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To Modeling of FACTS Devices and Their Application on the Intersystem Relations of Integrated Power System of Central Asia

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ABSTRACT: This article analyzes the issues related to the application of the technology of controlled flexible electric power transmissions of alternating current - FACTS, in order to effectively manage the power flows in the electric networks of the unified power system of Central Asian countries.

KEY WORDS: power system, modeling, regulation, mode control, flexible power transmission.

I. INTRODUCTION

The unified energy system of Central Asia provides electricity to consumers: the Kyrgyz Republic, the Republic of Uzbekistan, four regions of southern Kazakhstan and the "dead end" areas of the north of Tajikistan.

As of 01.01.2019, the installed capacity of the power plants of the Central Asian Power System amounted to 21,656.1 MW, and the electricity generation amounted to 89.3 billion kWh. The length of 220-500 kV power lines is 21,005.6 km, including VL-500 kV - 6054 km.

An analysis of the functioning of the UES of Central Asia (CA) made it possible to identify a number of "narrow places". Which, in particular, are the limited possibilities for parallel operation of the region's energy systems due to the insufficient transmission capacity of power lines between neighboring energy systems, problems with the regulation of nodal voltages.

II. THE TASKS OF EFFECTIVE MANAGEMENT OF THE CENTRAL ASIAN UNIFIED ENERGY SYSTEM

The Central Asian region purposefully strengthens backbone electric networks and increases generating capacities to meet the growing load of consumers.

At the same time, electric regimes in the Central Asian IPS are carried out under conditions that do not always allow ensuring voltage levels and cross-sectional flows in accordance with the standards and an insufficient technical level of emergency control.This circumstance reduces the quality of energy supply and the reliability of the operation of the association, creates the prerequisites for serious violations of the regimes with severe consequences for energy supply to consumers.

So, in 2018, the voltages on the tires of the Tashkent and Syrdarya HPS fell to 485 kV at the schedule set by 515 and 525 kV, respectively.

Instead of the set 510 kV, the voltage dropped to 478 kV at the Frunzenskaya substation, elevated voltage levels were noted at the YuKGRES substation (up to 542 kV), Almaty substation (up to 535 kV) due to insufficient operational control of the power balance over the power grid.Difficulties with voltage regulation occur at 500 kV "North-South" transit substations; the sharply variable nature of the overflow through this transit is the reason for frequent manual switching by reactors and emergency control operations to shut down (turn on) reactors.

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Vol. 6, Issue 10 , October 2019

In a number of operating modes of the Central Asia Unified Energy System, power flows over individual sections exceeded the permissible values up to 30%.

III. OPTIONS FOR RESOLVING REGULATORY ISSUES

The successfully developing theory and practice of applying the technologies of flexible controlled alternating current power transmission systems - FACTS devices (Flexible Alternative Current Transmission System) allows us to carry out research and develop recommendations on the implementation of this technology in the Central Asian Unified Energy System.

One of the key elements of FACTS is the RPS — a reactive power source, capable of both generating and consuming reactive power, depending on the required mode and the given characteristics of the power system.
The main goals of applying the FACTS technology are [1,5,6,7]: increasing the transmission capacity of power lines to the thermal limit; maintaining a given voltage, optimizing power flows in a complex heterogeneous network; increase of static and dynamic stability of UPS.

The application of FACTS technology allows to obtain various corrective actions depending on the conditions of a particular control task, to reduce the gap between controlled and uncontrolled UPS modes, presenting additional degrees of freedom to control personnel when controlling power flows and voltages in excess and scarce areas of the electric network.

FACTS is divided into types with a specific purpose. So, to maintain voltage limits, types SVC, STATCOM and TCSC are used, thermal limits are used as TCSC, SSSC and UPFC, and to improve stability, TCSC, SSSC are used.

As an example, consider the use of a thyristor-controlled series capacitor (TCSC) as a FACTS device, and two alternative models of power flow in an EES to evaluate the operation of a TCSC.
In the first model, the concept of variable series reactance is used as a state variable, which is automatically adjusted within the established limits to ensure the overflow of a given amount of active power.
In the second, more progressive model, the lead angle characteristic, specified in the form of a nonlinear dependence, is used. In this case, the lead angle TCSC is selected as a state variable in the problem of calculating the power flux using the Newton–Raphson method [2, 3].

