Design and electromagnetic analysis of switched reluctance linear generator in electric vehicle

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Abstract. The structural characteristics and basic design requirements of design of switched reluctance linear generator are introduced. According to the general principles and design experience of electromechanical design, the dimension of design of switched reluctance linear generator is determined, and the two-dimensional and three-dimensional static finite element models of design of switched reluctance linear generator are established in Flux 2D and Flux 3D respectively. By comparing the simulation results of the two-dimensional model and the three-dimensional model, it is found that the difference between the real simulation results of the 2D model and the 3D model is small, and the calculation time cost of the 2D finite element simulation is much lower than that of the 3D model. Therefore, the subsequent work of this paper adopts the 2D finite element model. Finally, the static electromagnetic field and electromagnetic characteristics of the design of switched reluctance linear generator are analyzed by finite element analysis.

1. Introduction
The dimensions of the main structural parameters of DSRLG(Design of Switched Reluctance Linear Generator) are determined firstly. Then, according to the dimension of the motor, the finite element method was used for modeling. Considering the end effects of the two sections of the linear motor, the 2D and 3D static finite element models of DSRLG were established respectively, and the electromagnetic analysis of DSRLG was carried out. By comparing the results of 2D and 3D electromagnetic analysis, the finite element modeling method in the subsequent optimization process was selected.

2. Dimension design of DSRLG
Due to the current literature for bilateral linear motor design is less, also did not form a standardized design criteria[1-4]. In this paper, the author studies on bilateral linear motor is made by rotating the Switched Reluctance Machine(SRM) development change, such as smooth and symmetry, the determination of the dimension of DSRLG will refer to traditional rotary SRM design principles and design experience [5]. Combined with the structural particularity of linear motor and the consideration of bilateral stator structure, the specific values of each structural parameter in the design process were adjusted, and the structural parameters of DSRLG were obtained [6]. In order to make reasonable use of the existing universal SRM design criteria and experience, the design process thought of DSRLG in this paper adopts: firstly, the design criteria of traditional rotary SRM and the design experience of linear motor are referred to determine the size of unilateral Switched Reluctance Linear
Machine(SRLM) generated by rotating SRM to be paved in the circular direction [7]. Then, the structure size of bilateral DSRLG is obtained by adjusting the structural parameters and making symmetrical changes. Considering the overall size of the generator suitable for reciprocating wave power generation environment and the existing manufacturing process and cost of the motor, the stator and actuator stack thickness $L_0, L_1$, total width $L$ and air gap $g$ of single-side SRLM are determined to be 90mm, 90mm, 174mm and 0.5mm respectively. The dimension of the width $L_a$ of the actuator is calculated as follows:

$$L_a = k_1 \cdot L$$  (1)

where $k_1$ is specified as the ratio of the width of the actuator to the total width. According to the general design rules of rotary SRM, the value range of $k_1$ is generally between 0.4 and 0.7. However, in the linear motor, since it is paved along the radial direction from SRM, there is no corresponding rotor shaft in SRM. Therefore, the $k_1$ value of the linear motor can be slightly smaller. In this case, $k_1$ is valued at 0.29.

The dimensions of the yoke thickness $H_m$ are calculated as follows:

$$H_m = \frac{(L_a - L_b)}{2}$$  (2)

In formula (2), $L_b$ is the width of the actuator shaft. As can be seen from the foregoing, there is no moving sub-shaft in the linear motor, so $L_b$ is 0.

According to the design experience of rotating SRM, the thickness of stator yoke $H_s$ is generally slightly smaller than that of actuator yoke. In this example, the dimension of the stator yoke thickness $H_s$ is tentatively set at 18.5mm.

The stator slot depth $H_{s\text{slot}}$ can be obtained by the following formula (3):

$$H_{s\text{slot}} = L - L_a - H_s - g$$  (3)

The dimension of the actuator slot depth $H_{m\text{slot}}$ is calculated as follows:

$$H_{m\text{slot}} = L_a - H_m$$  (4)

According to the general design rules of rotating SRM, the relationship between stator extreme width $B_s$ and stator yoke thickness $H_s$ is generally:

$$H_s = k_2 \cdot \frac{B_s}{2}$$  (5)

Among them, $k_2$ is the scale coefficient, which is generally between 1.2 and 1.4 in rotary SRM design. In the design of the linear motor in this example, considering the motion and structure characteristics of the linear motor, its output pulsation may have a greater impact on the structural strength of the motor. In order to reduce the output pulsation and noise of the motor, the proportional coefficient $k_2$ in this example should be large, which is temporarily set as 1.85.

