Abstract - The main purpose of this paper is to investigate power flow regulating capabilities of an UPFC’s injection model by using all three UPFC’s control parameters simultaneously. The control system of the model is developed and its contributions to power flow regulation are explored on a multi-machine test system. The analysis is carried out from dynamic aspect utilising time-domain simulations. With the UPFC being embedded in the system, the analysis is concentrated on a transmission system compensation issues. It is shown that the model can fulfil functions of reactive shunt compensation, series compensation and phase shifting meeting multiple control objectives by applying boosting transformer injected voltage and exciting transformer reactive current.

Keywords: FACTS-devices, Unified Power Flow Controller (UPFC), injection model, power flow regulation, series and shunt compensation, phase shifting

I. INTRODUCTION

The rapid development of power electronics has made it possible to design power electronic equipment of high rating for high voltage systems. Many regulation problems resulting from transmission system may be, at least partly, improved by use of the equipment well known as FACTS-controllers. The de-regulation (restructuring) of power networks will probably imply new loading conditions and new power flow situations. This is an additional reason to face the FACTS. In order to deal with the power flow regulation problem, the solutions with FACTS-devices must provide mathematical and computer models of the controllers. This is considered to be rather new impetus in the field [1-3].

Within this paper, which is on the trace of our previous works [4-6], the impact of the Unified Power Flow Controller (UPFC) on power flow regulation is analysed within dynamic approach. Formulation of the problem from a transmission system compensation viewpoint is well-established [7] and it is used here in a quite straightforward manner. The UPFC in its general form can provide simultaneous, real-time control of all basic power system parameters (transmission voltage, impedance and phase angle) and dynamic compensation of ac system. Thereby, it can fulfil functions of reactive shunt compensation, series compensation and phase shifting meeting multiple control objectives by applying boosting transformer injected voltage and exciting transformer reactive current. Besides the power flow regulation, it is useful in oscillations damping, and in supporting voltage magnitudes, helping the voltage unstable situations solved.

II. SYSTEM MODELLING

The benefits of the UPFC and its injection model with several types of control strategies contributing to transmission system compensation problem are explored by analysing a simple 6-machine, 20(22)-bus test system with 400 kV nominal voltage (Fig. 1). The system is based on a one often used in CIGRE reports. It is comprised of six generators located in two areas, which are modelled by using two-axis E’ model [8]. The transient effects are accounted for, while the subtransient ones are neglected. The generators are equipped with excitation system including overexcitation limiter (OEL) and speed governor - turbine system and are connected via interties. The loads are located in both of the two main areas and are of the ZIP type (constant current in active power and constant impedance in reactive one). The UPFC, in the middle of one of the interties carrying a fraction of the total power transmission, is aimed to control the power flow on the intertie in the steady state. The task is considered to be typical in attempt of removing a constraint that limits the possible power transfer between the areas.

III. THE UPFC’s INJECTION MODEL

The UPFC (Fig. 2) can provide simultaneous control of all basic power system parameters (transmission voltage, impedance and phase angle) and dynamic compensation of ac system. The controller can fulfill functions of reactive shunt compensation, series compensation and phase shifting meeting multiple control objectives by applying boosting transformer injected voltage and exciting transformer reactive current (Figs. 3, 4). The UPFC’s injection model [9, 10] is used enabling three parameters to be simultaneously controlled (Fig. 5), namely the shunt reactive power, $Q_{\text{conv}1}$, and the magnitude, $r$, and angle, $\gamma$, of the injected series voltage. The control system [4, 5, 6] is of decoupled single-input single-output type. The selection of input/output signals depends on the predetermined control mode, which could be changed during the simulation. At external level, following locally measured variables of the UPFC are controlled: the shunt side bus voltage magnitude, $V_i$, (by changing $Q_{\text{conv}1}$), the series side bus voltage magnitude, $V_j$, reactive power flow into series side bus, $Q_j$, reactive power requirement of the series side converter 2, $Q_{\text{conv}2}$, or compensating voltage magnitude, $V_{\text{comp}}$, (by changing $r$) and active power flow into the series side bus, $P_j$, active power requirement of the series side converter 2, $P_{\text{conv}2}$, bus voltage angle difference, $\Theta_{ij}$, or compensating voltage angle, $\phi_{\text{comp}}$, (by changing $\gamma$).
In the model, the shunt side could be controlled only in voltage mode \( V_i \leftrightarrow Q_{conv1} \) emphasising that \( Q_{conv1} \) represents reactive power loading of the shunt converter 1. The series side could be controlled through the \( r \leftrightarrow \gamma \) pair in several different modes: bus voltage and active power flow \( V_i \leftrightarrow P_i \), reactive and active power flow \( Q_i \leftrightarrow P_i \), series compensation \( Q_{conv2} \leftrightarrow P_{conv2}(=0) \), phase shifting of Phase Angle Regulator (PAR) type \( V_i(=V_S) \leftrightarrow \Theta_S \), and phase shifting of Quadrature Boosting Transformer (QBT) type \( V_{comp} \leftrightarrow \Phi_{comp}(=\pi/2) \). The variables are chosen satisfying general \( V_i \leftrightarrow Q \) and \( \Theta \leftrightarrow P \) decoupling. The internal level control provides fast response converter regulation.