Power flow model for sequential impedance control.

This mathematical model of the EPS power flow with a series capacitor with thyristor control TCSCis based on the concept of variable series impedance. Its value is automatically set to limit a certain value of the power flow in the line and can be effectively determined using the Newton-Raphson method.
Let the X_{TCSC} variable reactance shown in fig. 1 represents the equivalent reactivity of all series-connected modules that make up the X_{TCSC} and operate in either inductive or capacitive mode.

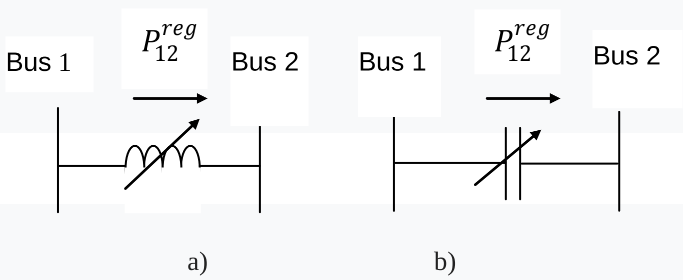

Fig. 1. TCSC equivalent circuit: a) inductive mode; b) capacitive mode

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Vol. 6, Issue 10 , October 2019

The TCSC matrix of mutual total conductivity, the equivalent circuits of which are shown in Fig. 1 is defined by the equation

$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} jB_{11} & jB_{12} \\ jB_{21} & jB_{22} \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \end{pmatrix} \tag{1}$$

For inductive mode, we obtain

$$B_{11} = B_{22} = -\frac{1}{X_{TCSC}}\ ; \quad B_{12} = B_{21} = \frac{1}{X_{TCSC}}\ , \tag{2}$$

in capacitive mode

$$B_{11} = B_{22} = \frac{1}{X_{TCSC}}\ ; \quad B_{12} = B_{21} = -\frac{1}{X_{TCSC}}\ ,$$

i.e. there is a change of signs in (2).

The equations of active and reactive powers on bus 1 (Fig. 1) have the following form [4]:

$$P_1 = U_1 U_2 B_{12} \sin(\delta_1 - \delta_2); \tag{3}$$

$$Q_1 = -U_1^2 B_{11} - U_1 U_2 B_{12} \cos(\delta_1 - \delta_2); \tag{4}$$

To obtain power equations on bus 2 in equations (3) and (4), it is necessary to perform a dual replacement of lower indices 1 and 2:

$$P_2 = U_2 U_1 B_{21} \sin(\delta_2 - \delta_1);$$

$$Q_1 = -U_2^2 B_{22} - U_2 U_1 B_{21} \cos(\delta_2 - \delta_1).$$

In solutions obtained using the Newton-Raphson method, the power equations lead to a linear form with respect to the series reactance. For the conditions shown in fig. 1, where the value of the active power flux P_{12}^{reg} from bus 1 to bus 2 is regulated using serial reactance, the system of power flux equations reduced to a linear form will look as follows:

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \Delta Q_1 \\ \Delta Q_2 \\ P_{12}^{TCSC} \end{bmatrix}^{(i)} = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} & \frac{\partial P_1}{\partial \delta_2} & \frac{\partial P_1}{\partial \delta_1} U_1 & \frac{\partial P_1}{\partial \delta_2} U_2 & \frac{\partial P_1}{\partial X_{TCSC}} U_{TCSC} \\ \frac{\partial P_2}{\partial \delta_1} & \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial U_1} U_1 & \frac{\partial P_2}{\partial U_2} U_2 & \frac{\partial P_2}{\partial X_{TCSC}} U_{TCSC} \\ \frac{\partial Q_1}{\partial \delta_1} & \frac{\partial Q_1}{\partial \delta_2} & \frac{\partial Q_1}{\partial U_1} U_1 & \frac{\partial Q_1}{\partial U_2} U_2 & \frac{\partial Q_2}{\partial X_{TCSC}} U_{TCSC} \\ \frac{\partial Q_2}{\partial \delta_1} & \frac{\partial Q_2}{\partial \delta_2} & \frac{\partial Q_2}{\partial U_1} U_1 & \frac{\partial Q_2}{\partial U_2} U_2 & \frac{\partial Q_2}{\partial U_{TCSC}} U_{TCSC} \\ \frac{\partial P_{12}^{TCSC}}{\partial \delta_1} & \frac{\partial P_{12}^{TCSC}}{\partial \delta_2} & \frac{\partial P_{12}^{TCSC}}{\partial U_1} U_1 & \frac{\partial P_{12}^{TCSC}}{\partial U_2} U_2 & \frac{\partial P_{12}^{TCSC}}{\partial X_{TCSC}} U_2 \end{bmatrix}^{(i)} \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \frac{\Delta U_1}{U_1} \\ \frac{\Delta U_2}{U_2} \\ \frac{\Delta U_2}{U_2} \\ \frac{\Delta X^{TCSC}}{X^{TCSC}} \end{bmatrix}^{(i)} ; \tag{5}$$

