Application of Orthogonal-Core Transformer to Series Compensation for Power System

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***Abstract*—This paper presents an orthogonal-core type series compensator for a power flow control in an electric power system. The orthogonal-core type series compensator is constructed with the variable inductors using the orthogonal-cores and capacitors. For reduction of harmonic currents, the orthogonal-core utilizes wedge gaps and third windings. The orthogonal-core type series compensator is able to control the active power and its flow direction.**

***Index Terms*—Linear variable inductor, orthogonal-core, series compensation, wedge gap.**

I. Introduction

In recent years, the importance of a power flow control in the existing power system is increased because the demands rise for electric power. The thyristor controlled series compensator (TCSC) and thyristor controlled phase shifter (TCPS) have been reported for a power flow control [1], [2]. TCSC, which is one of the series compensators, is constructed with a series capacitor and a thyristor controlled reactor. TCSC controls a power flow by changing a net reactance in the power line. However, TCSC needs harmonic filters because the reactor current has harmonics due to the thyristor phase control. In order to improve the problem, it is necessary to develop a variable inductor with sinusoidal output current.

Several magnetic devices for a variable inductor have been presented [3]–[5]. The operating principle of the variable inductors is based on the nonlinear magnetization characteristic of the core. However, the nonlinear characteristic causes harmonics in the output current.

In those devices, an orthogonal-core, it can be used as variable inductor because a net inductance of the secondary winding is controlled by the primary dc exciting current [3], [4], has a good controllability and a less harmonic current. However, the harmonics of the output current cannot be disregarded for large power applications.

In the previous paper, we proposed a three-phase linear variable inductor, and presented an application of the inductor to var compensator in 6.6 kV ac distribution line [6].

In order to cope with the increase of electric demands, a series compensation for power flow control is also needed. In this paper, we examined an application of the orthogonal-core to a series compensator.

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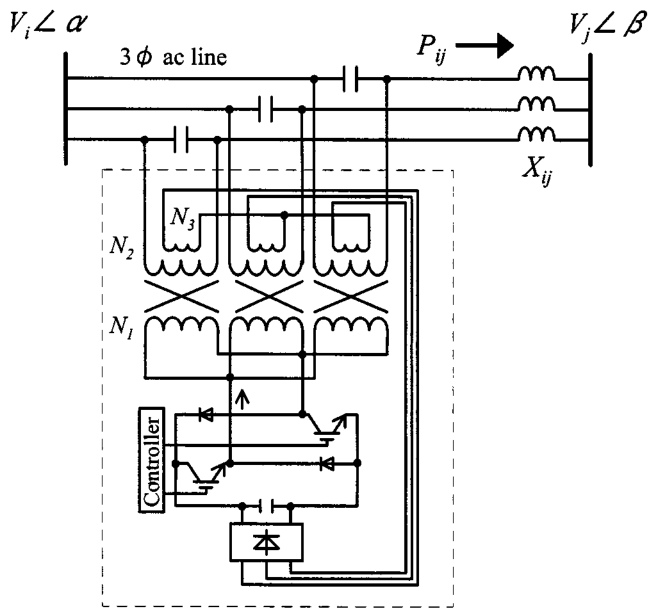

Fig. 1. Orthogonal-core type series compensator.

II. Operating Principle of Series Compensator

Fig. 1 shows a fundamental circuit of the series compensator using the variable inductors. The series compensator is constructed with series capacitors and variable inductors. In the figure, the dotted rectangle shows the three-phase variable inductor using the orthogonal-cores. In the figure, N_3 is the third winding for power supply to control circuit. V_i and V_j are node voltages. α and β are voltage phases. X_{ij} is a line reactance. Let X_{sc} be a reactance of the orthogonal-core type series compensator. Then the active power P_{ij} is calculated as:

$$P_{ij} = \frac{|V_i||V_j|}{X_{SC} + X_{ij}} \sin(\alpha - \beta). \tag{1}$$

Therefore, if the reactance of the series compensator changes, the active power and its flow direction can be controlled.

When the orthogonal-core is applied to the series compensator, the harmonic distortion of the output currents is the problem to be solved. Over 5th harmonics are reduced by the wedge gaps of the orthogonal-core [6]. However, the 3rd harmonics remains, due to the operating principle of the variable inductor.

