THE IMPACT OF UNIFIED POWER FLOW CONTROLLER IN POWER FLOW REGULATION

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Abstract—The application of a global control based on the combination of the voltage, active and reactive power to investigate and fully understand the control capabilities and the impact of the UPFC in power flow regulation is presented. The models are presented and analysed in details in this paper. The effectiveness and convergence of the method proposed is tested on the 30 bus IEEE system. The results prove that the application of UPFC in electric power system is intended for the control of power flow, improvement of stability, voltage profile management, power factor correction, and loss minimisation.

Key Words: Power Flow, FACTS, SVC, TCSC, UPFC, Newton-Raphson, Reactive Power Compensation

1. INTRODUCTION

Better, faster, cheaper and more reliable utilization of electrical energy is an important subject that electric power companies are concerned about. Harmonics and reactive power flowing to the supply system, transients caused by switching or faults, and other problems cause less reliable electrical supply systems. In order to cope with these kind of problems and increase usable power transmission capacity, FACTS (Flexible AC transmission systems) where developed and introduced to the market. FACTS philosophy was first introduced by N.G.Hingorani [1] from the Electric power research institute (EPRI) in the USA in 1988, although the power electronic controlled devices had been used in the transmission network for many years before that. The objective of FACTS devices is to bring a system under control and to transmit power as ordered by the control centers, it also allows increasing the usable transmission capacity to its thermal limits. With FACTS devices we can control the phase angle, the voltage magnitude at chosen buses and/or line impedances. Among a variety of FACTS controllers, UPFC is one of the more interesting and potentially the most versatile. It can provide simultaneous and independent control of important power system parameters: line active power flow, line reactive power flow, impedance and voltage [4]. The UPFC operation mode (terminal voltage Regulation, series compensation, phase shift, or any combination of them) can be changed from one state into another without hardware alterations to adapt to particular changing systems conditions. This feature makes it competent device. UPFC consists of two switching power converters connected to each other through a dc link capacitor as shown in Fig.1. The shunt inverter operates as a Static Synchronous Compensator (STATCOM) [5]. It compensates reactive power flow in the transmission line and keeps constant the dc voltage across the dc link capacitor. The series converter performs the function of the Static Synchronous Series Compensator (SSSC) by inserting a series voltage with variable magnitude and phase angle. By this inserted voltage, the active and reactive power flow in the transmission line can be regulated [7].

2. MODELING APPROACH OF UPFC

In this paper the configuration shown in Fig.2, is used to model the UPFC. This model has a wide range of applications for investigating the effect of UPFC on the system.
The UPFC may be seen to consist of two VSC sharing a common capacitor on their DC side and a unified control system. A simplified schematic representation of the UPFC is given in fig.2. The UPFC allows simultaneous control of active power flow, reactive power flow, and voltage magnitude at the UPFC terminals. Alternatively, the controller may be set to control one or of these parameters in any combination [2]. The active power demanded by the series converter is drawn by the shunt converter from the AC network and supplied to bus m through the DC link. The output voltage of the series converter is added to the nodal voltage, at say bus k, to boost the nodal voltage at bus m. The voltage magnitude of the output voltage provides voltage regulation, and the phase angle determines the mode of power flow control [2]. The UPFC voltage sources are:

$$E_{cr} = V_{cr} \cos(\delta_{cr}) + j V_{cr} \sin(\delta_{cr})$$  \hspace{1cm} (1)
$$E_{vr} = V_{vr} \cos(\delta_{vr}) + j V_{vr} \sin(\delta_{vr})$$  \hspace{1cm} (2)

Where $V_{cr}$ and $V_{vr}$ are the controllable magnitude $V_{cr_{min}} \leq V_{cr} \leq V_{cr_{max}}$, and phase angle $0 \leq \delta_{cr} \leq 2\pi$ of the voltage source representing the shunt converter. The magnitude $V_{vr}$ and phase angle $\delta_{vr}$ of the voltage source representing the series converter are controlled between limits:

$V_{vr_{min}} \leq V_{vr} \leq V_{vr_{max}}$, and $0 \leq \delta_{vr} \leq 2\pi$.

3. BASIC RELATIONSHIP FOR POWER FLOW CONTROL

Fig.4 Shows single line diagram of a simple transmission line, modelized by inductive reactance $X$, connecting a sending-end voltage $V_A$ to a receiving-end voltage $V_B$.

