Design and Optimization for the Linear Switched Reluctance Generator

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Abstract-In this paper, a novel double-sided direct-drive linear generator based on switched reluctance principle is proposed. In order to acquire a higher power density, the optimization of structure parameters for the double-sided linear switched reluctance generator (DLSRG) is carried out. To observe the nonlinear phenomena in SR generator, two dimensional (2D) magnetic static field distributions is obtained. For imitation of real-time operation, transient magnetic field is analyzed by finite element method (FEM). Then through a series of simulation and analysis, a group of appropriate parameters for the DLSRG are obtained. It is expected that the novel direct-drive generator finds its applications in power conversion fields such as wave power utilization.

Keywords- direct-drive, DLSRG, FEM

I. INTRODUCTION

The switched reluctance motor has been applied in many industrial fields such as hybrid electric vehicles and wind power systems. The rotary switched reluctance motor applications are mainly characterized by high speed and low-speed high-torque operations. A certain amount of scientific work is dedicated to switched reluctance (SR) machines including drive and control [1-2], and some researchers work on the linear switched reluctance motors [3]. For motor generation, rotary generator and system studies based on switched reluctance have also been carried out [4]. In motor structure design, research on double sided linear switched reluctance machine has been started [5]. However, there exist disadvantages such as narrow winding space and coupling between phases, furthermore, long distance between two poles may introduce mechanical vibration and noise.

In this paper, a novel double sided linear generator based on linear switched reluctance principle is proposed. This linear generator has separated winding structure with no coupling effects between any phases and a smooth operation can be achieved with a compact pole-pitch structure.

Switched reluctance generator has a lot of advantages—simple structure, mechanically robust, and it can operate in some hostile conditions. At present, all wave energy power systems adapt traditional power generation method—by mechanical translation to convert wave linear motion form to rotational mechanical power for rotary generator. Though this is the widely used method, however, it has the disadvantages of complicated mechanical structure and reduced energy conversion efficiency, etc. Since direct-drive linear SR generators can absorb wave energy directly in form of linear translation, it is suitable for the low-speed and high-force wave power generation and it can improve the power generation efficiency. This paper focuses on the design and optimization of a novel double-sided linear switched reluctance generator.

II. PRINCIPLE OF THE DLSRG

2.1. Magnetic circuit basics.

In previous study, a single-sided linear switched reluctance motor has been researched [6]. For the DLSRG, the equivalent magnetic circuit for one phase under a certain position can be represented in reluctance form as shown in Fig.1.

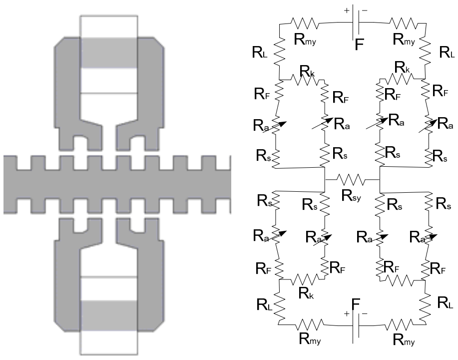


Fig. 1: Equivalent magnetic circuit of the DLSRG

The above magnetic circuit can be formulated as,

$$\Phi = \frac{F}{2R_{my} + R_{sy} + R_{v} + 2R_{L}} \qquad (1)$$

where $R_v = (R_f + R_a + R_s)//(R_k + R_f + R_a + R_s)$.

The typical inductance profile with positions is shown in Fig.2.

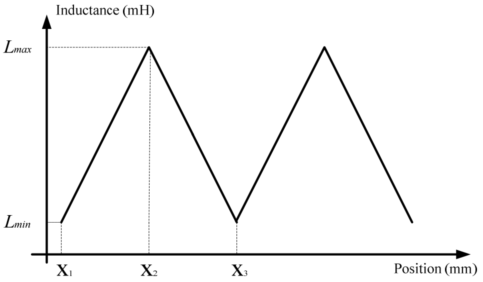


Fig. 2: The inductance vs. position

Inductance $L(x)$ can be expressed as,

$$L(x) = \begin{cases} K(x_2 - x_1) + L_{\min}, & x_1 \le x \le x_2, \\ L_{\max} + K(x_3 - x_2), & x_2 \le x \le x_3. \end{cases} \qquad (3)$$

where K is a constant coefficient.

