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Analysis of the System Impact upon Thyristor Controlled Series Capacitor Relocation Due to Changes in the Power System Environment

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Abstract: Owing to geographical and political influences, Korea has an independent electric power system and the highest density of electric power facilities in the world. Large-scale base power generation complexes are located in non-metropolitan coastal areas, while the most expensive combined cycle power plants are operating or under construction in the metropolitan areas, which have the largest electricity demand. It has become difficult to secure a site for power plants, and the existing power transmission network is insufficient because of the additional construction of generators in existing power generation complexes, the increase in capacity of facilities, and the rapid increase in new and renewable energy. In particular, the East Coast region has a problem of transient stability for this reason, which is being addressed in advance through power generation restrictions. In addition, TCSC (Thyristor Controlled Series Capacitor) is installed and operated to expand the capacity of existing power transmission lines and improve stability in the failures of nearby high-voltage lines until new transmission lines that take more than 10 years are installed to resolve power generation restrictions. However, after the construction of a new transmission line, the efficiency of the existing TCSC is degraded, and for efficient use, it is necessary to rearrange the installation location to utilize the optimal TCSC according to changes in the configuration of the nearby power system. Moreover, a detailed analysis is needed on whether the TCSC designed according to the existing grid configuration exhibits accurate control performance even after the relocation and whether it interferes with nearby generators. In addition to the dynamic performance based on real-time simulations, it is necessary to study the control performance and interaction for this power electronic equipment. This study verified the need to change controller parameters, the interaction effect with nearby generators for stable operation, and the system effect of TCSC relocation using the same replica controller as the actual field controller, as well as RTDS (Real Time Digital Simulation) simulating the entire power transmission system.

Keywords: TCSC; RTDS; replica controller; SSTI; damping analysis

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1. Introduction

Korea's 345 kV TCSCs (Thyristor Controlled Series Capacitor) were installed at SJC and SYJ substations to reduce power constraints and improve stability ahead of the construction of the new transmission lines, although large-scale new generators, including renewable energy sources, are expected to be connected on the East Coast. The TCSCs were installed because the transmission power flow maintained is more stable and system attenuation is improved. Figure 1 is a simplified schematic diagram showing the TCSCs installed. These TCSCs are connected in series to the transmission line and are used to resolve transmission restrictions and stabilize the power system by quickly compensating the impedance of the 345 kV transmission line in case of nearby 765 kV line failure [1–7]. In addition, since LCC (Line Commutated Converter) HVDC (High Voltage Direct Current) is scheduled to be installed for large-scale transmission, the transmission line of TCSC installed in SYJ

substation was changed to analyze the possibility of normal operation and SSTI with nearby generators as the sum of the electrical damping of the power system and the generator mechanical damping [8]. The RTDS (Real Time Digital Simulation) test using TCSC replica controllers analyzed the system effectiveness of the transmission line changes to assess the adequacy of control, the TCSC's operational strategy and impact, and pre-reviewed future actions from a facility and system operational perspective [9–16].

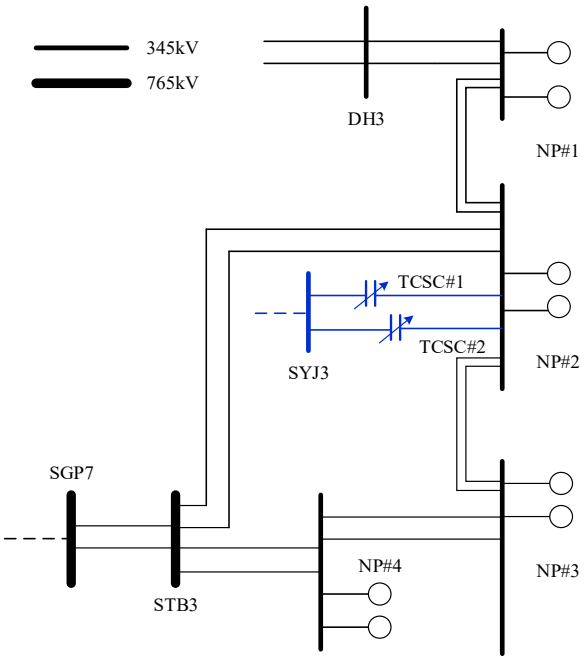


Figure 1. Simplified East Coast power grid configuration.

