Analytical Calculation of Flux-Linkage Characteristics of Switched Reluctance Linear Generator

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Abstract — This paper presents the analytical calculation method of the Switched Reluctance linear generator. The details of the magnetic paths configuration for flux region 1-5 on the minimum inductance position and region 6-9 on the maximum inductance position are also described. The equations for calculating the length of the flux path, the fraction of amp-turns linked with the unit flux path, the field strength along the unit flux path and the inductance of each region are given. The equations for calculating the phase inductance on the minimum inductance position and on the maximum inductance position are also provided. The testing results of the prototype confirm those.

I. INTRODUCTION

The Switched Reluctance rotary machine system has been extensively exploited [1]-[6] nowadays with its high ratio of performance to costs. The Switched Reluctance linear generator also has been exploited [7][8] by taking advantage of its ability to produce direct linear motion without the problems of rotary-to-linear drives. The Switched Reluctance linear generator is an electric machine that consists of a simple structure with a concentrated winding only on the stator and not on the mover. The costs are lower than those of other linear generators due to its simple construction. The magnetic force production of Switched Reluctance linear generator relies on the variation of the generator phase inductances with position. The generator has a doubly-salient structure. The mathematical model for the Switched Reluctance linear generator, which is expressed through the static "flux-linkage/ mover position/ phase current" magnetization curves, provides the foundation for the electromagnetic design and the nonlinear simulation. Computation of the set of static magnetization curves can be carried out entirely by using a software package based on the 2-D finite-element method for field analysis, but computational task is heavy. In order to provide a fast, effective method for estimation of the static "flux-linkage/ mover position/ phase current" magnetization curves, an analytical approach for calculating the phase inductance and the flux-linkage based on magnetic paths analysis are presented in the paper.

II. STRUCTURE OF THE LINEAR GENERATOR

The proposed Switched Reluctance linear generator is a three-phase 6/4 structure Switched Reluctance linear generator, and the sketch diagram of the generator was shown in Fig.1. There are six poles in the stator. There is a centralized coil installed in each stator pole. One phase winding has two coils, such as *A1* and *A2* is for *A* phase winding, *B1* and *B2* is for *B* phase winding, *C1* and *C2* is for *C* phase winding. For example, *B* phase winding is made up of two coils on *B1* pole and *B2* pole, which is shown in Fig.1. There are four poles per mover unit. The mover consists of two units or more. There is no winding, no magnet and no brush in the mover.

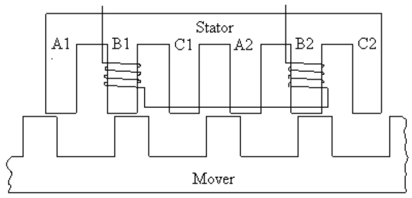


Fig. 1. Sketch diagram of the three-phase 6/4 structure Switched Reluctance linear generator

III. MINIMUM INDUCTANCE POSITION

The relative position between stator and mover is shown in Fig.2, while the excited stator pole axis aligns with the mover slot axis and the excited phase inductance reaches the minimum value. The field lines of flux paths 1, 3 and 5 are formed of concentric circular arcs, and the field lines of flux paths 2 and 4 are formed of parallel straight-line segments, which are shown in Fig.3. According to the minimum reluctance principle, the demarcation points of two adjacent regions are determined by the condition of equal length of diverging lines. Considering one phase winding made up of two coils on two stator pole, the phase inductance formed by two coils on symmetrical poles can be expressed as,

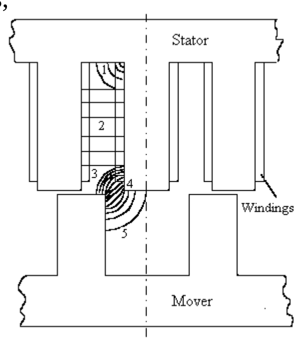
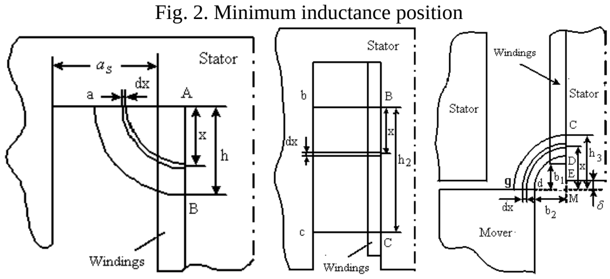
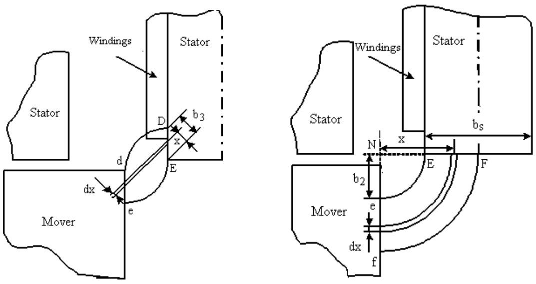