Since the flux-linkage is the multiplication of inductance and current. The value of λ vs. position is obtained as

$$\lambda(x)=\begin{cases}\frac{u}{v}(x_2-x_1), x_1\le x\le x_2\\ \frac{u}{v}(2x_2-x_1-x), x_2\le x\le x_3\end{cases} \tag{4}$$

2.2. Energy conversion principles of one phase.

The main circuit of the DLSRG is shown in Fig.3.

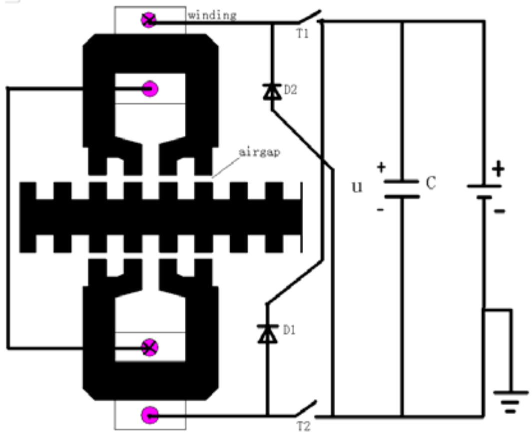


Fig. 3: Main circuit of a phase

The DLSRG is excited through a common asymmetric bridge. Any phase of this inverter uses the same DC source for excitation and for generation each phase utilizes two controllable switches and freewheeling through the diodes. For example, T1 and T2 are closed at positions between x_1 and x_2 , the phase current begins to rise and absorb electrical energy at the same time. At positions between x_2 and x_3, the switches are shut off, the DLSRG begins to generate.

According to the principle of energy conversion, the DLSRG must comply with (6) at any condition as,

$$dW_{mech}=dW_{elec}+dW_{fld} \tag{6}$$

where

$dW_{mech}=f_{fld}dx$ =differential mechanical energy input and f_{fld} is mechanical force.

$dW_{elec}=id\lambda$ =differential electric energy output (7)

dW_{fld} =differential change in magnetic stored energy (8)

Mechanical terminal can be derived as,

$$f_{fld}=m\frac{d^2x}{dt^2}+f_s\frac{dx}{dt} \tag{9}$$

where f_s is friction coefficient.

The electrical terminal of LSRG according to (10) can be expressed as

$$\pm u=Ri+e \tag{10}$$

where u is the voltage of source and e is the EMF across the winding.

According to Faraday's law,

$$\begin{aligned}e&=-\frac{d\lambda(i,x)}{dt}\\ &=(\frac{\partial L(i,x)}{\partial i}+L(i,x))\frac{di}{dt}+\frac{\partial L(i,x)}{\partial x}\cdot v_x\cdot i\end{aligned} \tag{11}$$

Substitute (11) to (10),

$$\pm u=Ri+(\frac{\partial L(i,x)}{\partial i}+L(i,x))\frac{di}{dt}+\frac{\partial L(i,x)}{\partial x}\cdot v_x\cdot i \tag{12}$$

The back-EMF can be defined as,

$$e^{'}=\frac{\partial L(i,x)}{\partial x}\cdot v_x\cdot i \tag{13}$$

where v_x is the mover's speed. When $\frac{\partial L(i,x)}{\partial x}<0$ the back-EMF is negative and it intends to increase the current and convert the mechanical energy into electrical energy and the DLSRG begins to generate electricity.