2. TCSC System

2.1. TCSC System Configuration

The TCSC consists of a capacitor connected in parallel with a thyristor-controlled reactor (TCR), a metal oxide varistor (MOV) for protection, and a bypass breaker. The TCSC increases the transmission capacity by controlling the transmission line impedance. Equation (1) is a general power transfer calculation formula of an alternating current system, and the amount of power transfer is determined by the transmitter voltage V_1, receiver voltage V_2, phase difference θ, and transmission line reactance X_L [17,18]. Figure 2 shows the transmission line impedance compensation and transmission capacity increase according to TCSC.

$$\mathrm{P} = \frac{V_1 \cdot V_2}{X_L - X_C} \sin\theta \tag{1}$$

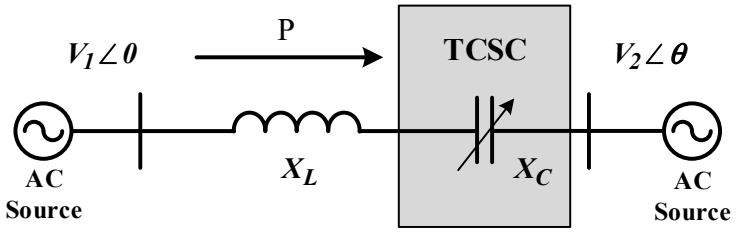


Figure 2. Transmission line impedance compensation and transmission capacity increase according to TCSC.

As shown in Equation (1), the smaller the transmission line reactance, the larger the power transmission amount. For the reason the general transmission line reactance is

mostly inductive, the TCSC can increase the power transmission amount by reducing the line reactance through series compensation of the capacitive reactance X_C.

In addition, in preparation for the simultaneous failure of two nearby 765 kV transmission lines, 50% of the transmission line reactance is compensated in the normal state, with a maximum of 70% compensation for 10 s in case of failure, which significantly improves system stability and reduces restriction costs. Figure 3 shows the composition of the TCSC installed at the SJC and SYJ substations, and the roles of each part are as follows.

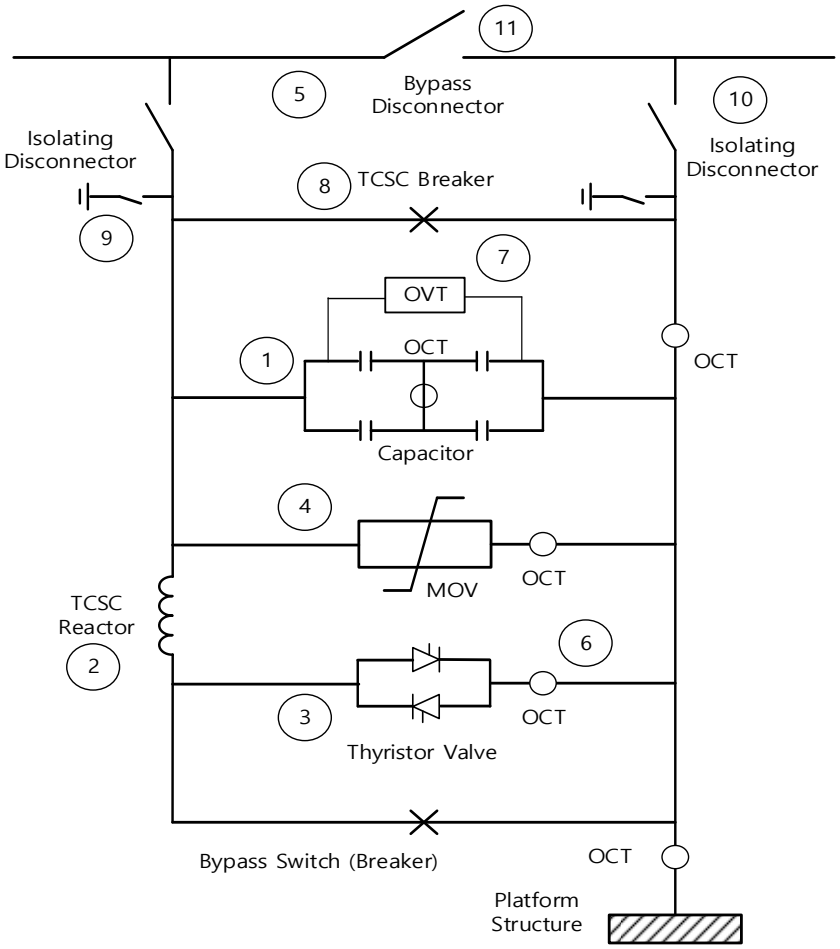


Figure 3. TCSC main components.

- Series capacitor (1)

It is the main circuit component of the TCSC and is connected in series with the line. It is connected in series with the line, which is an inductive reactance component and serves to compensate for the line impedance through a capacitor.

