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Calculation of Power Flow in a Three-Phase Network, Containing Static Reactive Power Compensator

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ABSTRACT: Alternative models are formulated for calculating the power flow in a three-phase network of an electric power system in order to evaluate the effect of a static reactive power compensator, which is an integral part of devices of controlled flexible AC systems. A detailed mathematical model has been developed that corresponds to a three-phase thyristor controlled reactor; the influence of a static compensator on the operation of unbalanced three-phase power systems has been evaluated.

KEY WORDS: alternative models, static compensator, power system, modeling, regulation, mode control, flexible power transmission.

The installation of compensating devices on power lines and load nodes is used to improve voltage modes, increase transmission system capacity, and increase the reserves of static and dynamic stability. These devices use static unregulated devices - capacitor banks, adjustable synchronous compensators, astatic thyristor regulated reactive power sources - FACTS devices (Flexible Alternative Current Transmission System)[1].

I. STATIC REACTIVE POWER COMPENSATOR SVC IN A THREE-PHASE NETWORK.

In order to evaluate the effect of the SVC static reactive power compensator on the operation of unbalanced three-phase power systems, a more detailed model of this FACTS device should be developed than for single-phase ones.

Consider the SVC model, which corresponds to a three-phase reactor with thyristor control TCR, connected according to the triangle circuit and installed in parallel with a three-phase capacitor bank, which, in turn, is connected according to the "star" scheme.

In fig. 1 shows equivalent circuits for capacitor banks and SVCs. We assume that individual TCR modules are individually controlled using lead angles of thyristors β.

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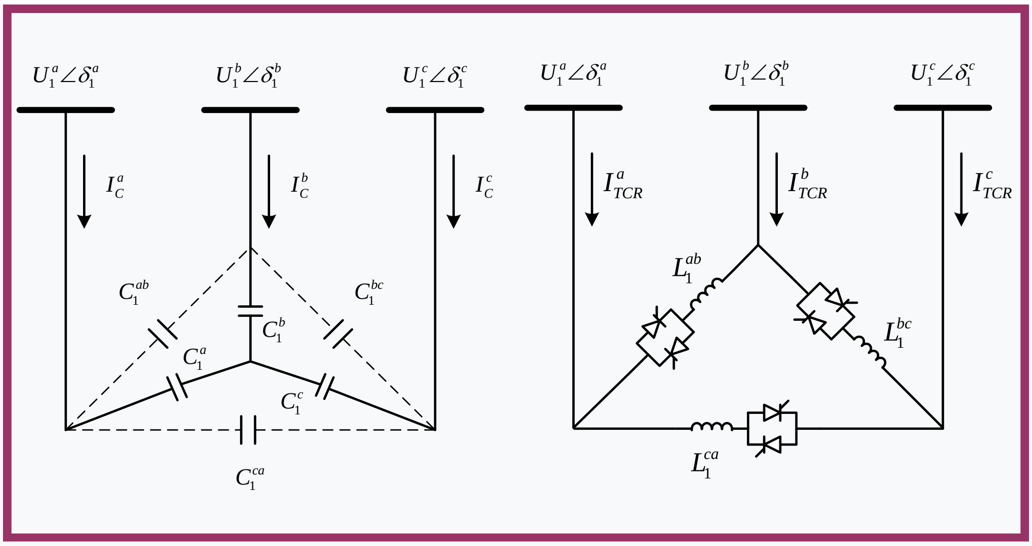

a) b)

Fig. 1. The equivalent circuit of the battery of capacitors (a) and reactors with thyristor control TCR in a three-phase network (b).

Consider two SVC models for power flow. In this case, in the first model, we will use the values of controlled reactive conductivity B_{SVC} as state variables, and in the second model, the values of the lead angles of thyristors β.

II. Model 1

The use of B_{SVC} controlled reactance values in calculating power flow.
As shown in fig. 1, a three-phase battery of capacitors connected in a star configuration may have an alternative representation in the form of an equivalent circuit connected in a triangular pattern. The three-phase SVC model for the first three-phase bus is described by the following matrix equation [2]:

$$\begin{pmatrix} \underline{I}_1^a \\ \underline{I}_1^b \\ \underline{I}_1^c \end{pmatrix} = \frac{1}{3}\begin{pmatrix} jB_{SVC}^{aa} & -jB_{SVC}^{ab} & -jB_{SVC}^{ca} \\ -jB_{SVC}^{ba} & jB_{SVC}^{bb} & -jB_{SVC}^{bc} \\ -jB_{SVC}^{ca} & -jB_{SVC}^{cb} & jB_{SVC}^{cc} \end{pmatrix}\begin{pmatrix} \underline{U}_1^a \\ \underline{U}_1^b \\ \underline{U}_1^c \end{pmatrix}, \tag{1}$$

