Simulation of hybrid propulsion system using LSRG and single cylinder engine

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Abstract. Nowadays, more and more people are beginning to use hybrid vehicles (HVs). The drive system of HVs needs to produce the electric energy with the electric generator and gearbox powered by an engine. Therefore, the structure becomes complex and the cost is high. To solve this issue, this research proposes a new drive system design that combines the engine and a linear switched reluctance generator (LSRG). When the engine is operating, the LSRG can simultaneously assist the engine's mechanical output or can generate power to charge the battery. In this research, three research steps are executed. In the first step, the LSRG is designed according to the size of normal engine. Then, finite element analysis is used to get the data of flux linkage and calculate the inductance and translator force. Finally, Simulink models of control system are constructed to verify the performance of LSRG.

1. Introduction

Nowadays, global warming and air pollution have been caused in part by the rapid development of vehicles. In order to reduce the negative effects of using vehicles, more and more researchers are working on designing clean energy vehicles. Some researches focus on the natural gas consumption in vehicle. However, there are problems about the climate implications of increasing natural gas in vehicles and methane leakage from natural gas infrastructure [1]. Another strategy is the electric vehicles (EVs), compared with fuel energy resources, the EVs are environment-friendly, however, they are underpowered due to the limitation of batteries. Therefore, EVs are mainly used for small vehicles and short distance purposes [2]. The HVs have been the subject of intense scholarly debate [3].
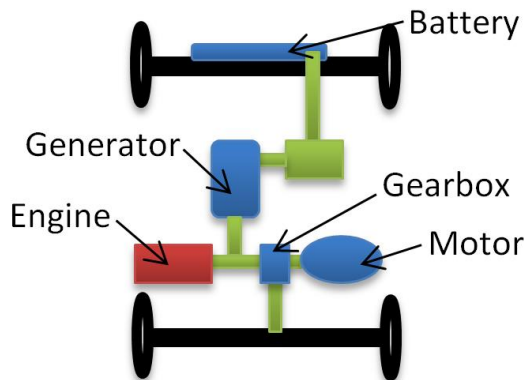
However, the drive system of HVs needs to produce the electric energy with the use of an electric generator and gearbox powered by an engine. Therefore, the structure becomes complex and the cost is high. Normal HVs have the engine, generator, motor, and so on as shown in figure 1 [4].

According to the compositions, if a generator or motor can be a part of the engine, it will accomplish the purpose of simplifying the structure. That means the generator can work together with the engine.
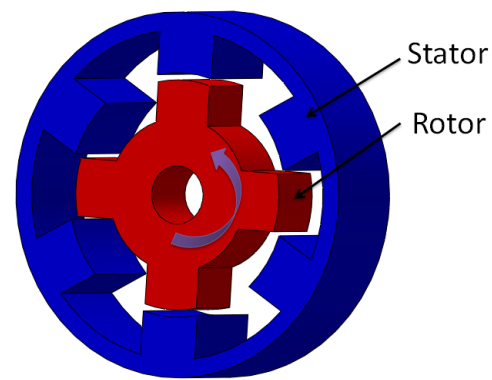
Switched Reluctance Generators (SRGs) use the reluctance torque that is produced by the change of magnetic resistance in magnetic circuits. Figure 2 is the basic structure of the SRG.

