Application of UPFC to Increase Transient Stability of Inter-Area Power System

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***Abstract*—Unified Power Flow Controller (UPFC) is a power electronic based device that has capability of controlling the power flow through the line by controlling appropriate its series and shunt parameter. It has been reported that UPFC can improve transient stability of a simple system. This paper investigates the improvement of transient stability of inter-area power system. The mathematical model of UPFC is present in this paper. The UPFC is modeled as the variable susceptance and is incorporated into the model of power system. The simulation results are tested on the Kundur's inter-area power system.**

***Index Terms*—power system, transient stability, FACTS, UPFC, inter-area power system.**

I. INTRODUCTION

Modern power systems are becoming increasingly stressed because of growing demand. Because of variety of factors, such as environmental legislation, rights of way issues, capital investment, deregulation policies, etc. constrain the construction of new transmission lines, electric utilities are now forced to operate their system in such a way that makes better utilization of existing transmission facilities. It is well known that the power flow through transmission line is a function of line impedance, magnitude and phase angle of bus voltage. If these parameters can be controlled, the power flow through the transmission line can be controlled in a predetermined manner. Flexible AC Transmission System (FACTS) uses advanced power electronics to control the parameters in the power system in order to fully utilize the existing transmission facilities [1].

A Unified Power Flow Controller (UPFC) is a member of FACTS devices. It consists of two solid state synchronous voltage source converters coupled through a common DC link as shown in Figure 1[2]. The DC link provides a path to exchange active power between the converters. The series converter injects a voltage in series with the system voltage through a series transformer. The power flow through the line can be regulated by controlling voltage magnitude and angle of series injected voltage. The injected voltage and line current determine the active and reactive power injected by the series converter. The converter has a capability of electrically generating or absorbing the reactive power. However, the injected active power must be supplied by the DC link, in turn taken from the AC system through the shunt converter. The shunt converter also has a capability of independently supplying or absorbing reactive power to regulate the voltage of the AC system. When the losses of the converters and the associated transformers are neglected, the overall active power exchange between the UPFC and the AC system become zero. However, both the series and shunt converters can independently exchange reactive power [3]. UPFC can improve both steady sate stability, dynamic stability and transient stability [4-5]. For the convenience practical of application, the series voltage angle of UPFC is kept in perpendicular with a line current [6].

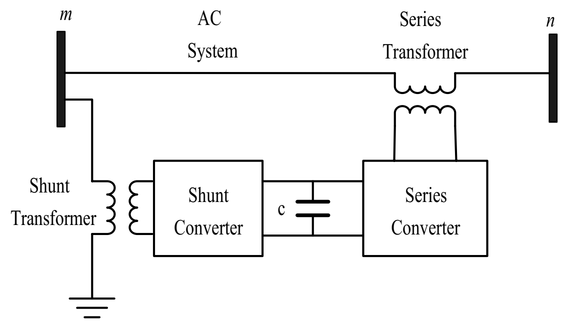


Figure 1 Configuration of UPFC.

It has been reported in many papers that UPFC can improve stability of simple system or single machine infinite bus (SMIB) system and multimachine system [5,7]. The inter-area power system has special characteristic of stability behavior [8]. Reference [9] and [10] presented the application of SVC, and TCSC to damping power stability in the inter-area power system.

This paper investigates the improvement of inter-area system with a UPFC. This paper suggests the method to incorporate UPFC model into the power system model for studying transient stability. The proposed method is then tested on Kundur's inter area-system.

II. MATHEMATICAL MODEL

A. UPFC Model

Consider the configuration of UPFC inserted between bus *m* and bus *n* of power system as shown in Figure 1. UPFC can be modeled as fictitious active and reactive power injection at bus *m* and bus *n*, respectively as can be seen in Figure 2.

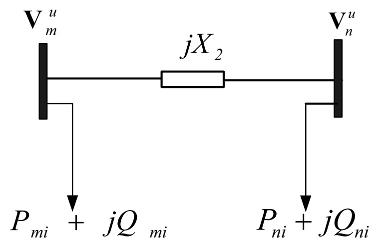


Figure 2 Fictitious active and reactive load model of a UPFC.

The detail of deriving the UPFC model can be found from the previous author's publication in [7,11].

