Dynamic Modeling and Control of UPFC for Power Flow Control

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Abstract

Unified Power Flow Controller can control the power system parameters like voltage, line reactance and phase angle to control power flow in the transmission line. The control of power flow in the transmission line done by injecting a suitable voltage with a phase angle. In this paper design a decoupled control scheme for shunt and series converter to track the reference power inputs by using conventional PI controller. Modeling is done by using MATLAB/SIMULINK software. The analysis is done on the system with different power factors and load conditions. The results show that UPFC is able to track the power changes and inject a suitable voltage into the power system so that power flow can be maintained.

Keywords: UPFC (unified power flow controller), FACTS (Flexible AC transmission systems), Modelling of UPFC, Power Flow Control

1. Introduction

Power System, in general are interconnected and there is a great need of improvement in electric power utilization by maintaining reliability and security. The power demand is growing considerably and the extension in transmission is restricted with the limited availability of recourses. This will cause some of the transmission lines are overloaded and others will loaded well below their normal limits [1]. With the fast growing research on power electronic components, Flexible AC Transmission Systems (FACTS) is used in the present deregulated electric market in order to transmit more power through transmission line. This will help to improve the performance of existing transmission line up to its maximum limit [2]. The FACTS devices will offer rapid response, smoothly adjustable output, responds to frequent variations in output without violating stability and thermal limits [3].

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The power flow control in the line is changed by series compensation, shunt compensation and phase angle regulation. All series controllers will inject a voltage in series in the line. If the phase difference between the line voltage and injected voltage is 90˚, series controllers will absorb/consumes reactive power. Shunt controllers can deliver/absorb reactive power demanded by the load [4].Phase shifter is considered to be sinusoidal ac voltage source with the controlled amplitude and phase angle. The phase angle regulator will inject a voltage which will change the effective phase angle at the sending end and thereby changing the power flow in the line. Third generation of FACTS controllers contains the Unified Power Flow Controller (UPFC) and Interline power flow controller (IPFC). They will have two Voltage Source Converters (VSC) connected though a DC link. By using UPFC, many FACTS devices distributed in the line can be avoided, thereby the problem of unwanted interactions between the devices can be eliminated up to a great extent [5]. UPFC proposed by Dr. Gyugyi in 1991[1] is the most versatile and powerful device that can provide effective means of controlling the power flow and improving the stability of a power network.

In this paper, the mathematical modeling of UPFC is done and analyzes its performance in a single machine infinite bus (SMIB) system. The control of UPFC is done using decoupled control strategy [8] and is found that this enables the device to follow the changes in reference values of active and reactive power. The power flow control is done by the UPFC by changing the injected voltage magnitude and phase angle. The performance is analyzed with different power factors and load conditions.

| Nomenclature | Description |
|--------------|-------------|
|  $v_i, v_j$  | voltage of $i_{th}$ and $j_{th}$ bus |
|  $X_{ij}$  | reactance of transmission line |
|  $\delta_{ij}$  | phase angle between $i_{th}$ and $j_{th}$ bus |
|  $v_{id}$  | direct axis component of voltage at the $i_{th}$ bus |
|  $v_{iq}$  | quadrature axis component of voltage at $j_{th}$ bus |
|  $\omega$  | synchronously rotating frequency in rad/s |
|  $S_i = P_i + jQ_i$  | Complex power in $i_{th}$ bus = Active power in $i_{th}$ bus + j (reactive power in $i_{th}$ bus) |
|  $v_{dsh}$  | d-component of shunt converter voltage |
|  $v_{qsh}$  | q-component of shunt converter voltage |
|  $v_{dsr}$  | d-component of series converter voltage |
|  $v_{qsr}$  | q-component of series converter voltage |
|  $r_{se} + jx_{se}$  | series transformer resistance and reactance |
|  $r_{sh} + jx_{sh}$  | shunt transformer resistance and reactance |
|  $V_{DC}$  | DC link voltage |
|  $g_{cap}$  | representing conductance |
|  $b_{cap}$  | representing susceptance |