Similarly, according to the design criterion of rotational SRM, the relation between the pole width of the actuator $B_m$ and the yoke thickness of the actuator $H_m$ is generally:

$$H_m = k_3 \cdot \frac{B_m}{2}$$  (6)

In the formula, $k_3$ is the proportional coefficient, which is usually between 1.2 and 1.4 according to design experience. In this example, the proportional coefficient $k_3$ of the linear motor is larger than that of the rotating motor, which is tentatively set as 1.9.

Through the above design steps, a reasonable dimension of the single-side SRLM can be obtained. In order to eliminate the serious normal electromagnetic force of unilateral SRLM and improve the
power density of the motor, a symmetric stator can be placed on the other side of the actuator, and the actuator is changed from a single salient pole structure to a symmetric double salient pole structure, so as to obtain the corresponding bilateral stator type DSRLG. The dimensions of DSRLG are shown in Table 1.

| Geometric dimension                  | Dimension /mm |
|-------------------------------------|---------------|
| air gap \( g \)                     | 0.5           |
| The stator pole pitch \( T_s \)     | 40            |
| Mover pole pitch \( T_m \)          | 60            |
| The stator yoke thickness \( H_s \) | 18.5          |
| Mover yoke thickness \( H_m \)      | 25            |
| Stator stack thickness \( L_s \)    | 90            |
| Mover stack thickness \( L_m \)     | 90            |
| Stator pole width \( B_s \)         | 20            |
| Mover pole width \( B_m \)          | 26            |
| Stator slot depth \( H_{slot} \)    | 105           |
| Mover slot depth \( H_{mslot} \)    | 12.5          |

3. Finite element modeling and simulation

The finite element method is adopted in this paper to establish the two-dimensional finite element model and three-dimensional finite element model of DSRLG respectively, and the calculation results of the two are compared. Based on the accuracy of the calculation results and the calculation time, the appropriate finite element model was selected and applied to the electromagnetic analysis of DSRLG, as well as the sensitivity analysis.

The process of using Flux 2D and Flux 3D to establish the finite element model of DSRLG is similar, as shown in the Figure 1.

The relationship of flux and magnetic common energy with respect to position and current calculated by Flux 2D and Flux 3D DSRLG models are shown in Fig 2 respectively. By comparing the calculation results of the two models, it is found that the main error of the two models is that the flux value of the two models is smaller than the flux value of the three models when the actuator is in the misaligned position. Similarly, the magnetic common energy value obtained by two-dimensional finite element model simulation is smaller than that obtained by three-dimensional finite element model simulation when the actuator is in the misaligned position. This is because the three-dimensional finite element model can take into account the longitudinal MFL of the motor, while the two-dimensional finite element model does not take into account the longitudinal MFL and the MFL effect at the misaligned position of the motor are more serious, so the flux value obtained by 3D simulation is slightly larger than that obtained by 2D simulation. Although there are some errors in the simulation results of the two-dimensional model and the three-dimensional model, the accuracy of DSRLG model established by Flux 2D can be guaranteed. The calculation time of the two-dimensional finite element model is only about one-tenth of that of the three-dimensional model of the same size. Therefore, after considering the accuracy of the model and the cost of calculation time, Flux 2D model is selected as the electromagnetic calculation method in the subsequent analysis.
Figure 1. Workflow of DSRLG finite element modelling

Figure 2. Variation trend of flux and co-energy with position and current
4. Electromagnetic analysis of the DSRLG

A complete actuator period of DSRLG studied in this paper is 60mm. According to the common design custom, the alignment position of the stator salient pole and the axis of the actuator salient pole is defined as 30mm, and the position of the reverse movement along the direction of the actuator movement is defined as 0mm. The position 30mm along the direction.

