\) and \(F_c\) can be calculated by the following formula:

\[
\Phi_r = B_r S_m \quad (8)
\]

\[
F_c = H_c h_m \quad (9)
\]

\(B_r\) and \(H_c\) represent coercive force and remanence respectively. The \(B_r\) and \(H_c\) parameters of N42SH can be obtained by looking up the table.

By combining formulas (6)-(9), we can get the relationship between \(F_m\) and \(l_m\):

\[
\frac{F_m}{2R_g + R_m} = B_r S_m (1 - \frac{F_m}{H_c * h_m}) \quad (10)
\]

By substituting different thicknesses of magnetic steel, the magnetomotive force can be calculated, and the magnetic flux in the magnetic circuit can be calculated. The change curve of magnetic flux and the mass of the PM with the thickness of the PM is shown in the Fig.6.

With the increase of the thickness of the PM, the magnetic flux in the magnetic circuit also increases. Then the increase of the thickness of the magnetic steel brings the increase of the mass of the mover, so it is necessary to choose an appropriate thickness of the magnetic steel. It can be seen from the Fig.6 that after the thickness of the magnetic steel reaches 12 mm, the growth rate of the magnetic flux begins to slow down, so it is determined that the thickness of the magnetic steel is 12 mm.

When the thickness of the magnetic steel is 12 mm, it can be concluded that when the mover is in the initial position without load, the magnetic induction intensity on the surface of the magnetic steel is 0.87 T, and the magnetic induction intensity in the stator magnetic circuit is 1.8 T. Table 1 lists the main structural parameters of PMMLG. Fig.7 shows the prototype of PMMLG.

**TABLE 1. Main structure parameters of the PMMLG.**

| Name                      | Parameters                  |
|---------------------------|-----------------------------|
| Outer dimension           | 180 mm*188 mm*132 mm        |
| PM                        | 100 mm*40 mm*12 mm          |
| PM material               | N42SH                       |
| Max working temperature of PM | 423 K                      |
| Stator material           | 47F240                      |
| Winding area              | 30 mm*30 mm                 |
| Coil turns                | 92                          |
| Coil diameter of winding  | 2 mm                        |
| Effective winding resistance | 0.053 Ω                    |
| Terminal winding resistance | 0.037 Ω                    |
| Max stroke                | 40 mm + 2 mm                |

**FIGURE 5.** Equivalent magnetic circuit model of the PMMLG under no load. (a) \(x = 0\text{mm}\), (b) \(x = 20\text{mm}\).

**FIGURE 6.** Magnetic flux VS. Mass of the PM mover.

**FIGURE 7.** Prototype of PMMLG.
in the middle of two PMs. The two coils on the upper and lower stators have the same winding direction. The magnetization directions of the two PMs are opposite. The specific magnetization directions are shown in Fig.2. The position of the mover as shown is the starting point (x = 0 mm) of the displacement. The rightward movement is the positive movement, the maximum stroke of the movement is 40 mm. Fig.8 (b) shows the finite element model after meshing. The entire model is divided by triangular meshes. In the magnetic circuit parts of the PMs and the core, a denser mesh is used than other regions.

Fig.9 (a) and (b) shows the magnetic field distribution of the PMMLG when the mover is at the initial position (x = 0 mm) and the midpoint position (x = 20 mm) under no load. It can be clearly seen that the upper and lower cores form a common circuit with the middle PMs. When the mover is in the initial position of displacement, it mainly works by the left two teeth of the iron core. Different colors in the picture represent different magnetic fluxes. Because the width of the magnetic circuit in the iron core is the same, the magnetic flux distribution in the magnetic circuit of the core is uniform, which is about 2 T [19], [20]. The magnetic field distributions of the mover and the upper and lower air gaps around the mover are also uniform, which is about 1 T. When the mover moves to the midpoint position, the left and right teeth of the upper and lower stators form a common magnetic circuit with PMs. Relative to the entire magnetic circuit, the size of the pole shoe is small, so the maximum field strength appears, which is about 2 T. The other parts of the magnetic circuit are uniformly distributed, which is about 1 T. There is not much difference between the results of the finite element analysis and the magnetic induction intensity calculated by the equivalent magnetic circuit method.

### B. STATIC ELECTROMAGNETIC FE SIMULATED RESULTS

When the magnetic flux changes with time, induced electromotive force is generated in the coil. The electromotive force is equal to the negative value of the change rate of the magnetic flux linkage with time [21]. The change of flux and EMF coefficient with displacement is shown in Fig.10. The magnetic flux curve is obtained by static solution, and the EMF coefficient curve is obtained by transient solution under
The condition that the moving speed of the mover is 1 m/s. When the displacement of the mover is between 0-10 mm, the slope of the flux curve increases and the EMF coefficient increases. When the displacement of the mover is between 10-20 mm, the flux curve approximates a straight line and the EMF coefficient remains unchanged. When the displacement of the mover is between 30-40 mm, the EMF coefficient reduces because the magnetic flux is center-symmetric about the midpoint ($x = 20$ mm) of the displacement, and the EMF coefficient is axisymmetric about the midpoint of the displacement. When the mover moves to the midpoint, the magnetic fluxes of the two left coils and the two right coils are equal, and the directions of the magnetic induction lines are opposite, so the magnetic flux is 0 Wb. The magnetic chain shows such a change law due to the symmetry of the PMMLG structure.

