Research on Application Characteristic of Electric Inertia Unit for Free-piston Linear Alternator

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Abstract. Electric inertia unit can have an impact on electromagnetic force generated by induced current through regulating the value of load resistance. The electromagnetic force can be precisely controlled to restraint the motion of the piston. The proper electric inertia unit for the Free-piston linear alternator can lessen the energy fluctuation caused by the reciprocating piston for different cycles. The load resistance regulation on the electric inertia unit at the predetermined piston stroke can improve the control preciseness for the top dead center or bottom dead center.

Introduction

Free-piston linear alternator (FPLA) is a new power equipment in recent years. For its simple structure and variable compression ratio, it can enjoy a high thermal efficiency and wonderful multi-fuel adaptation [1, 2].

With its many advantages, however, the FPLA have also some disadvantages. First, for there no connecting rod equipment and crankshaft in FPLA, the engine have no fixed top dead center (TDC) and bottom dead center (BDC) which may cause a problem to control the compression ratio. Under this condition, the ignition for the engine may become un-stability which easily causes misfired in the engine. Besides, the energy fluctuation may be transferred to the opposite compression stroke of the other cylinder. For the FPLA also having no fly-wheel, the compression ratio of the opposite cylinder varies for this fluctuation which may also cause misfire in the engine [3].

In this paper, the dual cylinder opposition FPLA was researched with the application of the electric inertia unit (EIU) made up of super capacitor and its control device. Through improving the energy fluctuation, it can restraint the piston motion so the piston can reach the predetermined TDC with minor error.

Principle Analysis

Traditional reciprocating engine can operate stability for simple control for the flywheel can improve the energy fluctuation caused by combustion fluctuation and inhibit the angular acceleration caused by energy fluctuation which can guarantee the engine being in stable operation. For FPLA design, without the fly-wheel, the two opposite cylinders can be affected by one another which may form strong coupling correlation. The little fluctuation of combustion may induce chain reaction which may at last cause misfire or striking cylinder [2].

In this paper, the EIU can be regard as the flywheel in the traditional engine. The energy released in combustion is converted into electricity by generator. The super capacitor in the EIU can be used for electricity power cache. The additional electromagnetic force increment, which is generated by absorbing and releasing the electricity power, can influence the piston motion by negative feedback which can control the free piston motion for its effect on compression stroke. Meanwhile, due to the variable load design of EIU as can control precisely the load current, it can establish solid foundation for the next combustion cycle by controlling the electric-magnetic force on the mover component to reach the TDC precisely.

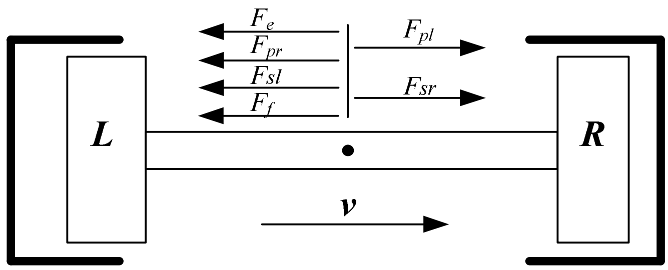

Fig. 1 Schematically force.

The kinetic equation which can elaborate the static operation process of FPLA can be briefed as follows:

$$m \cdot \frac{d^2 x}{dt^2} = (F_{pl} - F_{pr}) + (F_{sr} - F_{sl}) - F_e - F_f \quad (1)$$