Where $P_{12}^{TCSC} = P_{12}^{reg} - P_{12}^{subt}$ mismatch of the active power flux for the series reactance, $\Delta X^{TCSC} = X_{TCSC}^{(i)}$-$X_{TCSC}^{i-1}$ - increment of series reactance. Power flow $P_{12}^{subt} = U_1 U_2 B_{12} \sin(\delta_1 - \delta_2)$.

The elements of the last column of the Jacobian in the matrix iterated linear equation (5) have the following form:

$$\frac{\partial P_1}{\partial X} X = -U_1 U_2 B_{12} \sin(\delta_1 - \delta_2)\,;$$

$$\frac{\partial Q_1}{\partial X} X = -U_1^2 B_{11} + U_1 U_2 B_{12} \cos(\delta_1 - \delta_2);$$

$$\frac{\partial P_{12}^X}{\partial X} X = \frac{\partial P_1}{\partial X} X$$

At the end of each i-th iteration, the variable component X_{TCSC} is updated by the formula:

$$X_{TCSC}^{(i)} = X_{TCSC}^{(i-1)} + \left[\frac{\Delta X_{TCSC}}{X_{TCSC}}\right]^{(i)} X_{TCSC}^{(i-1)}$$

Power flow model for advancing angle control.

After determining the reactance X_{TCSC} using the Newton-Raphson method, the lead angle β_{TCSC} can be calculated. This makes practical sense only when all TCSC thyristor series capacitor modules have identical technical characteristics and are designed to work with the same lead angles.The calculation of the lead angles implies an iterative solution,

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since the reactance of the TCSC and the lead angles are connected by a nonlinear dependence. One way to avoid an additional iterative process is to use the alternative power flow model below.
Consider the scheme:

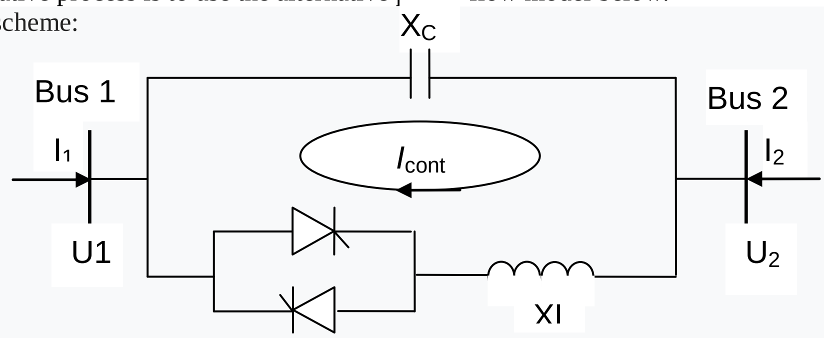

Fig. 2. TCSC equivalent circuit

The reactance X^{HOM}_{TCSC} corresponding to the rated frequency of the network is [2, 3]:

$$X^{HOM}_{TCSC} = -X_c + C_1\left(2(\pi-\beta) + \sin(2(\pi-\beta))\right) - C_2\cos(\pi-\beta)\left(\varpi tg(\varpi(\pi-\beta)) - \tan(\pi-\beta)\right), \quad (6)$$

where

$$C_1 = \frac{X_c + X_{LC}}{\pi};\quad C_2 = \frac{4X_{LC}^2}{\pi X_L};\ X_{LC} = \frac{X_c X_L}{X_c - X_L};\quad \varpi = \sqrt{\frac{X_c}{X_L}}$$