2. Operating principle of UPFC

![UPFC configuration](image-url)
In the UPFC configuration shown in Fig. 1 had two voltage source converters, one is shunt converter connected via a shunt transformer and another is series converter connected via a series transformer. The two converters are connected back to back with a common DC link capacitor. This arrangement has three major functions namely series, shunt and phase angle regulation to be unified in the same circuit. The basic function of the shunt converter is to absorb or generate active power from the line similar to that of shunt compensator. The shunt converter can charge the DC link capacitor and satisfy the power demand of series converter through the DC link capacitor. Thus shunt branch is required to compensate for any real power drawn/supplied by the series branch and the losses. If power balance is not maintained, $V_{DC}$ cannot remain at a constant voltage. Series converter can provide series and phase angle compensation by injecting a series voltage of proper phase relationship. The active power can have a closed path through the converter because of the coupled DC link capacitor between the two converters but reactive power does not have a closed path between the converters [6]. Series converter voltage can be represented as $V_{se} \angle \sigma$ where $V_{se}$ is voltage with controllable magnitude $0 \leq V_{se} \leq V_{se\text{max}}$ and phase angle $\sigma (0^\circ \leq \sigma \leq 360^\circ)$ with respect to sending end voltage and this voltage will inject in series with the line via a series transformer. The line current flows through this voltage source causing real and reactive power exchange in the line. The real power exchanged at the ac terminal (i.e., at the terminal of insertion transformer) is converted by the inverter into dc power that appears at the dc link as positive or negative real power demanded. The reactive power exchanged at the ac terminal is generated internally by the inverter (provided it is a three-phase balanced system).

3. UPFC Modeling

The modeling is done by considering a test power system with UPFC. All the power system parameters are transformed to its direct and quadrature axis components based on synchronously rotating reference frame. A decoupled control strategy for controlling shunt and series controllers independently in UPFC [7, 8]. Fig. 2 shows the one line diagram of the equivalent system model used in this paper. Three buses are shown to represent the whole UPFC connected to an infinite bus from a source through the transmission line. Shunt controller is connected to bus 1 via shunt transformer which has resistance and reactance $r_{sh}$ and $x_{sh}$ respectively. Three phase source is connected to the same bus. Bus 2 represents the internal bus of UPFC. Series controller injects a voltage $V_{se}$ through a series transformer having line parameters $r_{se}$ and $x_{se}$. Bus 3 is the external bus of UPFC where the power is to be controlled. The transmission line resistance and reactance $R$ and $X$ is connected from bus 3 to the receiving end bus.

![Fig. 2 The power system model with UPFC configuration](image-url)
3.1 Source Modeling

Three phase source is connected to the bus 1. The voltage and current components is converted to d-q frame of references,

\[ v_d = v_{rms} \cos \omega t \]  \hspace{1cm} (1)

\[ v_q = -v_{rms} \sin \omega t \]  \hspace{1cm} (2)

\[ [C] = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \]  \hspace{1cm} (3)

The d-q axis real power component is \( P = v_d i_d + v_q i_q \)  \hspace{1cm} (4)

and the reactive power is given by \( Q = -v_q i_d + v_d i_q \)  \hspace{1cm} (5)

Let \( v_{ryb} \) be the column vector of voltage drops across the series combination of resistance and reactance in all the three phases and let \( i_{ryb} \) be the column vector of currents flowing through \( Z_{ryb} \) impedance column matrix.

Balanced three phase system having the V-I relationship \( v_{ryb} = Z_{ryb} \times i_{ryb} \)

\[
\begin{bmatrix}
    ea' - va' \\
    eb' - vb' \\
    ec' - vc'
\end{bmatrix}
= \begin{bmatrix}
    R + pL & 0 & 0 \\
    0 & R + pL & 0 \\
    0 & 0 & R + pL
\end{bmatrix}
\begin{bmatrix}
    ia \\
    ib \\
    ic
\end{bmatrix}
\]  \hspace{1cm} (6)

In the equation (6) the first column matrix representing the matrix of voltage drops at either side of impedances in all the three phases

When we transformed into \( \alpha \beta \) components

\[ Z_{ab} = \begin{bmatrix}
    R + pL & 0 & 0 \\
    0 & R + pL \\
    0 & 0 & R + pL
\end{bmatrix} \]  \hspace{1cm} (7)

Now transform into the synchronously rotating reference frame

\[ Z_{dq} = \begin{bmatrix}
    R + pL & -\omega L \\
    \omega L & R + pL
\end{bmatrix} \]  \hspace{1cm} (8)

So the voltage equation after transformation become

\[
\begin{bmatrix}
    ed' - vd' \\
    eq' - vq'
\end{bmatrix}
= \begin{bmatrix}
    R + pL & -\omega L \\
    \omega L & R + pL
\end{bmatrix}
\begin{bmatrix}
    id \\
    iq
\end{bmatrix}
\]  \hspace{1cm} (9)

where \( \omega \) is the synchronously rotating frequency

3.2 Shunt Controller Modeling

Fig. 3 shows the block diagram of shunt controller. Shunt inverter will generally operate in automatic voltage control mode. In voltage control mode the shunt inverter reactive current is maintaining the transmission line voltage at the point of connection to a reference value, with a defined drooping characteristics. The actual voltage measured from the sending end bus or substation bus feeding the shunt transformer. In the control scheme, the controlled quantity is the current \( i_{sh} \) drawn by the shunt converter.