- Reactor (2)

It is an inductive reactance device connected in parallel with a series capacitor. It operates as a thyristor-controlled reactor (TCR) and is designed according to a specific resonance frequency to increase the capacitor voltage using the resonance characteristic of the series capacitor.

- Thyristor valve (3)

It controls the current flowing to the reactor by increasing the capacitor voltage through the thyristor firing angle control and performs a bypass control to protect the series capacitor in case of overcurrent due to line failure.

- MOV (4)

It protects the series capacitor and valve from overvoltage in case of a power transmission line failure.

- Bypass switch (5)

As a circuit breaker, it maintains an open state during the normal operation of the series capacitor and closes it in case of line failure to protect the series capacitor, valve, and MOV.

- OCT (Optic Current Transducer) (6), OVT (Optic Voltage Transducer) (7)

It measures the capacitor voltage for current measurement and thyristor control.

- TCSC Breaker (8), Isolating DS (Disconnect Switch) (9,10), Bypass DS (11)

It is a switching device for insulating and bypassing the series capacitor during maintenance and operation and for connecting and disconnecting the TCSC equipment from the line.

2.2. TCSC Control Operation

In TCSC, the operation mode is classified as follows according to the thyristor control. Figure 4 shows the various TCSC control modes.

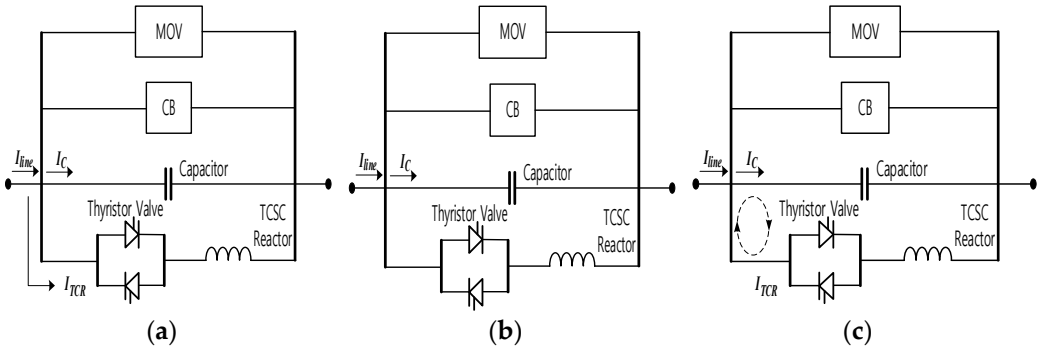


Figure 4. TCSC control mode. (**a**) Bypassed-thyristor mode. (**b**) Blocked-thyristor mode. (**c**) Capacitor vernier mode.

- Bypassed-thyristor mode

It is a control mode that completely conducts the thyristor firing angle at 90°. Because reactors are small compared with series capacitors, most of the line current flows into the thyristor-controlled reactor. This mode is used to protect the series capacitors from fault currents in the event of a line fault.

- Blocked-thyristor mode

The firing angle of the thyristor is set to 180°, or the firing signal is blocked so that the line current flows only through the series capacitor.

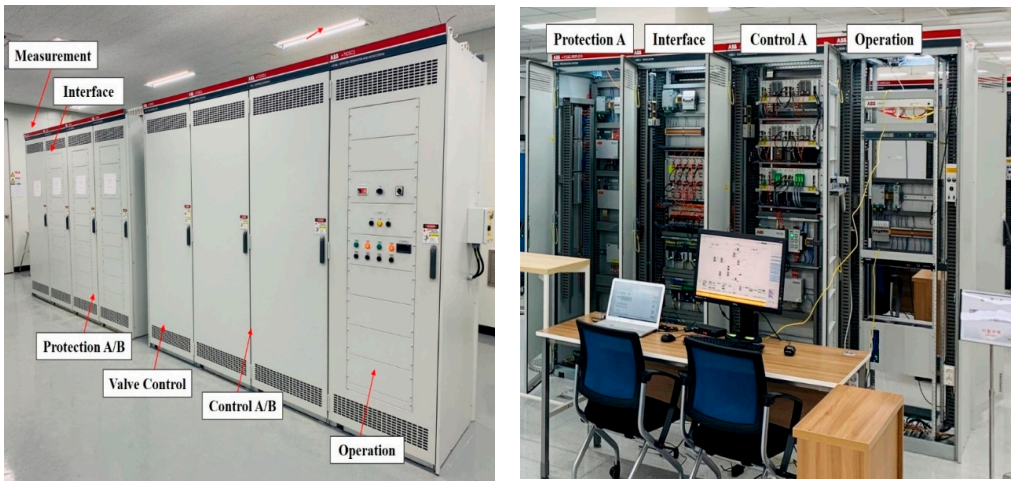
- Capacitor vernier mode

The firing angle of the thyristor should be between 90° and 180° and a parallel resonance between the series capacitor and the reactor should be made. Because the TCSC has inductive and capacitive characteristics based on the size of the firing angle and is mainly used for impedance compensation control of transmission lines, the capacitive region is used, and the inductive region is not used.

