Analysis of Orthogonal-Core Type Linear Variable Inductor and Application to VAR Compensator

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***Abstract*—This paper presents a quantitative analysis of the orthogonal-core type linear variable inductor. The orthogonal-core has wedge gaps for reduction of harmonics of the output currents. The analysis is based on a 3-dimensional nonlinear magnetic circuit of the orthogonal-core. Using the magnetic circuit, we can calculate accurately the operating characteristics of the variable inductor. Furthermore, we develop a var compensator for 6.6 kV ac distribution system using the three-phase variable inductor.**

***Index Terms*—Linear variable inductor, orthogonal-core, reluctance network analysis, var compensator.**

I. INTRODUCTION

IN RECENT years, increase of load causes voltage variation in the electric power system. One method for the voltage regulation is a reactive power control in the system. Power apparatus such as static var compensator (SVC) and static var generator (SVG) are introduced to the reactive power control [1]–[3]. Another effective solution is utilization of a linear variable inductor with sinusoidal output. Several magnetic devices for variable inductor have been presented [4]–[6]. However, the harmonics of the output current can not be neglected for large power applications.

In the previous paper, we proposed a three-phase variable inductor using the orthogonal-cores with wedge gaps [7]. The variable inductor has sinusoidal output current and good controllability. The basic characteristics of the trial three-phase 100 kVA variable inductor have been reported.

In this paper, we present a quantitative analysis of the orthogonal-core type linear variable inductor. The analysis is based on the 3-dimensional nonlinear magnetic circuit of the orthogonal-core. Using the magnetic circuit, we can calculate accurately the operating characteristics of the orthogonal-core type variable inductor when the orthogonal-core has wedge gaps. Furthermore, we develop a var compensator for 6.6 kV ac distribution system using the variable inductor.

II. CALCULATION METHOD AND RESULTS

Fig. 1(a) shows a schematic diagram of the orthogonal-core with wedge gaps. The core material is grain oriented silicon steel with a lamination thickness of 0.23 mm. The wedge gaps are made on the contact surfaces of the primary core. Fig. 1(b) shows the windings arrangement.

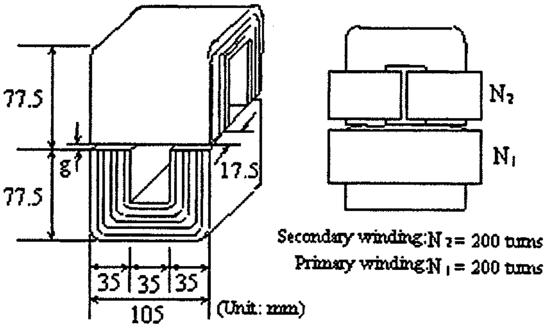

Fig. 1. Schematic diagram of the orthogonal-core with wedge gaps.

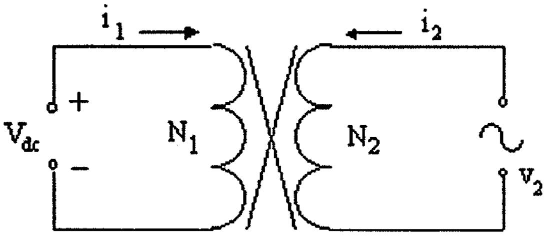

Fig. 2. Basic circuit of the variable inductor.

Fig. 2 shows a basic circuit of the variable inductor using the orthogonal-core. The primary winding is connected to a dc voltage source, and the secondary winding to a sinusoidal supply voltage. The secondary current is controlled by the primary dc current.

For the operation analysis of the variable inductor, a 3-dimensional nonlinear magnetic field calculation of the orthogonal-core is needed. We proposed one calculation method called a reluctance network analysis based on a 3-dimensional nonlinear magnetic circuit [8].

