Examination and Comparison of Thyristor and Gate-Controlled Series Capacitors Performance for the Voltage Stabilization of Sensitive Loads

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2021 12th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC) | 978-1-6654-0366-5/20/$31.00 ©2021 IEEE | DOI: 10.1109/PEDSTC52094.2021.9405938

***Abstract*—This paper investigates and analyzes a new application of two types of controllable series compensators, GCSC and TCSC, in fixing a bus voltage feeding a sensitive load. After introducing the operation principles of the GCSC and TCSC, it is revealed that the studied system provides good performance neither without compensation nor with series compensation with a fixed capacitor. Then, it is shown that if controllable compensators are used, it is possible to prevent voltage variations of the bus that feeds the sensitive load. Finally, a comparison is made between the rating of the components of the GCSC and TCSC, which results indicate the superiority of the former. In this study, all time-domain simulations are done using MATLAB/Simulink.**

***Keywords*— series compensation, voltage stability, GCSC, TCSC, controllable series compensator**

I. Introduction

In the power system, power quality has great importance for electrical equipment and end consumers. For sensitive loads, this issue is becoming more and more of a concern, so all discussions about the reliability of power systems should include the issue of power quality. The definition of power quality is generally based on holding the voltage of the system on a nominal range, nominal frequency, and sinusoidal waveform [1]. In recent years, the injection of reactive power into transmission lines has been used to improve the power quality problem in feeding specific loads and increasing the power capability of transmission lines using series and parallel compensators. In this regard, the use of series compensators is preferable to parallel compensators. One of the most important reasons for this superiority is the lower sensitivity of the series compensators to the load characteristics of the system and the position of the equipment in the transmission line [2].

Series compensating of transmission lines has many benefits for the power system. First of all, it is a drastically economical way to increase the power transfer capability of the existing transmission lines [3]. For instance, following an investigation carried out by ABB Group, it has been concluded that employing a series compensator leads to the expansion of an existing power transmission line capacity from 1300 MW to 2000 MW which is 90% less than the construction cost of a new transmission line [4]. Furthermore, not only does it improve the transient stability, but it also reduces the voltage drop across the line[2].

Revolutionary developments in the areas of high power electronic devices alongside their advanced electronic control methods have paved the way for the emergence of controllable series capacitors [5]. The thyristor controlled series capacitor (TCSC) has been introduced as the first generation of series controllable compensators. The amount of power transferring by transmission lines would be boosted using this device. [4].

The second generation of such devices has been named the gate-controlled series capacitor (GCSC). This simple device is comprised of two anti-parallel GTOs which a fixed capacitor is connected in parallel with them. By changing the GTOs' conduction times, various compensation degrees will be obtained [6].

In this paper, a new application of controllable series capacitors is going to be presented. For this purpose, the functionality of the GCSC and the TCSC in fixing a bus voltage feeding a variable load will be examined. Also, a comparison will be made in which the performance of GCSC and TCSC in a common system is considered. It will be shown that wherever series controllable compensation is needed, employing the GCSC would be a better choice compared to the TCSC due to some benefits. The rest of the paper is organized as follows. The operating principles of TCSC and GCSC are presented in Section II; The studied power system is described in Section III; Voltage stabilization using three types of series compensators namely fixed series capacitor, GCSC, and TCSC is studied in Section IV; A comparison is made between the main component ratings of GCSC and TCSC in Section V; finally, the whole paper summarized in Section VI.

II. TCSC and GCSC Operation Principles

The single-line diagram of TCSC can be seen in Fig. 1. As depicted in this figure, this device is made up of a fixed capacitor paralleled with a thyristor controlled reactor (TCR). By changing the thyristors firing angles α, TCSC's impedance can be controlled [6]. Fig. 2 shows the typical waveforms of the TCSC including the line current (i_L), the capacitor current (i_c) the TCR current (i_{TCR}), the capacitor voltage (v_c), and the pulses of the thyristors T_1 and T_2 [4].