In the SRG, coils are only installed in the stators, coils and permanent magnet are not used in the rotor. The stator and rotor are made from grain oriented silicon steel plates. Based on above, the SRG has the simple structure and low cost. Even in high-temperature environment, there is no issue with demagnetization [5]. The rotor of normal SRG rotates about a fixed axis as shown in figure 2.
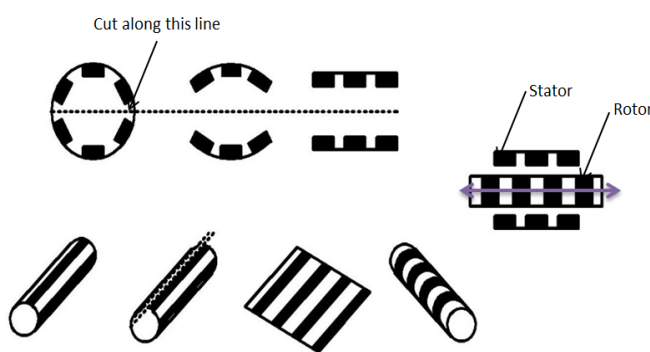
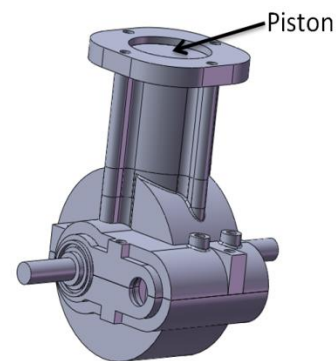**Figure 1.** Hybrid vehicle compositions.

Figure 2. SRG structure.

A Linear Switched Reluctance Generator (LSRG) is deformed from the SRG as shown in figure 3. The processing is cutting and unrolling the basic SRG to obtain a LSRG. The rotor can be treated as a translator, and the translator moves in a linear [6]. The LSRG will be an effective candidate when high-speed and high-precision are necessary conditions, since the LSRG has a quicker response and more sensitivity compared with the normal SRG.

Figure 3. Cutting and unrolling processing of LSRG.

Figure 4. Single cylinder engine for combining with LSRG.

On the other hand, the LSRG is difficult to control, and maybe it has a high force ripple because of its nonlinear magnetic circuit. Also the LSRG obeys the same principle with that of SRGs. In other words, the magnetic flux must always pass through the minimum path with which the magnetic resistance becomes the minimum one.
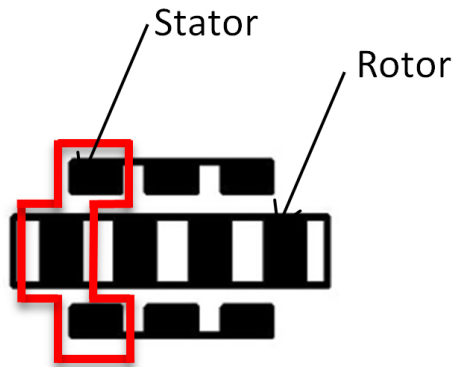
A Single Cylinder Engine (SCE) represents the basic structure of complex engines. The SCE has a simple structure, and it is shown in figure 4. This SCE does not include an intake system since it is used only for experimental testing.

This paper presents the new structure to combine the LSRG with the SCE into a hybrid propulsion system. When the SCE is operated, the LSRG can simultaneously assist the SCE's mechanical output or can generate power charge a battery. Here, the LSRG is designed by using finite element method (FEM) magnetic field analysis software JMAG. Moreover, the controlling parts are tested by using MATLAB Simulink.
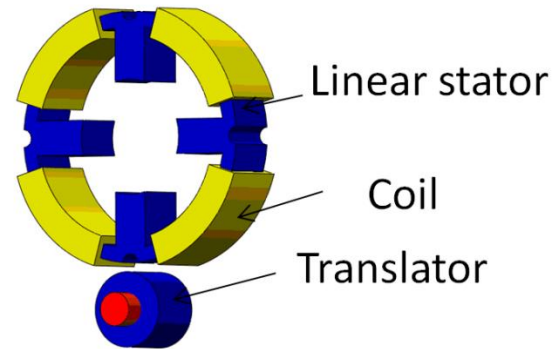
2. Design of new LSRG structure
According to the basic LSRG, the new structure is designed. One phase of LSRG is chosen as shown in figure 5. In order to combine with the SCE, the shape of stator is designed to adapt to the SCE. The rotor, which is the translator of LSRG, is linked with the piston of SCE through a non-magnetic shaft.

