Analyze of Real Switching Angle Limits in TCSC on Capacitor and Inductor Values and their Selection Factors

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Abstract

Thyristor-controlled series capacitor (TCSC) as one of the most important FACT devices can be used for various purposes such as reactive power compensation, voltage control, dynamic stability improvement and power oscillation damping in power systems. Practical aspects on sizing of TCSC elements must be considered to have the fast and reliable switching from capacitor to inductive region and vice versa which is described in this paper.

The influencing factors on TCSC characteristic, the requirements of L and C, practical and exact limits of firing angle are presented by detailed analyzing and simulations. Also exact firing angle limitation and stable thyristor trigger angle are discussed for the first time.

Keywords: *Thyristor controlled series capacitor, Inductor and capacitor selection, fire angle limits*

1. Introduction

Several power electronics equipments have been proposed for improving power system behavior in recent decades. These equipments are in series and shunt, active and passive, controlled and switched categories. Each of them is used for one or some purposes like reactive power compensation, voltage control, dynamic stability improvement and power oscillation damping [1].

Thyristor Controlled Series Capacitor (TCSC) consists of a series compensating capacitor shunted by a thyristor controlled reactor (TCR). TCSC is one of the Flexible AC Transmission Systems (FACTS) devices which is used for all mentioned purposed. TCSC has shown good capabilities in researches [2-4]. TCSC has advantages of using thyristor (with natural commutation) and low frequency switching. Therefore its cost, complexity and power loss have reduced.

TCSC requirements are less considered and studied in aspect of design view like capacitor and inductor sizing and switching conditions. Thyristor and Gate-Controlled Series Capacitors are compared in [6]. The reactance characteristic and resonance condition of TCSC are discussed in [7]. A prototype, laboratory scale TCSC design is described in [8]. Proper thyristor triggering base on inductor and capacitor size is presented in [9].

Impedance of transmission line for compensation, switching time, capacitive and inductor mode switching, minimum voltage necessary for switching, harmonics and components ratings, thyristor ratings and other factors are considered in this paper.

Considering ideal switching angle may lead to unsuccessful switching or instability. Therefore practical limits of switching angle, capacitor and inductor reactance are discussed in details here.

At the first, main structure and operation of TCSC is brought up. Then, the capacitive and inductive operation mode of TCSC is analyzed in details. The requirements of L and C and practical limits of firing angle are mentioned in the third section. Validation of those conditions is satisfied by simulation in the last section and checking with practical installed three TCSC's.

2. Operation of TCSC

TCSC is consisted as a series compensating capacitor (C) shunted by a thyristor controlled reactor (TCR) as shown in Figure 1 which is placed series in transmission line [1].

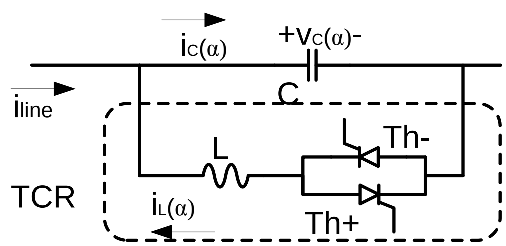


Figure 1. Schematic Diagram of TCSC

TCSC has four operation modes: Blocking, Bypass, Capacitive and Inductive mode. TCSC impedance consists of capacitor and inductor reactance as equation (1) where $jX_L(\alpha)$ is reactance of the inductive branch and depends on the firing angle (α) of thyristors. The four mode operations are made by this angle.

$$jX_{TCSC}(\alpha) = \frac{jX_L(\alpha) * (-jX_C)}{jX_L(\alpha) + (-jX_C)} \tag{1}$$

Blocking Mode Operation

If thyristors are off during the each period, The TCSC impedance will be equal to capacitance reactance XC. It is obvious that TCSC will be like a series capacitor and will have all effects of series capacitor in the transmission line. The firing angle of the thyristors is 90 degree in this mode [5].

Bypass Mode Operation

When two anti-parallel thyristors are on in all time that they have turning on condition, TCSC will operate in Bypass mode. Thyristors conduct 180 degree in each cycle. The inductance of TCR branch is in circuit always and TCSC impedance is equal to equation (2) in this case [5].

$$X_{TCSC} = -\frac{X_L X_C}{X_L - X_C} \tag{2}$$

It is recommended to consider negative sign in equation (2) because the negative value of X_{TCSC} will mean capacitive reactance and the positive value will be equal inductive reactance. This is demonstrated in equation (3).

$$jX_{TCSC} = \frac{jX_L(-jX_C)}{jX_L - jX_C} = -j\frac{X_L X_C}{X_L - X_C} \tag{3}$$

TCSC impedance will be inductive because X_L is smaller than X_C.