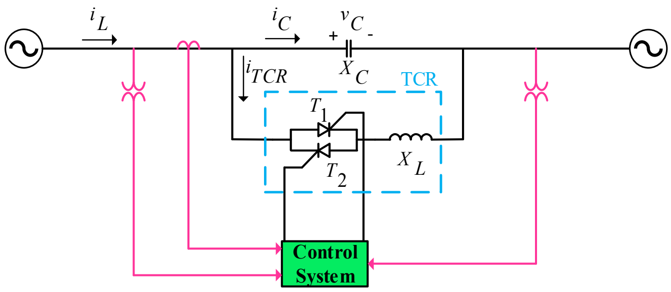

Fig. 1. Single line diagram of TCSC

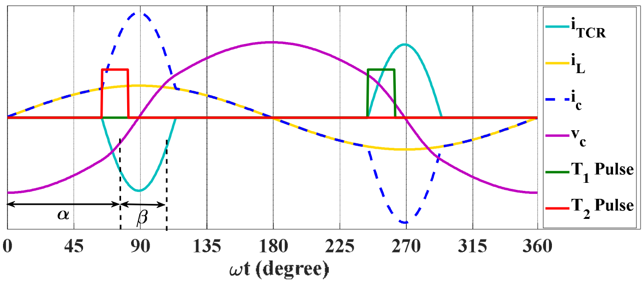

Fig. 2. Typical waveforms of the TCSC

Under a condition that the value of the TCSC inductor reactance, X_L, is adequately smaller than that of the TCSC capacitor reactance, X_C, this compensation system can operate in an on-off manner so that the inductance of the thyristor-controlled reactor (TCR) can be changed by altering the TCSC firing angle, α. Therefore, by performing this manner the TCSC can provide a continuously variable capacitor through the elimination part of the X_C impedance using the variable inductor, i.e. TCR. Generally, the X_L is chosen in such a way to have a value of 10% to 30% of the X_C [4].

The equivalent reactance of the TCSC with respect to the firing angle (α) is shown in Fig 3. As can be seen in this figure, the TCSC has two working modes around its parallel resonance area namely inductive and capacitive which is shown in Fig. 3. In order to avoid the resonance area, preemptive considerations must be applied [4].

The gate-controlled series capacitor (GCSC) is a very simple device connected in series with the transmission line. As depicted in Fig. 4, the GCSC is implemented for each phase by a fixed capacitor paralleled with two anti-parallel GTOs. It is controlled by varying the turn-off angle (γ) measured from the zero-crossing point of the line current [6].

The GCSC is a zero-voltage switching (ZVS) device, that is, the transition between switching states is conducted at zero voltage so that it can greatly reduce the switching losses. Fig. 5 shows the line current, capacitor voltage, and the GTOs pulses waveform, respectively. The transmission line current, i_{Line}, is considered to be purely sinusoidal. If the GTOs always switched on, the capacitor is no longer functions, and no compensation will be achieved. An alternate polarity will emerge in capacitor charging and discharging when both positive-GTO (G1) and negative-GTO (G2) turn off once per cycle, at a given turn-off angle, γ. Hence, a voltage v_C

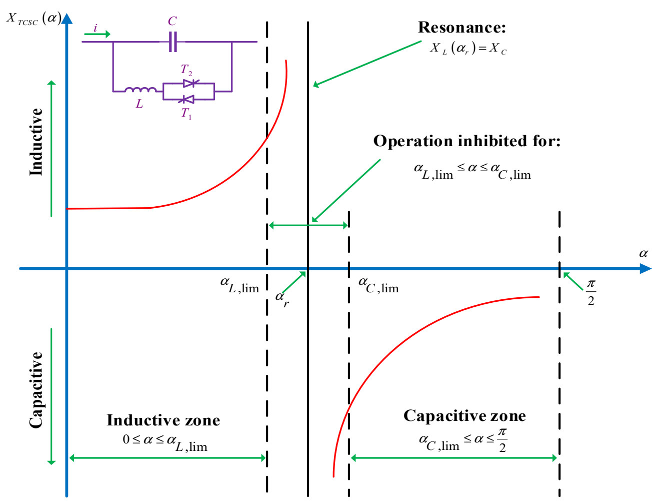

Fig. 3. TCSC function areas

appears in series with the transmission line. This voltage has a controllable fundamental component that lags the line current by 90 degrees. This leads to having a variable capacitor, which the effective reactance of this capacitor in terms of the turn-off angle is as follow [6]:

$$X_{C1}(\gamma) = \frac{X_C}{\pi}(-2\gamma + 2\pi + \sin(2\gamma)) \qquad (1)$$

where X_C is the fixed capacitor's reactance.

The equivalent reactance of the GCSC with respect to the turn-off angle is shown in Fig 6. As can be seen in this figure, the GCSC provides a continuously variable capacitor varying from X_C to zero at the fundamental frequency. Having a continuous equivalent reactance is one of the advantages of the GCSC compared to the TCSC [6].

III. STUDIED POWER SYSTEM DESCRIPTION

The studied power system is shown in Fig. 7 which is adopted from Kundur's two-area system [7]. This system is modeled in the MATLAB/Simulink in full detail. This network consists of a 300MVA synchronous generator. The series compensation is done in the center of the transmission line by a controllable capacitor plus a fixed series capacitor. A variable load with a nominal value of 417MW and a power factor of 0.9 is connected to the bus B2. Detailed information about the studied system is given in [7].

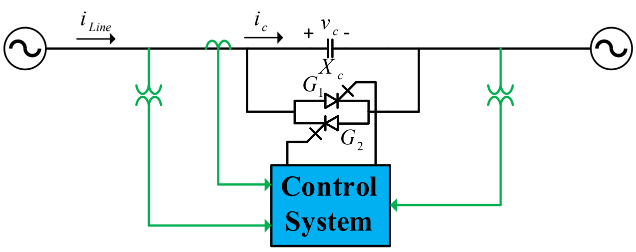

Fig. 4. GCSC single line diagram

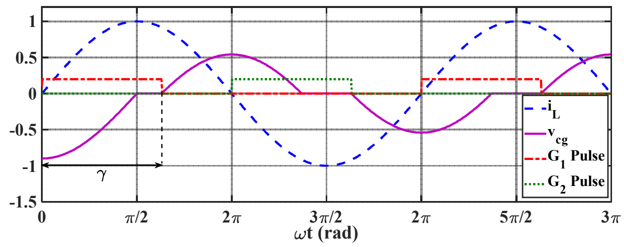

Fig. 5. Typical waveforms of the GCSC

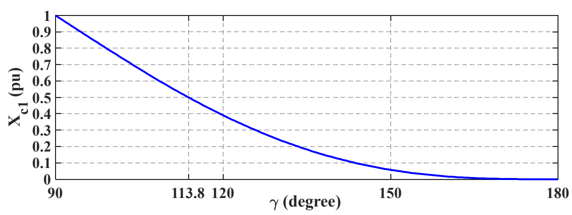

Fig. 6. The equivalent reactance of GCSC as a function of turn-off angle

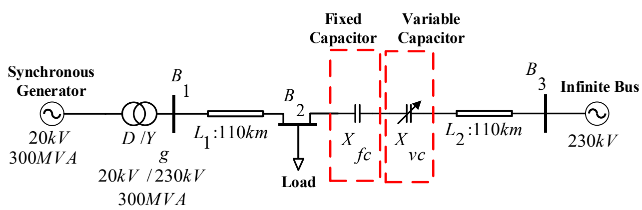

Fig. 7. Studied power system

IV. Voltage Stabilization Using Series Compensation

In order to examine the capability of the controllable capacitor in fixing a bus voltage feeding a variable load, three cases have been considered.

In the first case, there was no series compensation in the studied system, and the power of the variable load was changed at t_1=2s and t_2=4s from 117MW to 267MW and then to 417MW, respectively. In the second case, the system was compensated by series fixed capacitor with 55% compensation. Finally, in the last case, due to the whole required compensation, the two portions were provided with the fixed capacitor and one portion with the variable capacitor. In the following, each of these cases will be discussed in more detail.