![Fig. 3 Block diagram of Shunt controller](image-url)
The reactive power bearing component of shunt current $i_{shq}^*$ is obtained from a controller which is regulating ac bus voltage and reference for the real power bearing current $i_{shp}^*$ is generated by controlling DC bus voltage. Control scheme is developed by assume that shunt converter is switched off and sending end voltage is the reference [9].

### 3.3 Series Controller Modeling

Series inverter generally is operated in automatic power flow control mode. This control scheme regulating transmission line current, using a synchronous reference frame in which control quantities appear as dc quantities. The reference real and reactive components can be set from the proper controller which has the inputs $P_{ref}$, $Q_{ref}$ and the measured real and reactive power quantities. Series converter is designed by assuming that it is free from the dynamics of the power system and the dynamics of shunt converter. Fig. 4 shows the block diagram of series controller.

[Diagram of Series Controller]

Decoupled current and voltage equations are given below

$$v_{1d} + v_{dser} = v_{2d}$$
By using the values of $v_{2d}$, $v_{2q}$, $i_{dse}$, $i_{qse}$ we can calculate power at the bus3.

### 3.4 DC link capacitance

The design of DC link capacitance can be done by using power balance theory at the AC side of the inverter [8]. Power at the internal bus of UPFC is the difference between $P_{sc}$ and $P_{sh}$. DC voltage at the capacitor terminal is controlled by PI control regulating $V_{DCref}$ and actual $V_{DC}$.

Dynamic equation of capacitor voltage [9] is given by

\[ \frac{dV_{DC}}{dt} = \frac{aV_{DCref}}{b_{cap}} + \frac{a}{b_{cap}}(i_{dsh}-i_{dse}) \quad (20) \]

The power is drawn by the load is compensated by extracting more power from the source. The d-q components of the line current is same as that of $i_{dse}$ and $i_{qse}$. Using the voltage drop formula, we can calculate these currents. Here $V_{rref}=1$pu and $V_{qref}=0$pu is taken by assuming that a Single Machine infinite Bus system.

### 4. Simulation Results

Simulation is carried out in MATLAB/SIMULINK software. The switching of the converters is modelled as switching functions in the differential equations.

#### Table 1: Active power at different buses and loss in shunt converter

| P1(pu) | P2(pu) | P1loss(pu) | V2(pu) | \(\angle V_2\) (DEGREES) |
|--------|--------|------------|--------|-----------------|
| 0.231  | 0.2    | 0.031      | 1.02   | 0.91            |
| 0.831  | 0.8    | 0.031      | 1.02   | 4               |
| 1.431  | 1.4    | 0.031      | 1.02   | 7               |
| 2.231  | 2.2    | 0.031      | 1.02   | 11              |
| 3.031  | 3      | 0.031      | 1.02   | 15              |

From the Table 1, we observe that UPFC cannot absorb or supply real power in steady state. $P_1$ is the power at the bus1 and $P_2$ is power at bus 3 (which is to be controlled) and $P_{LOSS}$ is power loss in the shunt converter passive elements. A small amount of power is drawn from the supply in order to meet the power losses. Thus shunt branch is required to compensate any real power drawn or supplied by the series branch and the losses. Otherwise DC voltage cannot be maintained as constant.

#### Table 2: Active and reactive power flow at the receiving end at different power factors

| Power factor | Case 1 | Case 2 | Case 3 | Case 4 |
|--------------|--------|--------|--------|--------|
|              | $P_3$  | $Q_3$  | $P_3$  | $Q_3$  | $P_3$  | $Q_3$  | $P_3$  | $Q_3$  |
| 0.3          | 0.03   | 0.1    | 0.075  | 0.25   | 0.03   | -0.1   | 0.075  | -0.25  |
| 0.5          | 0.05   | 0.1    | 0.125  | 0.25   | 0.05   | -0.1   | 0.125  | -0.25  |
| 0.8          | 0.08   | 0.1    | 0.2    | 0.25   | 0.08   | -0.1   | 0.2    | -0.25  |
| 1            | 0.1    | 0.1    | 0.25   | 0.25   | 0.1    | -0.1   | 0.25   | -0.25  |