III. DESIGN OF THE DLSRG

As shown in Fig.4 the mechanical structure of the DLSRG, the machine "integrates" two single-sided machines into one double-sided generator. Although the DLSRG has double air gaps, compared with a single-sided LSRM, the winding area is doubled to provide more electromagnetic force input. Simulation is carried out for propulsion force comparison between a single-sided and double-sided machine with the same specifications as the result shown in Fig.5. It can be concluded that electromagnetic force of the DLSRG is two times larger than a single LSRM. Therefore, the DLSRG has a higher force to mass ratio.

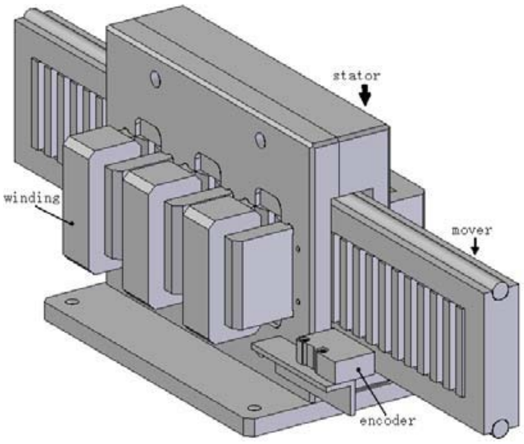


Fig. 4: Structure of the DLSRG

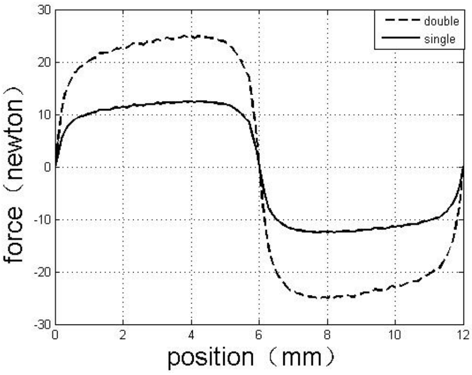


Fig. 5: Propulsion force output

IV. OPTIMIZATION OF THE DLSRG

4.1. Optimization of the moving platform

The mechanical structure of the mover is shown in Fig.6. It mainly includes salient poles and slots magnetically.

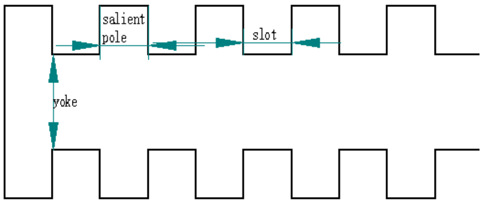


Fig. 6: Structure of the mover

Salient pole's height and yoke's thickness influence both magnetic circuit and the value of change of inductance. Therefore the two parameters should be optimized. If the height is set as 3, 6 and 9 mm with the same current excitation, it can be concluded from the FEM result in Fig.7 that the mover with the height of 6 mm provides the most force output.

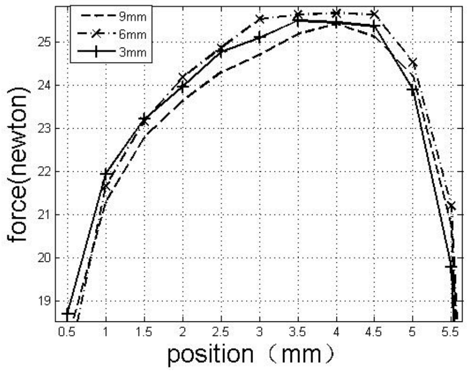


Fig. 7: Optimization of pole's height

The analysis of yoke's thickness is performed to investigate its influence on the value of flux-linkage. As shown in Fig.8 under the same excitation (8000 ampere turns), it can be seen that the flux-linkage increases with the yoke's thickness. When the thickness is 6 mm and 9 mm, the value of flux-linkage exhibits a flatten waveform since saturation dominates in the magnetic circuit. Saturation disappears when the thickness of yoke exceeds 15mm. But the mover's weight will increase with the growing thickness of yoke, which reduces the power generating efficiency.