The variation of thrust force with the displacement of the mover at different currents is shown in Fig.11. Cogging force of PMMLG is shown by the curve of $I = 0$. When the mover is at the displacement of 10-30 mm, the cogging force is approximately equal to 0; At the 0-10 mm and 30-40 mm of the displacement, the direction of cogging force is opposite and the value is not greater than 100 N. It can be seen from the figure that as the current increases, the thrust of the generator also increases. In the middle section of the displacement, the thrust is relatively stable, while the two ends are affected by the armature effect, the thrust curve appears asymmetric. A current of 30 A is applied to the coil, and the maximum thrust is 600 N. When the current in the coil reaches 42 A, the maximum thrust is about 800 N.

### C. TRANSIENT ELECTROMAGNETIC ANALYSIS

In addition to the static electromagnetic field analysis, the transient electromagnetic field analysis of linear generators is also very important. The transient electromagnetic field analysis can roughly simulate the electromagnetic force, EMF, coil inductance, generating power and losses of the linear generator [22], [23].

For the convenience of research, it is assumed one generating cycle is taken out to simulate the entire generating process. Fig.12 gives the motion of the mover under the standard condition. The displacement of the mover is a sine curve with a stroke of 36 mm and a frequency of 50 Hz. The motion of the mover is symmetrical about the midpoint, and the maximum speed is about 5 m/s. Cogging force is an important factor affecting the thrust wave fluctuation of linear generators, which can cause vibration and degrade operating characteristics. Fig.13 shows the electromagnetic force of PMMLG prototype under the standard motion condition. $I_g$ represents the amplitude of a sinusoidal current at a frequency of 50 Hz. Cogging force is an important factor affecting the thrust wave fluctuation of linear generators, which can cause vibration and degrade operating characteristics. Under no-current conditions, the cogging force of the prototype does not exceed 100N. When the mover reaches the midpoint, the electromagnetic force of the prototype reaches the maximum. When the $I_g$ is 40 A, the maximum electromagnetic force can reach 800N. The average thrust coefficient is 15.8 N/A.

Fig.14 shows the terminal voltage of the prototype under the standard motion condition. Under different current amplitude conditions, the terminal voltage curve shape is roughly
the same. As the current amplitude increases, the terminal voltage will lag slightly. Because in the presence of current, the magnetic flux generated by the coil’s self-inductance encounters the magnetic flux generated by the magnetic field of a permanent magnet first, the EMF will have a short delay when the current is applied. Fig. 15 shows the coil inductance of PMLLG at different current amplitudes, average coil inductance is about 2.6 mH.

Through the finite element method, the terminal voltage can be simulated based on the current and the motion of the mover input from the generator, then the generating power can be calculated. The generating power of the PMMLG is calculated by:

\[
\eta = \int_{t_1}^{t_2} u idt
\]

(11)

\(t_1\) is the start time of the cycle; \(t_2\) is the end time of the cycle; \(u\) is the simulated terminal voltage; \(i\) is the given standard coil current of the PMMLG.

Fig. 16 is the coil current and the generating power when the linear generator is driven by the standard reciprocating motion shown in Fig. 12. The coil current is controlled as the standard sinusoidal current with the amplitude of 40 A and the frequency of 50 Hz. The average output generating power is about 2 kW.

At the same time, the loss of each part of the generator can also be accurately obtained. Fig. 17 shows the instantaneous values of copper loss, pm loss, and mover support loss in a standard cycle. Losses are roughly the same for both strokes in a single cycle. It can be clearly seen in the figure that the main loss comes from the copper loss. Due to the use of silicon steel sheets, core loss accounts for a small proportion of losses. The specific loss distribution of the PMMLG is shown in Table 2.

Table 3 compares the main performance of the proposed PMMLG with that of two reported prototypes. As a type of moving-coil linear generator, MCLG [14] responds faster and has no cogging force. However, PMMLG as a moving-magnet linear generator has higher generating efficiency and power density. TMLM is also a moving-magnet linear genera-
TABLE 3. Main performance compared with two reported prototypes.

