Modeling of FACTS Devices and Their Application in Intersystem Tie Lines of the United Power System of Central Asia

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***Abstract* — The paper analyzes the issues related to the application of flexible alternating current transmission systems (FACTS) for effective control of power flows in the electrical networks of the United Power System of Central Asia.**

***Index Terms* — power system, modeling, regulation, mode control, flexible power transmission.**

I. Introduction

The United Power System of Central Asia (UPS CA) transmits electricity to consumers in the Republic of Kyrgyzstan, the Republic of Uzbekistan, four regions of southern Kazakhstan and the "dead-end" regions of Northern Tajikistan.

In January 2019, the installed capacity of the power plants in the UPS CA was 21.7 GW, electricity output – 89.3 b kWh. The length of 220-500 kV transmission lines was 21006.6 km, including 6054 km of 500 kV overhead lines.

An analysis of the UPS operation has revealed some "weaknesses", for example, limited capabilities of parallel operation of power systems in the region due to insufficient transfer capabilities of transmission lines between neighboring power sub-systems, and problems with the voltage regulation at nodes.

II. Effective control of UPS CA

The region of Central Asia purposefully strengthens the main electric networks and increases the generating capacity to meet the growing demand.

At the same time, the power flows in the UPS do not always allow providing the levels of voltage and flows in cutsets in accordance with the standards. The technical level of emergency control is insufficient. This circumstance reduces the quality of power supply and reliability of the power system, creates prerequisites for serious disturbances of power system operation with severe consequences for the power supply to consumers.

In 2018, the voltage on the busbars of the Tashkent and Syrdaria thermal power plants dropped to 485 kV, under specified 515 kV and 525 kV, respectively.

At the Frunzenskaya substation, the voltage went down below specified 510 kV, to 478 kV, increased voltage levels were noted at the YuKGRES substation (up to 542 kV) and Almaty substation (up to 535 kV) due to insufficient operational control of net power flow through the UPS networks. There are problems with voltage regulation at 500 kV North-South transit substations. The sharply variable nature of the flows through this transit is the cause of frequent manual switchings of reactors and the operation of emergency control to switch off (on) the reactors. In some of the UPS operating conditions power flows in individual cutsets exceeded the permissible values by up to 30%.

III. Options for the control of operating conditions

Successfully developing theory and practice of applying the technology of flexible controlled AC power transmission systems, i.e. FACTS devices, make it possible to carry out the studies and develop recommendations for the adoption of this technology in the UPS of Central Asia.

One of the key elements of FACTS is a reactive power source (RPS) capable of both generating and consuming reactive power depending on the required operating parameters and specified characteristics of the power system.

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The main objectives of the FACTS technology application are [1, 5, 6, 7] to increase the transfer capability of power lines to the thermal limit; maintain a set voltage, optimize power flows in a complex heterogeneous network; and increase the static and dynamic stability of the United Power System (UPS).

The use of FACTS technology allows obtaining various corrective actions depending on the conditions of a specific control problem, reducing the gap between controlled and uncontrolled operating conditions of the UPS, by providing the dispatching personnel with additional degrees of freedom to control power flows and voltage in the network areas with power surplus and shortage.

The FACTS devices are divided into several types depending on their specific purpose. For example, SVC, STATCOM, and TCSC types are used to meet voltage constraints; TC SC, SC, and UPFC types are used to satisfy thermal limits; TCSC and SSSC are used to improve stability. Among the above types of devices, TCSC (Thyristor Controlled Series Capacitor) can be used for control in all three of these cases.

Let us consider two models of power flow calculation in three-phase networks with TCSC device with the view to increasing the efficiency of control of the operating parameters in the UPS of Central Asia.

a) A model of power flow for variable impedance control

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

The TCSC admittance can be determined based on the equivalent circuit shown in Fig. 1. Assuming that index "ph" successively takes the values a, b, c, we obtain

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

Since all three TCSC modules are not related in terms 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 determined as follows:

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

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

where X^{ph} is the equivalent reactance for the fundamental frequency of the network.

In this case, the governing equation for the 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 bus 1 are defined by the following equations:

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

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

The equations of power at bus 2 are obtained by dual substitution of subscript 1 in equations (4), (5) by subscript 2.

