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Parameter correlation analysis for determining practical TCSC main circuit elements

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Abstract. The main circuit of the thyristor controlled series capacitor (TCSC) consists of a capacitor bank connected in series with the transmission line and a thyristor controlled reactor connected in parallel with the capacitor bank. To determine the parameters of capacitor banks and reactors used in TCSC, they must be designed with consideration not only of purpose and necessity but also manufacturing and economics.

This paper deals with the parameter selection method for effective TCSC design based on practical examples. TCSC was selected as the case for analysis for the first time in Korea. Capacitance and inductance, the main circuit design factors, were calculated according to the installation purpose. Based on these, the number of stacks and operating losses of the thyristors considered safety were analyzed. The results of this study can be effectively used for TCSC main circuit design.

Keywords; TCSC main circuit, TCSC parameter, TCSC design

1. Introduction

Nowadays, electric power transmission lines are under the stress of reaching the thermal limit due to the increase of the transmission power. A flexible alternating current transmission system (FACTS) is well known as an effective solution to improve the power transfer capability. The thyristor controlled series capacitor (TCSC) is one of the FACTS devices, which has the capability to improve the transmission capacity by inserting a capacitor in series with the line. Most of the line constants of transmission lines consist of resistance and inductive reactance[1].

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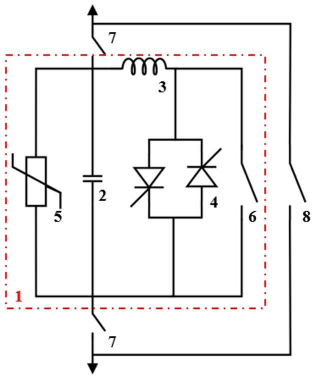
The inductive reactance of the line reduces the amount of power transfer. When the series capacitance is installed in the line, the capacitive reactance component increases and the amount of electric power transfer can be increased. Korea Electric Power Corporation installed TCSC at Shin-jecheon and Shin-youngju substations to stabilize power supply and improve power flow to the metropolitan area. In order to select an effective TCSC parameter, not only the purpose of the installation, but also loss and economics must be taken into account.

In this paper, we propose a method for parameter selection of TCSC main circuit elements. TCSC installed in Shin-jecheon substation was used as an example to select TCSC main circuit element parameters. First of all, various cases were selected for comparison by changing the boost factor and resonance factor. Steady and transient operating ranges were determined for each case, and then the most effective case was derived based on the number and operation loss of the appropriate thyristor valve stack. Finally, the lower the boost factor and the resonant factor, the more favorable the TCSC design and operation. This result can be effectively used to select the main component parameter of the actual TCSC.

2. TCSC main circuit configuration and parameter selection method

A. Configuration of a practical TCSC

Fig. 1 shows a typical configuration of a single phase of a TCSC. The TCSC consists of a main part for compensating the impedance of a transmission line and a protection part for protecting the TCSC from disturbances and faults[2].



	Component
1	Segment (1ϕ unit of TCSC)
2	Capacitor units
3	Thyristor controlled reactor
4	Bidirectional thyristor valve
5	Metal oxide varistor
6	Bypass switch
7	External isolating disconnect switch
8	External bypass disconnect switch

Fig 1. Configuration of a practical TCSC

The components in the red box are the main components of the TCSC and the whole is called a segment. One segment constitutes one TCSC. The TCSC main part consists of a parallel structure of a capacitor and a thyristor-controlled reactor (TCR). The firing angle (α) of the bidirectional thyristor is controlled to adjust the composite impedance value of TCR and capacitor. The TCSC can be operated in an inductive as well as a capacitive mode as per the system requirements.

B. TCSC main circuit element design process

The design process of the TCSC main circuit is shown in Fig. 2. First of all, it is necessary to confirm the purpose of TCSC installation and the characteristics of the installation line. The following changes the boost factor and resonance factor, resulting in various design cases. Based on the derived boost factor and resonance factor, the size of the reactor and capacitor are calculated. Check the operation characteristics of TCSC considering the firing angle and analyze the operation area. Based on the calculated operating area, proper thyristor parameter selection is performed. After that, the characteristics and harmonics of TCSC are analyzed under various operating conditions.