F_{pl} is the pressure due to gas expansion on the left side (combustion side) cylinder and F_{pr} is the pressure due to gas compression on the right side (compression side). F_{sl} and F_{sr} are the pressure of the sweep room respectively. The F_f is the friction force between mover components (piston, connecting rod, generator mover) and stator of which the direction is opposite to that of mover and the value is the function of piston speed; The direction of the F_e is opposite to that of mover and the value is the function of piston speed [2, 4]. Among these parameters, except F_e, other parameters are not affected by current directly. So in the EIU, the parameter F_e is only researched and the math description as follow:

$$F_e = \frac{k_f \cdot k_v}{R + r + j\omega L} \frac{dx}{dt} \quad (2)$$

As can be seen in above math model, k_f is the trust coefficient of the generator and the k_v is the Back-EMF coefficient of the generator. The x is the displacement of the piston. The load resistance R, internal resistance r and the inductive reactance L constitute the resistance characteristic for the electricity generation loop. Among the three parameters, the r and L are the intrinsic characteristics of the motor coil. As the R varies, the current in power generation loop can be influenced to affect the electric-magnetic force F_e. The correlation of the Fe and R and dx/dt can be derived from the Eq. (2). If the R can be controlled, the piston can be operated more precisely in expected speed for stable engine operation.

System Program Design

System Analysis. As can be seen in the above principle analysis, the basic characteristic of the EIU is listed as follows: 1, when the piston speed exceeds the predictive value to smooth the piston speed, the EIU can absorb the excess electricity energy; 2, when the piston speed lowers than the predictive value, the EIU can compensate the electricity needed for the engine. 3, the EIU won't influence the main load in steady operation. From the operation process of FPLA, it can be observed that the engine outputs the electricity power continuously though with energy fluctuation. So the strategy of absorption and compensation should be designed as follows: it can be defined as the absorption that the load side consumes the excess electricity power, and compensation that the load side consumes the electricity which lower the normal value. It means the load impedance can be regulated to amplify or reduce the electricity energy that need consume so as to restraint the piston motion by proper electric-magnetic force. The energy flow topology of the FPLA with EIU is shown in Fig. 2.

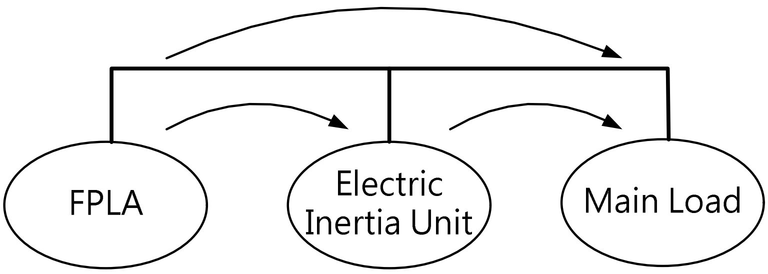

Fig. 2 Energy flow of FPLA.

Program Design. The EIU is composed of load control device and super capacitor as shown in Fig. 3. The electricity power generated by FPLA is output by two loops after rectification. One is main load loop and the other is EIU loop. The DC/DC of the main load loop can regulate voltage of the electricity to conform to the requirements of main load loop. The comparable result can control the loop current of super capacitor by controlling the gate source voltage of the MOSFET by transport charge output, then the equivalent variable load resistance R can be obtained.

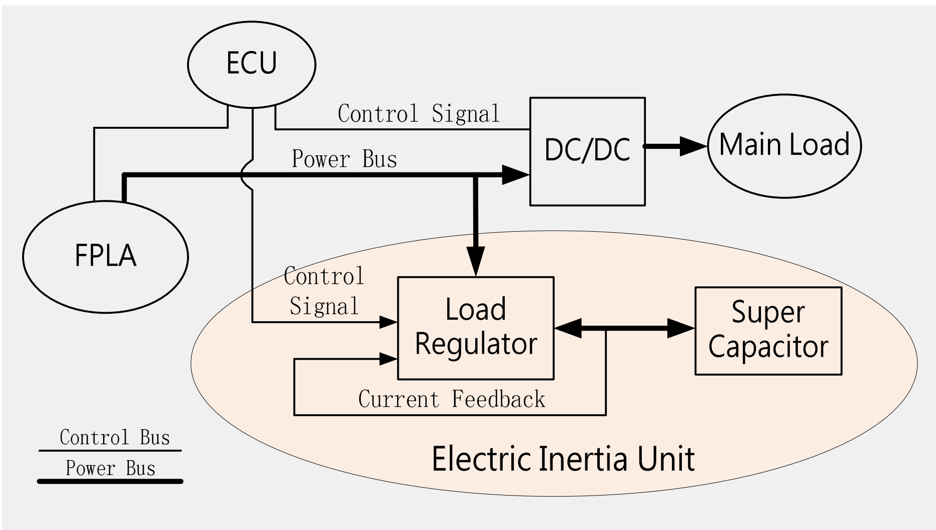

Fig. 3 System architecture.