The fictitious active P_{mi}^u and reactive Q_{mi}^u load of UPFC at bus *m* as shown are given by

$$P_{mi}^u = -abV_m^u V_n^u \sin(\theta_{mn}^u + \alpha) \quad (1)$$

$$Q_{mi}^u = -I_q V_m^u - ab(V_m^u)^2 \cos(\alpha) \quad (2)$$

The fictitious active P_{ni}^u and reactive Q_{ni}^u load of a UPFC at bus *n* are given by

$$P_{ni}^u = -abV_m^u V_n^u \sin(\theta_{mn}^u + \alpha) \quad (3)$$

$$Q_{ni}^u = abV_m^u V_n^u \cos(\theta_{mn}^u + \alpha) \quad (4)$$

Where

a = voltage magnitude from a series converter of a UPFC

α = voltage angle from a series conveter of a UPFC

I_q = shunt current from a shunt converter of a UPFC

b = susceptance equivalent between bus *m* and bus *n*

V_m^u = voltage magnitude at bus *m*

V_n^u = Voltage magnitude at bus *n*

θ_{mn}^u = Voltage angle difference between bus *m* and bus *n*

B. Power System with a UPFC Model

Consider the power system with a UPFC as shown in Figure 3 (a). In this Figure, UPFC is represented by its equivalent circuit of Figure 2. The power system can be represented by generator voltage behind transient reactance ($\mathbf{E}'$) and reduced admittance matrix $\boldsymbol{Y}_{int}$ excluding bus *m* and bus *n*. One of possible way to incorporate the UPFC into power system model is to convert fictitious active and reactive model to susceptance model. The admittance $\mathbf{Y}_m^u$ and $\mathbf{Y}_n^u$ as given in Figure 3(b) can be written by

$$\mathbf{Y}_m^u = \frac{P_{mi}^u - jQ_{mi}^u}{(V_m^u)^2} \quad (5)$$

$$\mathbf{Y}_n^u = \frac{P_{ni}^u - jQ_{ni}^u}{(V_n^2)} \quad (6)$$

Now the susceptance model of a UPFC can be incorporated into power system represented by the admittance matrix ($\mathbf{Y}_{\text{int}}^u$) as can be seen in Figure 3(c).

The dynamic equation of machine system in center of inertia (COI) is expressed by [12]

$$\dot{\tilde{\delta}}_i = \tilde{\omega}_i \quad (5)$$

$$\dot{\tilde{\omega}}_i = \frac{1}{M_i}[P_{mi} - P_{ei} - \frac{M_i}{M_T}P_{COI}] \quad (6)$$

i=1, 2…n_g

Where

$\tilde{\delta}_i$ = machine angle of the *i*-th machine

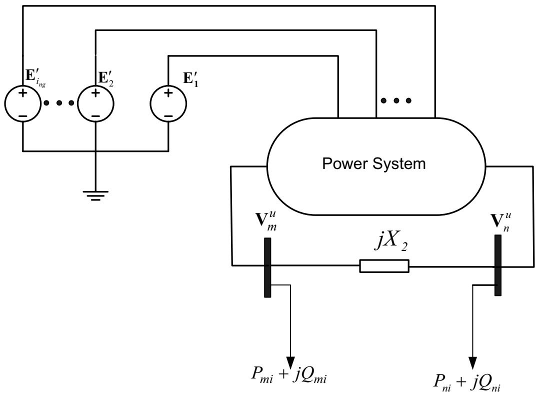
$\tilde{\omega}_i$ = machine speed of the *i*-th machine

P_{mi} = input mechanical power of the i-th machine

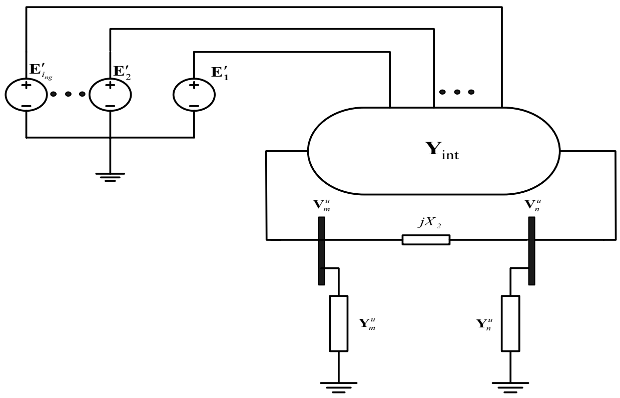
P_{ei} = output electrical power of the i-th machine

