Daniel HLUBEŇ[1], Ľubomír BEŇA[2], Michal KOLCUN[3]

Technical University of Košice (1), Technical University of Košice (2), Technical University of Košice (3)

Use of TCSC for Active Power Flow Control in the Electric Power System

***Abstract**. The article deals with possibilities of the thyristor controlled series capacitor (TCSC) to control power flows in interconnected electrical power systems. The main goal is to describe the working principle of TCSC and its possible use in the transmission system (TS) and advantages and disadvantages of using of such equipment in the electric power system.*

***Streszczenie.** Artykuł dotyczy możliwości sterowanych tyrystorowo układów kompensacji szeregowej (TCSC) w kontrolowaniu przepływu mocy między połączonymi systemami elektroenergetycznymi. Głównym celem jest opis zasad działania układów TCSC, możliwości ich wykorzystania w systemie przesyłowym (TS), oraz wad i zalet użytkowania takiego sprzętu w systemie elektroenergetycznym. (**Możliwości sterowanych tyrystorowo układów kompensacji szeregowej w kontrolowaniu przepływu mocy**)*

Keywords: TCSC, EPS, power flow
Słowa kluczowe: TCSC, EPS, przepływ mocy

Introduction

In some countries the transit of big amount of electricity via long transmission lines is required as well as interconnection of power systems. This cause, that some lines are extremely overloaded, it causes occurrence of faults and voltage non-stability. The result is decrease of reliability and quality of supplied energy.

Increase of transmission capacities of lines, resp. build-up of new lines is time and money consuming process connected with environmental and legislative restrictions. Due to increasing requirements on transit, the contemporary used form of increase of transmission capacity is non-sufficient.

While handling with electricity in liberalised market, the physical rules of power flows are not fully respected and differences between planned and real physical power flows occur. This will cause overloading of international, as well as national lines and limitation of transmission capacity used for another purpose. In so overloaded system can occur dangerous situations and long-lasting outages. In order to ensure reliable, safe and economical operation of consumers, operators of transmission and distribution systems have to fulfil defined requirements. Abroad are increasingly used specialised systems, based on power electronics, known as FACTS.

Thyristor controlled series compensator (TCSC)

TCSC is a device consisting of capacitor and TCR – thyristor controlled reactor connected in parallel. This TCSC is one of FACTS equipment, which are used for power flow control of active power in electric power system and for increase of capacities of transmission lines. The change of impedance of TCSC is performed by thyristor switched reactor connected in parallel to capacitor. Inductive reactance is defined by firing angle of thyristors.
TCSC usually connects in series with line and allows changing impedance of transmission way and by this change to influence power flows. Control is fast, efficient and increase limits of transmitted power. Basic scheme of TCSC is shown in the following figure.

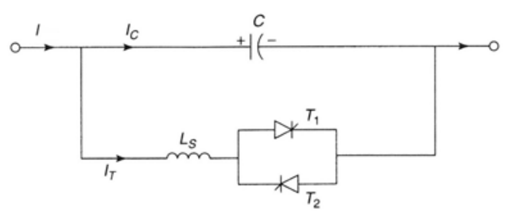

Fig. 1 Basic scheme of TCSC

Basic principle of TCSC

The total impedance of TCSC could be changed by TCR. Current flowing through the reactor i_L *(∝)* can be continuously controlled from maximum to 0 by control of firing angle. While considering harmonic progress of voltage on reactor: $u(t) = U_m \cdot \cos\omega t$, immediate value of current flowing though the reactor is:

$$i_L(t) = \frac{1}{L}\int u(t)dt = \frac{U_m}{\omega \cdot L} \cdot \sin\omega t . \tag{1}$$

Consider the firing angle of thyristor from interval $\langle 0, \pi/2 \rangle$, the current $i_L(t)$ flowing through 1-phase device of TCS is defined by the following equations:

$$i_L(t,\alpha) = \frac{1}{L}\int_{\alpha}^{\omega t} u(t)dt = \frac{U_m}{\omega \cdot L} \cdot (\sin\omega t - \sin\alpha) , \tag{2}$$

for $\alpha \le \omega \cdot t \le \pi - \alpha$ and

$$i_L(t,\alpha) = \frac{1}{L}\int_{\pi+\alpha}^{\omega t} u(t)dt = \frac{U_m}{\omega \cdot L} \cdot (\sin\omega t + \sin\alpha) , \tag{3}$$

for $\pi + \alpha \le \omega \cdot t \le 2\pi - \alpha$.