### A. Transmission voltage support

Bus voltage magnitudes could be supported at both sides of the UPFC. At the series side, voltage \( V_j \) is supported through \( r \)-loop with appropriate adjustment of angle \( \gamma \). At the shunt side, \( V_i \)-feedback enables support through \( Q_{conv1} \)-loop. If losses are neglected, the active power requirement is equal for both converters

\[
P_{conv1} = P_{conv2} = \text{Re}(V_i^*T_j^*) = -r_b V_i \sin(\theta_j + \gamma) + r_b V_j^2 \sin \gamma.
\]

Thereby, the nominal rating \( S_{conv1} \) of the shunt converter 1 is given as a maximum active power demanded by injected series voltage source max \( |P_{conv1}(r,\gamma)| \)

\[
S_{conv1} = \text{max}|P_{conv1}(r,\gamma)| - r_b V_i^2 \sin \gamma + Q_{conv1}.
\]

It is possible to allow a short-term overload capability, but mostly reactive power \( Q_{conv1} \) is in the range

\[
-\text{max}|Q_{conv1}| \leq Q_{conv1} \leq \text{max}|Q_{conv1}|.
\]

The impact of the \( Q_{conv1} \) comes through the reactive power \( Q_{Si} \) of the injection model (Fig. 5).

\[
Q_{Si} = -r_b V_i^2 \cos \gamma + Q_{conv1}.
\]

By setting appropriate \( V_i \)-feedback control in an SVG manner, the \( Q_{conv1} \) could keep \( V_i \) at a referent value whenever there is enough remaining reactive capacity in shunt converter.

### B. Series compensation

Series compensation mode of the UPFC could be attained by setting angle \( \gamma \) in a position that gives

\[
\gamma = \pi / 2 - \phi,
\]

where the angles are defined as in Fig. 4. In that case, the vectors \( V_j \) and \( V_{comp} \) are co-linear, and perpendicular to the current \( I_j \). Therefore, the following relation holds

\[
V_j \sin \gamma = V_j \sin(\theta_j + \gamma),
\]

which makes \( P_{conv2} \) from (1) equal to zero. It comes out that for \( \gamma \) regulation keeping \( P_{conv2} \) at zero enables characteristic \( (V=\mp 1) \) perpendicular form of the vector diagram. The current \( I_j \) is generally defined as

\[
I_j = \left( V_i - V_j \right) / j x_s = \left[ (P_{conv1} + j Q_{conv2}) / V_S \right].
\]

but this expression is not very convenient due to division by \( r \) \((V_S = r \times V_i)\) which could take zero value. To be used in the series compensation mode only, the following relation is applied instead

\[
I_j = \sqrt{P_{conv1}^2 + (Q_{conv1} - Q_{Si})^2} / V_S;
\]

\[
\phi = \Theta_j + \arctg \frac{-Q_{conv1} - Q_{Si}}{P_{conv1}}.
\]

Equation (9) enables \( V_S \) magnitude consideration, since \( V_j = V_{comp} + j x_s I_j \).

Multiplying (10) by \( I_j^* \), it results with

\[
V_S^* I_j^* = V_{comp}^* I_j^* + j x_s I_j^2.
\]

Using proportionality factor \( k_c \)

\[
k_c = V_{comp} / (x_s I_j).
\]

due to zeroed \( P_{conv2} \), equation (11) becomes

\[
Q_{conv2} = j k_c x_s I_j^2 + j x_s I_j^2
\]

which could be written more conveniently as

\[
(1 + k_c) x_s I_j^2 = Q_{conv2} = 0.
\]

Using (14) in the \( r \)-loop, it is enabled to adjust voltage magnitude \( V_{comp} \) by setting \( k_c \) at appropriate value. If \( k_c \) is set to zero, then \( V_S = x_s I_j \) and \( \Theta_j = \Theta_S \), making reactance between buses \( i \) and \( j \) totally compensated. Having \( k_c < 0 \) \((k_c \geq 0)\), the total reactance between buses \( i \) and \( j \) is made to be inductive (capacitive) with respect to current \( I_j \).