2.3. TCSC Replica Controller

TCSC replica controller is 100% identically designed, manufactured, and operated together with RTDS except for the duplication of the on-site controller and the control

and protection system. In conjunction with RTDS, pre-commissioning was performed on more than 100 test items before the on-site testing of the on-site controllers. It is used for reproducibility and causes an analysis of problems occurring in the field, analysis of the interaction with nearby facilities, and a verification before updating the on-site controllers. Figure 5a shows the TCSC field controller installed in the SYJ substation, and Figure 5b shows the replica controller installed in the laboratory [19–23].



(**a**) (**b**)

Figure 5. TCSC controller. (**a**) Actual controller in field operation. (**b**) Replica controller located in the lab.

3. Detailed Review Cases

To investigate the effect of relocation when changing the TCSC outgoing line, the RTDS experiment using the TCSC replica controller was conducted to analyze the appropriateness of control and the possibility of SSTI (Sub Synchronous Torsional Interaction) occurrence through the electrical damping of the connected busbar. In addition, the mechanical damping of the generator was analyzed in advance. Figure 6 shows a simplified single-line diagram of the East Coast for relocation review [24–28]. Table 1 shows the impedance changes due to line impedance.

Table 1. Line Impedance before and after relocation.

Items	Values		Unit
	Before	After	
Line length	Overhead Line: 90.958	Ov head Line: 90.003 Underground Cable: 1.5	km
Resistance	0.001364	0.001358	Ω/km
Inductance	0.569943	0.86011	Ω/km
Conductance	0.023194	0.023035	mS/km

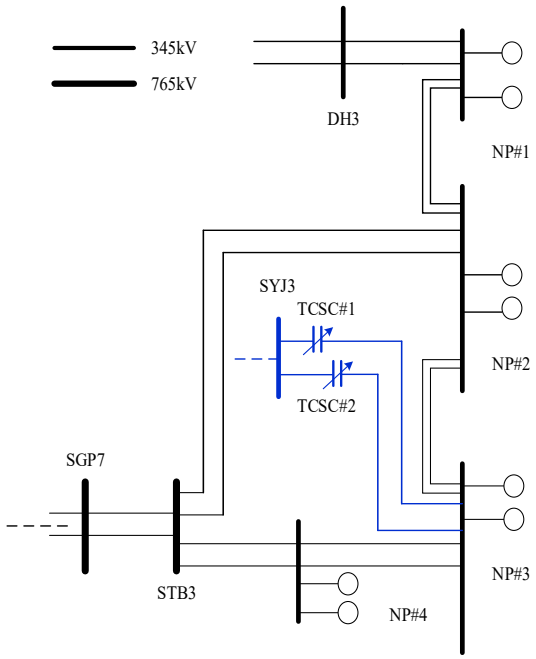


Figure 6. Simplified East Coast schematic for relocation review.

3.1. Scenarios for Control Adequacy Review

To review control adequacy, experiments were conducted on TCSC replicas and RTDS nationwide systems for maximum load in the 2022 summer operation plan, steady state operation of TCSC, boost factor step response, and instantaneous output increase control operation in the case of a 765 kV failure. TCSC's X_C is designed according to the X_L of the existing transmission line; however, because the X_L changes when it is relocated, the controller response performance may be affected by the suitability of control in the normal state and the system robustness of the connection location. The boost factor steps the response and analyzes the dynamic control performance in the case of failure. The boost factor is the ratio of the maximum achievable TCSC reactance to the minimum TCSC reactance.