That is, we divide the orthogonal-core into some elements as shown in Fig. 3(a). In order to consider the leakage fluxes, the surrounding space is also divided. The divided elements can be expressed by a unit magnetic circuit as shown in Fig. 3(b). In the core region, the characteristics of the magnetic reluctances in the unit circuit are determined by B–H curve of the core material. In the surrounding space, the magnetic reluctances are determined by permeability of free space. In the wedge gaps, we subdivided the gap into elements as shown in Fig. 3(c).

On the basis of the 3-dimensional nonlinear magnetic circuit, we can calculate the flux-MMF relationships of the

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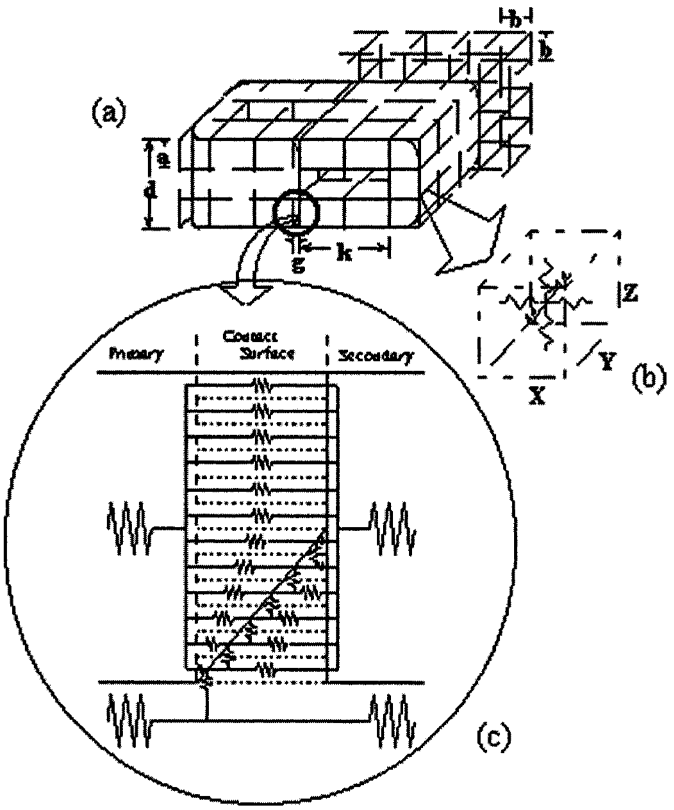

Fig. 3. 3-D magnetic circuit of the orthogonal-core with wedge gaps.

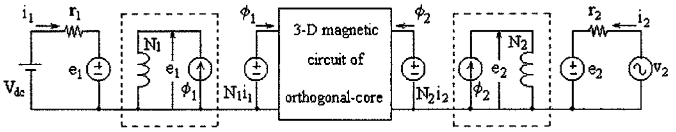

Fig. 4. Electric and magnetics coupling model of the orthogonal-core type variable inductor.

orthogonal-core. Furthermore, in order to analyze the application circuit, we proposed an electric circuit model of the orthogonal-core for use in SPICE based on the flux-MMF relationships [9]. On the other hand, if the 3-dimensional magnetic circuit and the external electric circuit are coupled by a proper method, we can directly calculate the operating characteristics of the application circuit utilizing SPICE simulation.

Fig. 4 shows the electric and magnetic coupling model of the orthogonal-core type variable inductor. In the figure, r_1 and r_2 are the primary and secondary winding resistances, e_1 and e_2 are the primary and secondary induced voltages, N_1i_1 and N_2i_2 are the primary and secondary MMF's. In the SPICE simulation, these are expressed by controlled voltage sources. The solid rectangle shows the 3-dimensional nonlinear magnetic circuit of the orthogonal-core, and the dotted rectangles show the convenient circuits for coupling the electric circuits to the 3-dimensional magnetic circuit.