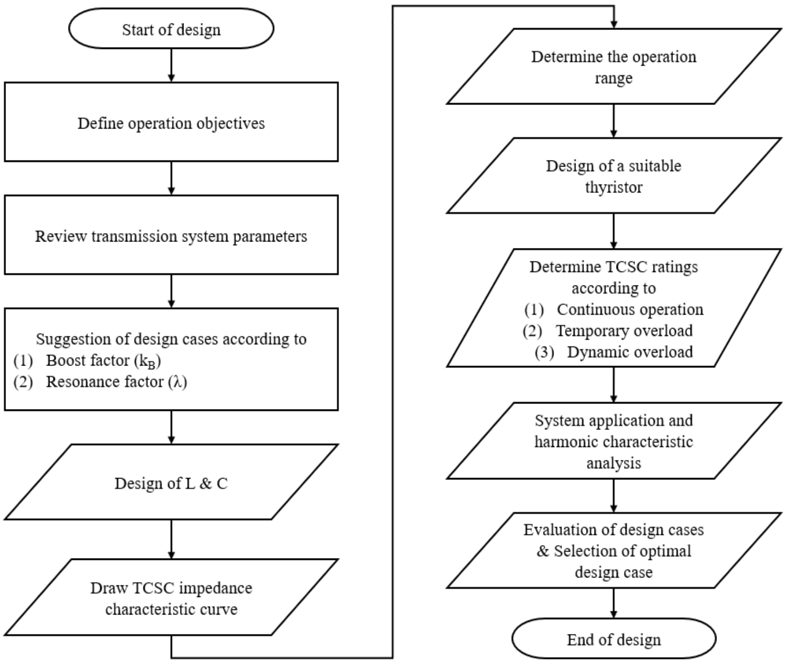


Fig 2. TCSC main circuit element design process

Finally, the analyzed results are compared to determine the most effective case.

3. Practical TCSC design and characteristic analysis

A. Suggestion of design cases according to boost factor and resonance factor

The parameters of the main circuit have three optional elements. It is the percentage compensation, boost factor and resonance factor. The three values are taken into consideration to determine the capacitance and inductance of the TCSC. The compensation rate, booster rate, and resonance rate are defined as in Equations (1) to (3).

$$k(\%) = \frac{X_{TCSC}(\alpha)}{X_L} * 100 \qquad (1)$$

$$k_B = \frac{X_{TCSC-app}}{X_{TCSC-min}} = \frac{X_{TCSC-app}}{X_C} \qquad (2)$$

$$\lambda = \frac{\omega_0}{\omega} = \frac{1}{\omega\sqrt{LC}} = \sqrt{\frac{X_C}{X_L}} \qquad (3)$$

where k(%) is the TCSC percent compensation level, k_B is the booster factor, λ is the resonance factor, X_L is the total line reactance where the TCSC is installed, $X_{TCSC-app}$ is the apparent reactance of the TCSC, ω_0 is the resonance angular velocity, and ω is the angular velocity.

The compensation level is generally the purchaser’s request, and KEPCO required a constant 50% transient 70% compensation level.

According to the IEEE Std 1534 standard, the booster rate is in the range of 1 to 3, and the most common booster factor is 1.2. In addition, if the booster ratio is 1.0, like the fixed series capacitor (FSC), there is no boosting effect by the firing angle control [3].

For the design parameter selection, 60 comparison groups were calculated by increasing the boost value by 0.01 from 1.01 to 1.6. A value of 1.6 or higher actually causes adverse conditions such as high thyristor current, high capacitance, and harmonic increase, and is considered to be meaningless for the optimization comparison, and thus the booster ratio comparison range is set to 1.6.

The resonance factor in the IEEE standard suggests a range between 2.5 and 3.5. However, when the resonance rate is higher than 3.0, multiple resonance phenomena as shown in Fig. 3 can occur on the impedance characteristic curve of TCSC according to the control of the firing angle of the thyristor. Therefore, the range of resonance rate was selected from 11 comparison groups up to 3 with increasing values from 2.5 to 0.05 [4].

Of the 660 cases derived above, 20 representative cases are shown in Table 1.

TABLE I. TCSC MAIN CIRCUIT BOOST FACTOR AND RESONANCE FACTOR

Case	Boost factor (kB)	Resonance factor (λ)	Case	Boost factor (kB)	Resonance factor (λ)
1	1.05	2.5	11	1.2	2.5
2		2.6	12		2.6
3		2.7	13		2.7
4		2.8	14		2.8
5		2.9	15		2.9
6	1.1	2.5	16	1.5	2.5
7		2.6	17		2.6
8		2.7	18		2.7
9		2.8	19		2.8
10		2.9	20		2.9

The capacitance of the capacitor bank and the reactance of the TCR are determined by equations (4) to (5).

$$C = \frac{1}{2\pi f X_C} \qquad (1)$$

$$X_L = \frac{X_C}{\lambda^2},\ L = \frac{X_L}{2\pi f} \qquad (2)$$

The value of capacitance is independent of the resonance factor and only the boost factor. Fig. 3 shows the magnitude of inductance due to the change of boost factor and resonance factor.

