Power System Stability Enhancement using The Unified Power Flow Controller

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Abstract - **With the growing demand of electricity, at times, it is not possible to erect new lines to face the situation. Flexible AC Transmission System (FACTS) uses the thyristor controlled devices and optimally utilizes the existing power network. FACTS devices play an important role in controlling the reactive and active power flow to the power network and hence both the system voltage fluctuations and transient stability. This paper proposes the Unified Power Flow Controller (UPFC) as a power electronic based device that has capability of controlling the power flow through the line by controlling its series and shunt converters, also combined with Distributed Generation (DG) connected in the DC link to mitigate power quality disturbances. The proposed control will enable increased connections of renewable energy sources in the smart grid. The function of the scheme has been investigated the improvement of transient stability and voltage fluctuations of inter-area power system.**

I. INTRODUCTION

The solutions to improve the quality of supply in the electrical networks with distributed generation go through the applications of the developments in semiconductor power devices, that is to say, the utilization of static power converters in electrical energy networks [1]. The technological advances in power semiconductors are permitting the development of devices that react more like an ideal switch, totally controllable, admitting high frequencies of commutation to major levels of tension and power [2].

The concept of distributed generation (DG) is generally associated to the development of the renewable energy sources such as fuel cells, wind energy and solar cells, another factor to keep in mind in the development and configuration of the electrical system. The DG will need an important electronic equipment based on power converters that facilitate the integration of these sources of energy, without damaging over the reception quality of the users connected to the electricity network [3].

The FACTS controllers offer great opportunities to regulate the transmission of alternating current (AC), increasing or diminishing the power flow in specific lines and responding almost instantaneously to the stability problems. The potential of this technology is based on the possibility of controlling the route of the power flow and the ability of connecting networks that are not adequately interconnected, giving the possibility of trading energy between distant agents [4].

One particular concept, called the Unified Power Flow Controller (UPFC), has been presented by Gyugi in 1992 [5], that combines the functions of some FACTS devices and is capable to control a wide range of typical transmission parameters, such as voltage, line impedance and phase angle. The UPFC is perhaps the most versatile of the FACTS controllers, offering a unique combination of shunt and series compensation and guaranteeing flexible power system control [6-7]. The flexible power flow control and high dynamics can be achieved by applying electronic power converters. It is particularly beneficial to use power converters based on full controlled switches, such as Gate Turn Off thyristors (GTO) and the more recently available high power Insulated Gate Bipolar Transistor (IGBT), which are suitable to handle higher switching frequencies [5].

The objective of this paper is to present the model and performance of a UPFC connected to a transmission line, when the active and the reactive power reference values are changed, respectively the behavior of the DC voltage must be reviewed because it will affect on the connected DG (section IV). Finally, investigates the stability improvement of inter-area system using the UPFC (section V). The simulation results are carried out using Power System Analysis Matlab Toolbox (PSAT) to validate the performance of the UPFC.

II. SYSTEM CONFIGURATION

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 "Fig. 1,". 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 [8]. 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. The shunt converter also has a capability of independently supplying or absorbing reactive power to regulate the voltage of the AC system [9].

The UPFC is a device placed between two buses referred to the UPFC sending bus (B1) and the UPFC receiving bus (B2), It consists of two voltage-sourced converters (VSCs) with a common DC-link. For the fundamental frequency model, the

VSCs are replaced by two controlled voltage sources as shown in “Fig. 1,”.

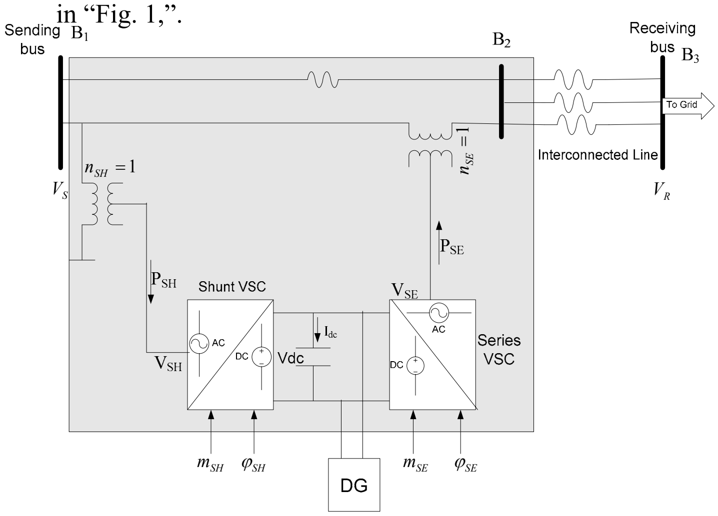


Fig. 1 Configuration of UPFC.