In this case, the equivalent reactance X^{HOM}_{TCSC} in equation (6) replaces the resistance X_{TCSC} present in equations (1) and (2), and the active and reactive power equations take the following form:

$$\left.\begin{aligned} P_1 &= U_1U_2B_{12}^{nom}\sin(\delta_1-\delta_2), \\ Q_1 &= -U_1^2B_{11} - U_1U_2B_{12}\cos(\delta_1-\delta_2) \end{aligned}\right],\quad (7)$$

Where

$$B_{11}^{nom} = -B_{12}^{nom} = B_{TCSC}^{nom}.$$

To obtain power equations for bus 2, it is sufficient to perform a dual replacement of the lower indices 1 and 2 in (7).

In the case where the TCSC controls the flow of active power from bus 1 to bus 2, the system of iterated equations reduced to a linear form has the form:

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \Delta Q_1 \\ \Delta Q_2 \\ \Delta P_{12}^{\beta TCSC} \end{bmatrix}^{(i)} = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} & \frac{\partial P_1}{\partial \delta_2} & \frac{\partial P_1}{\partial \delta_1}U_1 & \frac{\partial P_1}{\partial \delta_2}U_2 & \frac{\partial P_1}{\partial \beta_{TCSC}} \\ \frac{\partial P_2}{\partial \delta_1} & \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial U_1}U_1 & \frac{\partial P_2}{\partial U_2}U_2 & \frac{\partial P_2}{\partial \beta_{TCSC}} \\ \frac{\partial Q_1}{\partial \delta_1} & \frac{\partial Q_1}{\partial \delta_2} & \frac{\partial Q_1}{\partial U_1}U_1 & \frac{\partial Q_1}{\partial U_2}U_2 & \frac{\partial Q_2}{\partial \beta_{TCSC}} \\ \frac{\partial Q_2}{\partial \delta_1} & \frac{\partial Q_2}{\partial \delta_2} & \frac{\partial Q_2}{\partial U_1}U_1 & \frac{\partial Q_2}{\partial U_2}U_2 & \frac{\partial Q_2}{\partial \beta_{TCSC}} \\ \frac{\partial P_{12}^{TCSC}}{\partial \delta_1} & \frac{\partial P_{12}^{TCSC}}{\partial \delta_2} & \frac{\partial P_{12}^{TCSC}}{\partial U_1}U_1 & \frac{\partial P_{12}^{TCSC}}{\partial U_2}U_2 & \frac{\partial P_{12}^{TCSC}}{\partial \beta_{TCSC}}U_2 \end{bmatrix}^{(i)} \begin{bmatrix} \Delta\delta 1 \\ \Delta\delta 2 \\ \frac{\Delta U1}{U1} \\ \frac{\Delta U2}{U2} \\ \Delta\beta^{TCSC} \end{bmatrix}^{(i)};\quad (8)$$

where the power increment $\Delta P_{12}^{\beta_{TCSC}}$ is set as the difference

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 6, Issue 10 , October 2019

$$\Delta P_{12}^{\beta_{TCSC}} = P_{12}^{reg} - P_{12}^{\beta_{TCSC}\, subt}$$

increment of the lead angle$\Delta\beta^{TCSC} = \beta_{TCSC}^{(i)} - \beta_{TCSC}^{(i-1)}$.
The power $P_{12}^{\beta_{TCSC}\, subt}$ is calculated by formula (7).
The partial derivatives in the last column of the Jacobian in the iterated equation (8) are found by the formulas

$$\frac{\partial P_1}{\partial\beta} = P_1 B_{TCSC}^{nom}\frac{\partial X_{TCSC}^{nom}}{\partial\beta}; \qquad \frac{\partial Q_1}{\partial\beta} = Q_1 B_{TCSC}^{nom}\frac{\partial X_{TCSC}^{nom}}{\partial\beta}; \frac{\partial B_{TCSC}^{nom}}{\partial\beta} = (B_{TCSC}^{nom})^2\frac{\partial X_{\beta}^{nom}}{\partial\beta}$$

$$\frac{\partial X_{TCSC}^{nom}}{\partial\beta} = -2C_1(1+\cos(2\beta)) + C_2\sin(2\beta)(\varpi\,\mathrm{tg}(\varpi(\pi-\beta)) - \mathrm{tg}(\pi-\beta) +$$

$$+C_2\left(\varpi^2\frac{\cos^2(\pi-\beta)}{\cos^2(\varpi(\pi-\beta))} - 1\right).$$