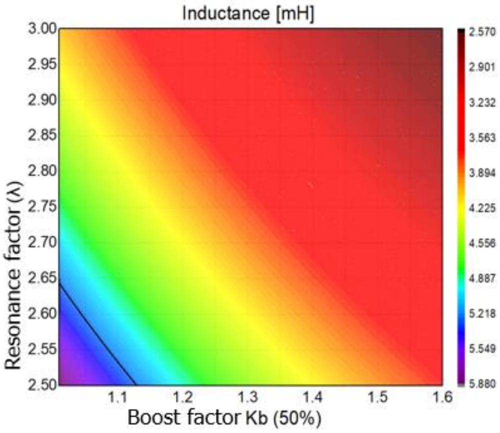


Fig 3. TCSC 50% compensation equivalent model

As can be seen in the figure, the magnitude of the inductance is affected by both the booster rate and the resonance rate. The smaller the two values, the larger the required inductance.

B. *Determine the opration range*

Fig. 4 shows part of the impedance curve for the change in boost factor and resonance factor. This area is the capacitive mode operation area where TCSC is actually operated. In the impedance graph, it can be seen that as the magnitude of the booster rate and the resonance rate increases, the slope increases. A steep slope means that the reactance change can be large for small changes in the firing angle. This requires more precision in the control and it can be seen that the deviation to the target may occur greatly in case of transient state or fault. As shown in Fig. 4, the smaller the boost factor and resonance factor, the better the operating characteristics.

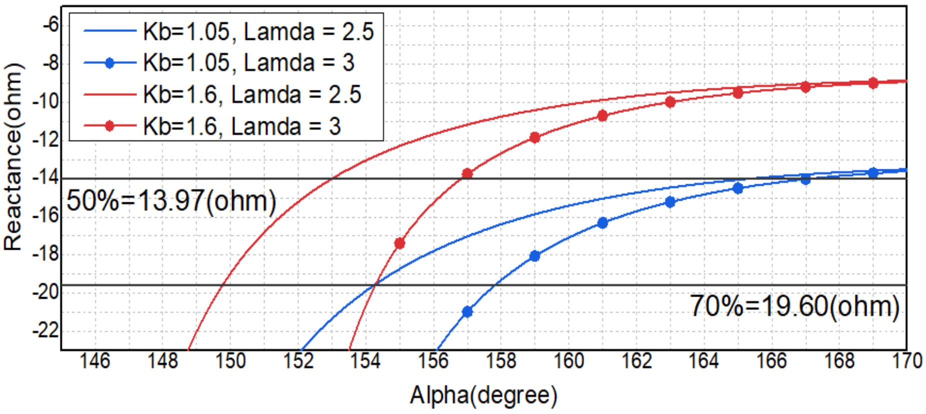


Fig 4. Difference in operating curve according to boost factor and resonance factor

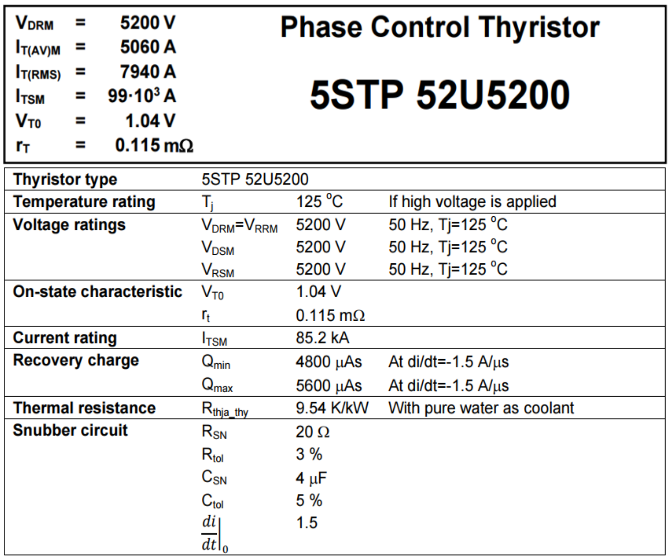
C. *Design of a suitable thyristor*

In the case of thyristor current, a waveform whose value changes with respect to the conduction angle magnitude, not a sinusoidal waveform, appears. The formula for calculating the thyristor current is as shown in equation (6) ~ (7). In the case of ITAV, the average value of bidirectional current in the state of thyristor conduction and ITRMS is the RMS value of the bidirectional current in state of thyristor conduction.