where

$$B_{SVC}^{ph_1 ph_2} = \begin{cases} \frac{B_C^{ph_1}}{\Delta B_C}\sum_{\substack{k=a,b,c \\ i\neq ph_1}} B_C^k - \sum_{\substack{k=a,b,c \\ i\neq ph_1}} B_{TCR}^{ph_1 k}, & provided\ ph_1 = ph_2 \\ -\frac{B_C^{ph_1} B_C^{ph_2}}{\Delta B_C} + B_{TCR}^{ph_1 ph_2}, & provided ph_1 \neq ph_2 \end{cases} \tag{2}$$

$$B_{TCR}^{ph_1 ph_2} = \frac{2(\pi - \beta_{TCR}^{ph_1 ph_2} - \sin(2\beta_{TCR}^{ph_1 ph_2}))}{\pi\omega L_{TCR}^{ph_1 ph_2}};$$

$$B_C^{ph_1} = \omega C_C^{ph_1};\ \Delta B_C = \sum_{k=a,b,c} B_C^k.$$

The indicators ph1 and ph2 are used in (2) to indicate phases a, b, and c. Note that the parameters with double exponents ph1 and ph2 correspond to the parameters of the module of the FACTS device connected between phases ph1 and ph2.

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The equations of a three-phase power flow for a power line with an connected SVC can be derived on the basis of an equivalent circuit (Fig. 1), when the variable reactance B_{SVC}^{ph1ph2} is considered as an alternating state. To limit the amplitude of the nodal voltage at a given value, the reactance should be automatically controlled using an iterative algorithm.
From the diagrams in Fig. 1 and formulas (1), the equations of power flow in a three-phase line with a reactive power compensator follow [3]:

$$P_1^{ph_1} = -U_1^{ph_1} \sum_{\substack{k=a,b,c \\ k\neq ph}} U_1^k B_{SVC}^{phk} \sin\left(\delta_1^{ph} - \delta_1^k\right);(3)$$

$$Q_1^{ph_1} = -\left(U_1^{ph}\right)^2 B_{SVC}^{phph} + U_1^{ph} \sum_{\substack{k=a,b,c \\ k\neq ph}} U_1^k B_{SVC}^{phk} \cos\left(\delta_1^{ph} - \delta_1^k\right);(4)$$

where$ph = a,b,c$.

By linearizing equations (3), (4), we arrive at the following iterated linearized equation:

$$\begin{pmatrix} \Delta P_1^a \\ \Delta P_1^b \\ \Delta P_1^c \\ \Delta Q_1^a \\ \Delta Q_1^b \\ \Delta Q_1^c \end{pmatrix}^{(i)} = \begin{pmatrix} \frac{\partial P_1^a}{\partial \delta_1^a} & \frac{\partial P_1^a}{\partial \delta_1^b} & \frac{\partial P_1^a}{\partial \delta_1^c} & \frac{\partial P_1^a}{\partial \beta_{SVC}^{ab}} & 0 & \frac{\partial P_1^a}{\partial \beta_{SVC}^{ca}} \\ \frac{\partial P_1^b}{\partial \delta_1^a} & \frac{\partial P_1^b}{\partial \delta_1^b} & \frac{\partial P_1^b}{\partial \delta_1^c} & \frac{\partial P_1^b}{\partial \beta_{SVC}^{ab}} & \frac{\partial P_1^b}{\partial \beta_{SVC}^{bc}} & 0 \\ \frac{\partial P_1^c}{\partial \delta_1^a} & \frac{\partial P_1^c}{\partial \delta_1^b} & \frac{\partial P_1^c}{\partial \delta_1^c} & 0 & \frac{\partial P_1^c}{\partial \beta_{SVC}^{bc}} & \frac{\partial P_1^c}{\partial \beta_{SVC}^{ca}} \\ \frac{\partial Q_1^a}{\partial \delta_1^a} & \frac{\partial Q_1^a}{\partial \delta_1^b} & \frac{\partial Q_1^a}{\partial \delta_1^c} & \frac{\partial Q_1^a}{\partial \beta_{SVC}^{ab}} & 0 & \frac{\partial Q_1^a}{\partial \beta_{SVC}^{ca}} \\ \frac{\partial Q_1^b}{\partial \delta_1^a} & \frac{\partial Q_1^b}{\partial \delta_1^b} & \frac{\partial Q_1^b}{\partial \delta_1^c} & \frac{\partial Q_1^b}{\partial \beta_{SVC}^{ab}} & \frac{\partial Q_1^b}{\partial \beta_{SVC}^{bc}} & 0 \\ \frac{\partial Q_1^c}{\partial \delta_1^a} & \frac{\partial Q_1^c}{\partial \delta_1^b} & \frac{\partial Q_1^c}{\partial \delta_1^c} & 0 & \frac{\partial Q_1^c}{\partial \beta_{SVC}^{bc}} & \frac{\partial Q_1^c}{\partial \beta_{SVC}^{ca}} \end{pmatrix}^{(i)} \begin{pmatrix} \Delta \delta_1^a \\ \Delta \delta_1^b \\ \Delta \delta_1^c \\ \Delta \beta_{SVC}^{ab} \\ \Delta \beta_{SVC}^{bc} \\ \Delta \beta_{SVC}^{ca} \end{pmatrix}^{(i)}; \quad (5)$$