Capacitive and Inductive Mode Operation

If the firing angle of the thyristors is greater than zero and smaller than 90 degree, The Impedance of TCR branch in fundamental frequency will be equal to equation (4) that α is firing delay angle respect to zero crossing of the line current. σ is conducting angle and is equal to $\sigma = 2\pi - \alpha$.

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - Sin 2\alpha}, X_L \le X_L(\alpha) \le \infty \quad (4)$$

In an angle, named resonance angle, $X_L(\alpha_{resonance})$ will be equal to X_C and equation (1) will be infinite. Therefore TCSC impedance characteristics gains as shown in Figure 2. TCSC will be in inductive mode for firing angle smaller than resonance angle and will be in capacitive mode for firing angle greater than resonance angle.

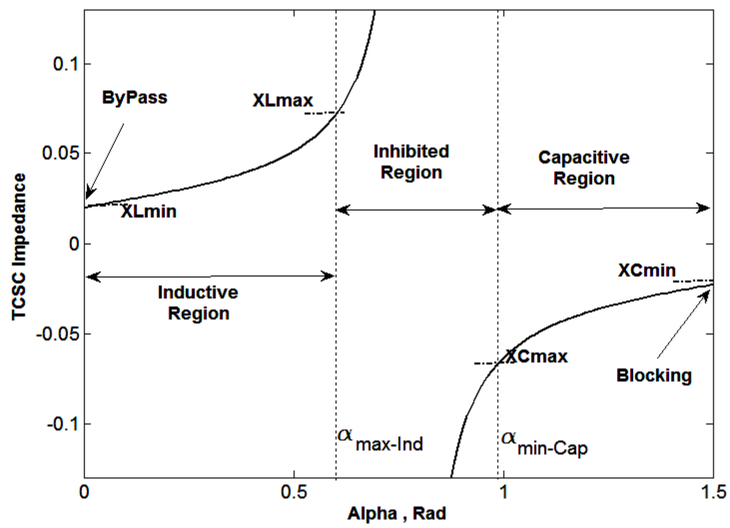


Figure 2. Mode Operations of TCSC

Changing of TCSC impedance is very fast near the $\alpha_{resonance}$ and sensitivity to the firing angle is high. Therefore, an inhibited region is defined between capacitive and inductive area. This area is shown in Figure 2 between $\alpha_{\min-Cap}$ and $\alpha_{\max-Ind}$.

Detail Analyses of Switching in Capacitive Mode

The firing angle of thyristors are controlled as $X_L(\alpha)>X_C$ in the capacitor mode operation. It happened for α greater than $\alpha_{\min\_Cap}$ and smaller than 90 degree.

As shown in Figure 3, when capacitor voltage and line current are in different polarity, proper thyristor will turn on in delay firing angle α from zero crossing of the line current in t_1. So a resonance circuit consisted of L and C creates witch resonates half cycle and thyristor turns off in t_2. Detail analyses of this resonance circuit will come in next section.

This resonance is shown in Figure 3. Result of this half cycle resonance is inversing polarity of capacitor voltage from V_{C0} volte in switching instant to $-V_{C0}$ at t_2 (end of half cycle resonance).

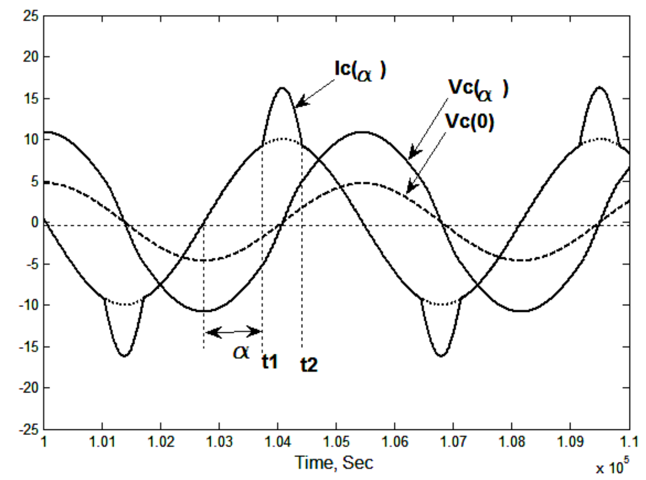


Figure 3. Switching in Capacitive Mode

As shown in Figure 3, the mentioned switching causes to increasing capacitor voltage and seeing larger capacitor effects. Rapid changing of capacitor voltage due to resonance circuit, in firing angle between 90^0 and α_{Cmin} degree, makes current more leading and the capacitive mode in TCSC.