Load control device is the key component of the EIU. It not only regulates the load but also does dual DC/CD. In EIU, the variable load value can be equivalent realized by controlling the current in the loop. The principle is shown in Fig. 4. R_s is the voltage sampling resistance. The sampling signal is compared with the V_{ref} in the operation amplifier to control the current of the MOSFET loop. It can be obtained the equivalent variable load resistance R by controlling the gate source cathode to regulate the loop current of super capacitor.

The super-capacitor *Cs* charged through MOSFET control and EIU connects at the power bus, and its internal DC/DC real-time adjusts the supply voltage V_s to meet the requirements of charging. Then we select generated electricity energy of 30 working cycle as the capacity of capacitance to ensure the capacitance has enough volume to absorb electric energy. This EIU includes two types of operating mode shown as follows:

Mode 1 as the engine steadily works. The loop of EIU absorbs 25% power. In each cycle, when the piston moves to the TDC nearby, it can releases electricity energy to bus which is delivered to load through DC/DC to balance the power sharing produced by the FPLA power at the maximum and minimum velocity [5].

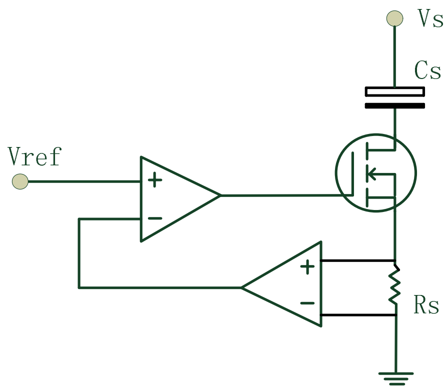

Fig. 4 Transformable load principle.

Mode 2 as the engine works with fluctuation. The fluctuation calculated by EIU has positive or negative influence on the system and then negative feedback control adjusts load value of EIU. As the fluctuation is positive, the engine generates excess power, EIU automatically reduces equivalent impedance to make its absorbed power become large and instantaneously absorb more energy. Then the larger electric-magnetic force caused by the powerful electric current makes the velocity of piston quickly decrease to the expected value. As the fluctuation is negative, the engine generates less power, EIU automatically increases equivalent impedance to make its absorbed power become small and absorb little power. Then the smaller electric-magnetic resistance caused by the smaller electric current makes the velocity of piston to the expected value by weaken the control of the piston. It is similar to mode 1 nearby the TDC, the electric energy of super-capacitor is delivered to main load through DC/DC.

Two types of mode coordinate to realize steadily operation of electric FPLA. In order to ensure the capacitance has enough adjusted volume, after capacitance SOC reaching a certain value, it can quickly deliver energy to load to keep its capacity.

The Design of Strategies. As shown in the Fig. 5, the free piston passes the key points when it moves from TDC (left top center) to BDC. The measured point is inserted between the points of right exhaust valve closed and the left sweeping valve opening. For the measured point in right side (piston down direction), to distinguish the two different measured points, the right measured point is defined as well as the left measured point being centrosymmetric.