Fig. 2. Minimum inductance position



a) Region 1 b) Region 2 c) Region 3



d) Region 4 e) Region 5

Fig. 3. Flux paths at minimum inductance position

$$L_{min} = 4\ (L_1 + L_2 + L_3 + L_4 + L_5) \quad (1)$$

$$L_1 = \frac{N_{ph}^2 \mu_0 l_{Fe} h^2}{4\pi\ c_m^2} \quad (2)$$

$$L_2 = \frac{N_{ph}^2 \mu_0 l_{Fe} [(h_2 + h)^3 - h^3]}{12 c_m^2 a_S} \quad (3)$$

$$L_3 = \frac{N_{ph}^2 \mu_0 l_{Fe}}{2\pi\ c_m^2} \int_{b_2}^{h_3} \frac{(c_m + b_1 - x)^2}{x} dx \quad (4)$$

$$L_4 = \frac{N_{ph}^2 \mu_0 l_{Fe} (b_2 - \delta)}{8 b_2} \quad (5)$$

$$L_5 = \frac{N_{ph}^2 \mu_0 l_{Fe}}{2\pi} \cdot \ln\left(\frac{b_2 + \frac{b_S}{2}}{b_2}\right) \quad (6)$$

IV. MAXIMUM INDUCTANCE POSITION

While the excited stator pole axis aligns with the mover pole axis and the excited phase inductance reaches the maximum value, the relative position between stator and mover is shown in Fig.4. The field lines of flux paths 6 and 8 are formed of concentric circular arcs, and the field lines of flux paths 7 and 9 are formed of parallel straight-line segments, which are shown in Fig.5. The analytical calculation of the flux region 6 for the maximum inductance position is same as the previous analytical calculation of the flux region 1 for the minimum inductance position. The phase inductance formed by two coils on symmetrical poles can be expressed as,

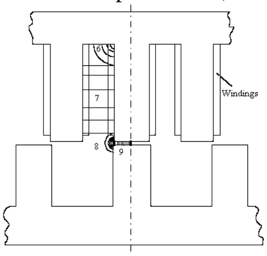
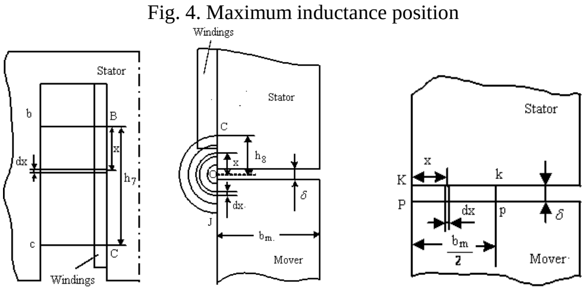


Fig. 4. Maximum inductance position



a) Region 7 b) Region 8 c) Region 9

Fig. 5. Flux paths at maximum inductance position

$$L_{max} = 4\ (L_6 + L_7 + L_8 + L_9) \quad (7)$$

$$L_6 = L_1 = \frac{N_{ph}^2 \mu_0 l_{Fe} h^2}{4\pi\ c_m^2} \quad (8)$$

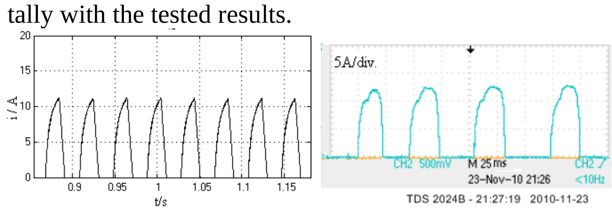
$$L_7 = \frac{N_{ph}^2 \mu_0 l_{Fe} [(h_7 + h)^3 - h^3]}{12 c_m^2 a_S} \quad (9)$$

$$L_8 = \frac{N_{ph}^2 \mu_0 (l_{Fe} + b_m)}{4\pi} \cdot \ln\left(\frac{h_S - h - h_7 + \frac{\delta}{2}}{\frac{\delta}{2}}\right) \quad (10)$$

$$L_9 = \frac{N_{ph}^2 \mu_0 l_{Fe} b_m}{8\delta} \quad (11)$$

V. RESULTS

The phase current waveforms in calculation and testing are shown in Fig.6. It is shown that the calculated results tally with the tested results.



a) Calculated b) Tested

Fig. 6. Phase current waveforms

VI. CONCLUSION

The fast and effective electromagnetic design and nonlinear simulation analysis of Switched Reluctance linear generator can be made by the analytical method. It contribute to setup the analytical model for real time control.

VII. ACKNOWLEDGMENTS

The authors would like to thank for the project supported by the International S & T Cooperation Program of China under Grant No.2008DFA61870.

VIII. REFERENCES

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