A UPFC MODEL FOR DYNAMIC STABILITY ENHANCEMENT

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Abstract

While the controllability of the line power flow by unified power flow controller (UPFC) has been recognised, only very limited information is available concerning the quantitative control of the UPFC to provide additional damping during system oscillations. This paper presents a current injection model of UPFC which is suitable for use in power system stability studies. To use the current injection model on dynamic stability studies, a proper control method is necessary. It is proposed that the shunt compensation of UPFC is controlled to maintain the system bus voltage and the two components of UPFC series voltage, which are in phase and quadrature with the line current, are controlled in coordination by Strip Eigenvalue Assignment method. The eigenvalue analysis and time domain simulation results show that the proposed model and control method can substantially improve the dynamic stability of the power system.

1. INTRODUCTION

Flexible AC Transmission System (FACTS) offers an alternative solution to transmission expansion by increasing the utilization of the existing facilities towards their thermal limits. A unified power flow controller (UPFC) is a type of FACTS controller. It is capable of both supplying to and absorbing from the power system through the excitation converter and transformer a controllable amount of reactive power and inserting a voltage of controllable magnitude and phase angle in series with the transmission system through the booster converter and transformer [1]. While the controllability of the line power flow by UPFC has been recognized, only very limited information is available concerning the quantitative control of the UPFC to provide additional damping during system oscillations. There is the need to further investigate the interaction of the UPFC with the rest of the electrical network [2].

The first part of the investigation is to establish a suitable UPFC dynamic model. This paper proposes a UPFC current injection model which is obtained from some modification of UPFC power injection model in [3]. The proposed model can easily be incorporated in the Power System Toolbox [4], which is a powerful dynamic simulation program.

After establishing the UPFC current injection model, a proper control method is necessary for the model to improve the dynamic stability of the power system. In [5] the improvement of transient stability using UPFC was investigated and a UPFC model and its control method were proposed. But the control method requires detailed information of the whole power system. It is difficult to realize the control method. In [1] the mechanism of the three control methods of UPFC, namely in-phase voltage control, quadrature voltage control and shunt compensation, in improving the transient stability of power systems was investigated. But the authors considered these three methods separately and did not give much information about dynamic performance. In [2] it proposed decoupled control algorithms of the two components of UPFC series voltage, which are quadrature and in phase with the line current, by active and reactive power respectively. The paper presents very helpful information about how to use UPFC to improve power system dynamic stability. However, the decoupled control algorithms are based on approximate relationship. The exact relationship inherently implies the coordinated control of active and reactive power. The paper also gives the time domain simulation of UPFC in a single-machine infinite-bus (SMIB) system. But in SMIB system it seems that we have better choices of input signals rather than active and reactive power. The best feedback signals to damp oscillations would be machine speed and rotor angle. So this paper proposes to use speed and rotor angle deviations as desired input signals in SMIB system. To demonstrate this, this paper compares the eigenvalue analysis and time domain simulation results in a SMIB system when using two different pairs of input signals: one, speed and rotor angle deviations; the other, active power and reactive power deviations.

2. UPFC MODEL AND ITS CONTROL

The current injection model of UPFC is obtained from some modification of UPFC power injection model in [3]. Suppose a UPFC voltage source is connected between nodes i and j in a power system. The series voltage source converter can be modeled as an ideal series voltage $\bar{V}_s$ in series with a reactance X_s. The shunt converter can be modeled as an ideal shunt current source $\bar{I}_{shunt}$. Thus, we have the UPFC model as shown in Fig. 1.

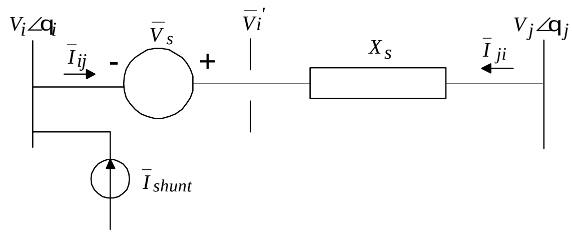


Fig. 1: Representation of a UPFC

In Fig.1,

$$\bar{I}_{shunt} = \bar{I}_t + \bar{I}_q \quad (1)$$

where $\bar{I}_t$ is the current in line with $\bar{V}_i$ and $\bar{I}_q$ is the current quadrature with $\bar{V}_i$. $\bar{V}_s$ models an ideal voltage source and $\bar{V}_i'$ represents a fictitious voltage behind the series reactance X_s. We have

$$\bar{V}_i' = \bar{V}_i + \bar{V}_s \quad (2)$$

The series voltage source $\bar{V}_s$ is controllable in magnitude and phase, i.e.

$$\bar{V}_s = r\bar{V}_i e^{j\gamma} \quad (3)$$

where $0 < r < r_{max}$ and $0 < \gamma < 2\pi$.