By applying the pulse width modulation (PWM) technique to the two VSCs, the following equations for magnitudes of shunt and series injected voltages can be obtained [10]:

$$V_{SH} = m_{SH} \frac{V_{DC}}{2\sqrt{2} n_{SH} V_B} \tag{1}$$

$$V_{SE} = m_{SE} \frac{V_{DC}}{2\sqrt{2} n_{SE} V_B} \tag{2}$$

Where,

m_{SH} = amplitude modulation index of the shunt VSC control signal.

m_{SE} = amplitude modulation index of the series VSC control signal.

n_{SH} = shunt transformer turn ratio.

n_{SE} = series transformer turn ratio.

V_B = the system side base voltage in kV.

V_{DC} = DC-link voltage in kV.

And the phase angles are:

$$\delta_{SH} = \delta_S - \varphi_{SH} \tag{3}$$

$$\delta_{SH} = \delta_S - \varphi_{SH} \tag{4}$$

$$\delta_{SE} = \delta_S - \varphi_{SE} \tag{5}$$

Where,

φ_{SH} = firing angle of the shunt VSC with respect to the phase angle of the sending bus voltage.

φ_{SE} = firing angle of the series VSC with respect to the phase angle of the sending bus voltage.

Both voltage sources are modeled to inject voltages of fundamental power system frequency only. The UPFC is placed on high-voltage transmission network; this arrangement requires step-down transformers to allow the use of power electronic devices for the UPFC. The series converter injects an AC voltage $\overline{V}_{SE} = V_{SE}\angle(\delta_S - \varphi_{SE})$ in series with the transmission line. The series voltage magnitude V_{SE} and its phase angle φ_{SE} with respect to the sending bus are controllable in the range of $0 \le V_{SE} \le V_{SE\,\max}$ and $0 \le \varphi_{SE} \le 360°$. The shunt converter injects controllable shunt voltage such that the real component of the current in the shunt branch balances the real power demanded by the series converter. The reactive power cannot flow through the DC-link. It is absorbed or generated (exchanged) locally by each converter. The shunt converter operated to exchange the reactive power with the AC system provides the possibility of independent shunt compensation for the line. If the shunt injected voltage is regulated to produce a shunt reactive current component that will keep the sending bus voltage at its prespecified value.

In order to show how the line power flow can be affected by the UPFC, it is placed at the beginning of the transmission as shown in “Fig. 1,” When the line conductance is neglected; the complex power received at the receiving end of the line is given by [10]

$$S = \overline{V}_R \overline{I}^*_{Line} = \overline{V}_R \left(\frac{\overline{V}_S + \overline{V}_{SE} - \overline{V}_R}{JX} \right)^* \tag{6}$$

Where,

$$\overline{V}_{SE} = V_{SE}\angle(\delta_S - \varphi_{SE})$$

The complex conjugate of this complex power can be expressed as:

$$S^* = P - JQ = \overline{V}_R^* \left(\frac{\overline{V}_S + \overline{V}_{SE} - \overline{V}_R}{JX} \right) \tag{7}$$

By performing simple mathematical manipulations and separating real and imaginary parts of Eq. (7), the following expressions for real and reactive powers received at the receiving end of the line are [10]:

$$P = \frac{V_S V_R}{X}\sin(\delta) + \frac{V_R V_{SE}}{X}\sin(\delta - \varphi_{SE})$$
$$P = P_o(\delta) + P_{SE}(\delta, \varphi_{SE}) \tag{8}$$

$$Q = -\frac{V_R^2}{X} + \frac{V_S V_R}{X}\cos(\delta) + \frac{V_R V_{SE}}{X}\cos(\delta - \phi_{SE})$$
$$Q = Q_o(\delta) + Q_{SE}(\delta, \varphi_{SE}) \tag{9}$$