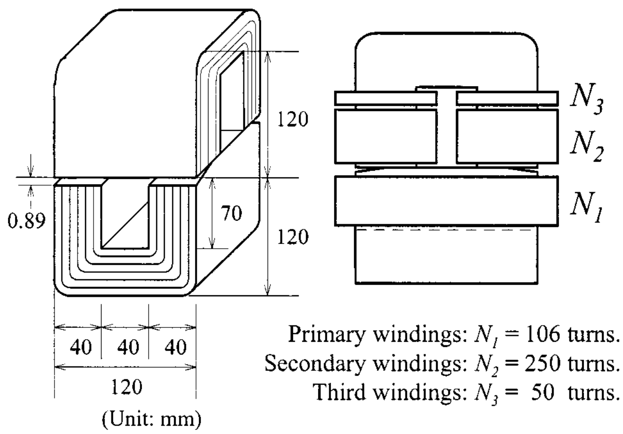

Fig. 2. Schematic diagram of the orthogonal-core with wedge gaps. (a) Core structure. (b) Windings arrangement.

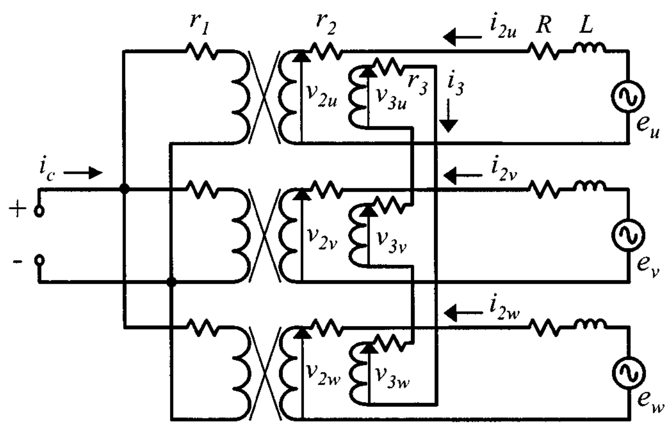

Fig. 3. Three-phase variable inductor with third windings.

When the three-phase variable inductor is connected to the line in parallel, the secondary windings of the orthogonal-core can be connected in delta configuration for reduction of 3rd harmonic current. On the other hand, when the variable inductor is connected to the line in series, the secondary windings can not be connected in delta.

To solve the problem, utilization of the third windings of the orthogonal-core is possible. In the next section, we examined the effect of delta connection of the third windings.

III. Analytical Consideration

Fig. 2(a) shows a schematic diagram of the orthogonal-core. The core has wedge gaps and the material is grain oriented silicon steel with a lamination thickness of 0.23 mm. Fig. 2(b) shows the windings arrangement. The secondary and third windings are winded in the same core.

Fig. 3 shows the fundamental circuit of the three-phase variable inductor with third windings connected in delta. In the figure, r_1, r_2 and r_3 are winding resistances. v_{2u}, v_{2v}, v_{2w} and v_{3u}, v_{3v}, v_{3w} are excitation voltages. i_{2u}, i_{2v}, i_{2w} are secondary winding currents, and i_3 is a current of the third winding. Now, we consider the effect of the delta connected third windings under simple assumptions. That is, we assume that the coupling coefficient between the secondary and third windings is 1, and

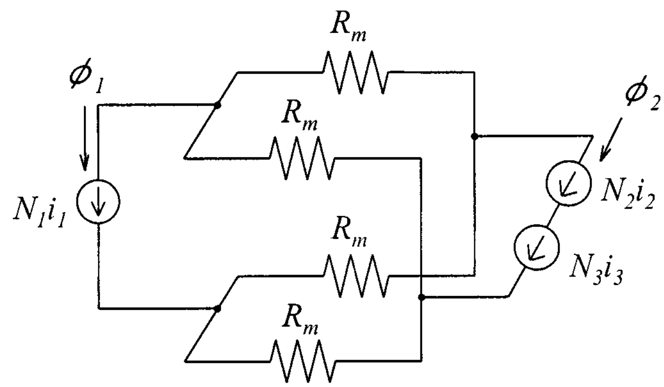

Fig. 4. Fundamental magnetic circuit of the orthogonal-core.

we consider only 3rd harmonic of the third windings current. The relations held in the electric circuit are:

$$\frac{v_{2u}}{N_2}=\frac{v_{3u}}{N_3}, \qquad \frac{v_{2v}}{N_2}=\frac{v_{3v}}{N_3}, \qquad \frac{v_{2w}}{N_2}=\frac{v_{3w}}{N_3} \tag{1}$$

$$e_j = v_{2j} + (r_2+R)i_{2j} + L\,\frac{di_{2j}}{dt} \qquad (j=u,\,v,\,w) \tag{2}$$

$$v_{3u}+v_{3v}+v_{3w}+3r_3 i_3^{\mathrm{3rd}}=0. \tag{3}$$

Here, i_3^{3rd} is the 3rd harmonics in the third winding currents.