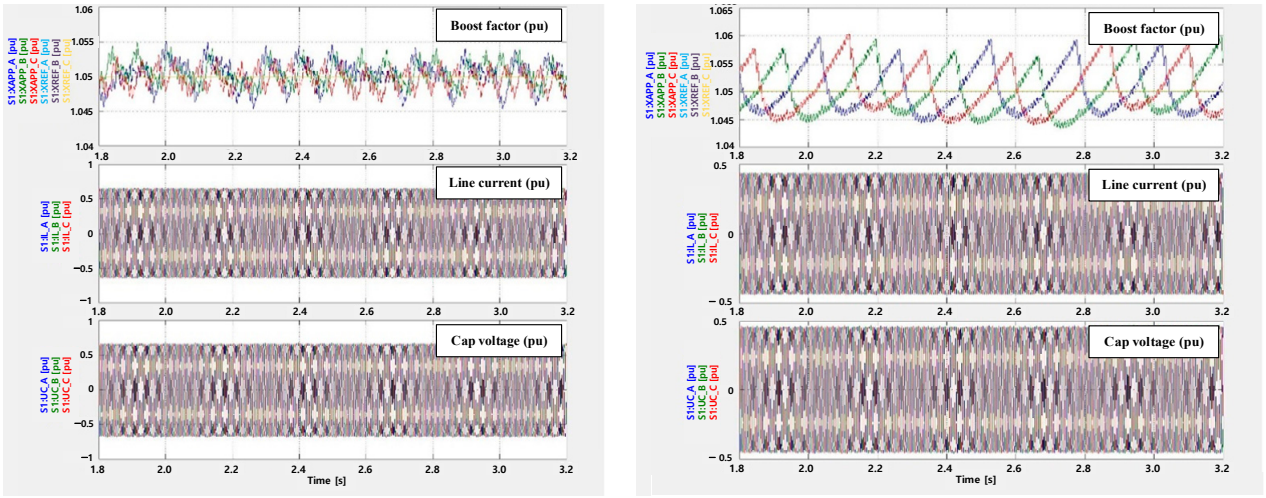
Table 2 shows the installation and operating conditions of nearby STATCOM (STATic synchronous COMpensator) and SVC (Static Var Compensator).

Table 2. FACTS installation and operation status near TCSC.

Installation Location	Equipment	Volume (Mvar)	Operating Capacity (Mvar)
SYJ S/S	STATCOM	±400	100 (Inductive)
SCJ S/S	STATCOM	±400	−200 (Capacitive)
DH S/S	STATCOM	±400	200 (Inductive)
SJC S/S	SVC	−225~+675	0

3.1.1. Steady State Operation

Figure 7 shows the comparison results of control adequacy before and after TCSC line relocation during the steady-state operation with a boost factor K = 1.05. During normal operation after relocation, a small vibration of 4 Hz level occurs, which is determined to be the effect of the gain of the internal controller due to a change in line impedance.

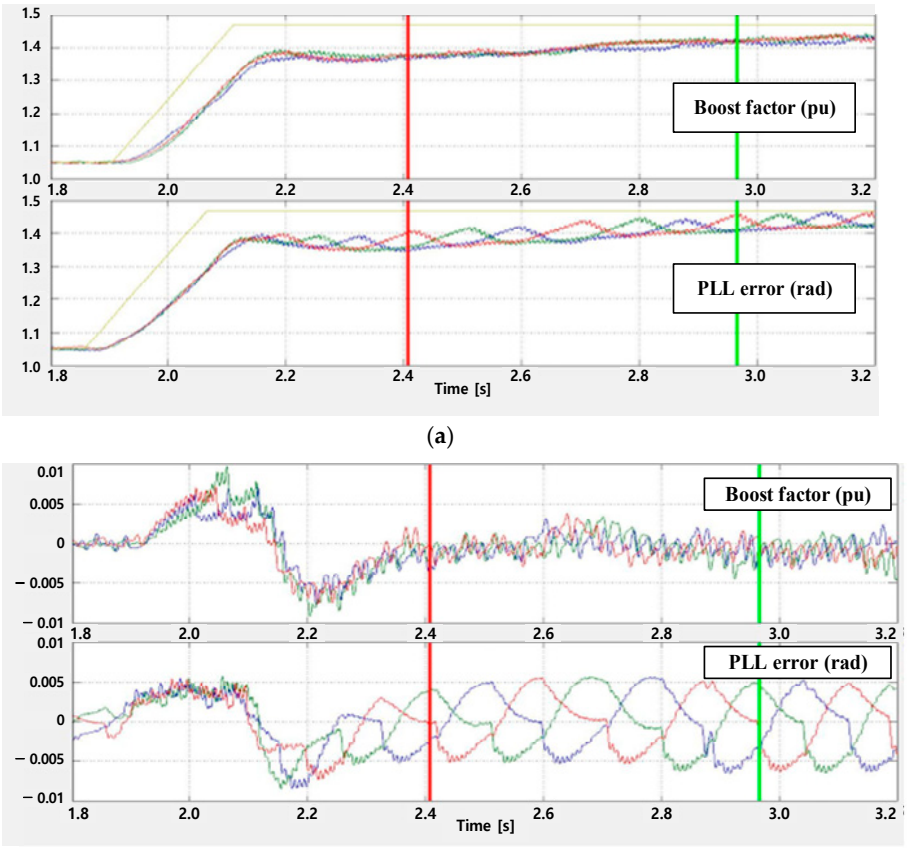


(**a**) (**b**)

Figure 7. Results of the review of steady state operation before and after relocation. (**a**) Before relocation. (**b**) After relocation.