Because in the solver setting of the DSRLG static finite element model, the position is set from 0mm to 60mm, increase by 2mm as an interval step, increase by 1A as a step from 0A to 15A, and obtain the data of the relationship between the static flux flux and magnetic common energy of DSRLG and the change of current and the position of the actuator. Fig 3 shows the three-dimensional curve of flux flux and magnetic common energy, in which the Z axis respectively represents flux flux and magnetic common energy. The X-axis and Y-axis in the Figure 3 represent the current and the position of the actuator, respectively.

![Figure 3. Variation trend of flux and co-energy of DSRLG with current and position](image)

As can be seen from the figures above, the trend of the flux - position curve is the same for any current value. When the actuator is at 0mm of the asymmetrical position, the flux value is low. When the actuator moves from 0mm to 30mm, the flux reaches its maximum value. If the current value at this point is larger, the variation trend of the flux chain gradually tends to be nonlinear. The larger the current is, the more serious the saturation phenomenon of the magnetic circuit will be, and the more obvious the nonlinear variation trend will be. When the actuator continues to move from the position of 30mm to the position of the next asymmetrical position of 60mm, the flux decreases in a nonlinear to linear trend, and finally reaches the lowest value. It is obvious from the figure that the value of the flux linkage is symmetric about the 30mm point where the position of the actuator is perfectly aligned. For any position of the actuator, the flux - current curve is gradually increasing. It should be noted that at the misaligned position of the actuator, the flux flux increases linearly with respect to the current; However, the increase of the current of the flux linkage increases non-linearly with the increase of the current value as the alignment position of the actuator increases. This is because, when the actuator is in the misaligned position, the magnetic circuit reluctance is large, and the magnetic circuit is always in the unsaturated state during the process of the gradual increase of current. When the actuator is in alignment position, the magnetic circuit reluctance is the least, and the magnetic circuit is gradually saturated with the increasing current. The variation trend of the three - dimensional magnetic co-energy - position - current curve is roughly similar to that of the magnetic linkage curve.

In addition to the three-dimensional curves of flux linkage and magnetic co-energy, the static finite element model can also obtain the curves of the static electromagnetic force of DSRLG at different current currents changing with its position, as shown in Fig 4 below. It can be seen from the figure that the static electromagnetic force increases first and then decreases when the electromaneuvers move from the unaligned symmetrical position of 0mm to the aligned position of 30mm. This is because in the process from 0mm to 10mm, the edge of the actuator salient pole has not coincided with the stator salient pole, and the inductance change rate has not reached the maximum. When the position of the actuator reaches around 10mm, the edge of the salient pole of the actuator just begins to coincide with the salient pole of the stator. At this time, the inductance change rate reaches the maximum, so the
static electromagnetic force reaches the maximum. After that, as the position of the actuator gets closer to the alignment position, the inductance change rate decreases gradually, and finally the static electromagnetic force reaches the lowest value at 30mm. In addition, it can be seen from the figure that the static electromagnetic force tends to increase with the increase of current at the fixed position of the actuator. With the increase of current value, the static electromagnetic force gradually tends to be non-linear. This phenomenon is more obvious the closer to the aligned position. This is because, near the alignment position of the actuator, the magnetic circuit reluctance is small, and with the increase of the excitation current, the ferromagnetic material gradually becomes saturated, so the growth of the static electromagnetic force tends to be gentle.

Figure 4. Variation trend of static electromagnetic force with position

5. Conclusion
According to the application requirements of wave linear power generation and the design criteria and experience of the traditional rotary SRM, the structure parameters of the corresponding unilateral SRLM are determined, and the unique structural characteristics of the bilateral DSRLG are combined to improve the dimension of the DSRLG studied in this paper, which lays a foundation for the follow-up research.

Based on the finite element analysis, the finite element modeling method applicable to this study was determined by comparing the simulation calculation results and calculation time cost of 2D finite element simulation and 3D finite element simulation.

Through the data processing of the DSRLG two-dimensional static finite element simulation results, the three dimensional curves of the flux flux, the magnetic co-energy and the static electromagnetic force with respect to the position and the current are obtained respectively, and the electromagnetic characteristics of DSRLG are analyzed accordingly.

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