

Modification of structure of the TCSC controller regarding optimum use of current-carrying capacity of its elements

Abstract In the paper, the rules of choice of the TCSC controller's elements have been reported. Computer simulation defining the load of the individual elements as well as the controller's influence on the higher harmonics content in the grid have been carried out. It was found that the controller can not be fully loaded without filtration. The filter capacity to the controller capacity ratio as sine qua non condition for the controller's proper operation under full load of its elements has been determined. A new structure of the controller's principal networks when the sine qua non condition is not fulfilled has been proposed.

Streszczenie W artykule podano zasady doboru elementów sterownika TCSC. Przeprowadzono symulacje komputerowe określające obciążenie poszczególnych elementów, jak i wpływ sterownika na zawartość wyższych harmonicznych w sieci. Stwierdzono, że bez filtracji sterownik nie może być w pełni obciążony. Określono stosunek pojemności filtra do pojemności sterownika, warunkujący możliwość prawidłowej pracy sterownika przy pełnym obciążeniu jego elementów. Zaproponowano nową strukturę obwodów głównych sterownika przy niespełnionym warunku. (Modyfikacja struktury obwodów sterownika TCSC ze względu na optymalne wykorzystanie obciążalności jego elementów)

Key words: FACTS, TCSC, principal circuits' structure

Słowa kluczowe: FACTS, TCSC, struktura obwodów głównych

Introduction

The Thyristor Controlled Series Compensator (TCSC) performs the system's control by changing its reactance [1]. By introducing the capacitive reactance, the inductive reactance of the transmission system is partially compensated and, in effect, an increase in its active power transmission capability is obtained with simultaneous limiting of the reactive power. In radial networks, the compensation of the line reactance reduces the voltage fluctuations due to the varying reactive power consumption by the consumers with varying load-type. By introducing the inductive reactance (unavailable with some TCSCs), the transmitted active power in the closed networks is limited; it can be applied to attenuate the power swings and also affects the short-circuit currents' reduction.

Two basic ways of the reactance's control are known: with direct control of the voltage across the capacitor and with the coil current control (Fig. 1) [1].

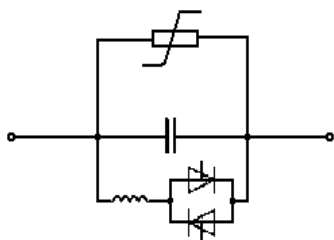


Fig.1 TCSC controller principal circuit with coil current control

Both systems as equipped with over-voltage protectors. However, the system with direct regulation of capacitor's voltage provides introduction of the capacitive reactance only whilst that with the reactor current control, at properly chosen elements, provides both the capacitive and the inductive reactance (Fig.2). In an ideal controller, the valve setting angle was between $\pi/2$ and π . In the true controller, this range will be slightly shifted due to the reactor's resistivity. In addition, due to the current-carrying capacity of elements, a range of forbidden angles will occur adjacent to the current resonance. Nearby the resonance, the current is mainly limited by resistivity of elements. In effect, the character of the controller's impedance can become undesired; it can result in extension of the forbidden region

of the valve setting angle. This type of the TCSC controller introduces the odd harmonics into the grid [2]. This fraction of the odd harmonics rises when the valve control angle rises, and the energy quality in the system has to be provided.

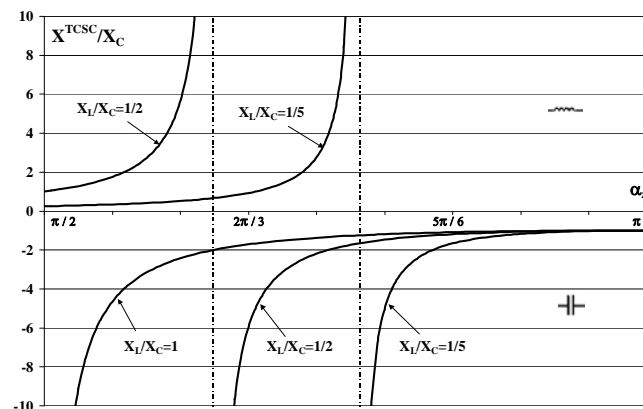


Fig.2 Ideal reactance curve of TCSC controller vs valve setting angle for different X_l/X_c values