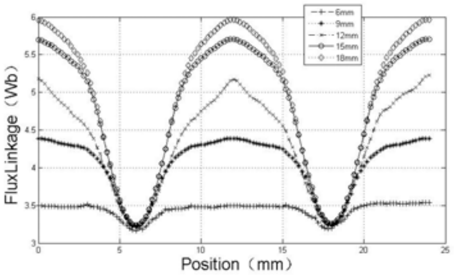


Fig. 8: Value of flux-linkage in various yoke's heights

Taking into account the power generating efficiency with the value of flux-linkage and thickness of yoke, the value of thickness 12mm is selected.

4.2. Optimization of the stator

The flux distribution at aligned positions is shown in Fig.9. From the simulation result, there exists saturation and uneven distribution of magnetic field lines. In aligned positions the flux-path is susceptible to saturation, especially in part A and B and the flux isn't well-distributed since there exist a few flux lines in corner C.

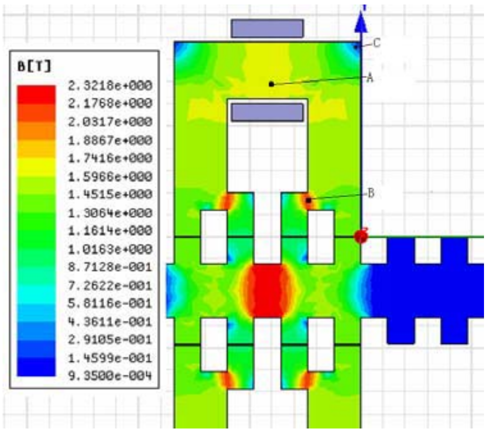


Fig. 9: Flux distribution in the stator

The optimization of the stator includes the following two steps. First, design the suitable thickness of part A to make the space of winding broad enough and the flux line well-distributed. Second, smooth the corner, so that magnetic inductance line can pass through more easily. As shown in Fig.10, first, the thickness of part A is increased to avoid possible magnetic filed saturation. Then, part C is appropriately reduced where there are few flux lines to save magnetic materials. Last, the corner of part B is smoothed in order to make flux lines easier to pass through.

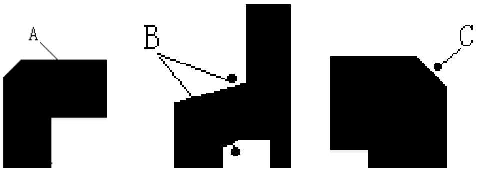


Fig. 10: Optimization part of the stator

According to the improved parameters the flux distribution is reanalyzed as shown in Fig11. Compared with Fig.9, saturation only appears at the moving platform. It can also been concluded that there is no mutual flux distribution between any adjacent stators. Therefore each phase is decoupled magnetically.

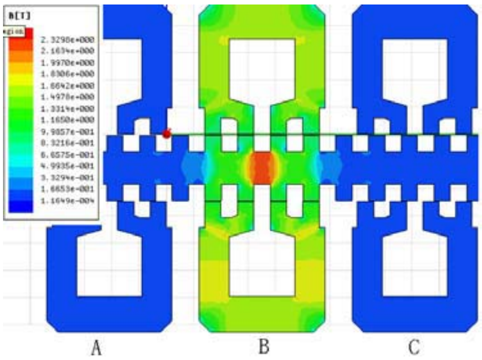


Fig11: Flux distribution after optimization

The specifications of the designed prototype of the DLSRG are shown in table 1.

Table 1: parameters of the DLSGR

parameters	size	Unit
stator height	48	mm
stator width	46	mm
salient height	6	mm
salient width	6	mm
slot height	6	mm
slot width	6	mm
yoke thickness	12	mm

V. EXPERIMENTAL SETUP OF THE SYSTEM

Test is performed for one phase as shown in Fig.3. dSPACE platform is applied in the experiment with configurable Digital-to-analog Converters (DACs),Analog-to-digital Converters (ADCs) and digital incremental encoder channels. The schematic diagram of the control system is shown in Fig.12. For mechanical energy input, another LSRM is mounted to the DLSRG with synchronous movement. The hardware and experimental setup are shown in Fig.13.