The equivalent circuit vector diagram is shown in Fig. 2.

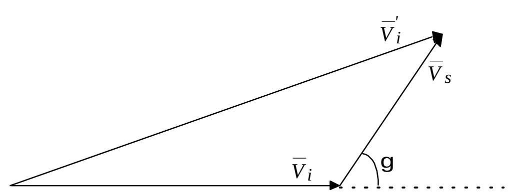


Fig. 2: Vector diagram of the equivalent circuit of series voltage source

The injection model is obtained by replacing the voltage source $\bar{V}_s$ by the current source $\bar{I}_s$ as shown in Fig. 3.

$$\bar{I}_s = -jb_s\bar{V}_s = -jrb_s\bar{V}_i e^{j\gamma} \quad (4)$$

where $b_s = 1/X_s$.

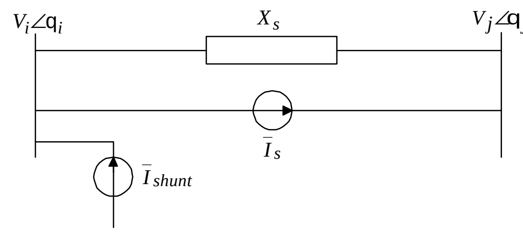


Fig. 3: Representation of a series voltage source by a current source

After some modification of Fig. 3, we have the current injection model of UPFC as shown Fig. 4.

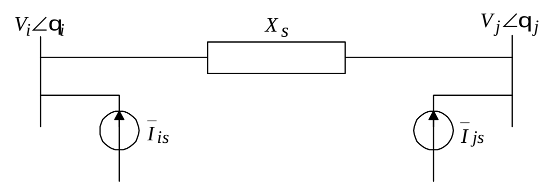


Fig. 4: Injected current model of UPFC

In UPFC, the shunt connected current source is used mainly to provide the active power which is injected to the network via the series connected voltage source. Let us denote converter 1 as the excitation converter of UPFC shunt part, and converter 2 as the boosting converter of UPFC series part. We have

$$P_{conv1} = P_{conv2} \quad (5)$$

The equality above is valid when the losses are neglected. The apparent power supplied by the series voltage source is calculated from

$$S_{conv2} = \bar{V}_s\bar{I}_{ij}^* = re^{j\gamma}\bar{V}_i\left[\frac{\bar{V}_i + re^{j\gamma}\bar{V}_i - \bar{V}_j}{jX_s}\right]^* \quad (6)$$

From (6), we have

$$P_{conv2} = rb_sV_iV_j\sin(\theta_i - \theta_j + \gamma) - rb_sV_i^2\sin\gamma \quad (7)$$

$$Q_{conv2} = -rb_sV_iV_j\sin(\theta_i - \theta_j + \gamma) + rb_sV_i^2\cos\gamma + r^2b_sV_i^2 \quad (8)$$

The active power supplied by the shunt current source is calculated from

$$P_{conv1} = R_e\left[\bar{V}_i\left(-\bar{I}_{shunt}\right)^*\right] = -V_iI_t \quad (9)$$

From (5), (7) and (9), we have

$$I_t = -rb_sV_j\sin(\theta_i - \theta_j + \gamma) + rb_sV_i\sin\gamma \quad (10)$$

The shunt current source is calculated from

$$\begin{aligned}\bar{I}_{shunt} &= (I_t + jI_q)e^{j\theta_i} \\ &= (-rb_sV_j\ \sin(\theta_i - \theta_j + \gamma) + rb_sV_i\ \sin\gamma + jI_q)e^{j\theta_i}\end{aligned} \tag{11}$$