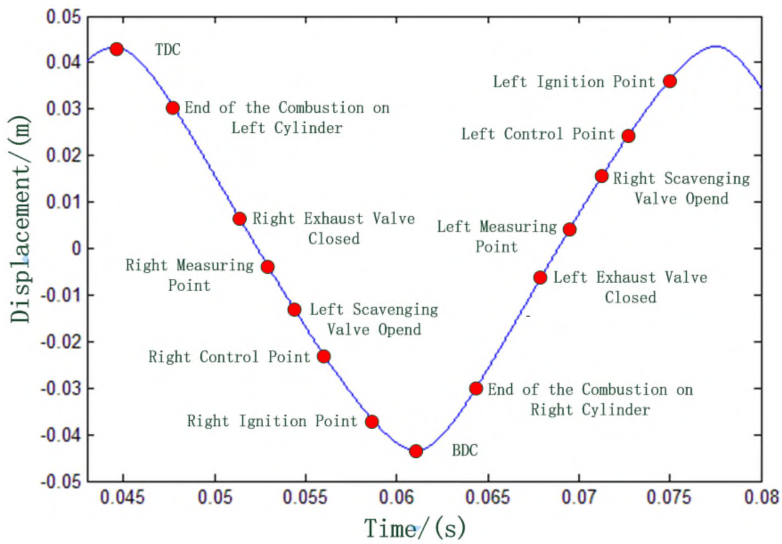

Fig. 5 Key points of control strategy.

$$E = U + P_c \cdot V_{cap} + \frac{1}{2} \cdot M \cdot V_{spd}^2 \tag{3}$$

$$\sigma E = E_1 - E_0 \tag{4}$$

$$R = \frac{9 \cdot \varepsilon \cdot k}{2 \cdot \sigma \cdot E} - r_i \tag{5}$$

For the compression process, it can be regarded the closed thermal system and the math model can be simplified as Eq. (3) and (4). Resuming the piston reaching the measure point at t_1, the parameters can be defined as follows: E is the whole energy including the energy of gas in combustion cylinder and the kinetic energy of mover components. E_O is the normal energy that piston need to reach the TDC. E_1 is the whole energy at time t_1 and σE is the energy increment. V_{spd} is the piston speed of the piston at time t_1 of the piston and U the thermal-dynamic energy at time t_1; P_c and V_{cap} are the pressure and volume of the combustion cylinder respectively at time t_1. P_c, V_{spd}, and σE are the key parameters and need establish the MAP by experiment. Through the MAP, the σE can be found to determine whether inject or release energy. In this paper, it means amplify or reduce the output energy. At last, the R can be deduced by Eq. (5) and the variable load resistance of electric inertia should be regulated to equal the R. the ε is the regulation coefficient; $k = k_f . k_v$; $r_i = r + j\omega l$.

Simulation Results

The model is established by MATLAB to validate the EIU as follows: It is shown in Fig. 6 that the cylinder pressure trace to simulate the combustion fluctuation of FPLA with the fluctuation being -3%~+5%. Fig. 7-1 and Fig. 7-2 shows that at the same pressure disturbance conditions, the simulation results of cylinder pressure and velocity curve without and with EIU respectively. It could be seen that with the application of EIU, the piston motion improves significantly compared with the TDC and the motion trace of the piston.