Choice of TCSC controller's principal elements

Even in an ideal TCSC controller (Fig.2), some limitations as to the minimum value of the introduced reactance exist. In effect, the reactance of the line-controller system varies first stepwise and then fluently; it determines the least of the available changes in the transmitted power. Referring to these power changes, the minimum values of the reactances introduced by the controller are found: (1)

$$\begin{aligned}
 X_N &= X_K^{S I} + X_K^{S II} + X_{Linii} \\
 X_{TCSC}^{C min} &\leq X_N \left(1 - \frac{P_{Nat}}{P_{TCSC}^{C min}} \right) \\
 X_{TCSC}^{L min} &\leq X_N \left(\frac{P_{Nat}}{P_{TCSC}^{L max}} - 1 \right)
 \end{aligned}
 \tag{1}$$

where X_N stands for a natural reactance of systems $X_K^{S I}$, $X_K^{S II}$ and line X_{Linii} without the TCSC controller; P_{Nat} value of the power transmitted then in natural way; $P_{TCSC}^{C min}$

minimum value of the transmitted power under the TCSC's capacitive operation conditions; P_{TCSC}^{Lmax} maximum value of the transmitted power under the TCSC's inductive operation conditions that corresponds to the minimum limitation of the transmitted power.

Regarding the fact the minimum value of capacitive reactance of the controller appears for the ignition angle $\alpha_z = \pi$, i.e. when the reactor is off, the value of the capacitor's capacitive reactance should be

$$(2) \quad X_C = X_{TCSC}^{Cmin}$$

and, regarding the cost of the capacitor, there is no tendency to take this value lower. The minimum value of the inductive reactance is when $X_L < X_C$ and the ignition angle is $\alpha_z = \pi/2$. For such a case, the reactor's reactance can be found from the relationship

$$(3) \quad X_L \leq \frac{X_C X_{TCSC}^{Lmin}}{X_C + X_{TCSC}^{Lmin}}$$

The value calculated from (3) can be lowered until it falls into the range $1/5 < X_L/X_C < 1/2$. Thus, the reactor's cost is lowered and, simultaneously, the relatively good control properties are maintained.

In the successive step, the nominal voltages and currents of the elements are to be determined. Increase in the transmitted active power means the voltage drop on the TCSC according to the formula

$$(4) \quad \Delta U_{TCSC}^{Cmax} = \left(\frac{P_{TCSC}^{Cmax}}{P_{Nat}} - 1 \right) \frac{U}{\sqrt{3}} \sqrt{2 - 2 \cos \delta_{12}}$$

where P_{TCSC}^{Cmax} denoted maximum value of transmitted power due to the TCSC system; δ_{12} denotes the angle of spread of the voltage vectors between subsystems.

However, with the short-circuit current being limited, voltage drop across the TSCS will be described by the formula:

$$(5) \quad \Delta U_{TCSC}^{Lmax} = \left(1 - \frac{I_K^{TCSC}}{I_K} \right) \frac{U}{\sqrt{3}}$$

where I_K stands for the short-circuit current without TCSC controller and I_K^{TCSC} denotes the short-circuit current limited by TCSC.

Capacitor's nominal voltage has to exceed the both values according to the relationship

$$(6) \quad U_{CN} \geq \max \{ \Delta U_{TCSC}^{Cmax}; \Delta U_{TCSC}^{Lmax} \}$$

The choice of the capacitor's nominal current is simple as the capacitor's reactance is constant at a given voltage. Thus, the current can be found according to the Ohm's law:

$$(7) \quad I_{LN} = I_{CN} = \frac{U_{CN}}{X_C}$$

On the reactor, when the maximum voltage occurs, the current is being limited by the thyristors; therefore, another way of finding its maximum value is necessary. This value appears when the controller approaches the parallel resonance (of currents), and the reactor's current approaches the capacitor's current; thus we have (7)

Admissible range of the valves settings of a standard TCSC

The TCSC controller preliminary set according to indications in section 2 is to be tested using simulation to prove its control properties and to check the current-carrying capacity of its elements. Therefore, it has been assumed that the TCSC controller is connected in series with a line section (100 km long, $X_0 = 0,408 \Omega/km$ and $R_0 = 0,07 \Omega/km$) linking together two subsystems (voltage $U_N = 220$ kV, short-circuit capacity $S_K = 2,66$ GVA and phase

