

Power System Stability Enhancement Using Unified Power Flow Controller

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Abstract: Problem statement: The enhancement of transient stability of the power system is one of the most challenging research areas in power engineer. **Approach:** This study presents the method to enhance transient stability of power system by Unified Power Flow Controller (UPFC). The mathematical model of power system equipped with a UPFC is systematically derived. The parameters of UPFC are modeled into power flow equation and thus it is used to determine control strategy. The swing curves of the three phase faulted power system without and with a UPFC are tested and compared in various cases. **Results:** The swing curve of system without a UPFC gets increases monotonically and thus the system can be considered as unstable whereas the swing curves of system with a UPFC can return to stable equilibrium point. **Conclusion:** From the simulation results, the UPFC can enhance transient stability of power system.

Key words: Power system, Unified Power Flow Controller (UPFC), transient stability, High Voltage Direct Current (HVDC), Flexible AC Transmission System (FACTS), injected current, thyristor controlled phase shifter, series transformer, voltage source, leakage reactance, equivalent circuit

INTRODUCTION

Modern power system network is getting much more complicated and heavily loaded than ever before. The consequence of such is the risk of stability problem. Transient stability is one of the important aspects in power system (Zarate-Minano *et al.*, 2010; Pizano-Matinez *et al.*, 2009; Augusto *et al.*, 2008). There are many advanced devices have been proposed during the last three decades to improve stability of power system such as High Voltage Direct Current (HVDC) system and Flexible AC Transmission System (FACTS) devices (Ahmad and Al-Husban, 2009; Moghadasi *et al.*, 2008; Kumkratug, 2010).

The Unified Power Flow Controller (UPFC) is a member of FACTS devices. It consists of two solid state converters. They are coupled through a common DC link (Hannan *et al.*, 2009; Jiang *et al.*, 2008). To verify the capability of UPFC on transient stability enhancement, its suitable mathematical model and control strategy are needed to be presented.

This study presents the mathematical model of power system equipped with a UPFC. The presented mathematical model is applied to design control strategy of a UPFC. The simulation results are tested on a Single Machine Infinite bus system.

MATERIALS AND METHODS

Mathematical model: Consider the schematic diagram of a UPFC as shown in Fig. 1a. The equivalent circuit of Fig. 1a is shown in Fig. 1b where the converters are replaced by synchronous voltage sources in series with the associate transformer leakage reactance. In the equivalent circuit, subscripts 's' and 'sh' are used to represent the quantities of the series and shunt converters, respectively. The shunt converter voltage and the associated transformer leakage reactance can be replaced by a shunt current source as shown in Fig. 1c. The value of the shunt current I_{sh} is given by:

$$I_{sh} = \frac{(V_{sh} - V_m)}{jX_{sh}} \quad (1)$$

Here V_m is the complex voltage of bus m. The injected shunt current can be controlled by adjusting the shunt converter voltage V_{sh} .

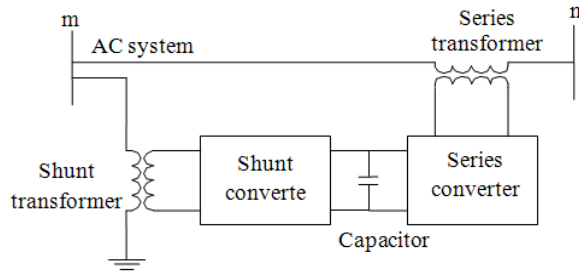
Consider a simple power system transferring power from a generating station to an infinite bus through a transformer and a transmission line having two parts as shown in Fig. 2a. A UPFC is placed in the transmission line at point m (between the two lines to enhance the dynamic behaviour of the system. The reactance diagram of the system is shown in Fig. 2b. E' and V_b

are the machine voltage and infinite bus voltage, respectively. The X_1 represents the equivalent reactance between the machine internal bus to bus m and X_2 represents the equivalent reactance between bus m to infinite bus.

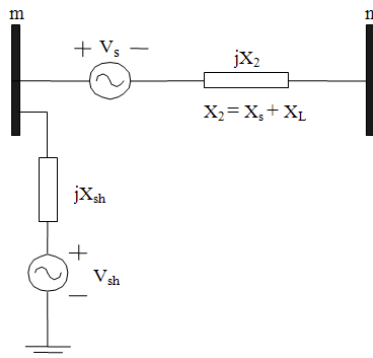
The complex power supplied by the series converter can be written as:

$$S_s^u = [P_s^u + jQ_s^u] = V_s (-I_u)^* \\ = V_s \left[\frac{-V_m^u + V_s + V_b}{jX_2} \right]^* \quad (2)$$

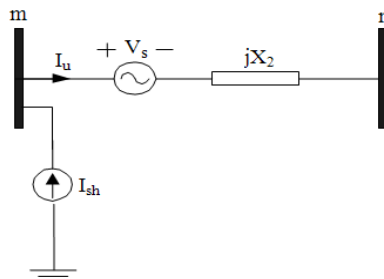
Here I_u is the line current.