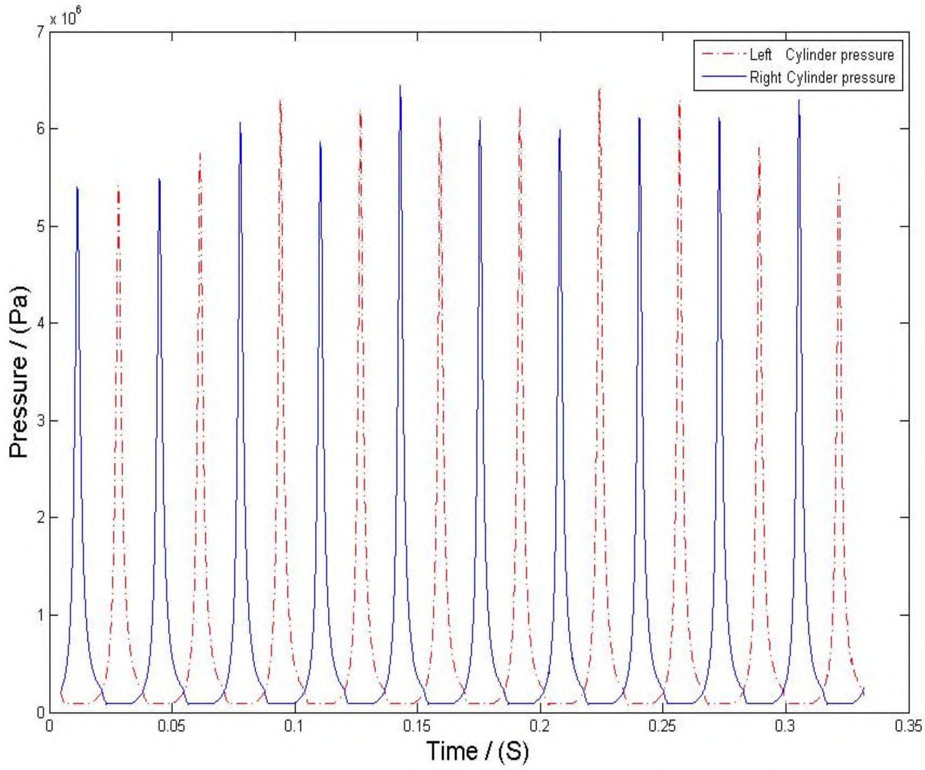

Fig. 6 In-cylinder gas pressures.

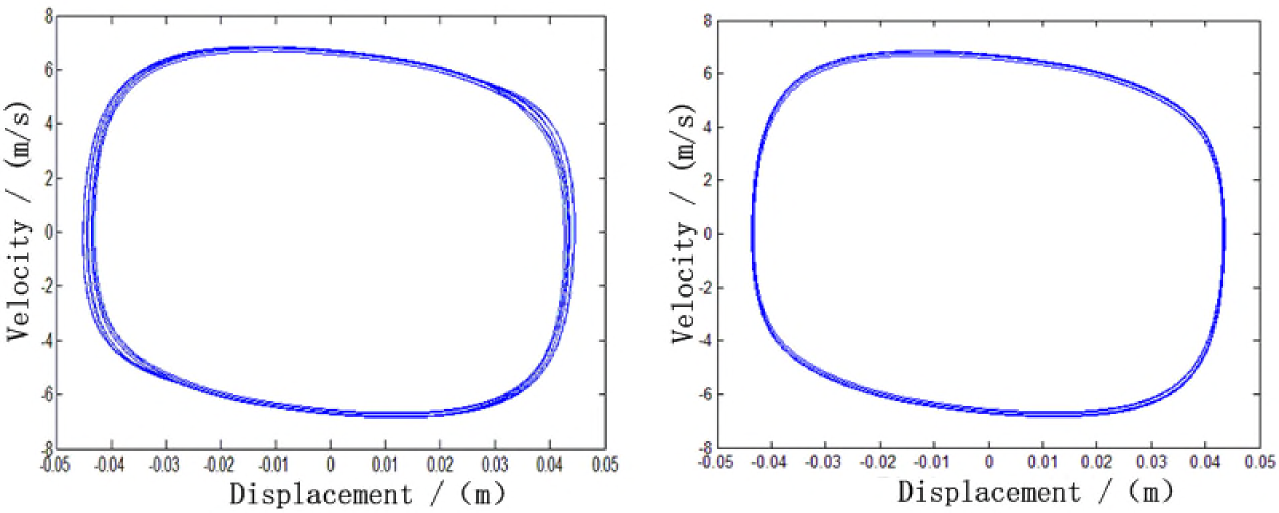

Fig. 7 Velocity vs displacement curve of piston.

Conclusion

The simulation results show that the EIU can restraint the speed of piston before it reaches the TDC for its steady operation of the FPLA. Meanwhile the deviation of the piston to the TDC is decreased. The conclusion can be briefed as follows:

a) The EIU can control the electricity output of the FPLA through adjusting the load power to smooth the energy fluctuation for each cycle. Then the FPLA can be in steady operation.

b) The application of the EIU improves the preciseness of the control on the TDC and BDC.

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