### C. Phase shifting

Phase shifting mode of the UPFC could be achieved by operating it either as a phase angle regulator (PAR) or a quadrature boosting transformer (QBT).

In PAR operation, the bus voltage magnitudes \( V_i \) and \( V_j \) should be set equal. It is done in the \( r \)-loop by setting \( V_i = V_j = 0 \).

Then, the bus voltage angle difference \( \Theta_{ij} \) is set at predetermined value \( \Theta_{ij,REF} \) through \( \gamma \)-loop. By changing referent value \( \Theta_{ij,REF} \) the PAR phase shifting is carried out.

In QBT operation, the voltage \( V_{comp} \) should be set perpendicular to the bus voltage \( V_i \), so as the angle \( \gamma \) is set at the position defined by

\[
\phi_{comp,REF} - \phi_{comp} = 0; \quad \phi_{comp,REF} = \pi / 2 \text{ or } 3 \pi / 2.
\]

Following relations concerning \( V_{comp} \) should be satisfied

\[
V_{comp} = \sqrt{V_i^2 + V_j^2 - 2V_i V_j \cos \Theta_j} ;
\]

\[
\phi_{comp} = \arccos \left( V_i \cos \Theta_j - V_j / V_{comp} \right)
\]

for \( \Theta_j \leq 0 \) \( \Rightarrow \phi_{comp} = \phi_{comp} \); for \( \Theta_j > 0 \) \( \Rightarrow \phi_{comp} = 2\pi - \phi_{comp} \).
D. Damping of electromechanical oscillations

Besides the regulators, the model allows implementation of strategy for damping of electromechanical oscillations. The strategy is of take-over type and based on a transient energy function (TEF) [10], using time derivatives of local variables from both sides of the UPFC. The shunt part of transient energy function block uses information from $dV_i/dt$, whereas the series part from $d\Theta_i/dt$. The control laws for both parts are given in [4-6] with detailed results.

IV. NUMERICAL RESULTS

Determination of operating region in terms of characteristic voltages and power flows could be initiated by simple two-parameter rotational change of additional voltage vector $\vec{V}_d$. Starting from a point defined by $r=r_{\text{max}}=0.15$ pu and $\gamma=0^\circ$, the change comprises rotation of the vector from $\gamma=0^\circ$ to $\gamma=360^\circ$, keeping its magnitude constant. Having one period completed, the magnitude is decreased and the change in the angle $\gamma$ is started all over again. Eventually, the magnitude is decreased to minimum ($r=0$ pu). Dependence of shunt and series side bus voltage magnitudes, $V_i$ and $V_j$, with respect to changes in $(r, \gamma)$ pair is depicted in Fig. 6 (the third parameter, $Q_{\text{conv}}$, and thereby $V_i$, is not controlled in this case). It is shown that the voltage magnitudes have opposite changes, i.e. since neither of the buses is voltage controlled, one of them could have magnitude increased if the other one is decreased and vice versa. Similar effect could be found in transformer operation in a network with low level of short-circuit capacity. The distortion becomes more pronounced whenever larger values are given to parameter $r$. The same case of the $(r, \gamma)$ change is also shown in Fig. 7, but in $V_j=f(P_{j2})$ domain showing voltage $V_j$ dependence on active power flow $P_{j2}$ at the series side of UPFC. As it could be seen, it would be necessary to have the operating region voltage limited due to low magnitude value. In addition, the latter diagram shows the range of active power flow $P_{j2}$ that could be achieved within the change.

Once having the operating region defined, it is necessary to adjust parameters of the PI regulator before encountering regulation problem. An example (Figs. 8-10) is provided with $V_j\equiv P_{j2}$ mode of regulation. Starting from the UPFC’s operating point $O$ ($r=r_{\text{max}}, \gamma=0^\circ$), by choosing appropriate values of the parameters, it is made possible to move operating point through all four quadrants ($0\rightarrow1\rightarrow2\rightarrow3\rightarrow4\rightarrow1$). The point is always kept inside allowed boundaries defined by $r_{\text{max}}$. The path is obtained by applying step-change in one variable while keeping the other one constant (the values of $V_j$ are 0.91 pu and 0.95 pu, and of $P_{j2}$ are $-1.75$ pu and $-2.75$ pu). It ends at point 1. Besides depicting it in two dimensions (Fig. 8), the same case could be shown in three dimensions (Figs. 9-10), with dependence of $(r, \gamma)$ pair respectively to $(V_j, P_{j2})$ domain. Thereby, the $\gamma$-dependence has a spiral form, whereas the $r$-dependence has a conical one. The operating point is found at the surface of the bodies.
Simultaneous control of all three UPFC’s parameters, \((r, \gamma, Q_{\text{conv}})\), enables its operation in several different modes of regulation.