(a)



(b)



(c)

Fig. 1: Representation of a UPFC: (a) schematic diagram; (b) equivalent circuit; (c) current injection model

The active (P_s^u) and reactive (Q_s^u) powers supplied by the series converter are given by:

$$P_s^u = \text{Re}[S_s^u] \\ = -bV_s V_b \sin(\theta_s - \theta_m^u) + bV_s V_m^u \sin(\theta_s - \theta_m^u) \quad (3)$$

$$Q_s^u = \text{Im}[S_s^u] \\ = -bV_s V_m^u \cos(\theta_s - \theta_m^u) + bV_s^2 + bV_s V_b \cos(\theta_s) \quad (4)$$

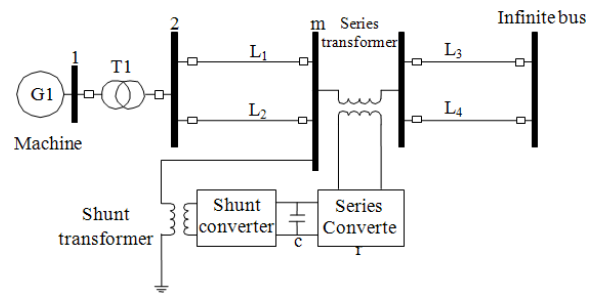
Here V_s and θ_s are the series voltage magnitude and angle, respectively and $b = 1/X_2$

The complex power down by the shunt converter can be written as:

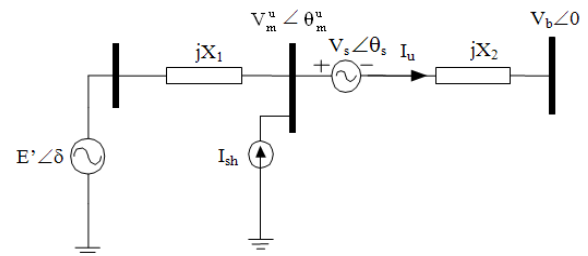
$$S_{sh}^u = [P_{sh}^u + jQ_{sh}^u] = V_m^u (-I_{sh})^* \quad (5)$$

The shunt injected current I_{sh} can be resolved into two components: one is in phase (I_p) with V_m and the other is in quadrature (I_q) with V_m as can be seen in Fig. 3. Thus I_{sh} can be expressed as:

$$I_{sh} = (I_p - jI_q) e^{j\theta_m^u} \quad (6)$$



(a)



(b)

Fig. 2: A simple single machine infinite bus system with a UPFC; (a) single line diagram; (b) Equivalent circuit of UPFC in a SMIB

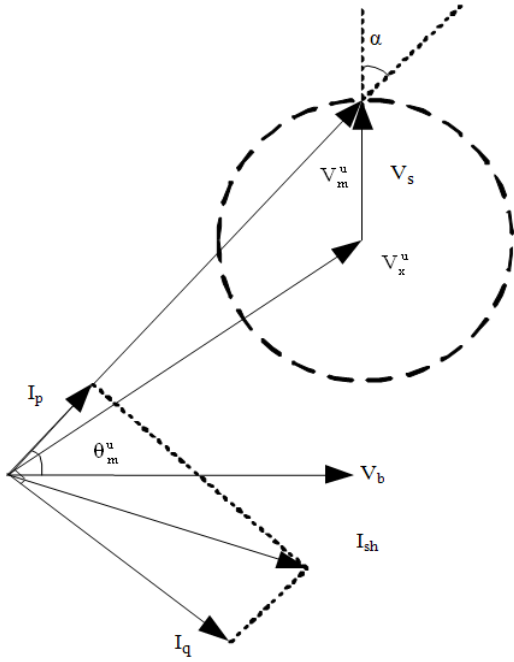


Fig. 3: Vector diagram of UPFC

The active P_{sh}^u and reactive Q_{sh}^u power drawn by the shunt transformer can be written as:

$$P_{sh}^u = \text{Re}[S_{sh}^u] = \text{Re}[\mathbf{V}_m^u (-\mathbf{I}_{sh})^*] = -V_m^u I_p \quad (7)$$

$$Q_{sh}^u = \text{Im}[S_{sh}^u] = \text{Im}[\mathbf{V}_m^u (-\mathbf{I}_{sh})^*] = -V_m^u I_q \quad (8)$$