Equation (2) defines progress of current in positive half-wave and equation (3) defines progress of current in negative halve-wave.

In the following figure (Fig. 2) is show the progress of voltage and current, if $\alpha = 0$ and if α is in interval $\langle 0, \pi/2 \rangle$.

On Fig. 3 is shown progress of current flowing through TCR together with progress of its harmonic component at 50 Hz, while considering various firing angles of thyristors.

Magnitude of current of fundamental frequency on the basis of angle α could be used (after application of Fourier transformation) by the following formula:

$$I_{L1}(\alpha) = \frac{U_m}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right) , \tag{4}$$

U_m is magnitude of voltage of reactor, L is inductance of reactor and ω is circular frequency of voltage.

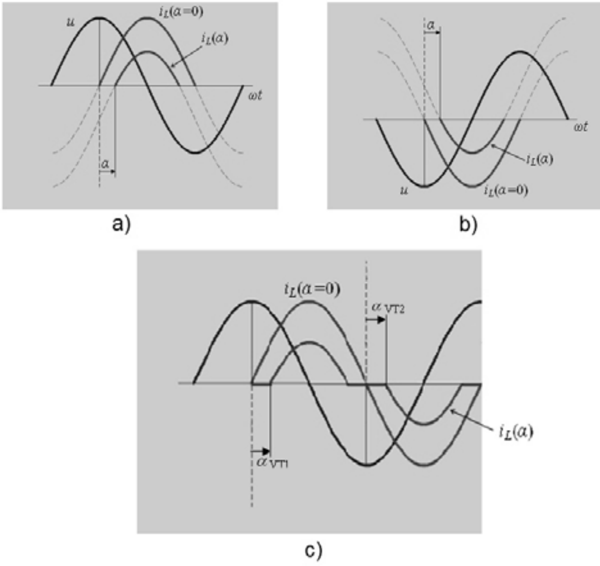

Fig. 2 Voltage and current of TCR a) positive wave, b) negative wave, c) period

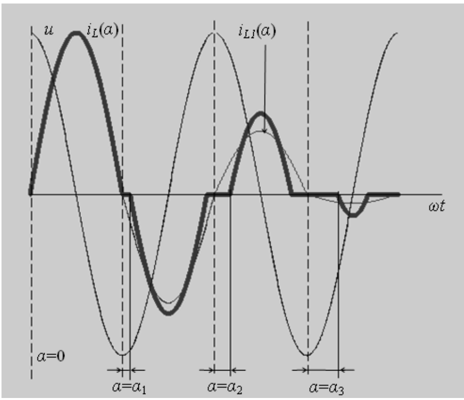

Fig. 3 Progress of voltage and current of TCR at various firing angles

Progress of magnitude of current of fundamental current in per unit depending on firing angle α of thyristors is shown in the following figure.

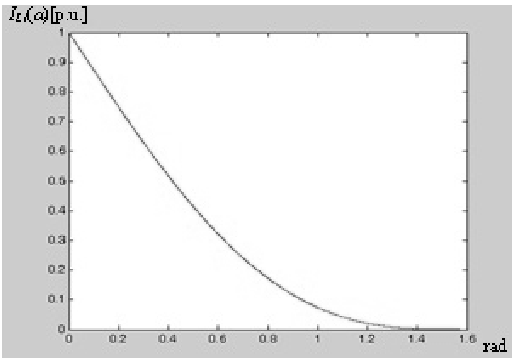

Fig. 4 Progress of current of fundamental component in per unit depending on firing angle

From the above given results, that it is possible to continuously control current flowing through the reactor from maximum to zero by firing angle of thyristor.

By use of formulas $I_{L1} = U \cdot B_{TCR}$, $B_L = \dfrac{1}{\omega \cdot L}$ and equation (4) it is possible to calculate inductive susceptance of TCR (while considering fundamental component of current) as a function of angle α as follows:

$$B_{TCR}(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right) = B_L \cdot \frac{\pi - 2\alpha - \sin 2\alpha}{\pi}. \qquad (5)$$

Inductive susceptance of TCR $B_{TCR}(\alpha)$ is changed by firing angle α in the same manner as the magnitude of fundamental component of current $I_{L1}(\alpha)$, it means, that it is possible to control it by in from maximal value $(\alpha = 0,\ B_{TCR} = B_L)$ up to zero $(\alpha = \pi/2,\ B_{TCR} = 0)$.