Partial derivatives of power equations with respect to

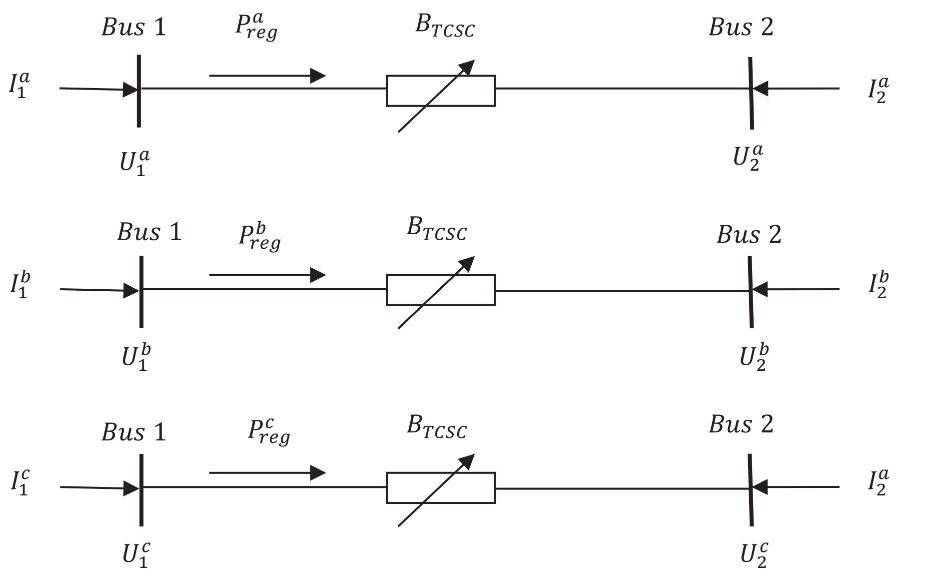

Figure 1. A TCSC equivalent circuit in a three-phase network (with a susceptance model.)

X^{ph} have the form

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

Then the process of TCSC-based control of active power flow from bus 1 to bus 2 will be described by the following iterated linearized equations:

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

Where $\Delta P_{12}^{ph.X}$ is the imbalance of active power flow calculated as $\Delta P_{12}^{ph.X} = P_{12}^{ph.Xreg} - \Delta P_{12}^{ph.X}$, ΔX^{ph} is a continuous increment of reactance of the series connected TCSC.

b) A model of power flow when controlling the advance angle

An alternative to equation (6) is the equation obtained using a three-phase model with thyristor advance angles considered as elements of the system state. Figure 2 shows the corresponding equivalent circuit of TCSC.

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

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

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

The admittance matrices in each of the considered TCSC models coincide (equations (1-3)). The equations of power (4), (5) also coincide. Therefore, in equation (6) for the case of advance angles control, one should make only the corresponding changes in the matrix elements:

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

IV. Conclusion

The application of FACTS technology in power systems will open up new opportunities to control power flows in transmission lines by providing transfer capabilities of lines up to the limit of thermal resistance of the wires; to maintain voltage at nodes within standard limits; and increase the static and dynamic stability margins in the system.

The presented two models for calculation of power flow in a three-phase network help effectively control the operating parameters of the power system by providing an almost inertia-free generation of control actions to the executive elements of FACTS devices.

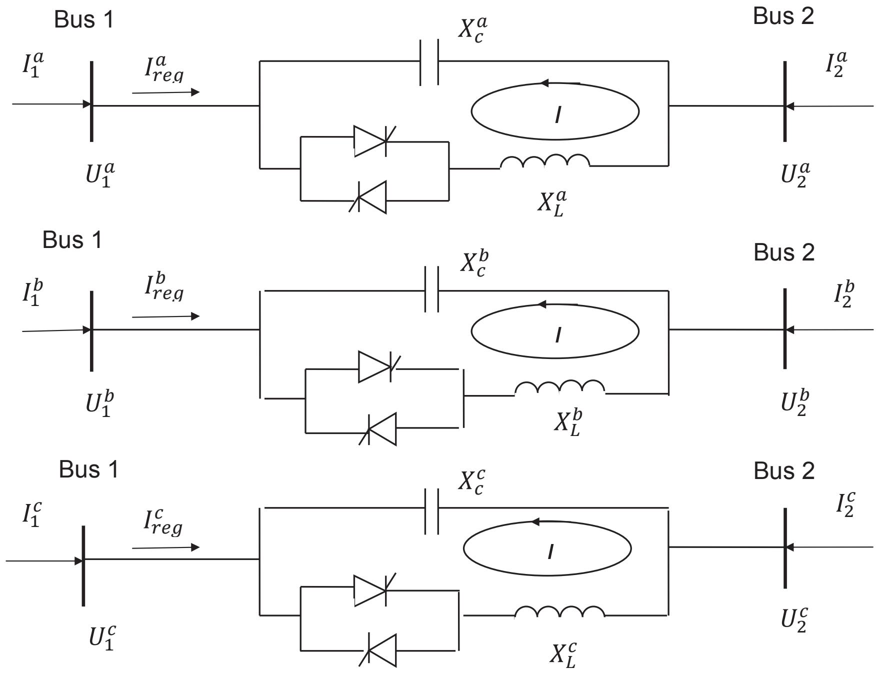

Figure 2. An equivalent circuit of TCSC in a three-phase network (with an advance angle model).

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