A. *Transmission line without series compensation*

In this section, there is no series compensation in the studied system. In order to show the voltage drop in the bus B_2, the value of the load that is connected to this point is changed initially with a value of 117MW, then in t_1=2s its value reaches 267MW, and at t_2=4s, its value is set to 417MW. Fig. 8 shows the voltage of the bus B_2. As can be seen in this figure, as the value of load connected to bus B_2 increases, the voltage of this bus decreases. And, for the load 417MW, the heaviest load, the voltage reaches its minimum value. It can be concluded that in order to avoid this voltage drop, the system requires series compensation.

B. *Transmission line compensation using fixed capacitor*

In this section, in order to prevent the voltage drop due to the increase in load, a series compensation with a fixed capacitor is used. The value of the capacitor is tuned in a way that in the heaviest load, the voltage of B_2 maintains 1p.u. It means that the required series capacitor is equal to 55% of the total reactance of the line. In Fig. 9, the voltage of B_2 is shown in this case. As seen in this figure, for lighter loads, this value is greater than 1 p.u .and the bus is overloaded.

C. *Transmission line compensation using a variable capacitor*

Due to the problems of using fixed capacitor in low loads, the necessity of using series compensation with variable capacitors is obvious. In fact, a variable capacitor in light loads reduces its reactance to prevent overvoltage in the system. For this purpose, two capacitive compensators with variable reactance (GCSC and TCSC) are used, and the performance of these two compensators are compared with each other. The structure of the control system of these two compensators is the same as in Fig. 10. In this structure, first, the voltage of the B_2 is compared with the reference voltage (i.e., 1p.u.), and the resulting error enters a lag controller and a PI controller and then passes through a saturation block. The output of the saturation block will be the desired angle of the switches. It should be noted that the mentioned angle is the GTOs turn-off angle for the GCSC and the firing angle of the thyristors for the TCSC. In general, variable compensators are used in conjunction with a fixed series capacitor to minimize the overall cost of compensation [8]. Due to the whole required compensation, the two portions were provided with the fixed capacitor and one portion with the variable capacitor.

a) Transmission line compensation using GCSC: In this section, in order to prevent the voltage drop and overvoltage of B2, the GCSC is used. The dynamic response of the studied system including B2 voltage, turn-off angle of the switches, the GCSC phase voltage and current and the pulses of the switches are plotted in Figs. (11) through (13), respectively. As shown in Fig. 11, as the load value changes, the B2 voltage remains constant at 1p.u. This fixity occurs by varying in the value of the effective capacitive reactance of GCSC, which can be seen in Fig. 12. As seen in this figure, the turn-off angle decreases, resulting in an increase in the effective GCSC capacitance. It can also be seen from Fig. 13 that, with an increase in load value, the GCSC voltage amplitude increases so the compensation is increased.

b) Transmission line compensation using TCSC: This section discussed the application of TCSC, the first generation of the controllable series compensators, in series compensation. In fact, the purpose of this section is to compare two controllable series compensators, GCSC and TCSC, in the same application and same degree of compensation. For this purpose, the following assumptions have been considered to replace GCSC with TCSC:

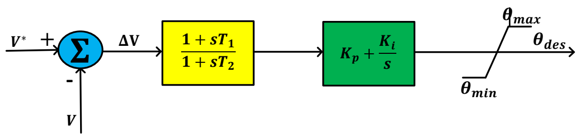

Fig. 10. The structure of the control system of GCSC and TCSC

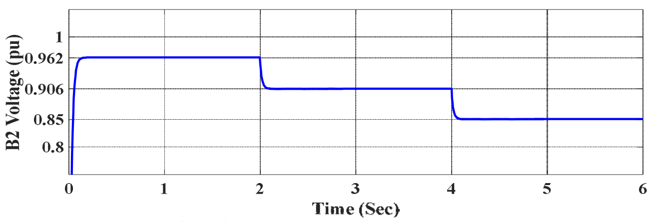

Fig. 8. B_2 voltage when there is no compensation in the transmission line

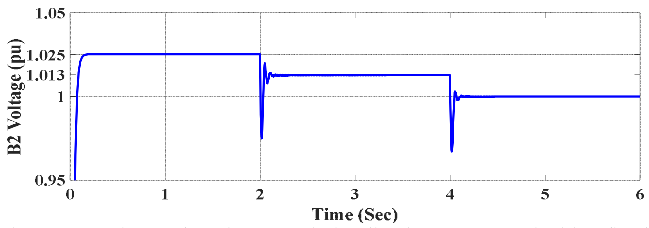

Fig. 9. B_2 voltage when the transmission line is compensated with a fixed series capacitor

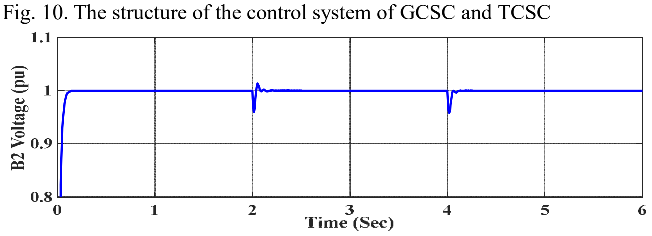

Fig. 11. B_2 voltage when the transmission line is compensated with GCSC in conjunction with a fixed series capacitor

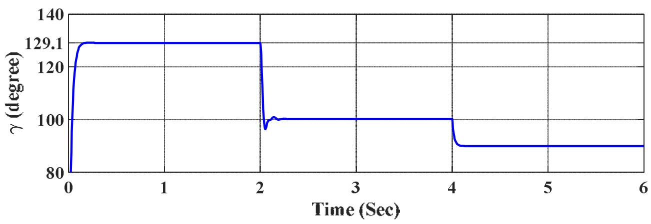

Fig. 12. Turn-off angle of the GCSC's switches when compensation was done by GCSC and fixed capacitor

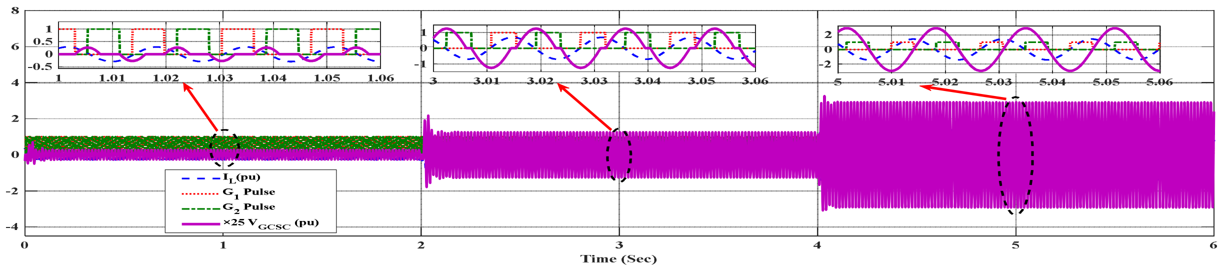

Fig. 13. GCSC phase voltage and current and the pulses of the GCSC's switches when compensation was done by GCSC and fixed capacitor

• GCSC and TCSC have the same maximum capacitive impedance.

• TCSC acts only in its capacitive region.

The maximum and minimum TCSC impedance values in the capacitance region are X_{max} and X_{min} , respectively. X_{min} is equal to TCSC constant capacitor reactance, related to the time that the thyristors do not conduct. X_{max} is related to the equivalent TCSC reactance that occurs at minimum firing angle $\alpha_{C(\mathrm{lim})}$.