Assuming the voltage magnitude of $V_A$ and $V_B$ are equal to $V$, the active and reactive power flow between two nodes A and B are given by the following expressions.

$$P_{AB} = \frac{V^2}{X} \sin \delta$$  \hspace{1cm} (3)

And

$$Q_{AB} = \frac{V^2}{X}(1-\cos \delta)$$  \hspace{1cm} (4)

The control of power flow can be performed by the following methods:

- **Line voltage control**

Fig.5 shows a single line diagram of a simple transmission line in which a voltage source is inserted. This source injects a voltage in phase with the sending voltage so as to regulate only the amplitude of the line voltage, $V_{sh} = \Delta V_A$. Active and reactive power transit becomes:

$$P_{sh} = (1+K_{sh})\frac{V^2}{X} \sin \delta$$  \hspace{1cm} (5)

and

$$Q_{sh} = \frac{V^2}{X}(1+K_{sh})(1+K_{sh}\cos \delta)$$  \hspace{1cm} (6)

with $K_{sh} = \frac{\Delta V}{V}$

This approach has for main drawback to be limited by the injected voltage in series with the line.
B. Line impedance control:
This method has for basic principle to insert a series voltage on the line. Fig.8

\[ X = X - X_c = X(1 - K_{ser}) \]  \hspace{1cm} (7)

\[ P_{AB} = \frac{V^2}{X(1 - K_{ser})} \sin \delta \]  \hspace{1cm} (8)

\[ Q_{AB} = \frac{V^2}{X} (1 - \cos \delta) \left(1 + K_{ser}\right) \frac{1}{(1 - K_{ser})^2} \]  \hspace{1cm} (9)

with \(-1 < K_{ser} < 1\)

The total reactance of the line becomes, and the line power transit can be controlled as given bellow.

The variation of the line power transit as a function of the coefficient \(K_{ser}\) is presented in fig.9.

C. Line impedance control:
This third method consists in the control of the electrical angle by inserting a voltage in series with the line.

In this case, the active and reactive power transferred between A and B becomes:

\[ P_{AB} = \frac{V^2}{X} \sin(\delta + \alpha) \]  \hspace{1cm} (10)

\[ Q_{AB} = \frac{V^2}{X} (1 - \cos(\delta + \alpha)) \]  \hspace{1cm} (11)

Fig.12 shows the effect of two inserted angles \(\alpha (\alpha = 15^\circ \text{ and } 30^\circ)\).

4. IMPLEMENTING UPFC IN THE POWER FLOW PROBLEM
The purpose of a power system is to deliver the required power to the customers, within acceptable voltage and frequency limits and in a reliable and economic manner. Power flow is an important issue in system planning and operation, and it is the most common of power system computer calculations. In this analysis, the transmission system is modelled by a
set of buses or nodes interconnected by transmission 
links. Generators and loads connected to various 
nodes of the system inject and absorb power from the 
transmission system. The model considered in power 
flow studies is appropriate for finding the steady-state 
powers and voltages of the transmission system [5]. A 
unified approach combines the state variables 
describing controllable equipment (FACTS) with 
those describing the network in a single frame of 
reference for unified, iterative solutions using the 
Newton-Raphson algorithm.

\[
f(X_{\text{AC}}, R_{\alpha\beta}) = 0 \\
g(X_{\text{AC}}, R_{\alpha\beta}) = 0 
\]

(12)

Where \( X_{\text{AC}} \) stands for the AC network state 
variables, namely, nodal voltage magnitude and phase 
angles, and \( R_{\alpha\beta} \) stands for the power system 
controller state variables. The structure of the 
modified Jacobian is shown in Fig. 13.

![Fig 13: Modified Jacobian](image)

General nodal power flow equations and the linearized 
power system model can be expressed in rectangular 
form by the following equations:

\[
P = f_V(V, 0, G, B) \\
Q = f_Q(V, 0, G, B) 
\]

(13)

\[
\begin{bmatrix} \Delta P \end{bmatrix} = \begin{bmatrix} H & N \end{bmatrix} \begin{bmatrix} \Delta V \end{bmatrix} \\
\begin{bmatrix} \Delta Q \end{bmatrix} = \begin{bmatrix} J & K \end{bmatrix} \begin{bmatrix} \Delta V \end{bmatrix} 
\]

(14)

Where \( P \) and \( Q \) are vectors of real and reactive nodal 
power injections, which are function of nodal voltages, 
\((V)\), and network conductances and susceptances, 
\((G \text{ and } B)\), respectively. \((\Delta P = P_{\text{ref}} - P_{\text{act}})\) is the real 
power mismatch vector and \((\Delta Q = Q_{\text{ref}} - Q_{\text{act}})\) is the 
reactive power mismatch vector. \((\Delta V \text{ and } \Delta \theta)\) are 
vectors of incremental changes in nodal voltages. \(H, \) 
\(N, J \text{ and } L\) denote the basic elements in the Jacobian 
matrix.