The behavior of the TCSC mathematical model is influenced by several internal resonances. These resonant points are determined by the following expressions [2, 4]:

$$\beta_{TCSC}^1 = \pi\left[1 - \frac{\dot{\omega}\sqrt{LC}}{2}\right];\beta_{TCSC}^2 = \pi\left[1 - \frac{3\dot{\omega}\sqrt{LC}}{2}\right];$$

$$\beta_{TCSC}^3 = \pi\left[1 - \frac{5\dot{\omega}\sqrt{LC}}{2}\right];\dots;\beta_{TCSC}^k = \pi\left[1 - \frac{(2k-1)\dot{\omega}\sqrt{LC}}{2}\right].$$

Theoretically, a TCSC can have n resonance points; in practice, in a well-designed controller in the operating range, there can be only one resonance peak.

IV. CALCULATION OF POWER FLOWS IN A THREE-PHASE NETWORK WITH TCSC

a) Power flow model for controlling variable series impedance.

A mathematical TCSC model based on three-phase reactance is obtained by combining separate single-phase TCSC modules (Fig. 1). To control the flow of active power passing through the three TCSC channels, the value of the required BTCSC conductivity is determined using the Newton-Raphson method [4].

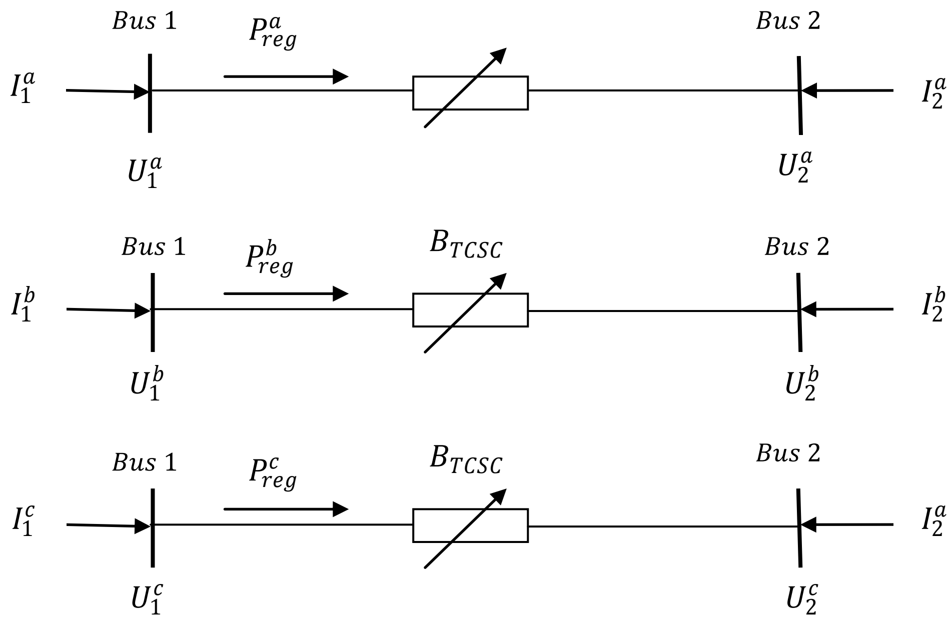

Fig. 3. TCSC equivalent circuit in a three-phase network (with conductivity model)

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 6, Issue 10 , October 2019

The total conductivity of the TCSC can be determined based on the equivalent circuit shown in Fig. 3. Assuming that the exponent φ consecutively takes the values a, b, c, we obtain

$$\begin{pmatrix} \underline{\mathbf{I}}_1^{\mathrm{ph}} \\ \underline{\mathbf{I}}_2^{\mathrm{ph}} \end{pmatrix} = \begin{pmatrix} j\underline{\mathbf{B}}_{11}^{\mathrm{ph}} & \underline{\mathbf{B}}_{12}^{\mathrm{ph}} \\ \underline{\mathbf{B}}_{21}^{\mathrm{ph}} & \underline{\mathbf{B}}_{22}^{\mathrm{ph}} \end{pmatrix} \begin{pmatrix} \underline{\mathbf{U}}_1^{\mathrm{ph}} \\ \underline{\mathbf{U}}_2^{\mathrm{ph}} \end{pmatrix};(1)$$