$$I_{TAV} = \frac{k^2}{K^2-1} \times \frac{\widehat{I_L}}{\pi} \times [\frac{1}{k} \times \cos\left(\frac{\sigma}{2}\right) \times \tan\left(\frac{k\sigma}{2}\right) - \sin\left(\frac{\sigma}{2}\right) \tag{6}$$

$$I_{TRMS} = \frac{k^2}{k^2-1} \times \widehat{I_L} \times \sqrt{\frac{\sigma}{4\pi}\left\{1 + \frac{\sin\sigma}{\sigma} + \frac{1+\cos\sigma}{1+\cos(k\sigma)} \times \left[1 + \frac{\sin(k\sigma)}{k\sigma}\right] - 4\frac{\cos\left(\frac{\sigma}{2}\right)}{\cos\left(\frac{k\sigma}{2}\right)}\left[\frac{\sin\frac{(k+1)\sigma}{2}}{(k+1)\sigma} + \frac{\sin\frac{(k-1)\sigma}{2}}{(k-1)\sigma}\right]\right\}} \tag{7}$$

where σ means conduction angle. In the case of thyristor, the most suitable '5STP 52U5200' model was selected. Fig. 5 shows the specifications of the selected model.



V_{DRM} = 5200 V
$I_{T(AV)M}$ = 5060 A
$I_{T(RMS)}$ = 7940 A
I_{TSM} = $99 \cdot 10^3$ A
V_{T0} = 1.04 V
r_T = 0.115 mΩ

Phase Control Thyristor

5STP 52U5200

Thyristor type	5STP 52U5200		
Temperature rating	T_j	125 °C	If high voltage is applied
Voltage ratings	$V_{DRM}=V_{RRM}$ V_{DSM} V_{RSM}	5200 V 5200 V 5200 V	50 Hz, Tj=125 °C 50 Hz, Tj=125 °C 50 Hz, Tj=125 °C
On-state characteristic	V_{T0} r_t	1.04 V 0.115 mΩ	
Current rating	I_{TSM}	85.2 kA	
Recovery charge	Q_{min} Q_{max}	4800 μAs 5600 μAs	At di/dt=-1.5 A/μs At di/dt=-1.5 A/μs
Thermal resistance	R_{thja_thy}	9.54 K/kW	With pure water as coolant
Snubber circuit	R_{SN} R_{tol} C_{SN} C_{tol} $\left.\frac{di}{dt}\right\|_0$	20 Ω 3 % 4 μF 5 % 1.5	

Fig 5. Specification of thyristor model

For the thyristor voltage, the design was carried out with the aim of 1.05 ~ 6 at the steady state for each case and the results of the design are shown in Table 2. As can be seen from the table, as the boost factor and resonance factor increase, the number of valve stacks required for stable thyristor valve increases and the operating loss increases.

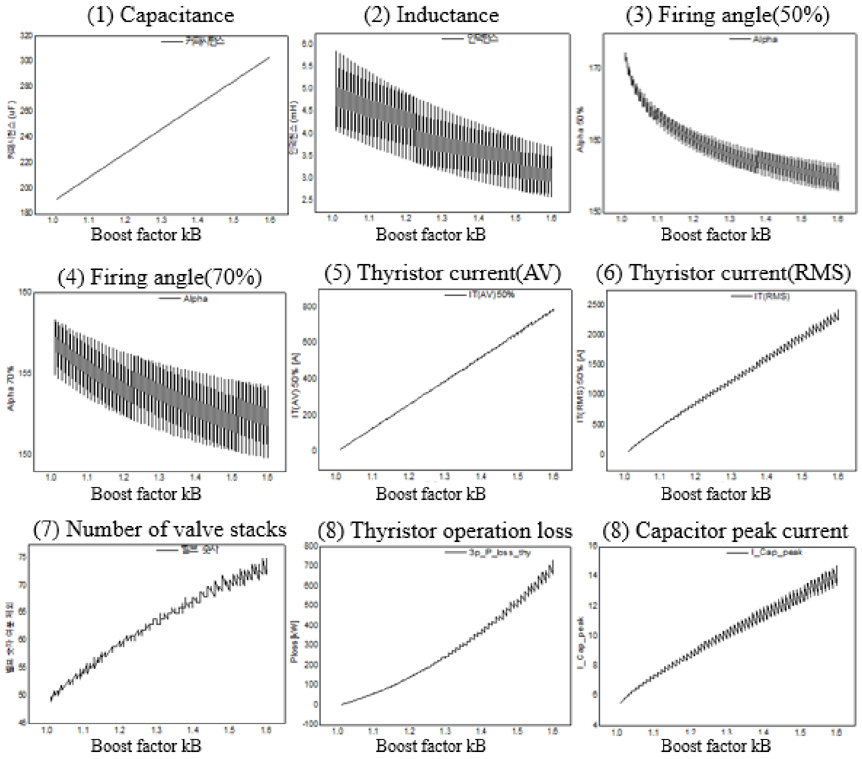
TABLE II. THYRISTOR DESIGN RESULTS FOR EACH CASE