and PCOI is given by

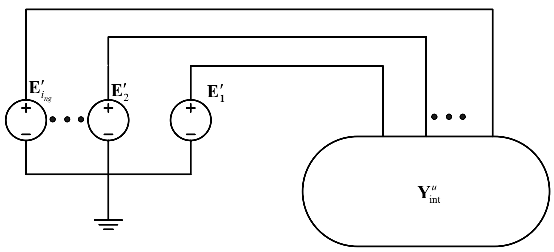
$$P_{COI} = \sum_{i=1}^{n_g} [P_i - P_{ei}] \quad (7)$$



(a)



(b)



(c)

Figure 3 Multimachine power system with a UPFC (a) fictitious load model of UPFC (b) susceptance model of a UPFC (c) the successive model of UPFC.

III. Control Strategy

It has been reported in [9] that the use of line power flow (P_f) of tie line (between area) to shunt FACTS can improve dynamic behavior of power system. This paper applied the line power flow to control parameters of UPFC (a, α and I_q). When the $d(Pf)/dt$ >0, parameter on a UPFC is controlled in capacitive mode; when the $d(Pf)/dt$ <0, parameter on a UPFC is controlled in reactive mode. The controlled strategy of a UPFC is given by

when $\frac{d(P_f)}{dt} > 0$

$$a = a_{\max} \quad (8)$$

$$\alpha = -90 \quad (10)$$

$$I_q = I_q^{\max} \quad (11)$$

when $\frac{d(P_f)}{dt} < 0$

$$a = a_{\max} \quad (12)$$

$$\alpha = +90 \quad (13)$$

$$I_q = I_q^{\min} \quad (14)$$

and when $\frac{d(P_f)}{dt} = 0$

$$a = 0 \quad (15)$$

$$\alpha = 0 \quad (16)$$

$$I_q = 0 \quad (17)$$

IV. Simulation Results

The proposed method of improving transient stability by using a UPFC is tested on Kundur's inter-area power system. The system consists of 4 generators, 4 transformers and 11 buses. The system data and initial operating point is given in [13]. UPFC is equipped between area 1(generator 1 and generator 2) and area 2 (generator 3 and generator 4) at bus 8. It is considered that a 3 phase fault appears at bus 8 at 100 msec and it is cleared at 140 msec.

It can be seen from Figure 5 that, without a UPFC (a=0, α and I_q=0), the different of generator rotor angle of area 1 (Generator 1 and Generator 2) and area 2 (Generator 3 and Generator 4) increases monotonically and thus the system can be considered as unstable.

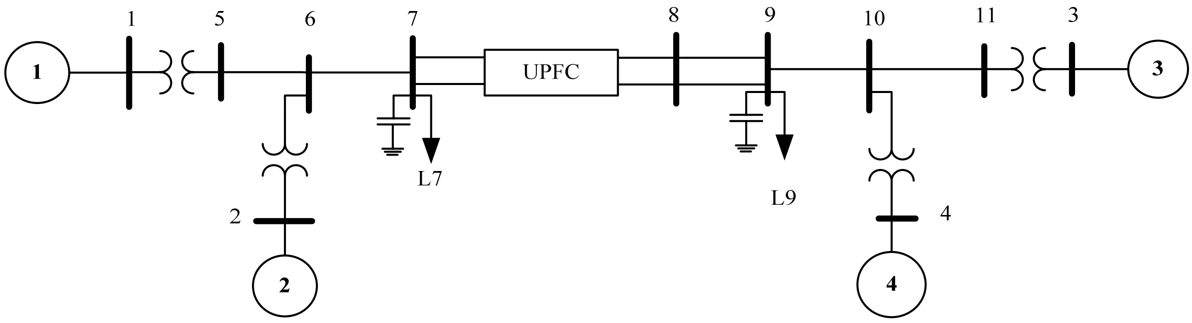


Figure 4 Kundur's inter-area power system with a UPFC.