Fig. 5 shows the relative harmonics contents of the secondary current when the orthogonal-core has not wedge gaps. Fig. 6(a) and (b) show the calculated and measured results of the harmonics contents when the orthogonal-core has various wedge gaps. Here the secondary rms voltage is 160 V, and the frequency is 50 Hz. From the figures, it reveals that the calculated values agree well with the experimental ones, and that the harmonic currents are reduced by the wedge gaps.

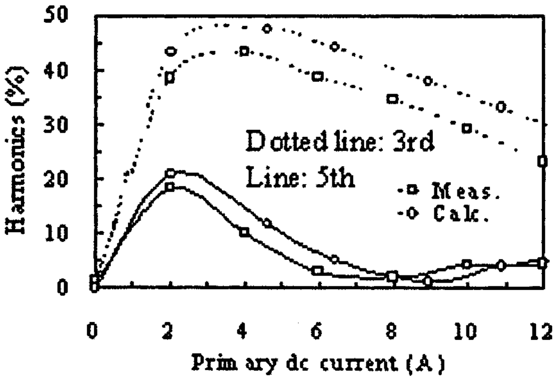

Fig. 5. Relative harmonics contents of the secondary current of the orthogonal-core without wedge gaps.

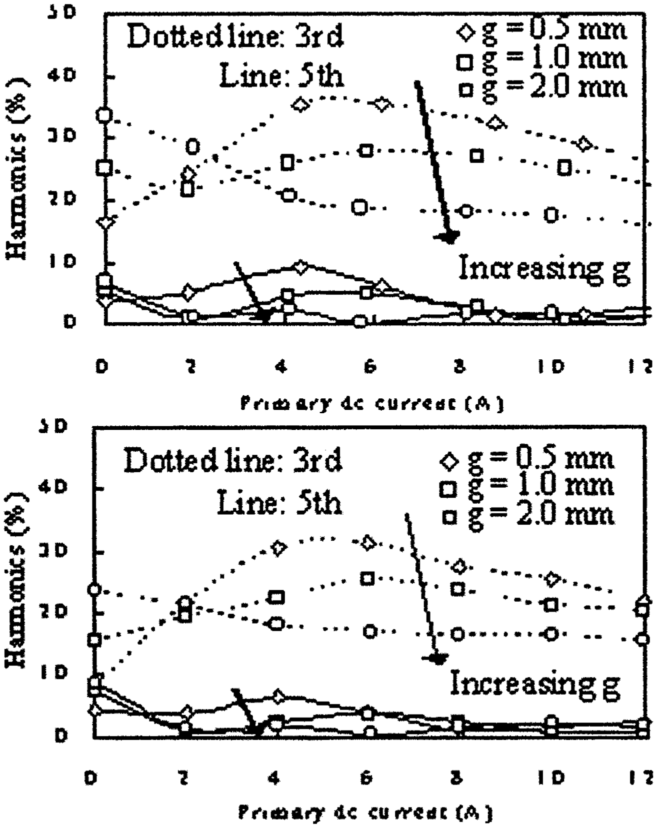

Fig. 6. Relative harmonics contents of the secondary current of the orthogonal-core with wedge gaps.

When the gap length g increases, the harmonics are decreased. However, the control characteristic is deteriorated as shown in Fig. 7. We must design the gap length considering the harmonics and controllability.

III. Application to Var Compensator

Fig. 8 shows the orthogonal-core for a three-phase 100 kVA variable inductor, and Fig. 9 shows the circuit configuration of

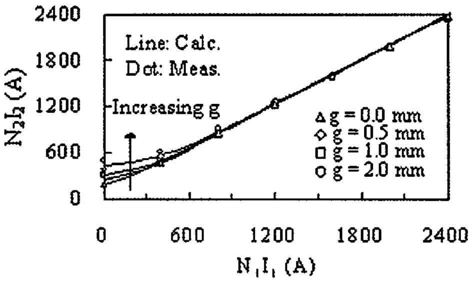

Fig. 7. Control characteristics of the variable inductor.