The new structure of LSRG is shown in figure 6. It is comprised of the translator and a 4-pole stator. The stator of LSRG is exactly the same as the stator of SRG. The translator is treated as the rotor of SRG [7]. In order to avoid to damage the coil of LSRG by the lubricating oil of SCE, the coil is fixed on the outside of SCE.
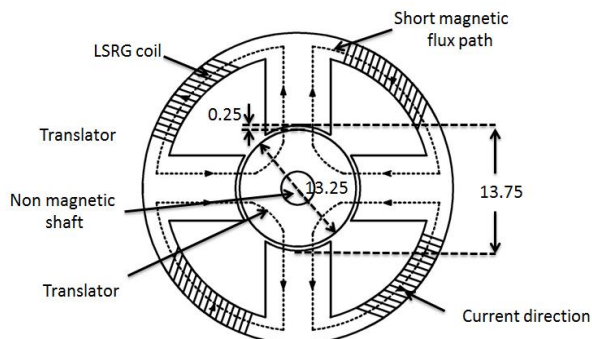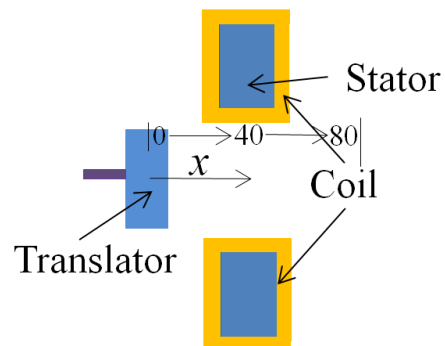

Figure 5. Basic LSRG.

Figure 6. Propose structure for LSRG.

All parts of the LSRG coil are given an electric charge at the same time in a way that creates two pairs north and south magnetic poles.

Hence, the magnetic flux would have short paths in the translators. The translator is fixed on a non-magnetic shaft under the piston of SCE. When the piston moves, the translator is moved simultaneously. The cross section of LSRG is shown in figure 7.

Figure 7. Front view of the LSRG.
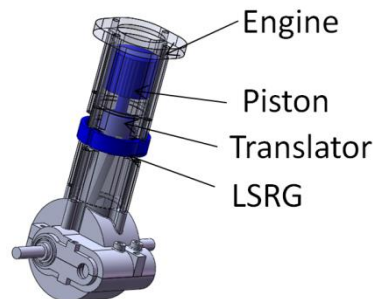

Figure 8. Side view of LSRG.

Table 1. The parameters of the LSRG.

Element	Style
Stator outer diameter	13.75 [mm]
Translator outer diameter	13.25 [mm]
Air gap	0.25 [mm]
Number of stator windings	440 [turn]

It is necessary to consider the motion of translator. Figure 8 shows the side view of LSRG. The x is the distance away from the initial position. This translator does reciprocating motion along with the piston.

Based above all, add the part of the LSRG into single cylinder engine shown in figure 9.

The parameters of LSRG are shown in table 1. The important sizes of stator outer diameter, translator outer diameter, and air gap are used to build a 3-D model in magnetic field analysis software JMAG. Also the details of the element listed in table 1 are shown in figure 7.
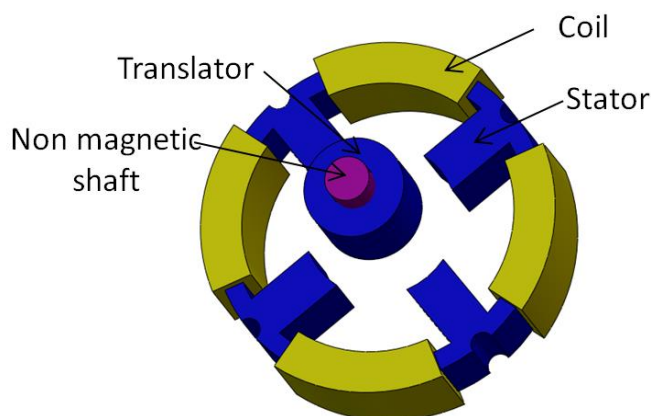

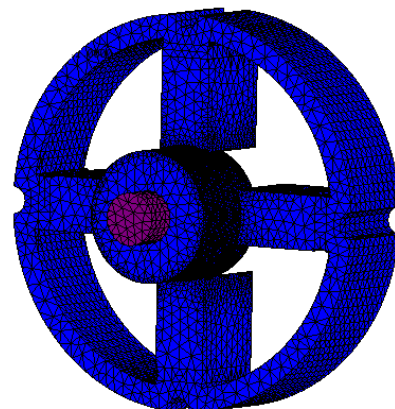**Figure 9.** Single cylinder engine LSRG.