When the secondary supply voltages are symmetric three-phase voltage, we can obtain the relation of 3rd harmonics of secondary and third winding currents based on (1)–(3).

$$i_{2u}^{\mathrm{3rd}}=i_{2v}^{\mathrm{3rd}}=i_{2w}^{\mathrm{3rd}}=\frac{N_2 r_3}{N_3\sqrt{(r_2+R)^2+9X^2}}\,i_3^{\mathrm{3rd}}. \tag{4}$$

Where i_{2u}^{3rd}, i_{2v}^{3rd} and i_{2w}^{3rd} are the 3rd harmonics of the secondary winding currents, R and X are the line resistance and reactance, respectively.

Fig. 4 shows the fundamental magnetic circuit of the orthogonal-core [7]. $N_1 i_1$ and $N_2 i_2$ are MMFs. ϕ_1 and ϕ_2 are the fluxes. R_m is the nonlinear reluctance. Now, we express the MMF's in the nonlinear reluctances as:

$$f(\phi)=a_1\phi+a_3\phi^3 \tag{5}$$

where a_1 and a_3 are constants.

The relations held in the magnetic circuit are:

$$\left.\begin{aligned} N_1 i_1 &= a_1\phi_1+\frac{3a_3}{4}\,\phi_2^2\phi_1+\frac{a_3}{4}\,\phi_1^3 \\ N_2 i_2 + N_3 i_3 &= a_1\phi_2+\frac{3a_3}{4}\,\phi_1^2\phi_2+\frac{a_3}{4}\,\phi_2^3 \end{aligned}\right\}. \tag{6}$$

As the winding resistances are very small, the primary flux is considered to be constant and the secondary flux is sinusoidal. That is:

$$\phi_1=\Phi_1, \qquad \phi_2=\Phi_2\cos\omega t. \tag{7}$$

From (6) and (7), the relation of the 3rd harmonics of secondary and third winding currents is given by,

$$N_2 i_2^{\mathrm{3rd}}=\frac{a_3}{16}\,\Phi_2^3\cos 3\omega t - N_3 i_3^{\mathrm{3rd}}. \tag{8}$$

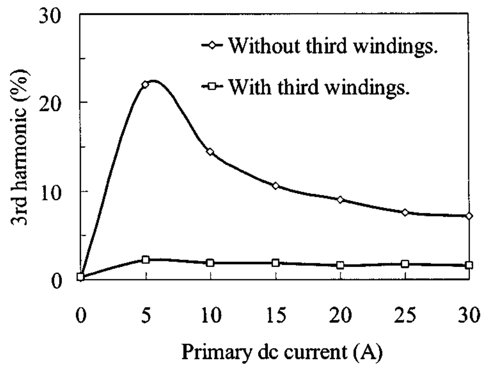

Fig. 5. Relative 3rd harmonic content of the output current of the three-phase variable inductor.

From (4) and (8), when the third windings are connected in delta configuration, the 3rd harmonics of the secondary winding current $i_{2t}^{3\mathrm{rd}}$ is given by

$$i_{2t}^{3\mathrm{rd}} = \frac{N_2^2 r_3}{N_2^2 r_3 + N_3^2\sqrt{(r_2+R)^2+9X^2}} \times \frac{a_3}{16N_2}\,\Phi_3\cos 3\omega t. \tag{9}$$

On the other hand, when the third windings are not connected in delta, $N_3 i_3$ in the (6) becomes 0. The 3rd harmonics of the secondary current $i_2^{3\mathrm{rd}}$ is given by

$$i_2^{3\mathrm{rd}} = \frac{a_3}{16N_2}\,\Phi_3\cos 3\omega t. \tag{10}$$

We can obtain the 3rd harmonic current ratio from (9) and (10) as:

$$\frac{i_{2t}^{3\mathrm{rd}}}{i_2^{3\mathrm{rd}}} = \frac{1}{1+\dfrac{N_3^2\sqrt{(r_2+R)^2+9X^2}}{N_2^2 r_3}} \ll 1. \tag{11}$$

In an electric power system, the line reactance X is larger than the line resistance and winding resistances generally. Therefore the 3rd harmonic of secondary windings current is reduced when the third windings are connected in delta.