Since all three TCSC modules are not interconnected from the point of view of electromagnetic interaction, the matrix elements from (1)

$$\begin{pmatrix} j\underline{\mathbf{B}}_{11}^{\mathrm{ph}} & \underline{\mathbf{B}}_{12}^{\mathrm{ph}} \\ \underline{\mathbf{B}}_{21}^{\mathrm{ph}} & \underline{\mathbf{B}}_{22}^{\mathrm{ph}} \end{pmatrix}$$

can be defined as follows:

$$\underline{\mathbf{B}}_{11}^{\mathrm{ph}} = j\underline{\mathbf{B}}_{11}^{\mathrm{ph}} = j\underline{\mathbf{B}}_{11}^{\mathrm{ph}} = -\frac{1}{X^{\mathrm{ph}}}; \quad (2)$$

$$\underline{\mathbf{B}}_{12}^{\mathrm{ph}} = j\underline{\mathbf{B}}_{21}^{\mathrm{ph}} = j\underline{\mathbf{B}}_{TCSC}^{\mathrm{ph}} = -\frac{1}{X^{\mathrm{ph}}}, \quad (3)$$

Where,X^{ph} is the equivalent reactance for the main frequency of the network.
Moreover, the general equation for a three-phase network is a system of three matrix equations (1), i.e.

$$\begin{pmatrix} \underline{I_1^a} \\ \underline{I_2^a} \\ \underline{I_1^b} \\ \underline{I_2^b} \\ \underline{I_1^c} \\ \underline{I_2^c} \end{pmatrix} = \begin{pmatrix} -j\frac{1}{X^a} & j\frac{1}{X^a} & 0 & 0 & 0 & 0 \\ j\frac{1}{X^a} & -j\frac{1}{X^a} & 0 & 0 & 0 & 0 \\ 0 & 0 & -j\frac{1}{X^a} & j\frac{1}{X^a} & 0 & 0 \\ 0 & 0 & j\frac{1}{X^a} & -j\frac{1}{X^a} & 0 & 0 \\ 0 & 0 & 0 & 0 & -j\frac{1}{X^a} & j\frac{1}{X^a} \\ 0 & 0 & 0 & 0 & j\frac{1}{X^a} & -j\frac{1}{X^a} \end{pmatrix} \begin{pmatrix} \underline{U_1^a} \\ \underline{U_2^a} \\ \underline{U_1^b} \\ \underline{U_2^b} \\ \underline{U_1^c} \\ \underline{U_2^c} \end{pmatrix}$$

The values of the three-phase power applied to the bus 1 are determined by the following equations:

$$P_1^{\mathrm{ph}} = U_1^{\mathrm{ph}} U_2^{\mathrm{ph}} B_{12}^{\mathrm{ph}\,k} \sin(\delta_1^{\mathrm{ph}} - \delta_2^{\mathrm{ph}}); \quad (4)$$

$$Q_1^{\mathrm{ph}} = -(U_1^{\mathrm{ph}})^2 B_{11}^{\mathrm{ph}\,k} - U_1^{\mathrm{ph}} U_2^{\mathrm{ph}} B_{12}^{\mathrm{ph}\,k} \cos(\delta_1^{\mathrm{ph}} - \delta_2^{\mathrm{ph}}). \quad (5)$$

The power equations on bus 2 are obtained by the dual replacement in equations (4), (5) of the subscript 1 by index 2. The partial derivatives of the power equations with respect to Xph. Have the form

$$\frac{\partial P_1^{\mathrm{ph}}}{\partial X^{\mathrm{ph}}} X^{\mathrm{ph}} = -P_1^{\mathrm{ph}}, \quad \frac{\partial Q_1^{\mathrm{ph}}}{\partial X^{\mathrm{ph}}} X^{\mathrm{ph}} - Q_1^{\mathrm{ph}}.$$

Then, the process of controlling the flow of active power from bus 1 to bus 2 using TCSC will be described by the following iterated linearized equations:

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 6, Issue 10 , October 2019

$$\begin{pmatrix} \frac{\Delta P_1^{ph}}{\Delta P_2^{ph}} \\ \frac{\Delta Q_1^{ph}}{\Delta Q_2^{ph}} \\ \Delta P_{12}^{ph} \end{pmatrix}^{(i)} = \begin{pmatrix} \frac{\partial P_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_1^{ph}}{\partial \delta_2^{ph}} & \frac{\partial P_1^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_1^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_1^{ph}}{\partial X^{ph}} X^{ph} \\ \frac{\partial P_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_2^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_2^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_2^{ph}}{\partial X^{ph}} X^{ph} \\ \frac{\partial Q_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_1^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial Q_1^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial Q_1^{ph}}{\partial X^{ph}} X^{ph} \\ \frac{\partial Q_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_2^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial Q_2^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial Q_2^{ph}}{\partial X^{ph}} X^{ph} \\ \frac{\partial P_{12}^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_{12}^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_{12}^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_{12}^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_{12}^{ph}}{\partial X^{ph}} X^{ph} \end{pmatrix}^{(i)} \begin{pmatrix} \frac{\Delta \delta_1^{ph}}{\delta_2^{ph}} \\ \frac{\Delta U_1^{ph}}{U_2^{ph}} \\ \frac{\Delta U_2^{ph}}{U_2^{ph}} \\ \frac{\Delta X^{ph}}{X^{ph}} \end{pmatrix}^{(i)} ;(6)$$

Where, $\Delta P_{12}^{ph.X}$is the imbalance of the active power flux, calculated as

$$\Delta P_{12}^{ph.X} = P_{12}^{ph.Xreg} - \Delta P_{12}^{ph.Xsubt},$$

ΔX^{ph} - continuous increment of the total reactance of a series-connected TCSC capacitor.

b) Power flow model for controlling the lead angle.

An alternative to equation (6) is the equation obtained on the basis of a three-phase model with thyristor lead angles considered as elements of the system state. In fig. 4 shows the corresponding TCSC equivalent circuit.