Detail Analyses of Switching in Inductive Mode

For TCSC operation in the inductive mode, the firing angle of TCR branch must be controlled as $X_{L(\alpha)}<X_C$. This condition occurs in α degree greater than zero and smell than α_{Lmax}.

As shown in Figure 4, in the firing angle α after zero crossing of the line current, in situation that capacitor voltage and line current are in opposite polarity, proper thyristor turn on in t_1. After that the resonance circuit is excited and a half cycle of resonance is executed, the thyristor will turn off in t_2. The result of this half cycle resonance is inversing of capacitor voltage from V_{C0} to $-V_{C0}$.

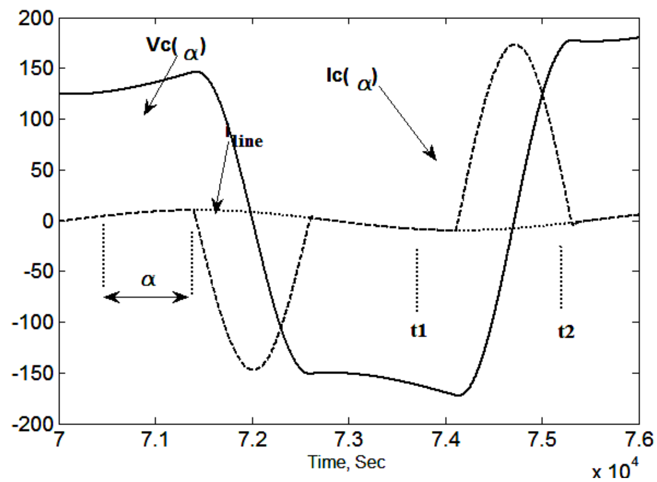


Figure 4. Switching in Inductive Mode

Rapid change of capacitor voltage due to exciting of the resonance circuit, in firing angle between zero and α_{Lmax}, causes lagging line current and inductive impedance of TCSC.

3. Requirements of L, C and Firing Angle

Practical requirements and limits of X_L, X_C and the firing angle are discussed in this section. At the first, selection of TCSC parameters and their results have been described and next precision limits of firing angle for stable and successful switching have been analyzed.

3.1. Requirements and Notes in Selection of C & L

(Requirement-1) to (Requirement-4) must be considered in the selection of L and C.

(Requirment-1): X_L must be smaller than X_C. Proportion of the inductor impedance to the capacitor impedance, K_{LC} , must be smaller than unit as equation(5).

$$K_{LC} = \frac{X_L}{X_C} < 1 \tag{5}$$

(Requirement-2): The resonance frequency $\omega_r = \frac{1}{\sqrt{LC}}$, must be away enough from power frequency (ω_1=2π*50 Rad/sec). It means that reversing polarity of the capacitor voltage must be fast as it longs smaller than half cycle of power frequency period.

$$\omega_r = \omega_1 \sqrt{\frac{X_C}{X_L}} = \frac{1}{\sqrt{LC}}, \qquad \omega_r >> \omega_1 \tag{6}$$

(Requirement-3): The resonance frequency, ω_r must be far enough from the harmonics of the power frequency, where ω_n is the n^{th} harmonics of the power frequency.

$$\omega_n \neq n\omega_r \qquad , n = 1, 2, 3, ... \tag{7}$$

(Requirement-4): The value of X_C must be sufficient to have proper line series compensation (typically until 70% compensation). As shown in Fig.2, the TCSC impedance never is equal to zero. The TCSC impedance is between X_{Lmin} and X_{Lmax} in the inductive mode and between $-X_{Cmin}$ and $-X_{Cmax}$ in the capacitive mode.

This boundary must be coordinated with practical requirements like the transmission line impedance and its thermal capacity.

$$X_{TCSC} = -K_{se} X_{Line} \tag{8}$$

Where X_{Line} is the transmission line impedance and K_{se} is percentage of the series compensation. The upper limit of the series compensation is also determined by the stability margin of the subsynchronous resonance [7-9].

Consideration of the above-mentioned requirements is necessary. In addition to these requirements, some notes are useful in TCSC designing.

(Note-1): If X_L is very smaller than X_C then TCSC acts as thyristor series switched capacitor (TSSC).