Elements corresponding to the partial derivatives of active and reactive powers with respect to the phase angles of the nodal voltage are:

$$\frac{\partial P_{\rho,l}^{ph1}}{\partial \delta_{\rho,l}^{ph1}} = -Q_\rho^{ph_1 subt} - \left(U_l^{ph_1}\right)^2 B_{\rho\rho}^{ph_1ph_2}, \quad \frac{\partial P_{\rho,l}^{ph1}}{\partial U_{\rho,l}^{ph1}} U_{\rho,l}^{ph_1} = P_\rho^{ph_1 subt} - \left(U_\rho^{ph_1}\right)^2 G_{\rho\rho}^{ph_1ph_2}, \quad (6)$$

$$\frac{\partial Q_{\rho,l}^{ph1}}{\partial \delta_{\rho,l}^{ph1}} = P_\rho^{ph_1 subt} - \left(U_l^{ph_1}\right)^2 G_{\rho\rho}^{ph_1ph_2}, \quad \frac{\partial Q_{\rho,l}^{ph1}}{\partial U_{\rho,l}^{ph1}} U_{\rho,l}^{ph_1} = Q_\rho^{ph_1 subt} - \left(U_\rho^{ph_1}\right)^2 B_{\rho\rho}^{ph_1ph_2}, (7)$$

- forρ=1,2 and $ph_1 \neq ph$:

$$\frac{\partial P_{\rho,l}^{ph1}}{\partial \delta_{\rho,l}^{ph2}} = U_\rho^{ph_1} U_\rho^{ph_2} \left(G_{\rho\rho}^{ph_1ph_2} sin\left(\delta_\rho^{ph_1} - \delta_\rho^{ph_2}\right) - B_{\rho\rho}^{ph_1ph_2} cos\left(\delta_\rho^{ph_1} - \delta_\rho^{ph_2}\right)\right), \quad (8)$$

$$\frac{\partial Q_{\rho,l}^{ph1}}{\partial \delta_{\rho,l}^{ph2}} = -U_\rho^{ph_1} U_\rho^{ph_2} \left(G_{\rho\rho}^{ph_1ph_2} cos\left(\delta_\rho^{ph_1} - \delta_\rho^{ph_2}\right) + B_{\rho\rho}^{ph_1ph_2} sin\left(\delta_\rho^{ph_1} - \delta_\rho^{ph_2}\right)\right), \quad (9)$$

- for the remaining elements:

$$\frac{\partial P_{1,l}^{ph1}}{\partial \delta_{2,l}^{ph2}} = U_1^{ph_1} U_2^{ph_2} \left(G_{12}^{ph_1ph_2} sin\left(\delta_1^{ph_1} - \delta_2^{ph_2}\right) - B_{12}^{ph_1ph_2} cos\left(\delta_1^{ph_1} - \delta_2^{ph_2}\right)\right), \quad (10)$$

$$\frac{\partial Q_{1,l}^{ph1}}{\partial \delta_{2,l}^{ph2}} = -U_1^{ph_1} U_2^{ph_2} \left(G_{12}^{ph_1ph_2} cos\left(\delta_1^{ph_1} - \delta_2^{ph_2}\right) + B_{12}^{ph_1ph_2} sin\left(\delta_1^{ph_1} - \delta_2^{ph_2}\right)\right), \quad (11)$$

