모델급 TCSC의 설계 및 구현

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Design and Implementation of a Laboratory Scale TCSC

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Abstract - Thyristor-controlled series capacitor (TCSC) is a power electronic-based device that provides a fast and controllable series compensation of transmission line reactance. To match with laboratory facilities and for further research initiatives, a practical laboratory scale TCSC was designed and fabricated in this paper.

The TCSC parameters were designed based on the terminologies such as percentage of compensation, boost factor and resonance factor. According to the design parameters, a prototype laboratory scale TCSC with a constant reactance controller was fabricated and tested. The measured results from the laboratory scale TCSC demonstrate the ability of the TCSC to provide rapid control of series reactance of a transmission line.

1. Introduction

The thyristor-controlled series capacitor (TCSC) has been proven to be an excellent solution in controlling the power flow, especially for long transmission lines. The TCSC can also be used for damping power oscillations and eliminating sub-synchronous resonance [1, 2]. To match with laboratory facilities and for further research initiatives, the authors designed and fabricated a practical laboratory scale TCSC.

Like a typical TCSC module, the laboratory scale TCSC module is composed of a fixed capacitor (FC) in parallel with a thyristor-controlled reactor (TCR). The capacity of FC and TCR were determined based on the terminologies such as percentage of compensation, boost factor and resonance factor [3]. According to the design parameters, a prototype laboratory scale TCSC was fabricated. Also, a constant reactance control scheme was developed for the prototype TCSC using LabVIEW/ComapactRIO. Finally, a hardware platform including a voltage source, an AC reactor and load was designed and set for testing the TCSC.

The proper and reliable operation of the laboratory scale TCSC was confirmed via the experiment results. In the future, it will be incorporated with the real time digital simulator to conduct more research activities.

2. Design and manufacture of a laboratory scale TCSC

2.1 Design of the laboratory scale TCSC

The terminologies related to the design are defined. The percentage of compensation, boost factor and resonance factor are defined as follows, and expressed in equations (1), (2) and (3), respectively. The percentage compensation (k) is the ratio of the reactance of the TCSC (X_{TCSC}) to the total line reactance (X_L). Boost factor (ω_{order}) is the ratio of the maximum achievable TCSC reactance ($X_{TCSC-max}$) to the minimum TCSC reactance ($X_{TCSC-min}$). The resonance factor (λ) is the ratio of resonance angular velocity of TCSC (ω_0) to power system angular velocity (ω).

$$k(\%) = \frac{X_{TCSC}}{X_L} \times 100 \quad (1)$$

$$\omega_{order} = \frac{X_{TCSC-\max}}{X_{TCSC-\min}} = \frac{X_{TCSC-\max}}{X_C} \quad (2)$$

$$\lambda = \frac{\omega_0}{\omega} = \frac{1}{\omega\sqrt{LC}} \quad (3)$$

where L is the inductance of the TCR inductor and C is the capacitance of the FC. Table 1 shows the supporting data related to the design.

The laboratory scale TCSC is designed to investigate the operation analysis of 200 km long 345 kV transmission line in the cases with and without TCSC. Table 2 summarizes the parameters of the 345 kV compensated transmission line.

Using (1) (2) and (3), and the data in the Table 2, the capacity of FC and TCR were calculated and shown in Table 3.

<Table 1> The supporting data related to the design

Items	Values
Percentage compensation of TCSC (k_{TCSC})	5-15 %
Boost factor (ω_{order})	3.0
The resonance factor (λ)	2.5

<Table 2> The compensated overhead line parameters

Items	Unit	Values
Resistance (R)	Ω/km	0.037
Inductance (X_L)	Ω/km	0.367
Conductance (BC)	mS/km	4.518
Line length (L)	km	200

<Table 3> The laboratory scale TCSC parameters

Items	Unit	Values
Minimum reactance of TCSC	Ω	3.67
Capacitance of the FSC	uF	722.77
Inductance of the TCR inductor	mH	1.56

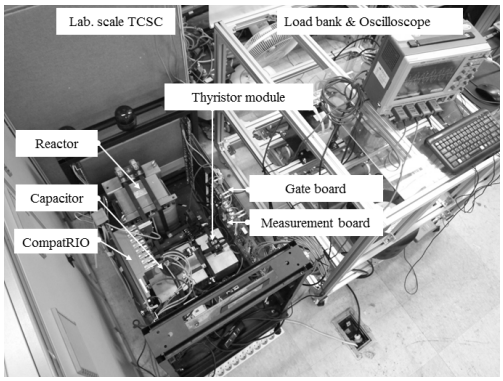
Other design factors that need to be considered when designing a TCSC device are the ratings of TCSC components such as the FC, the inductor and thyristors. The voltage that appears across the TCSC (V_C) and the current through the TCSC set the limits on the operating range of the device. A detailed PSCAD/EMTDC simulation model of a TCSC was developed to run some additional study cases in order to decide appropriate current and voltage ratings for the TCSC circuit components. The results are depicted in Table 4.