(Note-2): The small value for X_L has this benefit that duration of the hale cycle resonance will be short and reversing process of capacitor voltage will be fast and good.

(Note-3): The big value for X_L has this advantage that maximum current of inductor will be smaller and the overall cost will be lower due to decreasing the components ratings [6].

(Note-4): In Some protection schemes, the thyristors of TCR branch will be fired to operate in fully conducted mode to perform the bypass operation. In this case, the inductive impedance of TCSC will partly limit the fault current. Therefore, small value for X_L is an advantage [5, 11].

(Note-5): If X_L is small then the current harmonics will have bigger components. These harmonics affect the capacitor and power system.

(Note-6): Whatever X_L/X_C selects smaller, capacitor area operation will be shorter and whatever X_L/X_C is closer to 1.0, the resonance angle will happen in smaller angle and therefore the capacitive operation area will be wider(See requiremen-1 also).

(Note-7): If X_L/X_C is smaller than 1/9, then more than one resonance area will exist. Therefore, the available operating area of TCSC will be restricted [7, 8].

(Note-8): As TCSC impedance depends on the firing angle, the controllability and precision of TCSC compensation depends on the resolution of the firing angle controller [9].

(Note-9): The maximum current of LC circuit, $I_{L\max}$, depends on the capacitor voltage on switching instant, V_{C0}, L and C according to equation (9). Therefore, a large value for L and small value for C causes larger components rating and larger harmonics.

$$I_{L\max} = V_{C0}\sqrt{\frac{C}{L}} \tag{9}$$

Following relations are used for detail analyses.

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - Sin\alpha} = K_{LC} K_\alpha X_C \tag{10}$$

$$K_\alpha = \frac{\pi}{\pi - 2\alpha - Sin\alpha} \tag{11}$$

$$X_C = \frac{K_{LC} K_\alpha - 1}{K_{LC} K_\alpha} K_{se} X_{Line} \tag{12}$$

$$X_L(\alpha) = (K_{LC} K_\alpha - 1) K_{se} X_{Line} \tag{13}$$

The firing angle is formulated in K_α factor. The percentage of series compensation is defined between two boundary on the (Requirement-4) and (Note-4) as (14).

$$K_{se_{\min}} < K_{se} < K_{se_{\max}} \tag{14}$$

3.2. The Precision Details of Stable Firing Angle

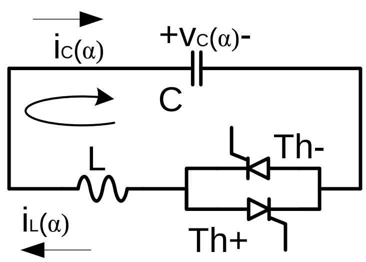
The firing angle for TCSC is defined as equation (2) theoretically, for the capacitive operation $\alpha_{\min-Cap} < \alpha < \pi/2$ and for the inductive operation $0 < \alpha < \alpha_{\max-Ind}$. But some practical limitation must be considered.

At first, it is necessary that LC resonance circuit must be analyzed in detail. Internal equations of TCSC can be considering as a LC resonance at each switching start with equations (15).

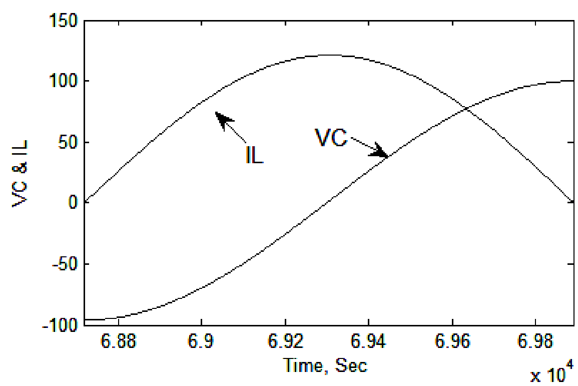
$$0 = v_c + LC\frac{dv_c}{dt}$$
$$v_c(0) = V_{C0}, \frac{dv_c}{dt}|_{t=0} = 0 \quad (15)$$

As shown in Figure 5, the LC resonance will work for half cycle because of conduction thyristors in one direction as a semiconductor. The resonance frequency is $1/(2\pi \cdot \sqrt{LC})$ Hz.

$$v_c(t) = V_{C0} \cdot Cos(\omega_r t)$$
$$i_L(t) = V_{C0}\sqrt{\frac{C}{L}} \cdot Sin(\omega_r t), \omega_r = \frac{1}{\sqrt{LC}} \quad (16)$$



a) The LC Circuit



b) Capacitor voltage and Inductor Current in half cycle

Figure 5. The LC Resonance Circuit and Capacitor Voltage Change

The result of this resonance is inversing of capacitor voltage according to equation (16) in both capacitive an inductive operation mode.