The active power drawn by the shunt converter is equal to the active power supplied by the series converter:

$$P_{sh}^u = P_s^u \quad (9)$$

Using Eq. 3, 7 and 9, the in phase component of shunt injected current I_p can be written as:

$$I_p = \frac{bV_s}{V_m^u} \sin(\theta_s) - bV_s \sin(\theta_s - \theta_m^u) \quad (10)$$

Consider $V_s / V_m^u = ae^{j\alpha}$. The control ranges of a and α are $0 \leq a \leq a_{max}$ and $-\pi \leq \alpha \leq \pi$, respectively. Thus Eq. 10 can be written as:

$$I_p = abV_b \sin(\theta_m^u + \alpha) - abV_m^u \sin(\alpha) \quad (11)$$

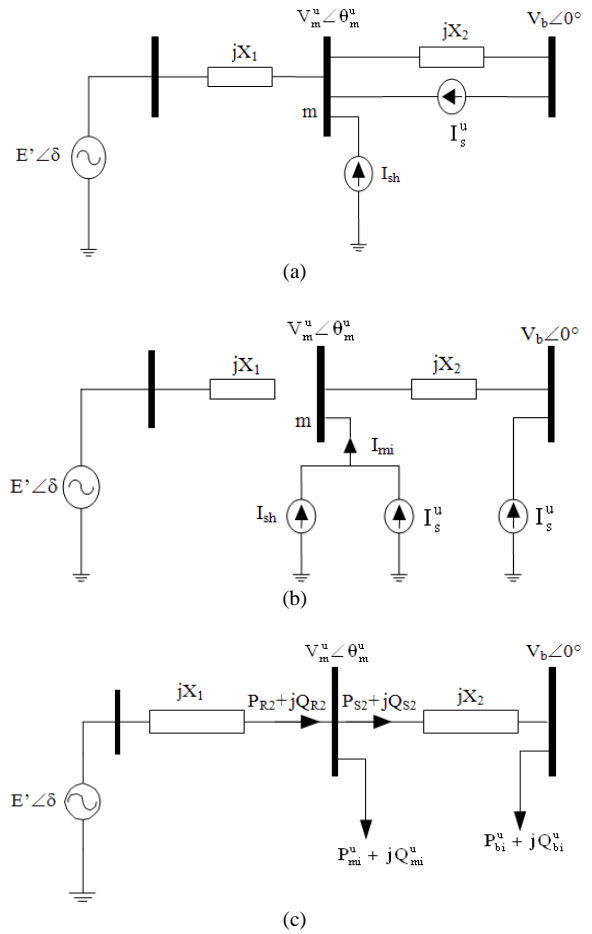


Fig. 4: Successive representation of series voltage source of the UPFC: (a) voltage source converted to a current source; (b) current source represented by two current sources; (c) fictitious load model

The series converter voltage V_s of Fig. 2b can be transformed into a current source I_s^u as shown in Fig. 4a. The value of I_s^u as shown in Fig. 4a is given by:

$$I_s^u = \frac{V_s}{jX_2} = -jabe^{j\alpha} V_m^u \quad (12)$$

The current source connected between bus m and n can be replaced by two shunt current source as shown in Fig. 4b. The net injected current I_{mi} at bus m can be written as:

$$I_{mi} = [I_{sh} + I_s^u] = [abV_b \sin(\theta_m^u + \alpha) - abV_m^u \sin(\alpha) - jI_q] e^{j\theta_m^u} - jabe^{j\alpha} V_m^u \quad (1)$$

The fictitious complex load at bus m as shown in Fig. 4c is given by:

$$S_{mi}^u = (P_{mi}^u + jQ_{mi}^u) = V_m^u (-I_{mi}^u)^* \quad (14)$$

The fictitious active P_{mi}^u and reactive load Q_{mi}^u at bus m are given by:

$$P_{mi}^u = \text{Re}[S_{mi}^u] = -abV_m^u V_b \sin(\theta_m^u + \alpha) \quad (15)$$

$$Q_{mi}^u = \text{Im}[S_{mi}^u] = -I_q V_m^u - ab(V_m^u)^2 \cos(\alpha) \quad (16)$$

The fictitious complex load at infinite bus b is given by:

$$S_{bi}^u = (P_{bi}^u + jQ_{bi}^u) = V_b (-I_s^u) \quad (17)$$

The fictitious active P_{bi}^u and reactive Q_{bi}^u load at infinite bus b are given by:

$$P_{bi}^u = \text{Re}[S_{bi}^u] = -abV_m^u V_b \sin(\theta_m^u + \alpha) \quad (18)$$

$$Q_{bi}^u = \text{Im}[S_{bi}^u] = abV_m^u V_b \cos(\theta_m^u + \alpha) \quad (19)$$