In the power flow mode with the shunt-side voltage supported, it is possible to control reactive, \(Q\), and active, \(P\), power flow at the series-side with the voltage magnitude \(V\) at the shunt-side simultaneously controlled (Figs. 11-12). After initial steady-state period, defined with \(r=0\) pu, \(\gamma=0^\circ\), and \(V\) being uncontrolled, a sequence of steps is implemented to show that the power flow \((Q, P, V)\) could be changed in steps and in the same time the voltage magnitude \(V\) kept constant at initial value. Thus, the first step is defined to bring the point to \((Q, P, V)\) \(= (-0.5\) pu, \(-3.5\) pu, \(0.9516\) pu) through \((r, \gamma, Q_{\text{conv}})\) feedback. Having this point achieved, the step back follows to bring the point at the initial state \((-1.01\) pu, \(-2.93\) pu, \(0.9516\) pu). Step 2 forces the point to move in different direction \((-1.5\) pu, \(-2.5\) pu, \(0.9516\) pu). The ending step brings the point to initial value. The time responses meet general control criteria showing that the control system parameters are appropriately tuned. Moreover, it is shown that in addition to the UPFC’s conventional power flow regulation \((Q, P, V)\), it is also possible to control bus voltage magnitude \(V\) whenever there is enough remaining reactive capacity of the shunt converter.

In the series compensation mode, the simultaneous control of UPFC’s set of parameters, \((r, \gamma, Q_{\text{conv}})\), could be achieved as well. An example (Figs. 13-15) is provided to illustrate the guidelines from section III.B. After initial steady-state period, defined by arbitrary values \(r=0.05\) pu, \(\gamma=150^\circ\), and \(V\) being uncontrolled, a sequence of steps operates the UPFC in series compensation mode. In the step 1, characteristic perpendicular form of V-I diagram is introduced by forcing active power of the series converter \(P_{\text{conv}}\) to zero (Fig. 13). Thus, the angle \((\gamma+\phi)\) from the vector diagram (Fig. 4) takes value of 90° in the first step (Fig. 14), where \(k_c=+10\). In the same time, voltage \(V\) is controlled to be 0.94 pu (Fig. 15). In the second step, the UPFC’s operation is still in the series compensation mode, but the change to \(k_c=-10\) forces the angle \((\gamma+\phi)\) to become 270°. Thereby, the character of impedance (capacitive / inductive) between buses \(i\) and \(j\) could be changed upon request. In the step 3, by setting \(k_c=0\), the voltages \(V_i\) and \(V_j\) become equal, neutralising any impedance between shunt and series sides of the UPFC.

The phase shifting mode is illustrated here by phase angle regulation, PAR, subtype (Figs. 16-17), again keeping simultaneous three-parameter control active. Similar considerations apply for quadrature boosting transformer, QBT, subtype. In both cases, the guidelines from subsection III.C help in having this mode understood. After initial steady-state period, defined by arbitrary values \(r=0.05\) pu, \(\gamma=150^\circ\), and \(V\) being uncontrolled, a sequence of steps introduces the PAR mode. The step 1 forces magnitudes of the voltages \(V_i\) and \(V_j\) to become equal (Fig. 16), but displaced in phase \((\Theta_i=\Theta_j-\Theta)\) by -4° (Fig. 17).
In the same time, the voltage magnitude $V_i$ is controlled to be 0.94 pu. In the second step, the PAR mode is preserved, but with the phase displacement value of $+4^\circ$. In the step 3, by setting $\Theta_{ij}^{\text{REF}}$ to zero, and still keeping the voltage magnitudes equalised ($V_i$ additionally controlled to 0.94 pu), the voltages $V_i$ and $V_j$ become equal.

V. CONCLUSIONS

Possible benefits of the UPFC’s injection model are investigated within power flow regulation problem. The analysis is carried out on a multi-machine test system and concentrated on a transmission system compensation problem. By using appropriate control system of the model it is made possible to control simultaneously three transmission system variables depending on the regulation mode (power flow, series compensation, and phase shifting). By describing these fundamental characteristics it is shown that the UPFC could be useful transmission system controller, and furthermore represented by the injection model with proposed control system.

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VII. REFERENCES

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VIII. BIOGRAPHIES

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