3.1.2. Boost Factor Step Response

The boost factor K = 1.05 is changed to K = 1.47 during operation, as shown in Figure 8. The oscillation of 4 Hz due to the error in the internal PLL(Phase Locked Loop) controller occurs as in the steady state operation. This can be resolved through PLL controller gain correction in the future.



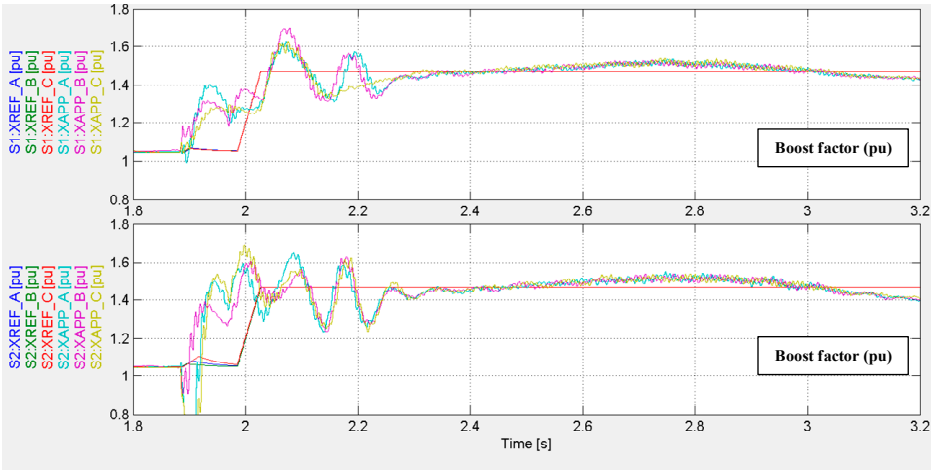
(**a**)

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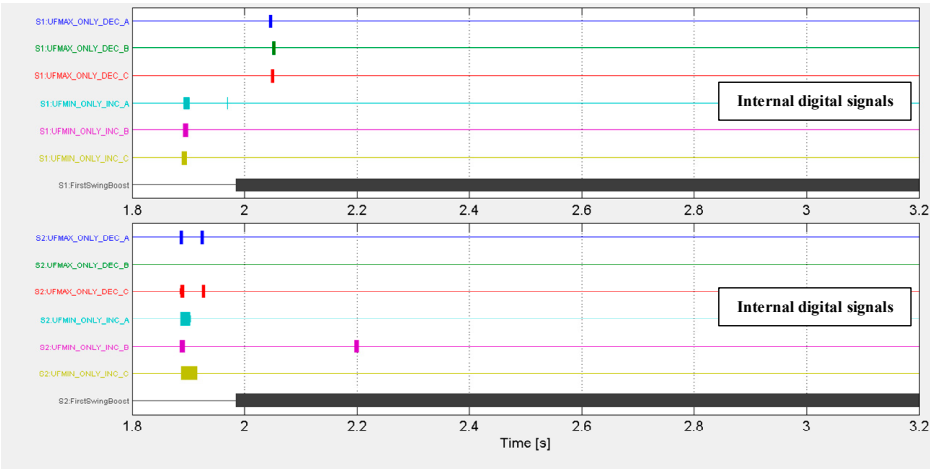
Figure 8. Results of Boost factor in the step response test. (**a**) Boost factor. (**b**) Internal PLL error.

3.1.3. Instantaneous Output Increase Control Operation in Case of 765 kV Failure

In the case of a 765 kV transmission line failure near the TCSC, as shown in Figure 9, the characteristics of the controller before and after relocation are indicated. Although there is a slight error in the transient state, there is no abnormal operation of control and protection, and the boost factor control and boost-up response characteristics by the SPS (Special Protection Scheme) signal are similar. Moreover, there is no bypass caused by the fault current in the case of the 765 kV fault.