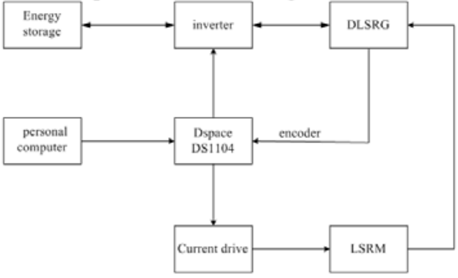
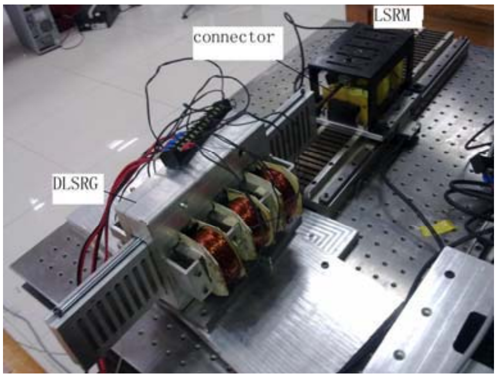
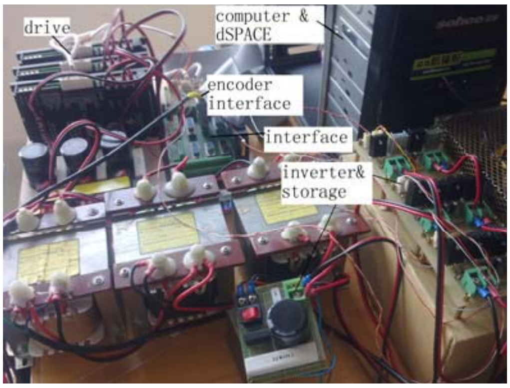


Fig. 12: Schematic diagram



(a)



(b)

Fig. 13: (a) hardware and (b) experimental setup

It can be seen from the preliminary test results of phase current waveforms as shown in Fig.14 that the generator is capable of power generation.

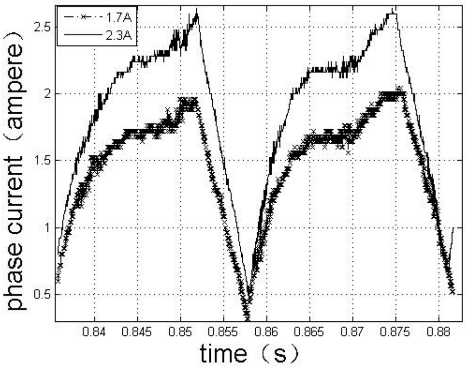


Fig. 14 Phase current waveforms

VII. CONCLUSION

In this paper, a novel DLSRG is designed and the parameters are optimized with FEM. Static magnetic field and characteristics of electromagnetic force are also investigated. The prototype is manufactured according to the optimized parameters. Generation control system is built and preliminary test shows that the generated current waveforms and further studies on power conversion efficiency will be carried out. It is expected that the DLSRG can be applied in power generation areas of renewable energy such as wave power generation systems.

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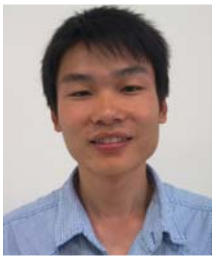
BIOGRAPHY

J.F. Pan graduated from Department of Electrical Engineering of Hong Kong Polytechnic University in Hong Kong for the Ph.D. degree in 2006. Currently he is working in College of Mechatronics and Control Engineering, Shenzhen University. His main research interests are design and control of switched reluctance motors and generators.



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