From equation (5) for inductive reactance of TCR we get:

$$X_{TCR}(\alpha) = \frac{1}{B_{TCR}(\alpha)} = X_L \cdot \frac{\pi}{\pi - 2\alpha - \sin 2\alpha}, \qquad (6)$$

where $X_L \le X_{TCR}(\alpha) \le \infty$, $X_L = \omega \cdot L$.

Progress of reactor reactance controlled by thyristors is in the following figure.

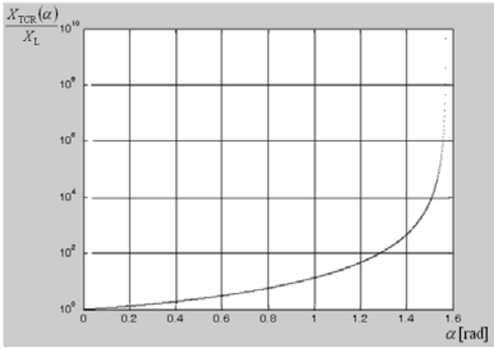

Fig. 5 Dependency of reactance of TCR in per unit values on firing angle of thyristors

Inductive reactance of the compensator is given by the following equation:

$$X_{TCSC}(\alpha) = \frac{X_C \cdot X_{TCR}(\alpha)}{X_{TCR}(\alpha) - X_C}, \qquad (7)$$

where $X_C = \dfrac{1}{\omega \cdot C}$ is capacitive reactance of capacitor and *C* is its capacity.

If inductive reactance of reactor is smaller than reactance of capacitor $(X_L < X_C)$, operating diagram of TCSC (Fig. 7) allows inductive and capacitive regime of operation of TCSC.

If $\alpha = 0$, reactance of TCR is small, capacitor is bridged by TCR, impedance of TCSC has inductive character and reaches its minimum.

For $\alpha \in \langle 0, \alpha_{L\lim} \rangle$, reactance of TCR is smaller than reactance of capacitor and TCSC has inductive character.

Area limited by $\alpha \in \langle \alpha_{L\lim}, \alpha_{C\lim} \rangle$ is area, in which TCSC is not operated.

If $\alpha \doteq \pi/4$, reactance of TCR equals to reactance of capacitor, occurs resonance and TCSC reaches theoretically indefinite value.

If $\alpha \in \langle \alpha_{C\lim}, \pi/2 \rangle$ reactance of TCR is higher than reactance of capacitor and impedance of TCSC has capacitive character.

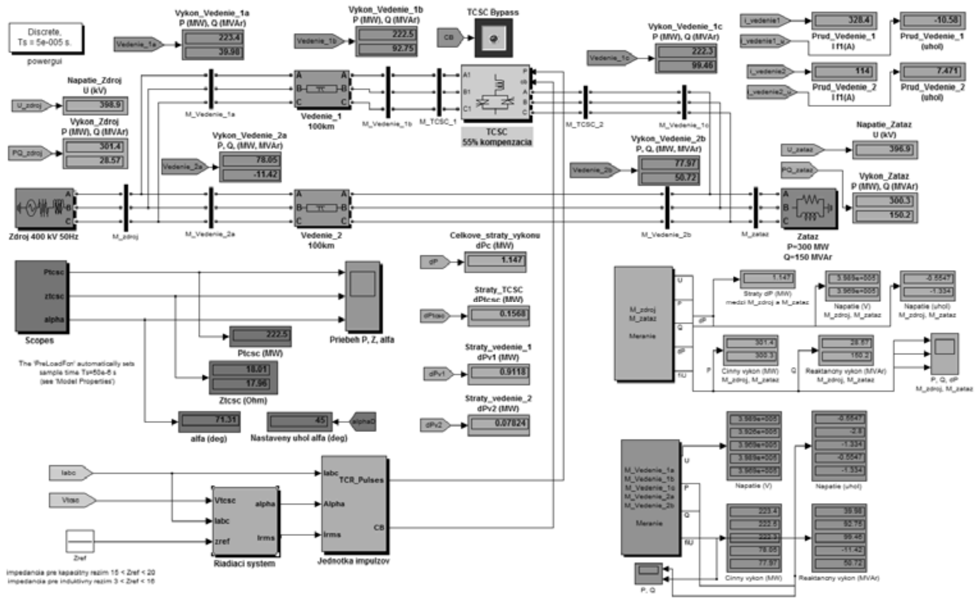

Fig. 6 Model of EPS with TCSC in capacitive regime

If $\alpha = \pi / 2$, the reactance of TCR is theoretically indefinite and TCSC has capacitive character, which equals X_C.