Then we have the injected current model of UPFC as (12) and (13)

$$\begin{aligned}\bar{I}_{is} = \bar{I}_{shunt} - \bar{I}_s &= (-rb_sV_j\ \sin(\theta_i - \theta_j + \gamma) \\ &+ rb_sV_i\ \sin\gamma + jI_q)e^{j\theta_i} + jrb_s\bar{V}_i e^{j\gamma}\end{aligned} \tag{12}$$

$$\bar{I}_{js} = I_s = -jrb_s\bar{V}_i e^{j\gamma} \tag{13}$$

In order to control the above model effectively, we propose the following control system:

Let B_q be the equivalent susceptance used to control $\bar{I}_q$. We have

$$\bar{I}_q = jB_q\bar{V}_i \tag{14}$$

Then the control of $\bar{I}_q$ can be seen the same as a static var compensator. The limits of B_q, $B_{q\,min}$ and $B_{q\,max}$ must be changed as the active power requirement of series branch varies because the shunt connected current source is used mainly to provide the active power. In any operating point (r,γ), the maximum reactive power $Q_{conv1}(r,\gamma)$ available in converter 1 is:

$$Q_{conv1}(r,\gamma) = \left[(S_{conv1})^2 - (P_{conv1}(r,\gamma))^2\right]^{\frac{1}{2}} \tag{15}$$

From (15), $B_{q\,min}$ and $B_{q\,max}$ can be easily calculated.

The series injected voltage $\bar{V}_s$ can be resolved into two components which are in phase and quadrature with the line current $\bar{I}_{ij}$ as shown in Fig. 5. We call them in-phase voltage $\bar{V}_P$ and quadrature voltage $\bar{V}_R$ separately. But these terms have different meaning compared with what appear in [1]. Suppose speed and rotor angle deviations are input signals. Using the Strip Eigenvalue Assignment control [7], we can coordinate the control of in-phase voltage and quadrature voltage.

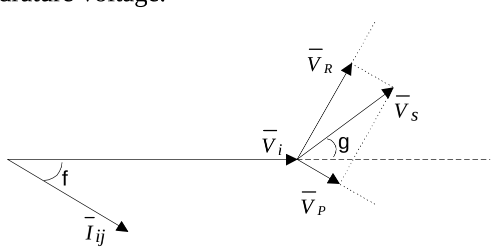


Fig. 5: Vector diagram of two components of series voltage source

If we know the two components of series voltage, from Fig. 5 we can calculate r and γ of the series voltage as follows:

$$r = \frac{\sqrt{V_R^2 + V_P^2}}{V_i} \tag{16}$$

$$\gamma = \tan^{-1}\left(\frac{V_R}{V_P}\right) - \phi \tag{17}$$

Then using current injection model defined by (12) and (13), we can calculate the interaction between UPFC and the rest of the system. Time domain simulations are performed by using the Power System Toolbox (PST) [4]. Within each step of simulation, UPFC is treated as a non-conforming constant current load. At the end of each step, use (12) and (13) to calculate $\bar{I}_{is}$ and $\bar{I}_{js}$ that will be used in the next step. The whole control system is shown in Fig. 6.