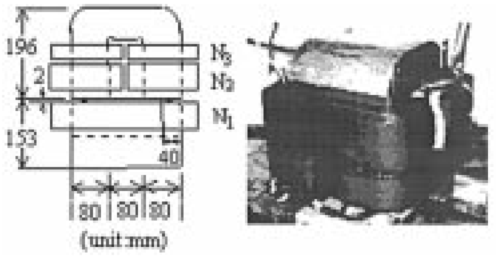

Fig. 8. Orthogonal-core used in the three-phase 100 kVA variable inductor.

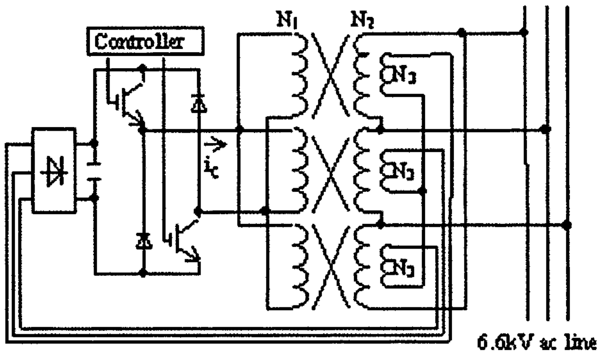

Fig. 9. Circuit configuration of the three-phase variable inductor.

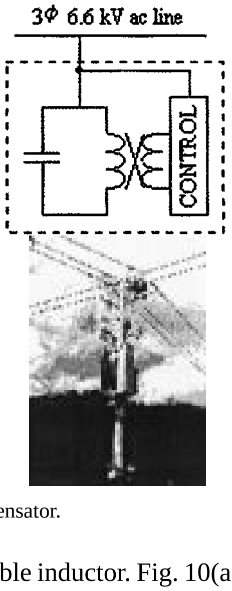

Fig. 10. Trial var compensator.

the three-phase variable inductor. Fig. 10(a) shows the basic circuit and (b) is the general view of the var compensator using the variable inductor.

Fig. 11 shows the variation of the line voltage of the 6.6 kV ac distribution system. In the figure, (a) is the line voltage without compensation and (b) is that with compensation. These figures reveal that the variation of the line voltage is improved by the var compensator.

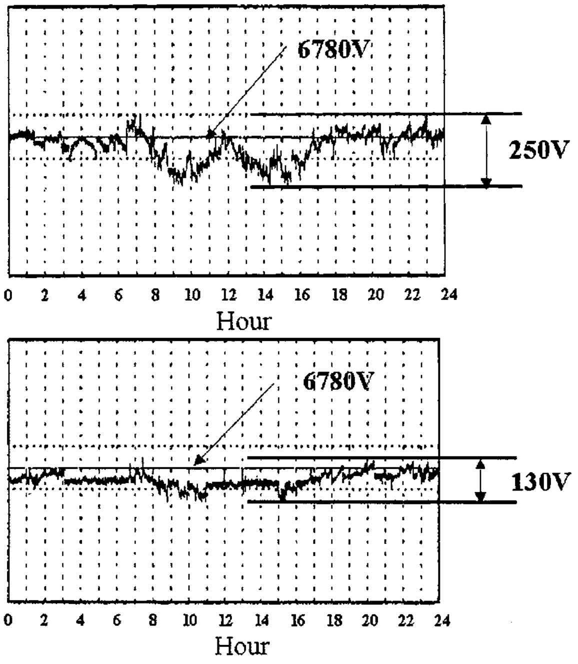

Fig. 11. Variations of the ac line voltage.

IV. CONCLUSION

Based on a 3-dimensional nonlinear magnetic circuit, we calculate accurately the operating characteristics of the variable inductor using the orthogonal-core with and without wedge gaps. The calculation method can be applied to optimum design. The trial var compensator is useful for voltage stabilization in the distribution system.

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