Operating diagram of TCSC is in the following figure.

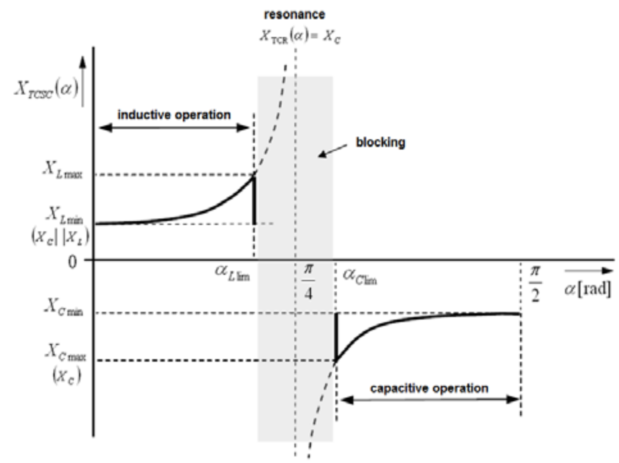

Fig. 7 Operating diagram of TCSC

Model of TCSC in MATLAB

Model of TCSC is shown in Fig. 8 and consists of the following blocks:

- Module of TCSC,
- Control System,
- Firing Unit.

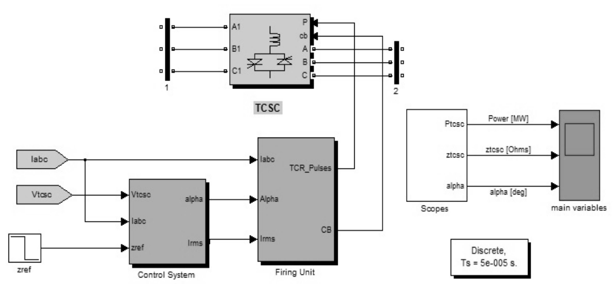

Fig. 8 Model of TCSC

Model of EPS with TCSC in capacitive regime

TCSC is connected into line No. 1 of simple EPS and in Control System of TCSC is selected capacitive regime. In first part, the reference value of impedance was $Z_{ref} = 18\ \Omega$, which was constant during simulation constant. The time – duration of simulation was set to $t = 5$ s. TCSC is in interval from 0 to 0,5 s in bypass. If $t = 0{,}5$ s, the bypass regime is ended and TCSC will start in capacitive regime. Consequently, power flowing through parallel lines is due to TCSC distributed. TCSC will influence longitudinal impedance of line No. 1. It results in increase of transmitted power by line No. 2. Capacitive reactance of TCSC is increased up to reference impedance, while the firing angle of thyristors is reduced.

Progress of increase of impedance and decrease of angle α in influenced by parameters of used PI controlled in block "Control System". If the reference value of impedance is reached, firing angle of thyristors is stabilised and also the power flow is stabilised.

On Fig. 8 is shown state of TCSC if $t = 5$ s. Value of firing angle in case the impedance equals reference impedance is approx. $\alpha = 71{,}3°$, power flowing through line increased from $P_{V1} = 148{,}4$ MW to $P_{V1} = 222{,}3$ MW (measured at site of consumption). Power flows in line No. 2 decreased to value $P_{V2} = 77{,}97$ MW.

Results of simulation

On Fig. 9 is shown change of power in two parallel lines, depending on set firing angle α of thyristors of TCSC in inductive or capacitive regime. By change of firing angle α can be seen different impact of TCSC on impedance of line No. 1. In this article is described just capacitive operation of TCSC.

In case of capacitive operation of TCSC, the impedance of line No. 1 is decreased and power flowing through the line No. 1 is increased, but power flowing through the line No. 2 is decreased.

On Fig. 10 is shown change of impedance of TCSC depending on firing angle of thyristors α, by which is influenced impedance of line No. 1, in inductive and capacitive regime.

