Current Compensation Method for the Unbalanced Three-Phase TCR (Thyristor Controlled Reactor)

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Abstract. The conventional TCR have been controlled on the premise that the inductances of reactors in TCRs have a same value. However, the inductances of reactors in TCRs are different; they will produce unbalanced three-phase current. In this paper, Current compensation method for the unbalanced three-phase TCR is proposed, and the compensation method is based on the control of firing angles of three-phase TCR.

1. Introduction
With the development of power electronics technology and the increment of various digital loads, the power quality is getting more significant than in the past. To compensate power quality, compensation devices have been used, and recently, FACTS equipment such as SVC has been broadly applied for compensating power quality. SVC is a device that is connected in parallel to a power system for absorbing or supplying the reactive power. Thereby, it can maintain a constant voltage or perform a desired control operation. The SVC has various configurations according to the purpose. Also, it has the form of TCR, TSC and FC. In this paper, we propose a method for solving the three-phase imbalance problem caused by the difference in the inductance of the reactors in the three-phase TCR.

2. Out current of TCR
TCR is a series of pair that consists of thyristor valves and reactors connected in parallel as shown in Figure 1. The connected thyristor valve operates as a bidirectional switch. The T1 thyristor valve and the T2 thyristor valve operate at a positive period and a negative period, respectively. The firing angle

![Figure 1. Single phase TCR equivalent circuit](image-url)
α is controlled between 90° and 180°. When the switch angle is 90°, the switch is turned on, and the maximum inductance is applied. As the point angle increases, the applied inductance decreases gradually. When the angle reaches 180°, the switch is turned off and opened.

The voltage applied to TCR can be formulated as:

\[ V_s(t) = V \sin \omega t \]  \hspace{1cm} (1)

\[ L \frac{di}{dt} - V_s(t) = 0 \]  \hspace{1cm} (2)

Equation (3) is derived by integrating Equation (2) and can be formulated as Equation (4), where C is a constant.

\[ i(t) = \frac{1}{L} \int V_s(t) dt + C \]  \hspace{1cm} (3)

\[ i(t) = -\frac{V}{\omega L} \cos \omega t + C \]  \hspace{1cm} (4)

Equation (6) can be derived by applying Equation (5), where α is the point angle.

\[ i(\omega t = \alpha) = 0 \]  \hspace{1cm} (5)

\[ i(t) = -\frac{V}{\omega L}(\cos \alpha - \cos \omega t) \]  \hspace{1cm} (6)

The current I(α) of the TCR is derived using Fourier analysis.

\[ I(\alpha) = a_1 \cos \omega t + b_1 \sin \omega t \]  \hspace{1cm} (7)

\[ a_1 = \frac{4}{T} \int_0^T f(x) \cos \frac{2\pi x}{T} dx \]  \hspace{1cm} (8)

The output current I(α) of the TCR is derived as follows.

\[ I(\alpha) = \frac{V}{\omega L} \left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi} \sin 2\alpha \right) \]  \hspace{1cm} (9)

3. Problems with existing TCR control

In the TCR, the susceptance value according to the firing angle α is determined by the value of reactor L. The value of L determines the compensation range of TCR. However, when the value of L in the three-phase TCR has a difference, outputs at each phase have a difference in susceptance value. Thereby, the difference in L caused three-phase imbalance. In order to solve this problem, it is necessary not to control the conventional method but it is required to control each phase individually to make the three-phase equilibrium. This problem can be noted, as follows.

- Previously, it was controlled on the premise that three-phase TCR is balanced.
- Actual reactor values have variations.
- If the reactor value differs by 10%, the susceptance value supplied also varies by roughly 10%.
- Control method considering the difference of reactor value is required.

4. Proposed method – Individual control of the firing angle

Figure 2 shows the equivalent circuit of a three-phase TCR with different reactor L values on phase C. The reactor values of phase A and phase B have the same values as \( L_a = L \) and \( L_b = L \) and the reactor values on phase C are different by \( L_c = L + \Delta L \). In order to control the three phase imbalance caused by
the difference of the L value, the susceptance value according to the firing angle $\alpha$ is required.

Figure 2. Three-phase TCR with different L value

The susceptance $B_{TCR}$ from the three-phase TCR can be derived as follows.

$$B_{TCR} = \frac{2\pi - 2\alpha + \sin 2\alpha}{\pi X_L}$$  \hspace{1cm} (10)

The susceptance value is the maximum value at 90 $^\circ$ according to the firing angle $\alpha$, gradually decreasing, and is output from 0 $^\circ$ to 180 $^\circ$. Figure 3 shows the output susceptance values when the reactance L according to the firing angle $\alpha$. When the angle is 90 $^\circ$, the output susceptance has the maximum value and we can say that the angle converges is to 0 at 180 $^\circ$.

Figure 3. TCR output susceptance according to the firing angle $\alpha$

Figure 4 shows the susceptance values for a three-phase TCR with assuming that the reactance L value of one phase is 10% different. The phases a and b have the same reactance L and the phase C have a reactance L value that is 10% different. $L_{a,b} = 10mH$, $L_c = 11mH$
Figure 4. Susceptance according to 10% variation of L value (ΔL=10%) 

If the value of reactance L is 10% different, the output susceptance value is also roughly 10% different. When the firing angle α is controlled to be 105.8 ° in the phase a and b, to compensate the difference of the inductance the firing angle α should be controlled to 112.4 ° in the phase c. As a result, the same susceptance value can be outputted on the three-phase TCR.

5. Conclusion
The conventional TCR has been controlled under the assumption that the three-phase reactors are equilibrium, but the reactors of the three-phase TCR have slightly different values. They will produce unbalanced three-phase current. In this paper, a new current compensation method for the unbalanced three-phase TCR (Thyristor Controlled Reactor) is proposed. The compensation method is based on the control of firing angles of three-phase TCR, and the compensation firing angle is derived from the susceptance of the three-phase TCR.

6. References
[1] “Power electronics in electric utilities: Static Var Compensators”, Laszlo Gyugyi, Preceedings of the IEEE, Vol.76, No.4, 1998.04
[2] “Reactive Power Compensation Technologies: State of the Art Review”, Luis Moran, Jose Rodriguez, Ricardo Domke, Preceedings of the IEEE, Vol.93, No.12, 2005.12
[3] “Adaptive Backstepping Sliding Mode H∞ Control of Static Var Compensator”, Li Ying Sun, Shaocheng Tong, Yi Liu, IEEE Transactions on control systems technology, Vol.19, No.5, 2011.07
[4] “Using a Static Var Compensator to Balance a Distribution System”, Jen Hung Chen, Wei Jen Lee, Mo Shing, IEEE Transactions on industry application, VOL.35, No.2, 1999.04
[5] “Fundamental Analysis of the Electromechanical Oscillation Damping Control Loop of the Static Var Compensator Using Individual Channel Analysis and Design”, Carlos E. Ugalde-Loo, Eduardo Liceaga-Castro, IEEE Transaction on power delivery, VOL.25, No.4, 2010.10

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