(Lemma-1): the capacitor must have a minimum voltage at switching instant for success switching.

As capacitor voltage and line current are orthogonal to each other (90 degree difference phase), and the capacitor current is equal to the line current before firing thyristors, the initial capacitor voltage can be written as:

$$V_C(t) = jX_C \cdot i_{line}(t) \quad (17)$$

The minimum capacitor voltage must be equal to minimum voltage for turning on ($V_{ON-\min}$) for thyristors. For this calculation, it is necessary to observe the condition that worth case may happen in near zero crossing of line currents.

$$\alpha_{C\max} = \sin^{-1}(V_{On-\min} / V_{C\max}) \tag{18}$$

The $V_{C\max}$ depends on transmission line current, firing angle operation of TCSC and Capacitor capacity. Therefore, maximum firing angle in capacitive mode is not 900. The angle $\alpha_{C\max}$ must be considered as shown in Figure 6.

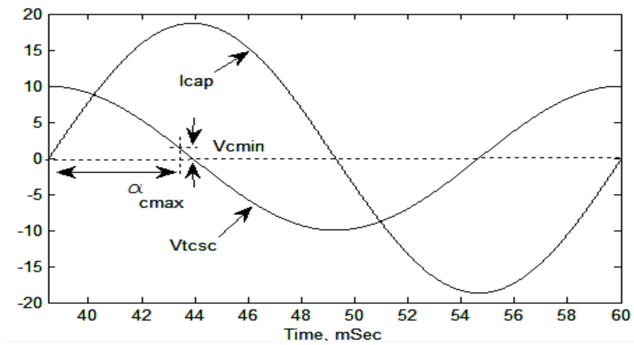


Figure 6. The Maximum Firing Angle in the Capacitive Mode

(Lemma-2): The resonance circuit operates for $\pi \cdot \sqrt{LC}$ seconds.

The required time for half cycle resonance is $t_2 - t_1 = \pi \cdot \sqrt{LC}$. This time must be less than half period of power frequency ($t_3 = 1/(2f)$). These two time duration are shown in Figure 7.

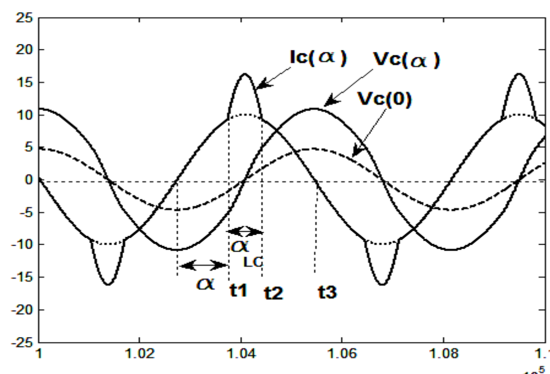


Figure 7. Power Frequency Period and Resonance Frequency Period

Therefore, the switching must be done and finished at the amount of α_{LC} degree before the termination of half power frequency cycle.

$$\begin{aligned} &\alpha_{LC} = \omega \cdot \Delta t = (2\pi f)(t_2 - t_1) = 2\pi^2 f \sqrt{LC} \\ &\alpha_{\max} + \alpha_{LC}/2 < \pi/2m \quad , \quad t_{1\max} = \frac{1}{2f} - \alpha_{LC} \end{aligned} \tag{19}$$

This lemma limits the firing angles that are shown in Figure 2.

Obviously these two lemmas are different; the first lemma clearly shows dependency of circuit to the capacitor and line current but second lemma is independent of current and voltage and only depends on L and C value.

4. Simulation and Evaluation of Requirements and Notes

In this section, evaluation of the mentioned requirements have been analyzed and simulated.

Following relations is useful for evaluation (Requirment-3).

$$\omega_r = \omega_1 \sqrt{\frac{X_C}{X_L}} = \frac{1}{\sqrt{LC}} \neq n\omega_1 \qquad n = 1, 2..11 \tag{20}$$

Although said that there are not even harmonics in the power networks and the major harmonics components are 5th, 7th, 11th and 13th. But there are all even and odd harmonics in power system because of unbalancing, faults, transformers inrush currents and switching transient. Therefore all low harmonic components must be considered in this requirement.