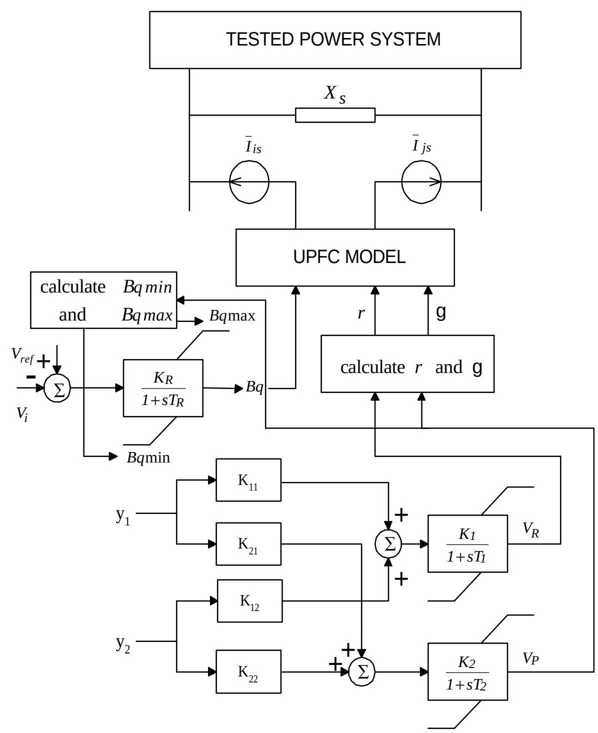


Fig. 6: Block diagram of the proposed UPFC controller

In Fig. 6, y_1 and y_2 are input signals. In studied case one, y_1 is speed deviation $\Delta\omega$ and y_2 is rotor angle deviation $\Delta\delta$. In studied case two, y_1 is active power deviation ΔP and y_2 is reactive power deviation ΔQ. In case one, input signals $\Delta\omega$ and $\Delta\delta$ can be directly used as shown in Fig. 6. But in case two, the controller includes a washout block to avoid resetting set points, and a simple filter to eliminate interactions at high frequencies [6]. These practical considerations eliminate excessive control action following a system disturbance.

3. STUDIED SYSTEM

Fig. 7 shows a single-machine infinite-bus system used in this study. The parameters of the system are obtained from PST. UPFC is connected between bus 2 and bus 3.

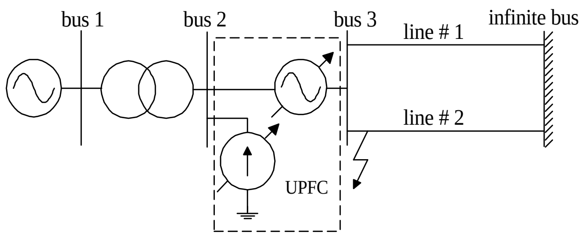


Fig. 7: Single-machine infinite-bus system

4. CONTROLLER DESIGN

The control method is based on Strip Eigenvalue Assignment [7]. The dynamic characteristics of a linear system are influenced by the location of eigenvalues. Using Strip Eigenvalue Assignment, the resultant controller is of the form $u = -K\,y$, and leads to a closed-loop system of the form

$$\dot{X} = (A - BKC)X \quad (18)$$

where A, B and C are the state, input and output matrices respectively, and K is a 2×2 matrix in the form

$$K = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \quad (19)$$

The procedure to compute K is described in detail in [7]. All eigenvalues of the closed-loop system are placed within a suitable region in the complex s-plane. When using ΔP and ΔQ as input signals, a transformation of state equation is necessary. After the transformation, the output matrix C' takes the form

$$C' = [I_m \quad 0] \quad (20)$$

where $I_m = n \times n$ identity matrix.

The transformation can be seen from [8]. Using the above method in the studied system, we have the UPFC controller in the form $u = -K\,y$, where in case one:

$$y = \begin{bmatrix} \Delta w \\ \Delta d \end{bmatrix} \text{ and } K = \begin{bmatrix} 20.8287 & -0.1114 \\ 0.4563 & 0.3005 \end{bmatrix}$$

in case two:

$$y = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \text{ and } K = \begin{bmatrix} 13.4481 & -0.6876 \\ 0.7547 & 0.7904 \end{bmatrix}$$

5. EIGENVALUE ANALYSIS

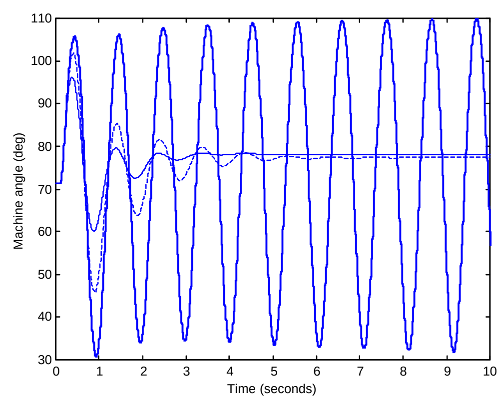
The eigenvalue analysis is performed using PST. The dominant mode of open-loop system and closed-loop system is shown in Table 1. The closed-loop system shifts the weakly damped dominant mode of the open-loop system to the desired location.