The active power balance equations at bus m of Fig. 4c is:

$$\begin{aligned} P_{R1} &= P_{mi}^u + P_{S2} \frac{E' V_m^u}{X_1} \sin(\delta - \theta_m^u) \\ &= -abV_m^u V_b \sin(\theta_m^u + \alpha) + \frac{V_m^u V_b}{X_2} \sin(\theta_m^u) \end{aligned} \quad (20)$$

After some mathematical manipulation of Eq. 20, the voltage angle θ_m^u of bus m can be expressed as:

$$\theta_m^u = \tan^{-1} \left[\frac{X_2 E' \sin(\delta) + X_1 V_b a \sin(\alpha)}{X_2 E' \cos(\delta) - X_1 V_b a \cos(\alpha) + X_1 V_b} \right] \quad (21)$$

Similarly, the reactive power balance equation at bus m of Fig. 4c is:

$$\begin{aligned} Q_{R1} &= Q_{mi}^u + Q_{S2} \frac{(V_m^u)^2}{X_1} - \frac{V_m^u E'}{X_1} \cos(\theta_m^u - \delta) \\ &= -I_q V_m^u - ab(V_m^u)^2 \cos(\alpha) + \frac{(V_m^u)^2}{X_2} - \frac{V_m^u V_b}{X_2} \cos(\theta_m^u) \end{aligned} \quad (22)$$

From Eq. 22, the voltage magnitude V_m^u of bus m can be found as:

$$V_m^u = \frac{X_2 E' \cos(\delta - \theta_m^u) + X_1 V_b \cos(\theta_m^u) + X_1 X_2 I_q}{X_1 + X_2 - X_1 a \cos(\alpha)} \quad (23)$$

It can be seen from Eq. 21 and 23 that the voltage magnitude angle at bus m can be controlled by UPFC control parameters (a , α and I_q). Thus in the presence of a UPFC, bus m of the system can be viewed as the terminal of a dependent voltage source whose magnitude and angle depend on the UPFC control parameters (a , α and I_q).

The electrical output power (P_e^u) of the machine can be written as:

$$P_e^u = \frac{E' V_m^u}{X_1} \sin(\delta - \theta_m^u) \quad (24)$$

The dynamic equations of a simple system with a UPFC can be represented by:

$$\dot{\delta} = \omega \quad (25)$$

$$\dot{\omega} = \frac{1}{M} (P_m - P_e^u) \quad (26)$$

Here δ , ω , M and P_m are machine angle, speed, moment of output electrical power, respectively, of the machine. The Eq. 26 clearly indicates that the P_e^u of the machine is main the main factor that dictates the dynamic behavior of machine because both P_m and H are usually considered as constant.

Control strategy: This study uses the machine speed control parameters on a UPFC. When the speed deviation is positive ($\omega > 0$), the P_e^u is raised by controlling parameters on a UPFC; When the speed deviation is negative ($\omega < 0$), the P_e^u is raised by controlling parameters on a UPFC.

RESULTS

The presented mathematical model and control strategy is used to study the effect of UPFC on transient stability enhancement of the system of Fig. 2a. In all cases, it is considered that a three phase self clearing fault appears at bus m and the fault is cleared without changing the network configuration. Figure 5 shows the machine angle curve of the system without and with a UPFC for clearing time (t_{cl}) = 150 msec.

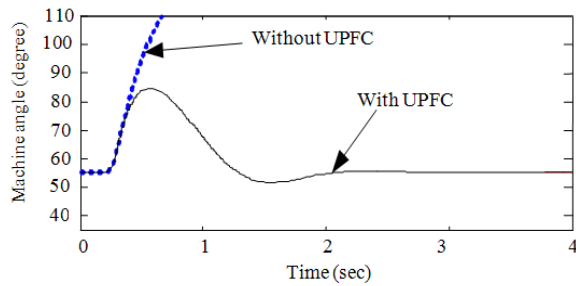


Fig. 5: Machine angle of the system without and with an TCPST for $t_{cl} = 150$ msec

DISCUSSION

It can be observed from the simulation results that the machine angle of the system without a UPFC increases significantly and thus the system is considered as unstable. However, with a UPFC, the system is considered as stable. The maximum value of swing curve is 85.45 degree and the system return to equilibrium point in about 2 msec.

CONCLUSION

This study investigates the capability of the Unified Power Flow Controller (UPFC) on transient stability enhancement of the system. The mathematical model is systematically derived. The presented mathematical model has shown that power flow and stability of system can be regulated by UPFC. This study uses machine speed to control parameters on UPFC. The speed deviation is the main factor to decrease and increase power flow of the system. The simulation results are tested on Single Machine Infinite Bus (SMIB) system. From the simulation results, it indicates that a UPFC can enhance transient stability of the system.

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