Case	Current change differential (nominal) [A/μS]	Trigger instantaneous maximum voltage [kV]	Current change differential (Maximum) [A/μS]	Number of Thyristor Valve	Thyristor maximum voltage (steady state) [kv]	Capacitive Mode Voltage Margin	Thyristor maximum voltage (transiant) [kv]	Block Mode Voltage Margin	Thyristor conduction loss [kW]
1	16.13	91.1	19.17	52	4.96	1.05	4.69	1.11	26.27
2	17.18	89.71	20.42	52	4.94	1.05	4.69	1.11	26.32
3	18.37	88.92	21.82	52	4.96	1.05	4.69	1.11	26.19
4	19.49	87.72	23.15	52	4.95	1.05	4.69	1.11	25.9
5	20.52	86.1	24.38	52	4.92	1.06	4.69	1.11	26.16
6	17.66	95.21	20.99	55	4.98	1.05	4.43	1.17	58.76
7	18.68	93.1	22.2	55	4.93	1.05	4.43	1.17	59.01
8	19.81	91.55	23.54	55	4.91	1.06	4.43	1.17	58.8
9	21.11	90.69	25.08	55	4.92	1.06	4.43	1.17	58.13

10	22.31	89.35	26.5	54	4.98	1.05	4.51	1.15	57.58
11	20.21	99.88	24.02	60	4.93	1.06	4.06	1.28	138.72
12	21.54	98.39	25.59	60	4.92	1.06	4.06	1.28	140.39
13	23.03	97.54	27.36	60	4.94	1.05	4.06	1.28	140.78
14	24.38	96.03	28.97	60	4.92	1.06	4.06	1.28	143.41
15	25.56	93.85	30.37	59	4.94	1.05	4.13	1.26	139.09
16	27.44	108.44	32.6	69	4.95	1.05	3.53	1.47	500
17	29.32	107.16	34.84	69	4.97	1.05	3.53	1.47	495.49
18	31.46	106.6	37.37	70	4.96	1.05	3.48	1.49	517.59
19	33.29	104.9	39.55	70	4.96	1.05	3.48	1.49	511.25
20	35.47	104.19	42.14	71	4.94	1.05	3.43	1.52	536.02

4. The results of TCSC parameter selection

Fig. 6 shows the trends for various items as the boost factor changes.


(1) Capacitance (2) Inductance (3) Firing angle(50%)

(4) Firing angle(70%) (5) Thyristor current(AV) (6) Thyristor current(RMS)

(7) Number of valve stacks (8) Thyristor operation loss (8) Capacitor peak current

Fig 6. Trend of TCSC characteristics with boost factor change

Except for inductance and firing angle corresponding to (2) ~ (4) in Fig. 6, all TCSC parameters can be seen to increase as the boost factor increases. The greater the vibration width of the increasing parameter, the more the parameter is affected by the resonance factor. Among the decreasing parameters, in the case of the firing angle, as shown in Fig. 4, the larger the value, the more favorable the characteristic. If the reactor can be manufactured with a high inductance value, the lower the boost factor is, the more advantageous it is.

5. Conclusions

This paper deals with the correlation of boost factor and resonant factor to be considered when determining TCSC main circuit elements, and the capacitor TCR and thyristor parameter determination. According to the process presented through the paper, each parameter of TCSC was classified and analyzed for each case. Within the range of standards proposed by IEEE standard, the smaller the boost factor and the resonant factor, the more effective the design and operation. Reactor inductance is difficult to produce as its capacity increases. However, if there is no such restriction, it is advantageous to set the resonance factor low. This paper can be effectively used to select the main circuit element parameters of the practical TCSC.

Acknowledgment

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