As mentioned in Section II, GCSC's reactance is continuous and varies from 0 to its maximum value, which is equal to the reactance of the fixed capacitor. For GCSC and TCSC to have the same equivalent impedance (in other words, to have the same maximum equivalent reactance), the constant capacitor values in the GCSC and TCSC are as follows:

$$X_{max} = (\omega C_{GCSC})^{-1}, \quad X_{min} = (\omega C_{TCSC})^{-1} \Rightarrow \frac{C_{GCSC}}{C_{TCSC}} = \frac{X_{min}}{X_{max}} \qquad (2)$$

Also, the value of the fixed reactor reactance in TCSC is set to 16% of TCSC capacitor reactance.

The dynamic response of the studied system including B_2 voltage, firing angle of the switches, the TCSC phase voltage and current, the capacitor and TCR currents and the pulses of the switches are plotted in Figs. (14) through (16), respectively. As shown in Fig. 14, as the load value changes, the B_2 voltage remains constant at 1p.u. This fixity occurs by varying in the value of the effective capacitive reactance of TCSC, which can be seen in Fig. 15. As seen in these figures, by increasing load value, the firing angle of switches will decrease, which will result in an increase in the effective TCSC capacitor reactance, and we will have a maximum compensation at 56.9 degrees. It can also be seen from Fig. 16 that, with an increase in load value, TCSC voltage increases.

V. Compare the Components Rating of the GCSC and TCSC

In this section, based on the simulation results of Section IV, a comparison between the rating of the components of the TCSC and GCSC is made, which is related to the maximum compensation of two devices. These results are summarized in Table 1. In the following, these results will be discussed in more detail.

A. Compare the capacitance of capacitors

According to the assumption, the values of the fixed capacitor were chosen in such a way that both devices have the same maximum compensation. Since the minimum TCSC compensation is equal to its fixed capacitor and the maximum GCSC compensation is equal to its fixed capacitor, and also according to (2), it is clear that in order to obtain the same maximum compensation, the capacitor of GCSC is always smaller than the capacitor of TCSC.

B. The nominal voltage of the capacitors

Since the compensation level of the TCSC and GCSC are the same, and also the current passing through them is equal to the line current, the first harmonic of capacitor voltage is the same for both of them. However, in full compensation, the voltage of the GCSC, in contrast to the TCSC, is pure sinusoidal, so its effective voltage is slightly lower than TCSC.

C. Nominal current of the capacitors

Assuming that the TCSC voltage is equal to v_c and its first-order harmonic component is V_{c1} the first harmonic of the current passing through the capacitor is as follows:

$$I_{C1} = \frac{V_{C1}}{X_{min}} = \frac{X_{max}}{X_{min}} I_{Line} \qquad (3)$$

Since at maximum compensation provided by GCSC, the current passing through the capacitor is equal to the line current and according to the (3) and the values of X_{max} and X_{min}, the first harmonic of the capacitor current in the TCSC is 4 times the capacitor current in the GCSC. Considering other current harmonics, this ratio will be greater than the one that is considered in Table (1). So, in general, it can be concluded that the nominal capacitor current in the TCSC is always higher than the GCSC.

D. The maximum current of switches

For GCSC, the maximum current of the switches is equal to the line current. In zero compensation, the whole line

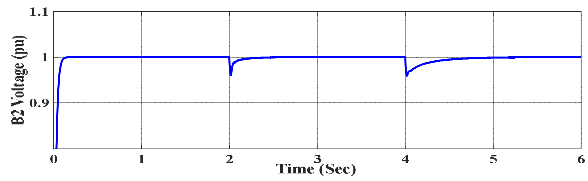

Fig. 14. B_2 voltage when the transmission line is compensated with TCSC in conjunction with a fixed series capacitor

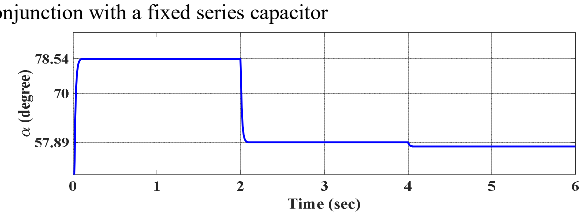

Fig. 15. Firing angle of the TCSC's switches when compensation was done by TCSC and fixed capacitor