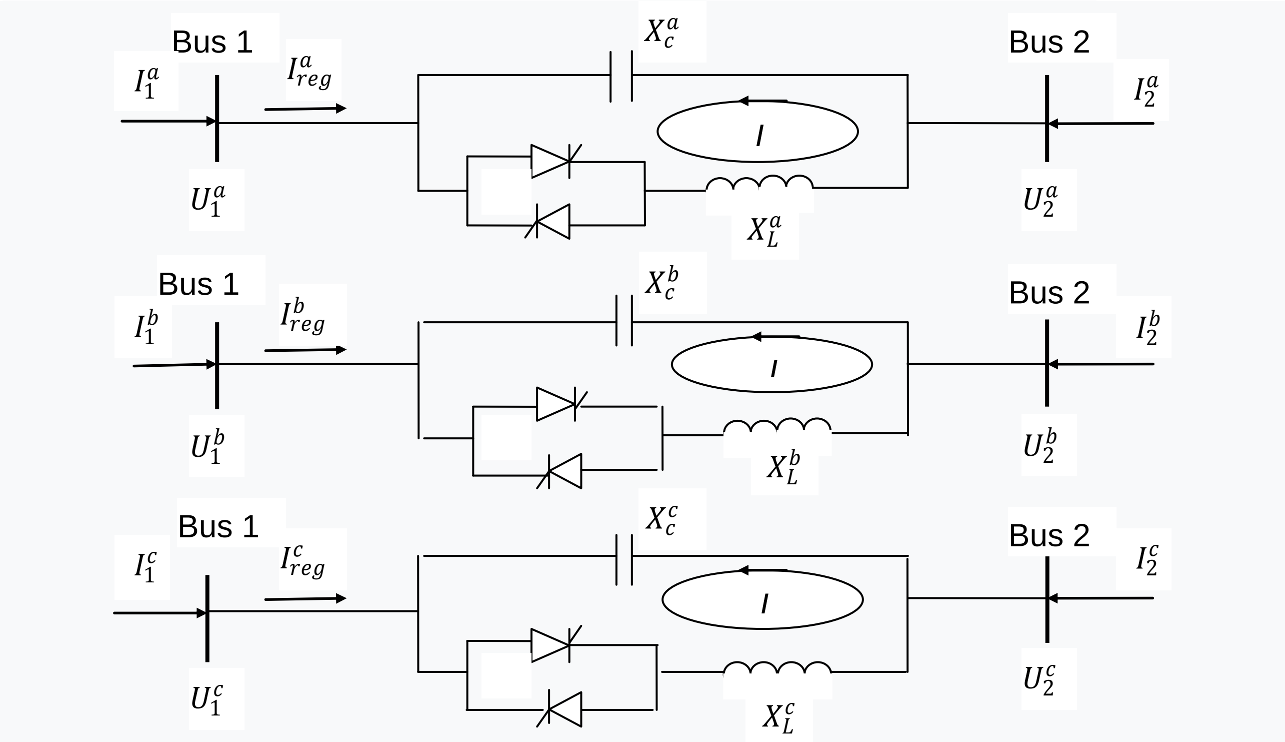

Fig. 4. TCSC equivalent circuit in a three-phase network (with a lead angle model.

The TCSC reactance at the main frequency of the network, as a function of the lead angle of the thyristors, can be represented by the following equation [2, 3]

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 6, Issue 10 , October 2019

$$X_{TCSC}^{\mathrm{ph}} = -X_C^{\mathrm{ph}} + C_1^{\mathrm{ph}}\,(2(\pi - \beta^{\mathrm{ph}}) + \sin(2\pi - \beta^{\mathrm{ph}}))) -$$
$$-C_2^{\mathrm{ph}}\cos(\pi - \beta^{\mathrm{ph}})(\varpi\,\mathrm{t}g\varpi(\pi - \beta^{\mathrm{ph}})) - \mathrm{t}g(\pi - \beta^{\mathrm{ph}})),$$

Where $C_1^{\mathrm{ph}} = \frac{X_c^{\mathrm{ph}} + X_{LC}^{\mathrm{ph}}}{\pi}; \quad C_2^{\mathrm{ph}} = \frac{4X_{LC}^{\mathrm{ph}\,2}}{\pi X_L^{\mathrm{ph}}}; \quad X_{LC} = \frac{X_c X_L}{X_c - X_L}$.

The total conductivity matrices in each of the TCSC models under consideration coincide (equations (1-3). The power equations (4), (5) also coincide. Therefore, in equation (6), for the case of controlling the lead angles, only the corresponding changes should be made to private derivatives of the matrix.

$$\begin{pmatrix} \frac{\Delta P_1^{ph}}{\Delta P_2^{ph}} \\ \frac{\Delta Q_1^{ph}}{\Delta Q_2^{ph}} \\ \Delta P_{12}^{phx} \end{pmatrix}^{(i)} = \begin{pmatrix} \frac{\partial P_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_1^{ph}}{\partial \delta_2^{ph}} & \frac{\partial P_1^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_1^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_1^{ph}}{\partial \beta^{ph}} \beta^{ph} \\ \frac{\partial P_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_2^{ph}}{\partial \delta_2^{ph}} & \frac{\partial P_2^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_2^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_2^{ph}}{\partial \beta^{ph}} \beta^{ph} \\ \frac{\partial Q_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_1^{ph}}{\partial \delta_2^{ph}} & \frac{\partial Q_1^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial Q_1^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial Q_1^{ph}}{\partial \beta^{ph}} \beta^{ph} \\ \frac{\partial Q_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_2^{ph}}{\partial \delta_2^{ph}} & \frac{\partial Q_2^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial Q_2^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial Q_2^{ph}}{\partial \beta^{ph}} \beta^{ph} \\ \frac{\partial P_{12}^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_{12}^{ph}}{\partial \delta_2^{ph}} & \frac{\partial P_{12}^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_{12}^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_{12}^{ph}}{\partial \beta^{ph}} \beta^{ph} \end{pmatrix}^{(i)} \begin{pmatrix} \frac{\Delta\delta_1^{ph}}{\delta_2^{ph}} \\ \frac{\Delta U_1^{ph}}{U_1^{ph}} \\ \frac{\Delta U_2^{ph}}{U_2^{ph}} \\ \frac{\Delta\beta^{ph}}{\beta^{ph}} \end{pmatrix}^{(i)}$$

V. CONCLUSION

Taking into account the above-mentioned operational problems in the nodes and sections of the UES of CA, the introduction of FACTS technology in power systems will open up new possibilities for controlling power flows in power lines with ensuring line throughput up to the limit of thermal resistance of wires, maintaining node voltage in the regulatory range, and static reserves and dynamic stability of the power system.

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