3. Finite element analysis

3.1. Magnetic simulation

The modified 3-D model is built by using FEM magnetic field software JMAG as shown in figure 10. The total distance of the translator's movement is 80 mm. When the piston is at the top of cylinder, the distance x is 0 mm. And when the piston is at the bottom of cylinder, the x is 80 mm. These positions are called unaligned position. When the x is 40 mm, it is called the aligned position.

The 3-D model is subdivided into small triangle elements. In order to improve the accuracy of FEM analysis, different mesh sizes are chosen for different areas. That means the corner and surfaces need finer meshes to satisfy higher accuracy requirements [8]. Figure 11 illustrates the meshed 3-D model.
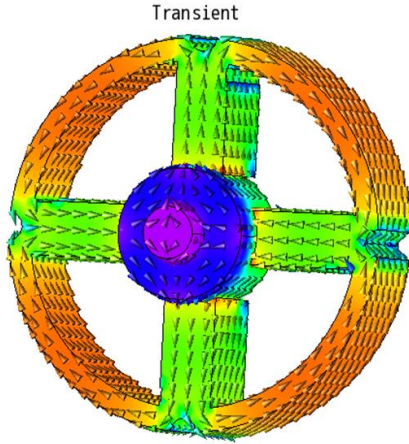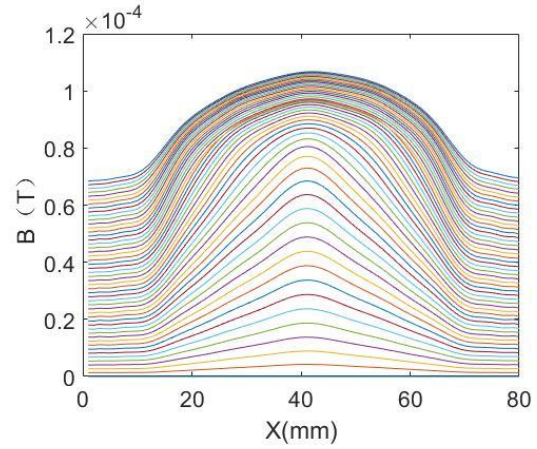

Figure 10. Side view of LSRG.

Figure 11. Finite-element mesh of LSRG.

The 3-D model is simulated with FEM magnetic field software JMAG. Figure 12 shows the finite element flux-plot when the current is 5 A. The same calculations are iterated for each position from the top to bottom. Also same calculations are executed to simulate the inductance for different currents and different positions. The current is changed from 0 A to 5 A, and the position is changed from 0 mm to 80 mm. Figure 13 illustrates the magnetic flux density through FEM magnetic field analysis. According to the calculated magnetic flux linkages, the inductance data are obtained as shown in
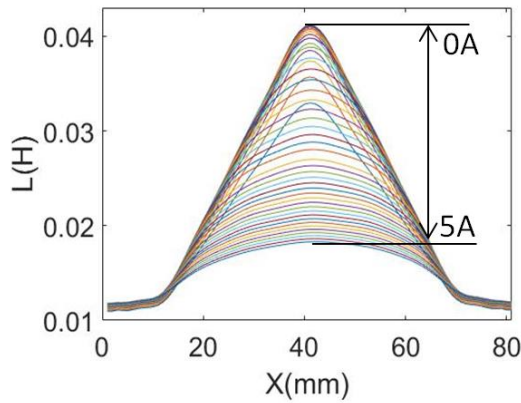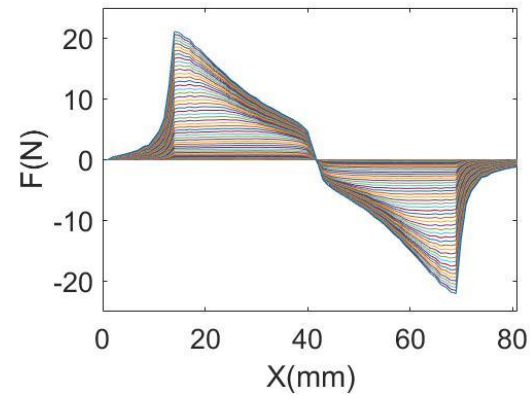
figure 14.