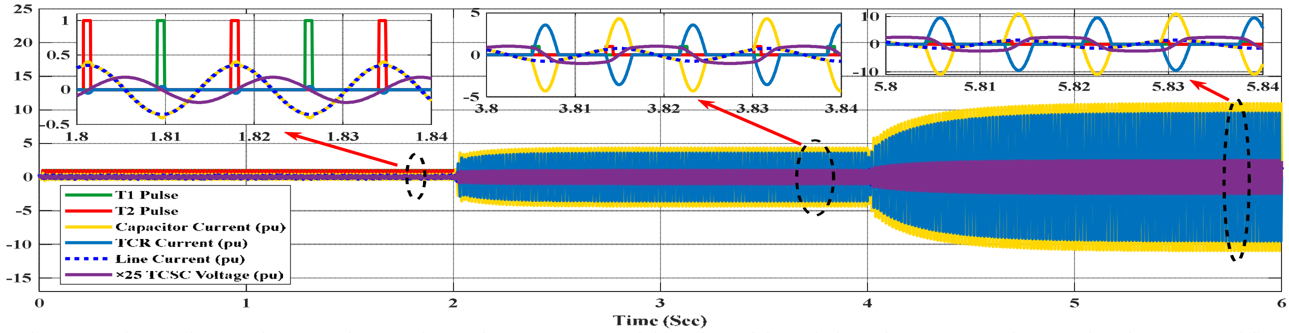

Fig. 16. The TCSC phase voltage and current, the capacitor and TCR currents and the pulses of the switches when compensation was done by TCSC and fixed capacitor

TABLE I. NOMINAL VALUES OF THE TCSC AND GCSC ELEMENTS

Parameter	TCSC	GCSC
Capacitor	5.33Ω	21.33Ω
Capacitance	497.31µF	124.33µF
Reactor	0.8534 Ω	---
Reactance Range	5.33-21.33 Ω	0-21.33 Ω
Nominal Capacitor Voltage (rms)	19.327kV	18.938kV
Nominal Capacitor Current (rms)	4.266kA	0.888kA
Nominal Reactor Voltage (rms)	8.27kV	---
Nominal Reactor Current (rms)	3.558kA	---
Maximum Switches Current	8.265kA	1.231kA
Average Switches Current	0.972kA	0.0617kA
Maximum Switches Voltage	22.984kV	26.795kV

current passes through the switches, but due to the low current in the non-compensated mode, the maximum current of switches cannot be considered equal to this current. On the other hand, in full compensation, where the line current has its maximum value, the conduction of the switches is zero. As a result, the maximum current passes through the switches can be considered equal to the current in the high compensations. Considering the worst-case and assuming that in this case the maximum current passing through the switches is equal to the line current in full compensation, the value of this current is obtained according to Table (1).

The current passing through the TCSC switches can be obtained from the following equation:

$$I_{TCR} = I_{C1} - I_{Line} = \frac{X_{max} - X_{min}}{X_{min}} I_{Line} \qquad (4)$$

According to (4) and the values of X_{max} and X_{min}, the first harmonic value of the current passing through the switches is 3 times the current of the line. But because the current passing through the switches has high-order harmonics, the maximum current passing through the switches is more than twice that value. It can be seen in Fig. 19. Therefore, it can be concluded that the maximum current passing through the switches in the TCSC is higher than the GCSC.

E. The maximum voltage of switches

In GCSC, the voltage of the two switches is exactly equal to the capacitor voltage. But in TCSC, the voltage of the TCR is equal to the capacitor voltage. As a result, the maximum voltage of two switches in the TCSC is always less than the GCSC.

VI. CONCLUSION

In this paper, the application and control of two types of controllable namely GCSC and TCSC in fixing a bus voltage feeding a sensitive load voltage were investigated. Simulation results show that if the controller is designed properly, these compensators can stabilize the load voltage and prevent it from variations. Finally, a comparison was made between these two types of controllable series compensators, which resulted in GCSC superiority over TCSC.

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