(**a**)



(**b**)

Figure 9. Instantaneous output increase control performance test results in case of 765 kV failure. (**a**) Boost factor in case of 765 kV failure, before relocation (top)/after relocation (bottom). (**b**) 765 kV failure TCSC internal control digital signal, before relocation (top)/after relocation (bottom).

3.2. Damping Analysis to Review the Possibility of SSTI Occurrence

The possibility of SSTI occurrence with generators in operation due to changes in the nearby system configuration was examined. SSTI requires a detailed review, as it may cause damage to the generator shaft because of the interaction between the generator turbine shaft and the power electronics-based control equipment. For the reason SSTI is affected by the electrical damping obtained from the associated generator, changing the connection location of the TCSC may cause the electrical damping change, thus necessitating a new analysis [29–31]. The review conditions were based on the maximum load of the 2022 summer operation strategy study data and the two connected TCSC replica controllers. The operating conditions of the adjacent parallel FACTS(Flexible AC Transmission System) are shown in Table 1 and simulated with a vendor's SW model. The possibility of SSTI occurrence was reviewed through the UIF(Unit Interaction Factor) index and the electri-

cal/mechanical damping analysis of TCSC, #1-#4NPs generators. There was no major topology change before and after the relocation. However, a review is essential because a reactor is connected to them.

3.2.1. UIF Index Analysis

The UIF expressed by Equation (2) is a value that quantitatively expresses the correlation between power electronic equipment and generators in terms of equipment rating and short-circuits capacity. If UIF > 0.1, a detailed study is recommended because of concerns about the possibility of SSTI [32]. There are a total of seven radial systems in which SYJ TCSC is connected in series with #NP1 and #NP3 generators, and their results are shown in Table 3.

$$\text{UIF} = \frac{P_{dc}}{MVA_i}\left(1 - \frac{SCL_{out}}{SCL_{total}}\right)^2 \quad (2)$$

P_{dc}: Active power transmission; MVA_i: Generator rating; SCL_{out}: Short-circuit capacity when generators subject to review are excluded; SCL_{total}: Short-circuit capacity with generator under review (ohm).

Table 3. UIF Screening results.

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Target generator	NP#1–1	NP#1–2	NP#2–1	NP#2–2	NP#3	NP#4–1	NP#4–2
UIF	0.0240	0.0039	0.0227	0.0016	0.0469	0.0619	0.0114

In all cases, UIF < 0.1, implying that the possibility of SSTI occurrence was minimal.

3.2.2. Damping Analysis

Although the UIF obtained a value smaller than 0.1 based on the review, the stability was analyzed in detail using the electrical damping characteristics of the generator and system, as well as the mechanical characteristics of the generator. Figure 10 shows the results of the damping analysis for four cases in which stable operation was achieved even after the configuration of the radial system. The stability was determined through the magnitude of the mechanical and electrical damping at the natural vibration frequency of the generator ($D_m > D_e \rightarrow D_m - D_e > 0$).

Based on the detailed analysis of the damping, although the electrical damping has a negative value in some frequency domains, the possibility of SSTI occurrence is very low because there is a sufficient margin with the mechanical damping.