Figure 12. Simulated FE magnetic flux plot.

Figure 13. Magnetic flux linkage curve of LSRG.

Figure 14. Inductance curve of LSRG.

Figure 15. Calculated results of translation force.

3.2. Calculation of static translation force

At translator position *x*, the magnetic co-energy W' is calculated according to the following equations [9].

$$W'(x, i) = \int_0^i \Psi(x, i) \cdot di \tag{1}$$

Then, the translation force is obtained by:

$$F(x, i) = \frac{\delta W'(x,i)}{\delta x} \tag{2}$$

Where $\Psi(x, i)$ is the magnetic flux linkage for different current and position, *i* is the excitation current.

For small intervals of positions (Δx) and currents (Δi), a practical expression can be made by:

$$F(x, i) \approx \frac{\Delta W'}{\Delta x} = \frac{\Delta i}{\Delta x} [\sum_0^i \Psi(x + \Delta x, i) - \sum_0^i \Psi(x, i)] \tag{3}$$
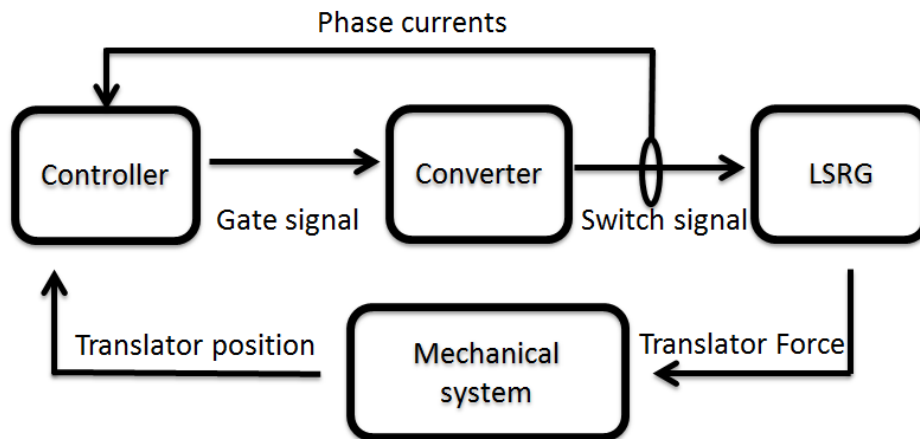
The translation forces for different positions and currents are showed in figure 15.
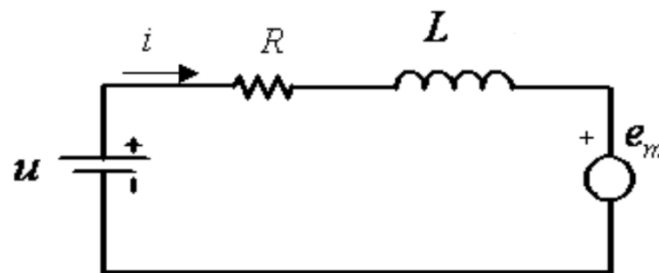
4. MATLAB simulink model

The simulation model of LSRG consists of four parts, as shown in figure 16: the LSRG model,

mechanical system model, controller model, and the converter model. The LSRG model is based on the electrical and mechanical equations of the LSRG. The mechanical system model is used to calculate the velocity and the position of translator. The converter model is treated as the power converter which has ideal switching. The controller model can generate drive signals to the converter.

Figure 16. Simulation model of LSRG.