**A. Power Flow Model**

Based on the equivalent circuit shown in fig.3, the 
active and reactive power equations are:

At bus \( k \):

\[
P_k = V_{k1}^2 G_{k1} + V_{k1} V_{k1}^* [G_{k1} \cos(\theta_k - \theta_1) + B_{k1} \sin(\theta_k - \theta_1)] \\
Q_k = V_{k1}^2 B_{k1} + V_{k1} V_{k1}^* [G_{k1} \sin(\theta_k - \theta_1) - B_{k1} \cos(\theta_k - \theta_1)] 
\]

(15)

At bus \( m \):

\[
P_m = V_{m1}^2 G_{mn} + V_{m1} V_{m1}^* [G_{mn} \cos(\theta_m - \theta_1) + B_{mn} \sin(\theta_m - \theta_1)] \\
Q_m = V_{m1}^2 B_{mn} + V_{m1} V_{m1}^* [G_{mn} \sin(\theta_m - \theta_1) - B_{mn} \cos(\theta_m - \theta_1)] 
\]

(16)

- Series converter:

\[
P_{sv} = V_{sv}^2 B_{sv} + V_{sv} V_{sv}^* [G_{sv} \cos(\delta_{sv} - \delta_{sv}) + B_{sv} \sin(\delta_{sv} - \delta_{sv})] \\
Q_{sv} = V_{sv}^2 B_{sv} + V_{sv} V_{sv}^* [G_{sv} \sin(\delta_{sv} - \delta_{sv}) - B_{sv} \cos(\delta_{sv} - \delta_{sv})] 
\]

(17)

- Shunt converter:

\[
P_{sc} = V_{sc}^2 B_{sc} + V_{sc} V_{sc}^* [G_{sc} \cos(\delta_{sc} - \delta_{sc}) + B_{sc} \sin(\delta_{sc} - \delta_{sc})] \\
Q_{sc} = V_{sc}^2 B_{sc} + V_{sc} V_{sc}^* [G_{sc} \sin(\delta_{sc} - \delta_{sc}) - B_{sc} \cos(\delta_{sc} - \delta_{sc})] 
\]

(18)

And assuming loss-less converter: \( P_{sv} + P_{sc} = 0 \)

**B. CONTROL STRATEGY FOR THE UPFC**

Consider again the generalized power flow controller 
shown in Fig.14. Assume that the voltage source 
\((V_{pq})\) in series with the line can be controlled without 
restrictions. That is, the phase angle of phasor \( V_{pq} \) 
can be chosen independently of the line current 
between 0 and \(2\pi\) and its magnitude is variable 
between zero at a defined maximum value, \(V_{pq\text{max}}\).

This implies that voltage source \( V_{pq} \) must be able to 
generate and absorb both real and reactive power. The 
reactive current source \( I_r \) is assumed to be either 
capacitive or inductive with a variable magnitude that 
is dependent of the terminal voltage.
In order to show the capabilities of the UPFC model and the performance of the proposed algorithm, two test cases have been investigated.

-Case A: Voltage and Active power Control
The UPFC device is positioned on line L34, between bus.3 and bus.4. Line L34 is the controlled line. Effects of UPFC parameters such as real and reactive power flows on line L34, overall total real and reactive transmission losses of the system are investigated. When a UPFC parameter is controlled, another is kept constant (Local Control), but when all parameters of UPFC are controlled together, voltage, active power and reactive power, this control strategy called a global control. Table.1 Voltage and active power control

<table>
<thead>
<tr>
<th>UPFC in Line 3-4</th>
<th>UPFC Parameters with ( Q_{ij,reg} = 0.02 \text{ p.u.} )</th>
<th>( V_{reg} = 1 \text{ p.u at bus 3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{ij,reg} )</td>
<td>( V_{se} )</td>
<td>( V_{sh} )</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0672</td>
<td>1.0061</td>
</tr>
<tr>
<td>0.6</td>
<td>0.0317</td>
<td>1.005</td>
</tr>
<tr>
<td>0.7</td>
<td>0.0444</td>
<td>1.031</td>
</tr>
<tr>
<td>0.8</td>
<td>0.0862</td>
<td>1.0005</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1319</td>
<td>0.9972</td>
</tr>
<tr>
<td>1</td>
<td>-0.1786</td>
<td>0.9932</td>
</tr>
</tbody>
</table>

-Case B: Voltage and Reactive Power Control
The UPFC device is positioned on line L34, between bus.3 and bus.4. Line L34 is the controlled line. Table.2 shows the effect of this type of control. One of the UPFC parameter is kept constant \( P_{ij,reg} = 0.7 \text{ p.u.} \) and the two others parameters are controlled, \( V_{reg} = 1 \text{ p.u.} \) and \( Q_{ij,reg} \).