Table 1. Eigenvalue analysis of a SMIB with UPFC

	Dominant Mode
Open-loop system	-0.22±j7.46
Closed-loop system (Δd and Δw as input singals)	-1.45±j6.79
Closed-loop system (ΔP and ΔQ as input singals)	-0.85±j7.27

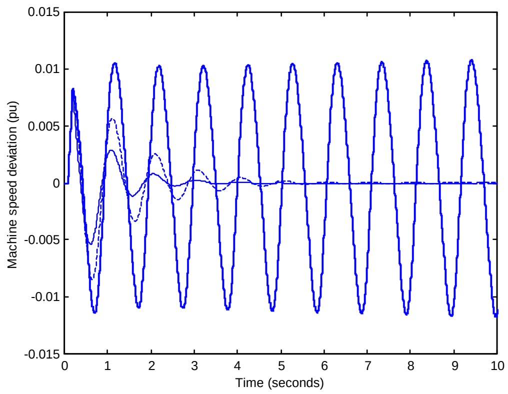
6. TIME SIMULATION RESULTS

To test the effectiveness of the proposed UPFC controller, a three-phase fault was applied to one line at the end close to the busbar connected to UPFC (see Fig. 7) when the generator is operating at its rated power level. The fault is cleared in 0.1s with no attempt at transmission line reclosure. The system responses are simulated using PST. Modifications of the software are needed to include the current injection model of UPFC. Fig. 8a-e show the system responses with and without UPFC. It can be observed from these figures that the UPFC with coordinated controller can greatly improve the damping of the system. The dynamic oscillations are well damped.

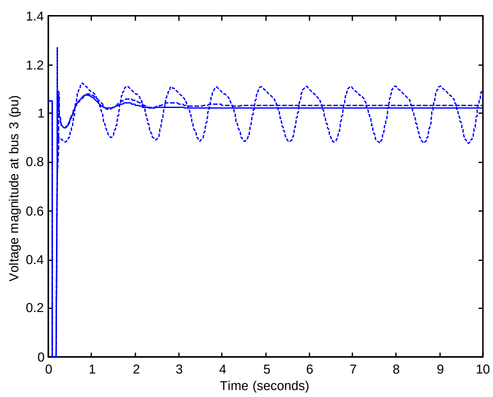


(a) Machine angle

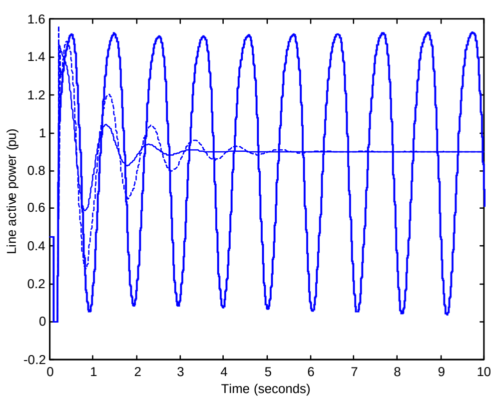
Dot: without UPFC
Solid: with UPFC and Δw and Δd as input signals
Dash: with UPFC and ΔP and ΔQ as input signals



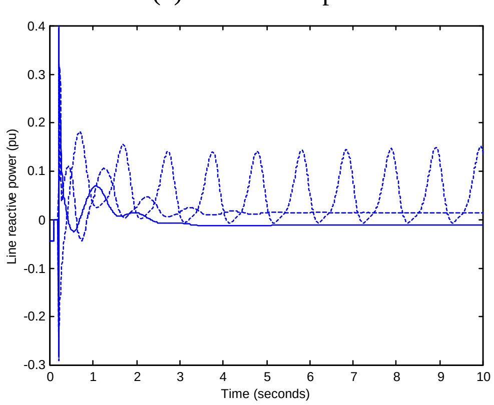
(b) Machine speed deviation



(c) Voltage magnitude at bus 3



(d) Line active power



(d) Line reactive power

Fig. 8: System responses with and without UPFC

7. CONCLUSION

In this paper, a current injection model of UPFC which is suitable for use in power system stability studies has been presented. The performance of the proposed UPFC model and controller has been evaluated in a single-machine infinite-bus system by eigenvalue analysis and nonlinear simulations. The results show that the controller significantly improves the dynamic stability of the system. It is also observed that using speed and rotor angle deviations as input signals provides better damping to electromechanical oscillations.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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