Figure 17. Equivalent electric circuit of LSRG.

4.1. LSRG model
Figure 17 illustrates the electrical equivalent circuit of LSRG. u is DC voltage, i is the phase current, R is the phase resistance, L is the inductance, e_m is the back electromotive force.

According to the equivalent electric circuit of LSRG, the voltage equation of the stator can be calculated by following equations [10]:

L can be calculated by:

$$L = \frac{\partial \Psi}{\partial i} \tag{4}$$

Where Ψ is the flux linkage, i is the phase current.

e_m is calculated by:

$$e_m = \frac{\partial \Psi}{\partial x} \frac{dx}{dt} \tag{5}$$

Where x is the position of the translator.

According to equations (4) and (5):

$$u = Ri + \frac{\partial \Psi}{\partial i} \frac{di}{dt} + \frac{\partial \Psi}{\partial x} \frac{d\theta}{dt} \tag{6}$$

The model is built based on the voltage equation. The data of $\partial\Psi/\partial i$ and $\partial\Psi/\partial x$ are obtained from the FEM magnetic field analysis and calculation with MATLAB.
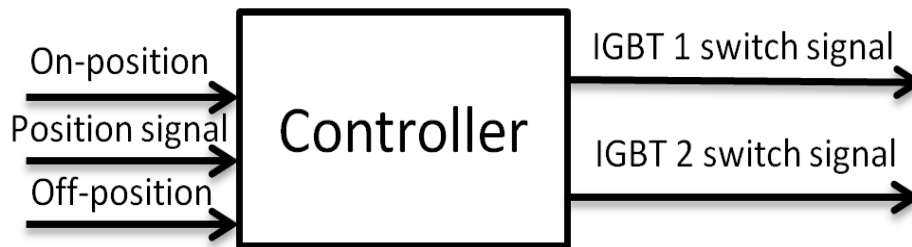
4.2. Mechanical system model

In reality, the external load is added from the engine, which gives the force to the translator. In this model case, the external load is chosen as a constant value of 1500 N. The velocity can be calculated with equation (7).

$$V = \int \frac{F_L - F - F_f}{m} dt \qquad (7)$$

Where F_L is the load force, F is the translator force of LSRG, F_f is the friction force, m is the mass of the piston and translator.
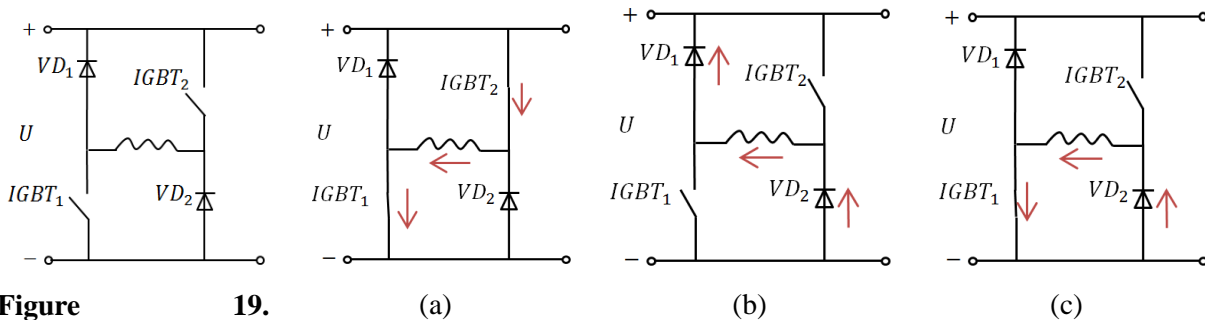
4.3. Controller model

The purpose of the controller model is to detect if the translator is between the on-position and off-position. When in the setting position, this model can deliver the signals to the converter for switching the IGBTs as shown in figure 18.

Figure 18. Controller model.