Table.1 shows the effect of this type of control. Voltage magnitude at bus 3 is set to 1 p.u, with \( Q_{ij,reg} = 0.02 \text{ p.u.} \) and by controlling power flow \( P_{ij,reg} \) at a value 0.9 p.u, the power loss is reduced to 0.1786 p.u and the voltage magnitude incremented to 0.9486. With the same control, but if we choose another location to UPFC at line 4-6, by controlling power flow \( P_{ij,reg} \) at a value 0.15 p.u, \( V_{reg} = 1 \text{ p.u.} \) at bus.6, the power loss become 0.1831 p.u which is greater than the first case and the voltage magnitude is reduced to 0.9394 p.u.

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**Table.1 Voltage and active power control**

<table>
<thead>
<tr>
<th>UPFC Parameters with ( Q_{ij,reg} = 0.02 \text{ p.u.} )</th>
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<td>0.6</td>
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<td>0.7</td>
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</tr>
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<td>0.8</td>
<td>0.0862</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1319</td>
</tr>
<tr>
<td>1</td>
<td>-0.1786</td>
</tr>
</tbody>
</table>

**Table.2 Voltage and reactive power control**

<table>
<thead>
<tr>
<th>UPFC Parameters with ( P_{ij,reg} = 0.7 \text{ p.u.} )</th>
<th>( V_{reg} = 1 \text{ p.u at bus 3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{ij,reg} )</td>
<td>( V_{se} )</td>
</tr>
<tr>
<td>0.02</td>
<td>0.0444</td>
</tr>
<tr>
<td>0.04</td>
<td>0.0463</td>
</tr>
<tr>
<td>0.1</td>
<td>0.0532</td>
</tr>
<tr>
<td>0.2</td>
<td>0.0666</td>
</tr>
<tr>
<td>0.6</td>
<td>0.1286</td>
</tr>
<tr>
<td>0.8</td>
<td>-0.1602</td>
</tr>
<tr>
<td>0.1</td>
<td>0.0521</td>
</tr>
</tbody>
</table>

**Fig. 15 Line Voltage and Reactive Power Control**
At a fixed Active Power –Normal Condition-Line 3-4
Fig. (15-16-19-20) give results of line voltage and reactive power control at a fixed active power in normal and abnormal condition (Load increase 10%), to improve the effect of a global control, UPFC is installed in different lines, Line 3-4, Line 6-10 and Line 9-10. The voltage magnitude is highly affected by this type of control.

- Impact in total loss minimization
Fig. (17-18-21) give results of total power losses with line voltage active and reactive power Control in normal condition when UPFC installed in line 3-4 and line 9-10.

We can conclude that the high performance of the index power quality require an optimal placement of UPFC in a network.

4. GENERAL INTERPRETATION OF NUMERICAL RESULTS

Numerical results are given for tests carried out on the IEEE 30-bus system. In the tests a convergence tolerance of $10^{-12}$ p.u for maximal absolute bus power mismatches is utilized.

-Impact in voltage regulation
One of the UPFC parameter is kept constant $P_{ij} = 0.1$ p.u and the two others parameters are controlled, $V_{ij} = 1$ p.u at bus 6, the power loss reduced to 0.1822 p.u, and the voltage magnitude become 0.9425 p.u.

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-We can conclude that the high performance of the index power quality require an optimal placement of UPFC in a network.
5. CONCLUSION

Among the FACTS components, Unified Power flow controller (UPFC) is one of the most efficient. It possesses a great aptitude to achieve an independent and simultaneous control of both, voltage active and reactive power flow. A global control based on the combination of the voltage, active and reactive power are proposed to improve the effectiveness of the method proposed and the impact of the UPFC in power flow regulation and loss minimization. Numerical results on the IEEE 30-bus system with single UPFC have demonstrated the feasibility and effectiveness of the established control functional model of the UPFC and the proposed Newton power flow algorithm. We can conclude that the high performance of the index power quality require an optimal placement of UPFC in a network.

6. REFERENCES