angle $\delta_{12} = 25^\circ$). In addition, the control range of the transmitted power of 130% - 200% or 60% - 80% of the naturally transmitted power as well as the opportunity to limit the short-circuit current by half have been assumed. Regarding these assumptions and the formulas reported in the section 2, the assumed control ranges: $X_{TCSC}^{Cmin} \leq 18,65 \Omega$, $X_{TCSC}^{Cmax} \geq 40 \Omega$, $X_{TCSC}^{Lmin} \leq 20 \Omega$, $X_{TCSC}^{Lmax} \geq 60 \Omega$ have been obtained. Consequently, the values $X_C \approx 18,65 \Omega$ i $9,65 \Omega \geq X_L \approx 1/3 X_C \approx 6,22 \Omega$ have been taken. Because the values $\Delta U_{TCSC}^{Cmax} = 55$ kV i $\Delta U_{TCSC}^{Lmax} = 63,5$ kV have been obtained, the $U_{CN} = U_{LN} = 65$ kV and $I_{CN} = I_{LN} = 3,5$ kA were taken. Effective values of currents and voltages versus valves' setting angle are shown in Fig. 3.

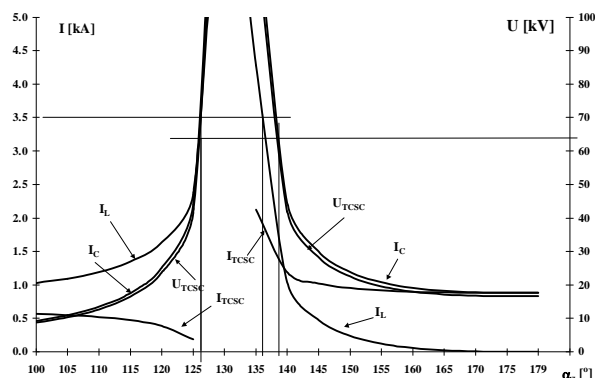


Fig.3 Effective values of currents and voltages across the elements of classic TCSC controller versus valve setting angle

On this base, the range of the forbidden valve setting range regarding the reactor's overload from 127° to 137° has been obtained; however, regarding the capacitor's voltage and overload, the range has been extended and was from 127° to 139° .

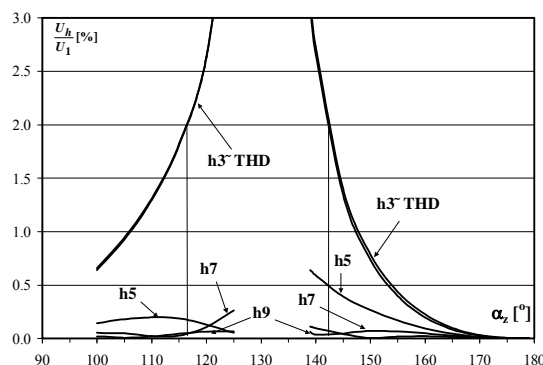


Fig.4 Percentage of harmonics in voltage vs valve setting angle

The next step was to evaluate the voltage harmonics introduced into the network. In Fig.4, the equivalent reactance and resistance of TCSC controller versus valve setting angle is presented. The role of the third harmonics is prevailing as its admissible share in the voltage is 2% [3]. In effect, the forbidden control range extends and is from 116° to 142° . Regarding the reactor's loss, the impedance characteristic for the case is as shown in Fig.5.

Assessing the capabilities of a classic TCSC and considering Fig.5, one can state that when its elements are chosen according to the formulas reported in section 2, the load of elements enables a precisely assumed control in the capacitive region and a control even higher than the assumed one in the inductive region. However, when the

equivalent ratio R_{TCSC} / X_{TCSC} and the resulting losses of active power are considered, the limiting of the setting angle from 120° as well as a precisely assumed control value in the inductive region are obtained.

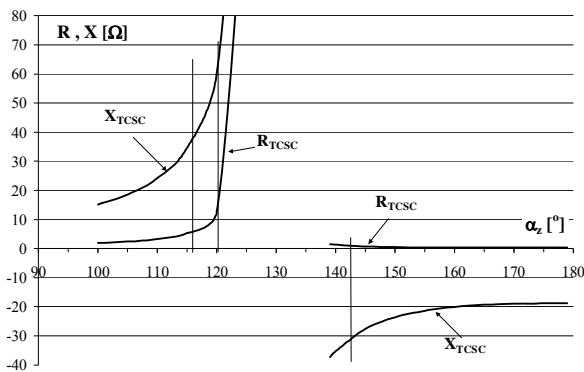


Fig.5 Equivalent reactance and resistance of TCSC controller versus valve setting angle

Unfortunately, the introduced higher harmonics are limiting the setting angle range; it results in a limitation of the controller's control properties from 60Ω to 40Ω in the inductive region and from 40Ω to 30Ω in the capacitive region.