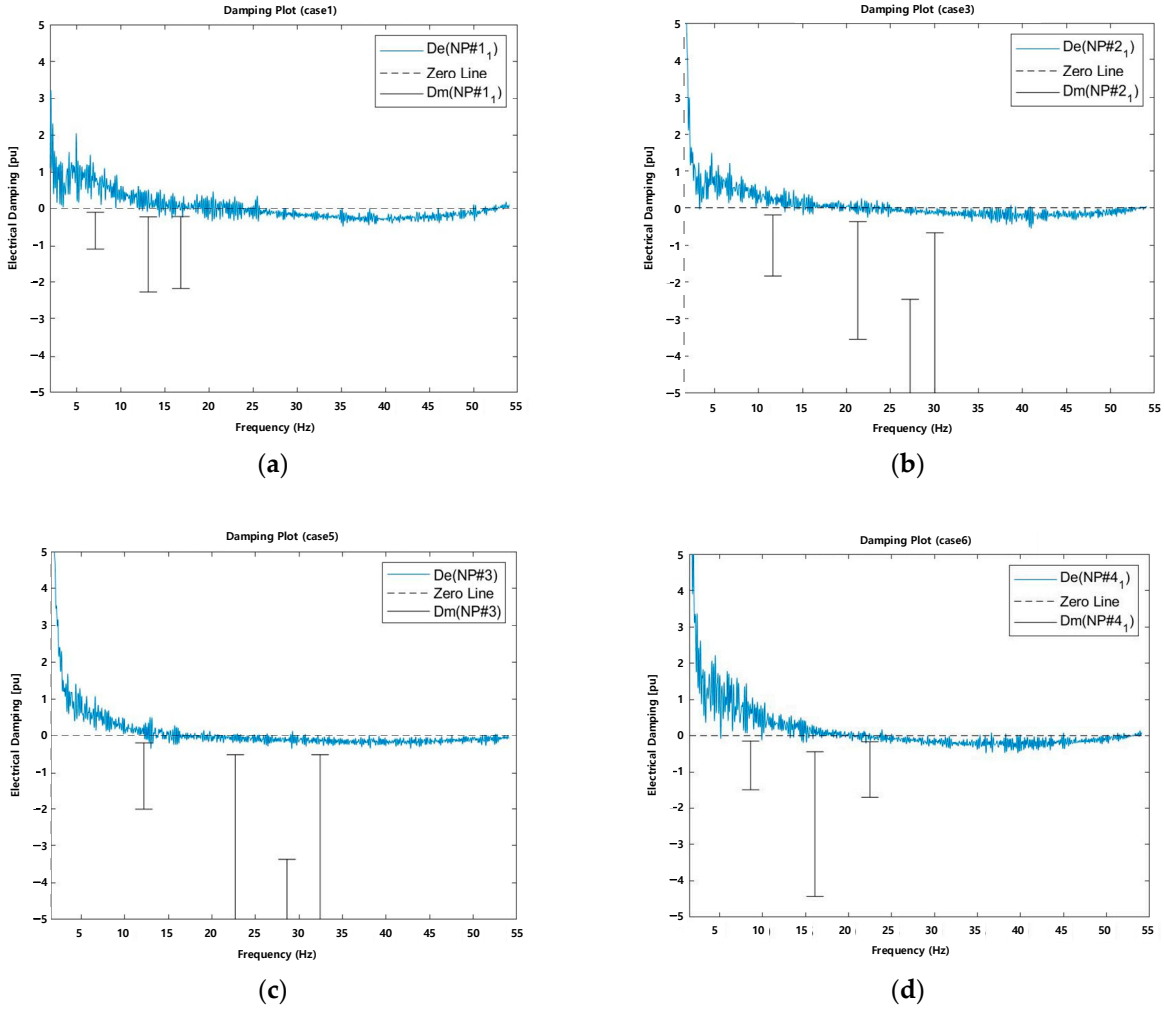


Figure 10. Damping analysis results of generators capable of running in series. (**a**) Case1 NP#1_1 Generator damping analysis result. (**b**) Case3 NP#2_1 Generator damping analysis result. (**c**) Case5 NP#3 Generator damping analysis result. (**d**) Case6 NP#4_1 Generator damping analysis result.

4. Conclusions

This study reviewed the possibility of control adequacy and the interaction of nearby generators due to the line impedance change of TCSC installed and operated in Korea's power system through replica controller and RTDS whole grid simulation. According to the results of the normal operation, step response, and 765 kV transmission line failure, the required instantaneous power increase performance of the system is normal, but a small oscillation of 4 Hz occurs in the steady state, so it is necessary to modify some of the controller parameters in cooperation with the manufacturer. The possibility of SSTI with nearby generators is low due to the electro-mechanical damping analysis, but it is necessary to review the interaction with new generators and large-capacity LCC HVDC and TCSC operation strategies in detail.

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Nomenclature

D	Damping
D_e	Electric damping
D_m	Mechanical damping
DS	Disconnect Switch
FACTS	Flexible AC Transmission System
HVDC	High Voltage Direct Current
I_C	Current flowing into the series capacitor
I_{line}	Current flowing from the AC grid to the TCSC
I_{TCR}	Current flowing into the thyristor valve
K	Boost factor
LCC	Line Commutated Converter
MOV	Metal Oxide Varistor
MVA_i	Generator rating
OCT	Optic Current Transducer
OVT	Optic Voltage Transducer
P	Active Power
P_{dc}	HVDC power transfer
PLL	Phase Locked Loop
Q	Reactive Power
RTDS	Real Time Digital Simulator
SCL_{out}	Excluded short-circuit capacity of generator
SCL_{total}	Total short-circuit capacity of generators
SSTI	Sub Synchronous Torsional Interaction
STATCOM	STATic synchronous COMpensator
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Capacitor
θ	Angle difference between the sending and receiving ends
UIF	Unit Interaction Factor
V_1	Sending end voltage
V_2	Receiving end voltage
X_C	Compensation impedance
X_L	Line impedance

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