However, with a UPFC (I_q=0.1 pu and a=0.05 pu), the system is considered as stable as can be seen in Figure 6. This paper also studies the effect of the ratings of a UPFC on stability improvement. Figure 7 shows trajectory of generator rotor angle of Kundur's inter-area system with a UPFC (a=0.08 and I_q=0.8). Table I summarizes the generator rotor angle of Figure 6 and Figure 7. It can be seen From the Figure and Table that the trajectory of the generator rotor angle is improved as the rating of a UPFC gets increase.

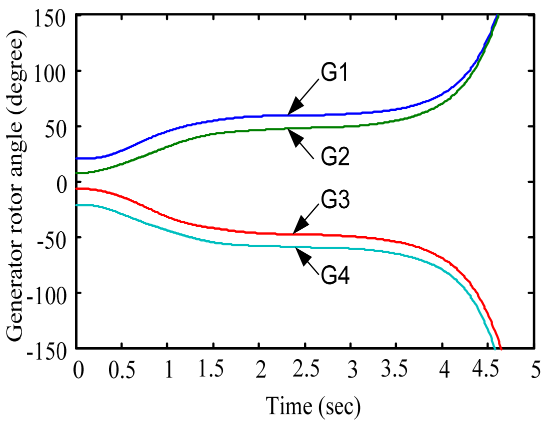


Figure 5 Trajectory of generator rotor angle of Kundur's inter-area system without a UPFC.

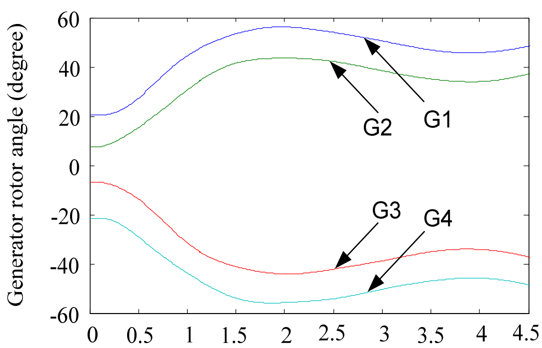


Figure 6 Trajectory of generator rotor angle of Kundur's inter-area system with a UPFC (a=0.05 and I_q=0.1).

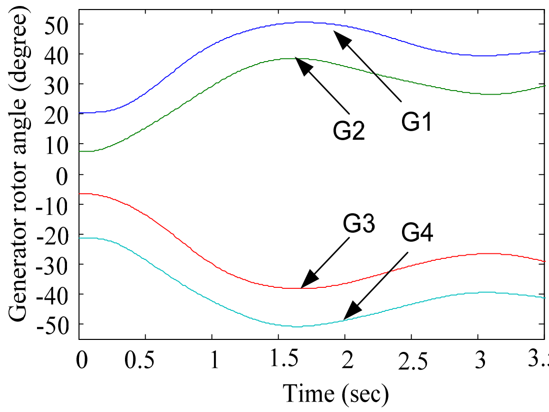


Figure 7 Trajectory of generator rotor angle of Kundur's inter-area system with a UPFC (a=0.08 and I_q=0.8).

TABLE I.

IMPROVEMENT OF GENERATOR ROTOR ANGLE FOR VARIOUS RATINGS OF UPFC

Gen. No.	First Swing		Second Swing	
	I_q=0.1,a=0.05 (deg.)	I_q=0.8,a=0.08 (deg.)	I_q=0.1,a=0.05 (deg.)	I_q=0.8,a=0.08 (deg.)
1	55.41	54.33	46.08	41.02
2	42.08	39.21	35.02	28.17
3	-46.24	-39.99	-35.13	-28.26
4	-57.42	-51.06	-46.74	-41.45

V. CONCLUSION

This paper investigates the capability of UPFC on transient stability of a inter-area power system. UPFC can be modeled as fictitious active and reactive load of power system. To incorporate UPFC into power system, the fictitious load models are transferred to susceptance models. These models can be controlled by parameters on a UPFC (a, α and I_q). This paper uses the line power flow between area 1 and area 2 to control a UPFC. The simulation results are tested on Kundur's inter-area power system. It was found from simulation results that UPFC can improve stability of inter-area power system and also was found that the stability of system is increased as the ratings of UPFC gets increase.

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