| Items                        | PMMLG  | MCLG | TMLM |
|------------------------------|--------|------|------|
| Volume (×10^{-3} m^3)        | 4.5    | \   | 0.7  |
| Rated frequency (Hz)         | 50     | 20   | 25   |
| Rated stroke (mm)            | 40     | 120  | 60   |
| Generating power (kW)        | 2.0    | 3.37 | 0.2  |
| RMS current (A)              | 28.3   | 120  | 8    |
| Coil resistance (Ω)          | 0.09   | \   | \    |
| Average inductance (mH)      | 2.6    | 1.3  | 3    |
| Average EMF (V/(m/s))        | 16.4   | 32   | \    |
| Average force (N/A)          | 15.8   | 31   | 20.2 |
| Max cogging force (N)        | 58     | 0    | \    |
| Moving mass (kg)             | 1.4    | 4.3  | \    |
| Generating efficiency        | 95%    | 87.5%| 82%  |
| Power density (W/kg)         | 183    | 47   | \    |
| Manufacturing cost           | High   | Low  | Medium |

V. THERMAL ANALYSIS OF THE PMMLG

Generator thermal research is an important part of generator design. There are three common methods [24]–[26]: simplified formula method, equivalent thermal circuit method, and temperature field method. Among them, the temperature field method uses modern numerical methods to solve temperature equations, mainly including the finite element method and the finite difference method. The finite element method combines the common advantages of the traditional finite difference method and analytical calculations, making this method very flexible and adaptable.

The permanent magnet of the moving-magnet linear generator can be passively cooled as a mover, and the stator part can be forcibly cooled by water-cooling or oil-cooling. Since permanent magnets are the main failure form of permanent magnet linear generators due to high temperature demagnetization, it is necessary to study the temperature rise of the moving-magnet of the PMMLG [27], [28].

Schematic diagram of PMMLG temperature field is shown in the Fig.18 (a). The model includes the mover part of PMMLG, air box and three types of interfaces. Surface $S_1$ is the contact surface between the mover support and the air box. Surface $S_2$ is the interface between the air box and the external environment. Considering that the stator part can be cooled by active cooling, the stator part is simplified to a constant temperature wall boundary condition to simplify the model and speed up the calculation efficiency. Surface $S_3$ is set to the ideal metal wall surface, which is the constant temperature surface. Three temperature monitoring points are established in the model. P1 is the temperature monitoring point of the geometric center of PM. P2 is the temperature monitoring point on the $S_1$, P3 is the temperature monitoring point on the $S_2$. As can be seen from the loss distribution in the previous chapter, the losses in the moving-magnet mainly include eddy current loss and hysteresis loss in PM, and the values can be calculated by finite element calculation. Adding PM loss as a heat source in the temperature field to the finite element calculation of the temperature field, the heating power of the two PMs is 12.4 W. Fig.18 (b) shows the temperature distribution of the moving-magnet running for 100min when the stator temperature is constant at 300K, and the highest temperature will be 333 K.

Using the stator at different constant temperatures as variables, the temperature rise at the three monitoring points are shown in Fig.19. It can be seen from the figure that after the generator runs for 100 minutes, the temperatures at the three monitoring points almost converge. The figure shows the temperature changes of the three monitoring points over time when the stator’s constant temperature is 300 K, 320 K and 340 K respectively. Because point P3 is on the contact surface of the air bag with the external environment and is close to the stator at constant temperature, the temperature at point P3 will stabilize at a point slightly higher than the
stator temperature. PM is the heat source, and the geometric center of PM is $P_1$, whose temperature rises fastest, and is highest after stabilization. As the edge of the moving-magnet, the temperature rise of $P_2$ is slightly slower than that of $P_1$, and the maximum stable temperature of $P_2$ is also slightly lower than that of $P_1$. The temperature difference between point $P_1$ and the stator decreases as the stator’s constant temperature increases.

Table 4 lists the maximum temperature when the three monitoring points are stable at different stator temperatures. The maximum temperature of N42SH is not higher than 423 K. The temperature of the moving-magnet can be stabilized at a maximum of 365 K, which is within the normal working range of this brand of permanent magnet. By analyzing the temperature field of the moving-magnet through the CFD method, it can be concluded that the designed heat dissipation conditions of the generator meet the needs of stable operation of the PMMLG.

VI. CONCLUSION

This paper presents a novel plate moving-magnet linear generator, which is developed for free-piston engines. The structure of PMMLG is introduced, and a finite element model is established based on the structure. Static and transient electromagnetic fields are analyzed by finite element methods to obtain the electromagnetic characteristics and generating performance. The generating current of PMMLG is a sinusoidal current with a magnitude of 40 A and a frequency of 50 Hz at the rated operating point. The generating efficiency can reach 95%, and the generating power is about 2 kW. Simplified PMMLG temperature field model is established and analyzed. The maximum temperature of the moving-magnet will be stable at 365K, within the normal working range of N42SH. Through the above works, we can get that the PMMLG has the advantages of simple structure, low cogging force, fast response, high generating efficiency, and good cooling.

At present, for the convenience of research, the stator part of the PMMLG temperature field model is simplified into an ideal constant temperature surface. A complete PMMLG temperature field model will be established and analyzed later. Due to the limited conditions, experiments are not yet available. In the future, experiments will be carried out to study the electromagnetic characteristics and temperature rise characteristics of the PMMLG prototype.

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