Recapitulating, one may either apply an oversized classic system or shall use a third harmonic filter.

Impact of filter's choice on choice of other elements of controller

As the third harmonics evidently dominates, the filter is constructed just for it; i.e. the filter shunts the TCSC controller. The filter is chosen in classic way [4] (8) according to the relationship

$$(8) \quad I_{CN} \geq \left[\frac{b^2 I_h^2}{p^2 - a^2 \left(\frac{U_F}{U_{CN}} \right)^2} \right]^{\frac{1}{2}}$$

$$X_{CF} = \frac{U_{CN}}{I_{CN}}$$

$$X_{LF} = \frac{X_{CF}}{9}$$

Where: I_h – h –harmonics current; U_F –voltage across filter, U_{CN} – capacitor's nominal voltage; I_{CN} – capacitor's nominal current; p – capacitor's permanent overcurrent factor; b – influence of harmonics higher than filtered ones; a – coefficient increasing the capacitor's load with basic current.

For fundamental frequency, the filter is capacitive. It bypasses the capacitor branch in the controller; in effect, the capacity of the principal circuit's capacitor should be reduced to keep the total reactance for the first harmonics unchanged as described by the relationship:

$$(9) \quad X_C = \frac{8 X_{TCSC}^{C \min} X_{CF}}{8 X_{CF} - 9 X_{TCSC}^{C \min}}$$

Inductive reactance of the principal circuit is being unchanged.

In practice, after having performed many choices of the TCSC controllers' elements, the author is convinced that there are two possibilities at such a way of choosing the filter: either the controller's elements can withstand the full load or a new group of dominating harmonics appear in the

voltage leading just to destabilization of the controller's operation. The figure of merit was which percentage of the capacity has been transferred from the principal branch to the filter. From that came the idea to determine the degree and the way the filter has affected the reactance that shunts the reactor for different frequencies; thus, the following formula has been derived:

$$(10) \quad K = \left| \frac{I + \frac{9 C_F}{8 C}}{I + \frac{9 C_F}{9 - h^2 C}} \right|$$

where K denotes the ratio of the shunt reactance of the reactor after having applied the filter to that before the filter application, C_F is the filter's capacitance and C is the principal branch's capacitance.

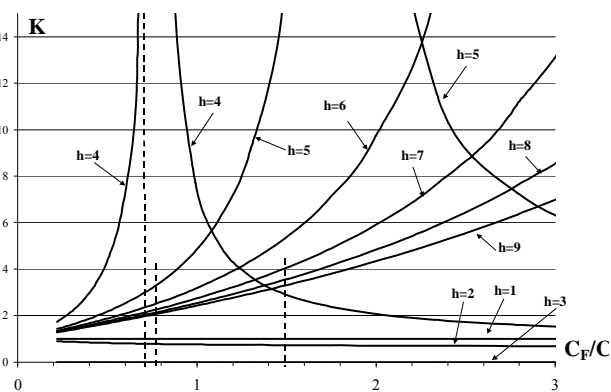


Fig.6 Ratio of the shunting reactance of the reactor in TCSC after having applied the filter to that before the filter application versus the ratio of the filter capacitance to the principal branch's capacitance

Plots for relationship (10) are presented in Fig.6. The filter was chosen in the way to have the fundamental harmonics ($h=1$) unaltered and the third harmonics shorted. In effect, the second harmonics was slightly attenuated whilst the other ones have constructed a stop filter for the determined C_F/C ratios. In an ideal TCSC controller, the even harmonics do not exist; however, they slightly appear in practice due to the reactor's resistance. The fourth harmonics ($h=4$) amplified 30 times exceeds 1% in voltage. Referring to the odd harmonics, the fifth one amplified 3 times and the seventh one amplified four times lead to the 2% exceeding in voltage. Therefore, to avoid the exceeding of the allowable values of harmonics in the voltage, the following condition is to be met:

$$(11) \quad \frac{C_F}{C} < 0,6$$

When condition (11) is met, the TCSC works properly and the full load of elements is possible.

Third harmonics is strongly attenuated and the fifth one becomes the dominant. However, in the range of the valve setting angles allowed by the load, any of harmonics does not exceed the allowable values in voltage (Fig.7).