<Table 4> Rating of the TCSC's components

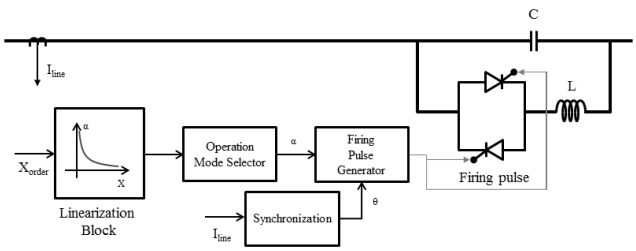
Items	Rated current (A)	Rated voltage (V)
Line current	15.0	
Fixed capacitor	40.4	148.5
TCR inductor	25.5	15.0

2.2 Manufacture of the laboratory scale TCSC

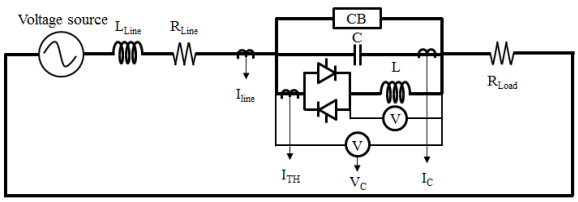
Based on the design parameters, a prototype laboratory scale TCSC was fabricated as shown in Fig. 1 . In this paper, the authors just fabricated a single-phase prototype TCSC.



<Fig. 1> Fabrication of the laboratory scale TCSC



<Fig. 2> The control algorithm of the lab. scale TCSC



<Fig. 3> Experiment circuit for the lab. scale TCSC

The power circuit is composed of a FC of 720 uF in parallel with a TCR that consists of a fixed reactor of 1.56 mH and a bidirectional thyristor valve. A fast-operating switch (CB) is connected in parallel with the TCSC to bypass the TCSC for several emergency cases.

The TCSC control system includes current and voltage transducers, gate driver and LabVIEW/CompactRIO, a product of National Instruments. The CompactRIO is utilized to develop the constant reactance control scheme for the TCSC as presented in Fig. 2. The compactRIO provides a voltage control signal to the gate driver to generate a firing pulse with a delay angle according to the size of control voltage.

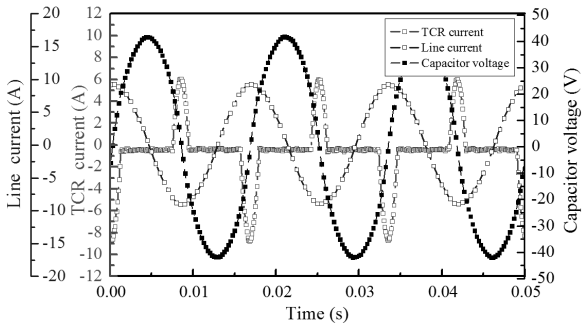
Hardware circuit is needed for the operation of the laboratory scale TCSC. The main components of the hardware platform are a voltage source, an AC reactor and load. Fig. 3 shows the experiment circuit used during the testing phase of TCSC. Table 5 indicates the detailed parameters of the hardware circuit for the laboratory scale TCSC.

<Table 5> The parameters of hardware circuit components

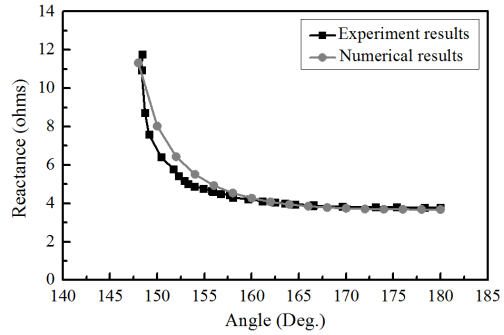
Items	Units	Values
Voltage source magnitude(V_s)	V	55.0
Line inductance (L_{line})	mH	7.5
Line resistance (R_{line})	Ω	3.4
Load (R_{load})	Ω	4.2

3. The Experiment Results

The impedance control function was performed in this work. Fig. 4 shows the operating characteristics of the laboratory scale TCSC including the TCR current, line current and capacitor voltage. As shown, the TCR current changes the capacitor voltage from that of the basic sinewave established by the line current. A higher TCR



<Fig. 4> The operating characteristics of the lab. scale TCSC



<Fig. 5> Comparison of reactance characteristics of the lab. cale TCSC

current will generate a higher capacitor voltage. Therefore, the reactance of the TCSC can be controlled. The Fast Fourier Transformation (FFT) is used to extract the fundamental components of the capacitor voltage and the line current. Then, the TCSC power frequency reactance is defined as the ratio of the fundamental component of capacitor voltage and that of line current. The experimental results are compared with the numerical results that are analyzed by using the TCSC reactance equation in [4]. As can be seen from the Fig. 5, the operating reactance of TCSC varies in the range of 3.67 to 11.01 ohms, and the firing angle changes from 148 to 180 degrees. The TCSC is operated in the capacitive mode only.

4. Conclusions

In this paper, the authors designed and fabricated a laboratory scale TCSC. Hardware circuit was also implemented to investigate its operating characteristics including the TCR current, line current and capacitor voltage. And, FFT was used to extract the fundamental components of the capacitor voltage and line current in order to calculate the TCSC power frequency reactance. It changes in the range of 3.67 to 11.01 ohms. The TCSC is operated in the capacitive mode only. In the future, it will be incorporated with the real time digital simulator to conduct more research activities.

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