4.4. Converter model

The asymmetric half-bridge converter is used to excite the coils of LSRG according to the switching signal from the controller model. The excitation voltage is given to the LSRG with IGBTs [11]. The asymmetric half-bridge is shown in figure 19. This circuit has three operation modes as shown in figure 20. Figure 20(a) is the excitation state, figure 20(b) is regenerating state, and figure 20(c) is the soft switching state.
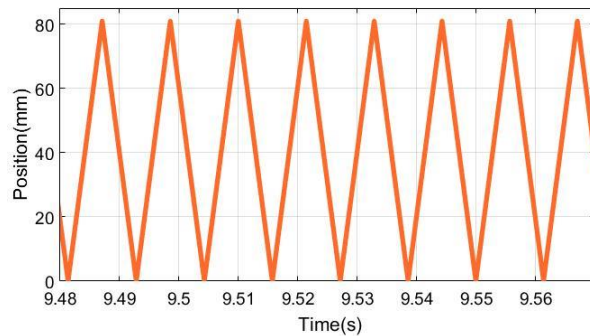

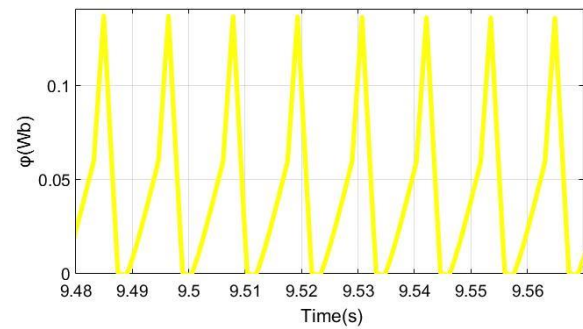**Figure 19.** Asymmetric half-bridge circuit.

(a)   (b)   (c)

Figure 20. Asymmetric half-bridge circuit operation modes.

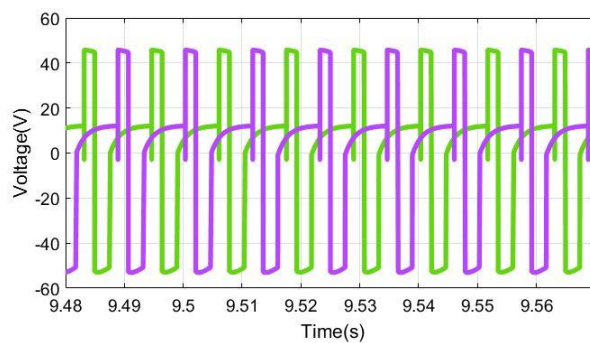## 5. Simulation results of MATLAB simulink

The simulation results are shown in figures 21-24. The position signal, flux linkage, phase voltage signal, and phase current signal are shown, respectively. In the simulation results, the LSRG is excited between the on-position and off-position. When the voltage is positive, the LSRG is in the excitation state. When the voltage is negative, the LSRG is in the regenerating state [12]. The current results are consistent with known theories, when the LSRG generates electricity.
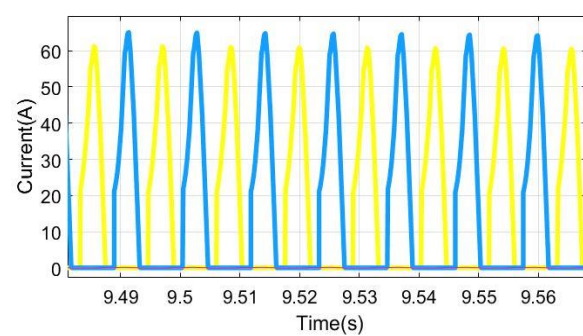
Figure 21. Position signal of LSRG.

Figure 22. Flux linkage of LSRG.

Figure 23. Phase voltage signal of LSRG.

Figure 24. Phase current of LSRG.

6. Conclusion

In this paper, the new LSRG structure is proposed to be combined with the SCE. When the piston is moving in SCE, the LSRG can assist the SCE's mechanical output or can generate power to charge the battery. Through the FEM magnetic analysis, the data of flux linkage and inductance are obtained, and the translator forces are calculated with the MATLAB. Also the LSRG system is simulated with MATLAB Simulink to verify the basic operations of LSRG.

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