The active and reactive power in Table 2 show that the study system responds properly for different power factors. Table 3 shows the controller parameters for shunt and series converters. The time of response in each step change is 0.007s and the waveform is shown in Fig. 5. The system responds after a transient period of 0.025ms. The switch $S_1$
is closed. It indicates that the load at Bus 1 is included in the circuit. The loading increases the power drawn from the supply. The analysis is done by changing $P_{\text{Lref}}$ and $Q_{\text{Lref}}$ kept at 0.25pu. Table 4 shows the results.

Table 3 Controller parameters for shunt and series converter

| Controller parameters | Converter1 | Converter2 | Time of response in each step change(seconds) | Transient period (seconds) |
|-----------------------|------------|------------|-----------------------------------------------|---------------------------|
| $K_p$                 | 1          | 0.1        | 0.007                                         | 0.025                     |
| $K_i$                 | 30         | 0.63       |                                               |                           |

![Fig. 5 Delay in responding from one step change of $P_3$ to another step.](image)

Table 4 Active and reactive power flow at different load conditions

| $P_1$(pu) | $Q_1$(pu) | $P_{\text{Lref}}$(pu) | $P_1$(pu) | $Q_1$(pu) |
|-----------|-----------|-----------------------|-----------|-----------|
| 1.2       | -0.71     | 0.2                   | 0.2       | 0.25      |
| 1.47      | -0.187    | 0.4                   | 0.4       | 0.25      |
| 1.67      | -0.201    | 0.6                   | 0.6       | 0.25      |
| 1.87      | -0.221    | 0.8                   | 0.8       | 0.25      |
| 2.07      | -0.238    | 1                     | 1         | 0.25      |
| 2.5       | -0.25     | 1.2                   | 1.2       | 0.25      |

5. Conclusion and Future work

In this paper, the working of unified power flow controller is analyzed by using an equivalent study system with decoupled control strategy. If the power factor is very low or the load at Bus 1 is very large, the PI controller gives oscillations at the output and took more time to settle down. Then PI controller has to be tuned to new values in order to get better results. So for a future work, online PI tuning methods like Fuzzy Neural Network (FNN) can be done in the system.

References

[1] L. Gyugyi, C.D. Schauder, S.L. Williams, T.R. Rietman, D.R. Torgerson, A. Edris. The Unified Power Flow Controller: A New Approach to Power Transmission Control. IEEE Transaction Power Delivery; Vol.10, No.2 April 1995, p.1085-1097.
[2] Tsao-Tsung Ma. P-Q decoupled control schemes using fuzzy neural networks for the unified power flow controller. Electrical power and energy systems 29(2007), p. 748-758.
[3] Padiyar, K.R., Kulakarni, A.M. Control Design And Simulation Of Unified Power Flow Controller. IEEE Tans. on Power Delivery, Vol.13, No.4, October 1998, pp.1348-1354.
[4] N. G. Hingorani and L. Gyugyi. Understanding FACTS: Concepts and Technology of Flexible AC Transmission systems. New York: IEEE Press, 2000.
[5] Kannan Sreenivasachar. Unified power flow controller: Modeling, Stability analysis, Control strategy and Control system Design. PhD Thesis, Electrical and Computer Engineering, University of Waterloo, Ontario, Canada, 2001.
[6] C. D. Schauder, L. Gyugyi, D. M. Hamai. Operation of the unified power flow controller under practical constraints. IEEE Transactions on Power Delivery, Vol. 13, No. 2, April 1998.

[7] C. Schauder and H. Metha. Vector Analysis and Control of Advanced Static Var Compensator. IEE Proc. C, Vol. 140, No. 4, July 1993, p. 299-306.

[8] I. Papic, P. Z unk o, D. Povh, M. Weinhold. Basic Control of Unified Power Flow Controller. IEEE Transactions on Power Systems, Vol. 12, No. 4, November 1997.

[9] T. Nireekshna, G. Kesava Rao, S. Siva Naga Raju. Modeling and control design of Unified Power Flow controller for various control strategies. International Journal of Engineering Science and Technology Vol. 2(11), 2010, p. 6293-6307.

[10] N. K. Sharma and P. P. Jagtap. Modelling and Application of Unified Power Flow Controller (UPFC). 2010 3rd Int. Conf. Emerg. Trends Eng. Technol., p. 350-355, 2010.