Fig. 5 shows the 3rd harmonics in the output current of the three-phase variable inductor with and without the third windings. This reveals that the 3rd harmonics is reduced remarkably when the third windings are connected in delta.

IV. Experimental and Simulation Results

Based on the above results, we examined the characteristics of the orthogonal-core type series compensator. Fig. 6 shows the experimental and simulation circuit of the series compensator.

Fig. 7 shows the calculated and measured results of the control characteristics of the series compensator. In the figure, the solid and dotted curves represent the calculated value of the active power and the line reactance including the series compensator, respectively. The symbol is the measured power. Active power P is a positive value when it flows from left to right in Fig. 6. P is a negative value when it flows from right to left conversely. This figure reveals that the line reactance is controlled by the orthogonal-core type variable inductor, and that the active power and its flow direction can be easily controlled by the orthogonal-core type series compensator.

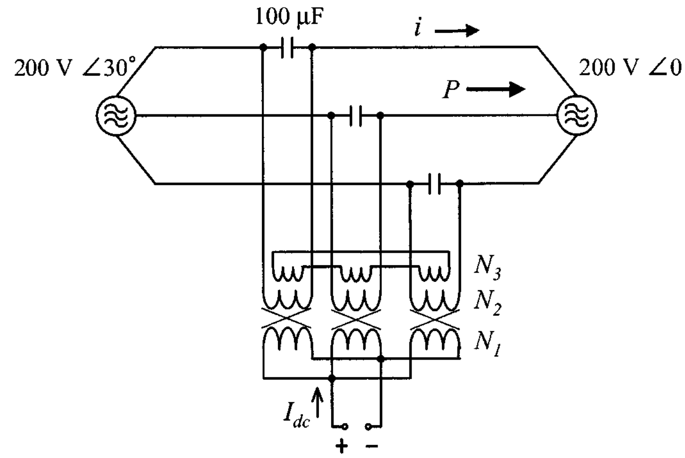

Fig. 6. Experimental and simulation circuit of the orthogonal-core type series compensator.

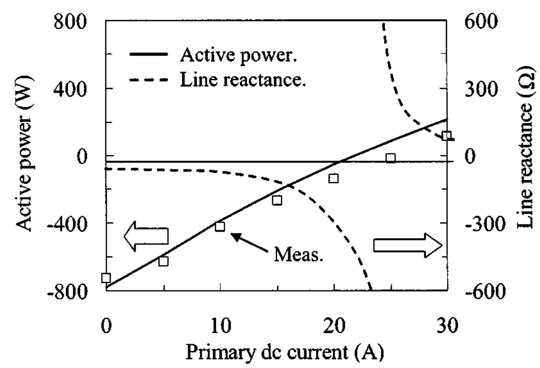

Fig. 7. Control characteristics of the series compensator.

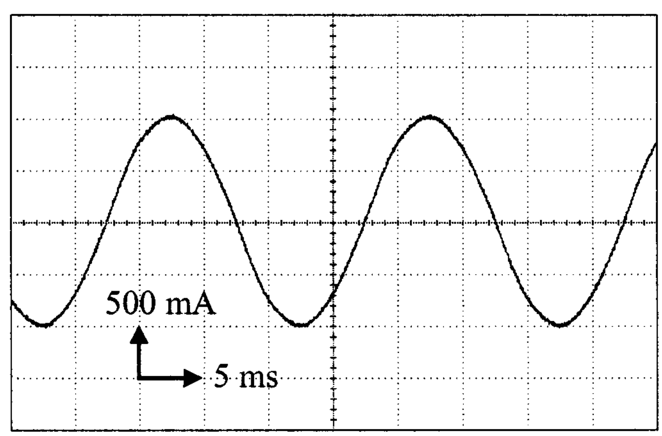

Fig. 8. Observed waveform of the line current, when the dc current of the orthogonal-core is 5 A.

Fig. 8 is the observed waveform of the line current, when the dc current of the orthogonal-core is 5 A. This reveals that almost sinusoidal current is obtained in the trial system.

V. Conclusion

We examined the fundamental characteristics of the series compensator. The application of the variable inductor to series compensator is expected because the orthogonal-core type variable inductor has a simple construction, a sinusoidal output current and a good controllability.

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