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$$\frac{\partial P_{2,l}^{ph1}}{\partial \delta_{1,l}^{ph2}} = U_1^{ph_1} U_2^{ph_2} \left(G_{21}^{ph_1 ph_2} sin\left(\delta_2^{ph_1} - \delta_1^{ph_2}\right) - B_{21}^{ph_1 ph_2} cos\left(\delta_2^{ph_1} - \delta_1^{ph_2}\right)\right), \quad (12)$$

$$\frac{\partial Q_{2,l}^{ph1}}{\partial \delta_{1,l}^{ph2}} = -U_1^{ph_1} U_2^{ph_2} \left(G_{21}^{ph_1 ph_2} cos\left(\delta_2^{ph_1} - \delta_1^{ph_2}\right) + B_{21}^{ph_1 ph_2} sin\left(\delta_2^{ph_1} - \delta_1^{ph_2}\right)\right). \quad (13)$$

Other elements of the Jacobian in (5) are equal:

$$\frac{\partial P_1^{ph}}{\partial B_{SVC}^{phk}} B_{SVC}^{phk} = -U_1^{ph} U_1^k B_{SVC}^{phk} \sin\left(\delta_1^{ph} - \delta_1^k\right), \quad (14)$$

$$\frac{\partial Q_1^{ph}}{\partial B_{SVC}^{phk}} B_{SVC}^{phk} = -2\left(U_1^{ph}\right)^2 B_{SVC}^{phk} + U_1^{ph} U_1^k B_{SVC}^{phk} \cos\left(\delta_1^{ph} - \delta_1^k\right). \quad (15)$$

After an estimate for the i-th iteration is obtained on the basis of the iterated linearized equations for SVC, it is combined with the linearized equation (16), which represents the EPS proper, and then a new set of state variables is calculated.

$$\left(\frac{\Delta \mathbf{P}_l^{ph}}{\Delta \mathbf{Q}_l^{ph}}\right)^{(i)} = \left(\begin{array}{cc} \frac{\partial \mathbf{P}_l^{ph}}{\partial \boldsymbol{\delta}_l^{ph}} & \frac{\partial \mathbf{P}_l^{ph}}{\partial \mathbf{U}_l^{ph}} \mathbf{U}_l^{ph} \\ \hline \frac{\partial \mathbf{Q}_l^{ph}}{\partial \boldsymbol{\delta}_l^{ph}} & \frac{\partial \mathbf{Q}_l^{ph}}{\partial \mathbf{U}_l^{ph}} \mathbf{U}_l^{ph} \end{array}\right)^{(i)} \left(\frac{\Delta \boldsymbol{\delta}_l^{ph}}{\frac{\Delta \mathbf{U}_l^{ph}}{\mathbf{U}_l^{ph}}}\right)^{(i)}. \quad (16)$$

SVC reactance values are updated using the following expression:

$$\left(B_{SVC}^{phk}\right)^{(i)} = \left(B_{SVC}^{phk}\right)^{(i-1)} + \frac{\Delta B_{SVC}^{phk}}{B_{SVC}^{phk}} \left(B_{SVC}^{phk}\right)^{(i-1)}.$$

This calculation completes the i-th iteration, then a check is made on the convergence of the equations of three-phase unbalanced power. If the convergence criterion is not met, a new iteration is performed.

III. Model 2

This alternative SVC model is implemented using lead angles of thyristors, which are used as state variables. In this setting, the iterated linearized SVC equation takes the form:

$$\begin{pmatrix} \Delta P_1^a \\ \Delta P_1^b \\ \Delta P_1^c \\ \Delta Q_1^a \\ \Delta Q_1^b \\ \Delta Q_1^c \end{pmatrix}^{(i)} = \begin{pmatrix} \frac{\partial P_1^a}{\partial \delta_1^a} & \frac{\partial P_1^a}{\partial \delta_1^b} & \frac{\partial P_1^a}{\partial \delta_1^c} & \frac{\partial P_1^a}{\partial B_{SVC}^{ab}} B_{SVC}^{ab} & 0 & \frac{\partial P_1^a}{\partial B_{SVC}^{bc}} B_{SVC}^{ca} \\ \frac{\partial P_1^b}{\partial \delta_1^a} & \frac{\partial P_1^b}{\partial \delta_1^b} & \frac{\partial P_1^b}{\partial \delta_1^c} & \frac{\partial P_1^b}{\partial B_{SVC}^{ab}} B_{SVC}^{ab} & \frac{\partial P_1^b}{\partial B_{SVC}^{bc}} B_{SVC}^{bc} & 0 \\ \frac{\partial P_1^c}{\partial \delta_1^a} & \frac{\partial P_1^c}{\partial \delta_1^b} & \frac{\partial P_1^c}{\partial \delta_1^c} & \underline{0} & \frac{\partial P_1^c}{\partial B_{SVC}^{bc}} B_{SVC}^{bc} & \frac{\partial P_1^c}{\partial B_{SVC}^{ca}} B_{SVC}^{ca} \\ \frac{\partial Q_1^a}{\partial \delta_1^a} & \frac{\partial Q_1^a}{\partial \delta_1^b} & \frac{\partial Q_1^a}{\partial \delta_1^c} & \frac{\partial Q_1^a}{\partial B_{SVC}^{ab}} B_{SVC}^{ab} & 0 & \frac{\partial Q_1^a}{\partial B_{SVC}^{ca}} B_{SVC}^{ca} \\ \frac{\partial Q_1^b}{\partial \delta_1^a} & \frac{\partial Q_1^b}{\partial \delta_1^b} & \frac{\partial Q_1^b}{\partial \delta_1^c} & \frac{\partial Q_1^b}{\partial B_{SVC}^{ab}} B_{SVC}^{ab} & \frac{\partial Q_1^b}{\partial B_{SVC}^{bc}} B_{SVC}^{bc} & 0 \\ \frac{\partial Q_1^c}{\partial \delta_1^a} & \frac{\partial Q_1^c}{\partial \delta_1^b} & \frac{\partial Q_1^c}{\partial \delta_1^c} & 0 & \frac{\partial Q_1^c}{\partial B_{SVC}^{bc}} B_{SVC}^{bc} & \frac{\partial Q_1^c}{\partial B_{SVC}^{ca}} B_{SVC}^{ca} \end{pmatrix}^{(i)} \begin{pmatrix} \Delta \delta_1^a \\ \Delta \delta_1^b \\ \Delta \delta_1^c \\ \frac{\Delta B_{SVC}^{ab}}{B_{SVC}^{ab}} \\ \frac{\Delta B_{SVC}^{ba}}{B_{SVC}^{ba}} \\ \frac{\Delta B_{SVC}^{ca}}{B_{SVC}^{ca}} \end{pmatrix}^{(i)};$$

(17)

The new Jacobian elements in the linearized equation have the following form:

$$\frac{\partial P_1^{ph}}{\partial \beta_{SVC}^{ab}} = U_1^{ph} U_1^k \sin\left(\delta_1^{ph} - \delta_1^k\right) \frac{\partial B_{SVC}^{phk}}{\partial \beta_{SVC}^{ab}}; \quad (18)$$

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$$\frac{\partial Q_1^{ph}}{\partial \beta_{SVC}^{ab}} = -\left(\left(U_1^{ph}\right)^2 - U_1^{ph}U_1^k\cos\left(\delta_1^{ph} - \delta_1^k\right)\right)\frac{\partial B_{SVC}^{phk}}{\partial \beta_{SVC}^{ab}};(19)$$

$$\frac{\partial B_1^{ph}}{\partial \beta_{SVC}^{ab}} = -\frac{2}{\pi X_L}\left(1 + \cos\left(2\beta_{SVC}^{phk}\right)\right).(20)$$

The Jacobian elements corresponding to the partial derivatives of the values of active and reactive powers with respect to other phase angles of the nodal voltage are calculated similarly to (18) - (20). After solving the system of equations (16) and (17), a new set of state variables describing EPS and SVC is determined.
SVC thyristor lead angles are updated using the expression:

$$\left(\beta_{SVC}^{phk}\right)^{(i)} = \left(\beta_{SVC}^{phk}\right)^{(i-1)} + \left(\Delta\beta_{SVC}^{phk}\right)^{(i)}$$

After the completion of the i-th iteration, the obtained solution is used to verify the convergence of the equations of three-phase unbalanced power. If the convergence criterion is not satisfied, a new iteration is performed.

IV. CONCLUSION

FACTS technology opens up new possibilities for managing power flows both in existing and in new or modernized power lines. These opportunities arise due to the ability of FACTS technology to manage interrelated parameters that determine the functioning of power lines, including reactance, current, voltage, phase angle between voltages, etc.

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