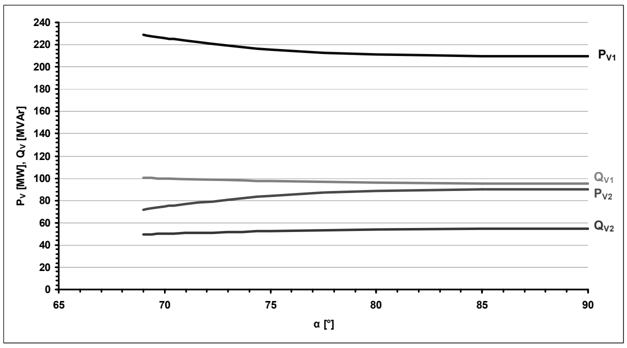

Fig. 9 Change in power flows in case of change of firing angle α in capacitive regime of TCSC

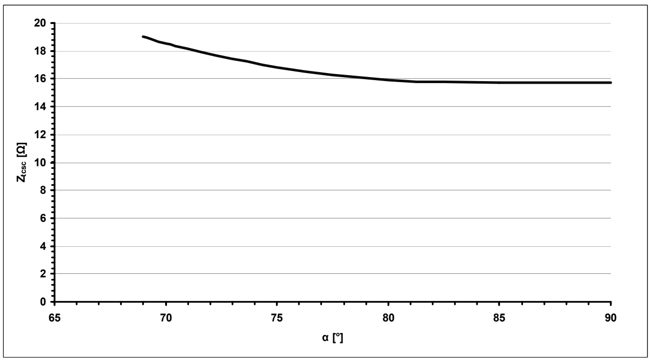

Fig. 10 Impedance of TCSC as a function of firing angle α in capacitive regime of TCSC

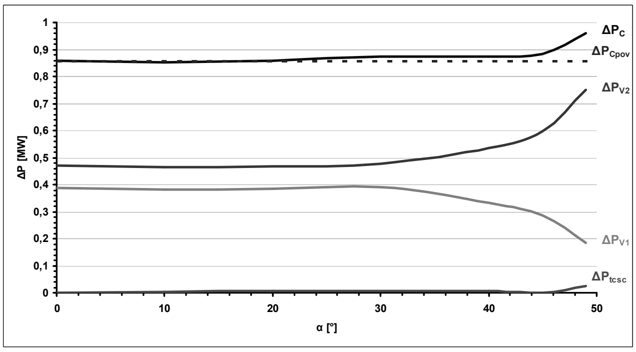

Fig. 11 Power losses in case of change of firing angle in inductive regime of TCSC

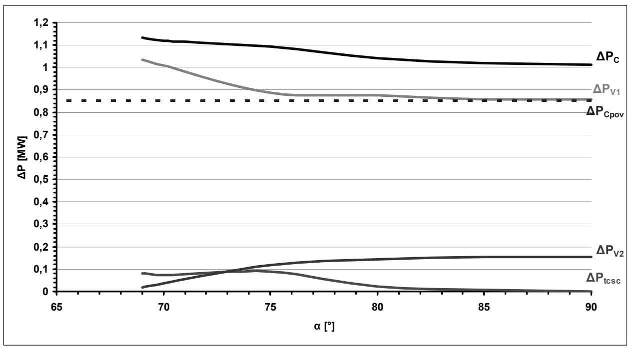

Fig. 12 Power losses in case of change of firing angle α in capacitive regime of TCSC

As it can be seen, change of impedance as well as change of power flows as a function of firing angle α is non-linear, which results from attributes of TCSC and its operating diagram.

Progress of losses in the system, in line No. 1 and line No. 2 and TCSC, which depend on firing angle α in inductive and capacitive regime, is shown on Fig. 11 and Fig. 12.

Results of simulation

In this article was in detail described TCSC model, its use in system and advantages of its use.

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***Authors**: Ing. Daniel Hlubeň, PhD., Technical University of Košice, Faculty of Electrical Engineering and informatics, Department of Power System Engineering, Mäsiarska 74, 041 20 Košice, E-mail: Daniel.hluben@tuke.sk;*
assoc. prof. Ing. Ľubomír Beňa, PhD., Technical University of Košice, Faculty of Electrical Engineering and informatics, Department of Power System Engineering, Mäsiarska 74, 041 20 Košice, E-mail: Lubomir.Bena@tuke.sk;
prof. Ing. Michal Kolcun, PhD., Technical University of Košice, Faculty of Electrical Engineering and informatics, Department of Power System Engineering, Mäsiarska 74, 041 20 Košice, E-mail: Michal.Kolcun@tuke.sk