In (Requirement-4), a condition must be fulfilled in minimum compensation percentage as this condition happened in α=π/2 as equation (21).

$$X_C = K_{se_{\min}} X_{Line} \tag{21}$$

A condition for $\alpha_{C\min}$ is achieved at maximum compensation as shown in equation (22).

$$X_{TCSC}(\alpha_{C\min}) = K_{se\max} X_{line} \tag{22}$$

For example, if a transmission line has 1.0 ohm reactance, and the compensation between 20% and 70% is considered, then on equation (21) and in minimum compensation, X_C will obtain 0.2 ohm for maximum capacitor compensation:

$$X_L(\alpha_{C\min}) = \frac{0.14}{0.9} = 0.156 = X_L \frac{\pi}{\pi - 2\alpha_{C\min} - Sin\alpha_{C\min}} \tag{23}$$

It seems that the capacitor reactance will obtain for α=π/2 for a minimum compensation.

As mentioned in (Requirment-5), the small inductances will increase harmonic components. The 5th and 7^{th} harmonic components are shown in Table 1 to different values of X_L/X_C as followings.

Table 1. Harmonic Components versus X_L/X_C

X_L/X_C	0.5	0.3	0.1	0.07	0.05	0.03
5^{th} harmonic	10.7	18.6	28.8	30.7	32.1	33.8
7^{th} harmonic	1.25	1.59	10.8	13.3	15.3	17.6

The Note-6 has simulated for different value of X_L/X_C. The resonance angle that X_L is equal to X_C and $X_{TCSC}=\infty$, is shown Table 2.

Table 2. The Resonance Angle versus X_L/X_C

X_L/X_C	0.5	0.3	0.1	0.07	0.05	0.03
$\alpha_{resonance}$	30.5	43.3	56.9	59.1	60.6	62.0

Therefore for small value of X_L/X_C, the operation area of capacitor mode will become narrow and the resonance will occur in lower angle.

On Note-6, a small value of X_L/X_C will result in more than one resonance angle in TCSC operation characteristics. For X_L=0.4 and X_C=10, TCSC characteristics is shown in Figure 8.

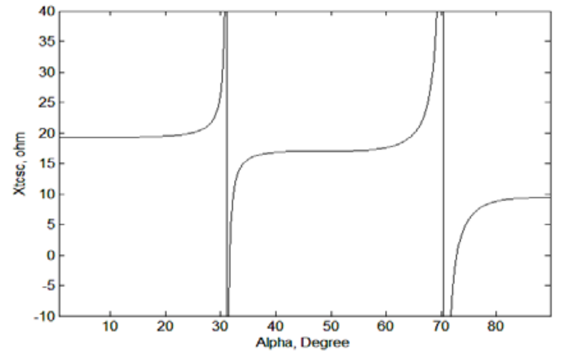


Figure 8. TCSC Impedance for X_L=0.4 and X_C=10

The requirements and notes of this paper is performed on three installed TCSC Specification [10]. The parameters of these TCSC are shown in Table 3.

Table 3. Performance Analysis of Proposed Requirement of Three Installed TCSC

TCSC	Kayenta in Arizona	Brazil	Tian Guang
X_L/X_C	2.42	2.74	2.5076
Resonance Anegle	142^o-143^o	144^o-144.5^o	144^o-144.5^o
X_{Cmin}/X_{Cmax}	1:4	1:3	1:3
Capacitive Range Ω	15-16	13.27-40.53	4.15-12.93

The analyses according to Reqirements1-4 and Notes1-9, presented that if X_L/X_C ratio was smaller (near to 2) then the capacitor area operation will be wider (Note-6) and the controllability and precision of TCSC compensation will be better (Note-8).

5. Conclusion

In this article, the effective factors on TCSC design have been analyzed in detail. As discussed in Requirment-4, the minimum series compensation will determine the capacitor reactance in $\alpha=\pi/2$. It is suggested to design capacitive operation area between two free angles versus power system condition. Besides, it is also suggested to use wider capacitive operation area base on philosophy of control for not using inductive operation area on the Note-6.

The minimum and maximum series compensation is determined by thermal rating and stability of line transmission.

The Lamma-1and Lemma-2 determines more limits on the firing angle. Considering these two lemmas will cause to stable operation of TCSC in its defined area.

As previous author work on fast mode switching of TCSC in [11], the requirements and Lemmas mentioned in this paper can be used in improvements of dynamic response of TCSC in future works. Sensitivity analyzes of firing angle to capacitor and inductor value must be done in the future for optimum design of control circuit.

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