When condition (11) is not met, the unallowable values of harmonics appear in the voltage. Sometimes, the unstable controller's operation occurs, especially in the range of the summarized inductive reactances.

If, regarding relationship (11), the capacitance C of the principal branch will be increased over the value required by the regulation purposes, the controller will operate properly but the elements will be oversized as it is also a case in the classic solution, i.e. without a filter.

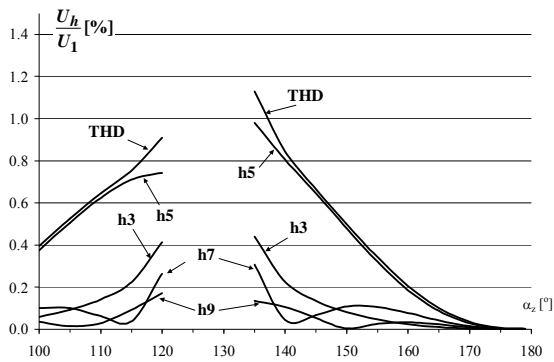


Fig.7 Percentage of harmonics in voltage vs valve setting angle with filter, when condition (11) is met

Modification of principal circuits of the TCSC controller

When the ratio C_F/C increases, the branch that bypasses the reactor for particular harmonics reaches its maximum reactance and then the reactance decreases again (see Fig.6). Therefore, when the requirement (11) is not fulfilled, the consequences of the C_F/C ratio approaching the infinity are to be considered; such a ratio value means the whole capacity from the principal branch is transferred to the filter [5] according to the relationship

$$(12) \quad X_{CF} = \frac{9}{8} X_{TCSC}^{C \min}$$

evidently with the condition (8) met.

Required capacity of the capacitor decreases; however, it works with a voltage which is of 10% higher than that for the classic system. As the total capacity is transferred to the filter, the required reactance of the filter's reactor is reduced as compared to the systems with a filter chosen in classic way.

In such a solution, like as in the system with classically chosen filter, the harmonics content in the voltage does not exceed admissible values even under full load (Fig.8).

Comparing to the solution with the filter chosen in the

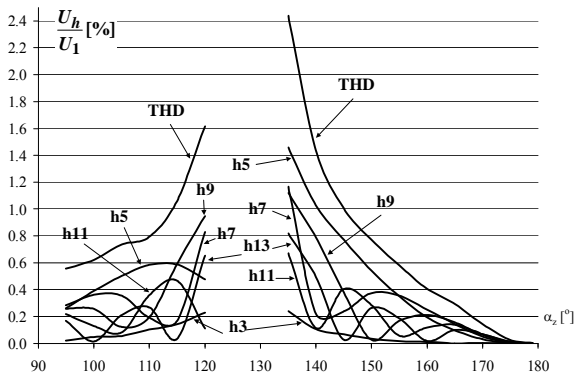


Fig.8 Percentage of harmonics in voltage versus the valves' setting angle when total capacity is transferred to the filter's branch

classic way, when the condition (11) is fulfilled, the modification is unprofitable because the number and value of important harmonics rises (compare Fig.7 and Fig.8). However, when the condition (11) is not fulfilled, the version with classic filter can lead to the THD of 20% and result in the unstable operation of controller; thus, the solution with filter is even worse than that without a filter. In such a case, if there is no wish to pay more for the construction of an oversized TCSC controller, the only reasonable solution is to apply the proposed modification of the principal circuits.

Final remarks

If there is no third harmonic's filter in the branch that shunts the reactor of the TCSC controller, the range of the available reactance regulation (found referring to the admissible load of the TCSC controller's elements) is limited by 1/3 approximately. It results from the fact that the controller introduces both the odd harmonics to the voltage and the limitations resulting from the energy quality; therefore, it requires a significant oversizing of elements and, consequently, related costs. First, for the power-related reasons, the filter has to be chosen regarding the third harmonic. Then, taking into account its capacitive character for the first harmonic, the principal branch's capacity shall be adequately modified. The best result is obtained when the ratio: filter capacity to the principal branch capacity is lower than 0,6. If such a requirement is not met, the control range is even more reduced by the arising resonance circuits. Then, two resolutions exist: either to increase the capacity in the shunting branch (it also results in extension of the TCSC controller's control range but is cost-consuming) or to modify the principal circuit by removing the capacity-containing branch and simultaneously increasing the required capacity of the filter (the odd higher harmonics' content in voltage increases but is still admissible and the system's cost is lower).

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