It was stated previously that the UPFC series voltage magnitude can be controlled between 0 and $V_{SE\,\max}$ and its phase angle can be controlled between 0 and 360° at any power angle δ. It can be seen from “(8),”, “(9),” and “Fig. 2,” that the real and reactive power received at bus R can be controlled when a UPFC is installed as:

$$P_{\min}(\delta) \le P \le P_{\max}(\delta) \tag{10}$$

$$Q_{\min}(\delta) \le Q \le Q_{\max}(\delta) \tag{11}$$

Where,

$$P_{\min}(\delta) = P_O(\delta) - \frac{V_R V_{SE\max}(\delta)}{X}$$

$$P_{\max}(\delta) = P_O(\delta) + \frac{V_R V_{SE\max}(\delta)}{X}$$

$$Q_{\min}(\delta) = Q_O(\delta) - \frac{V_R V_{SE\max}(\delta)}{X}$$

$$Q_{\max}(\delta) = Q_O(\delta) + \frac{V_R V_{SE\max}(\delta)}{X}$$

III. SYSTEM MODELLING

To simulate a power system that contains a UPFC, the UPFC needs to be modeled for steady-state and dynamic operations. Also, the UPFC model needs to be interfaced with the power system model. Hence, the modeling and interfacing of the UPFC with the power network are described [9].

A. UPFC Steady-State Model

For steady-state operation of the DC link voltage remains constant at its pre-specified value. In case of a lossless DC link the active power supplied to the shunt converter $P_{SH} = \mathrm{Re}(\bar{V}_{SH} * \bar{I}^*_{Line})$ satisfies the active power demanded by the series converter $P_{SE} = \mathrm{Re}(\bar{V}_{SE} * \bar{I}^*_{Line})$ [10]:

$$P_{SH} = P_{SE} \tag{12}$$

The Load flow (LF) model discussed here assumes that UPFC is operated to keep active and reactive power flow on the transmission line at the receiving bus, and the sending bus voltage magnitude at their pre-specified values [11]. In this case the UPFC can be replaced by an equivalent generator at the sending bus (PV-type bus) and a load at the receiving bus (PQ-type bus) as shown in "Fig. 3,".

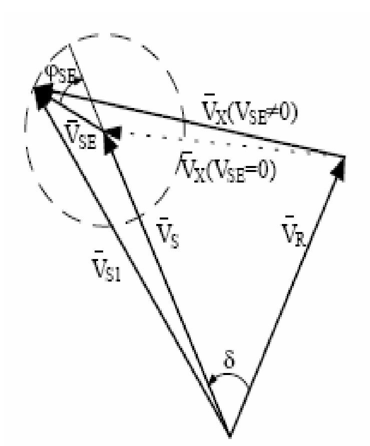


Fig. 2 Controlled series voltage

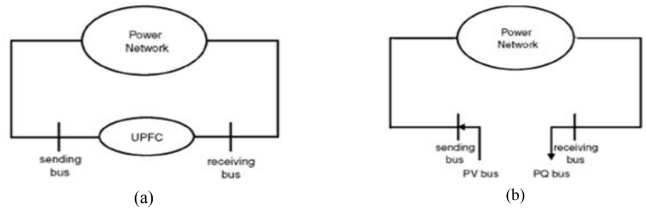


Fig. 3 UPFC with the power system: (a) Schematic (b) Load flow Mode.

Power demanded at the receiving bus is set to the desired real and reactive power at that bus. The real power injected into a PV bus for a conventional LF algorithm is kept constant and the reactive power is adjusted to achieve the prespecified voltage magnitude. With the UPFC, the real power injected into the sending bus is not known exactly. This real power injection is initialized to the value that equals the prespecified real power flow at the receiving bus. During the iterative procedure, the real power adjusted to cover the losses of the shunt and series impedances and to force the sum of converter interaction to become zero. The algorithm, in its graphical form, is given in "Fig. 4,". To obtain the LF solution of a power network that contains the UPFC an iterative procedure is needed. The active power injected at the sending bus is $P_S = \mathrm{Re}(\bar{V}_S * \bar{I}^*_S)$ [10].

$$\bar{V}_S = \bar{V}_{SH} + \bar{I}_{SH} Z_{SH} \tag{13}$$

And the expression for the adjusted injected active power Ps becomes

$$P_S = -P_{SE} - \mathrm{Re}(Z_{SH} I^2_{SH} + \bar{V}_{SH} \bar{I}^*_{Line} + Z_{SH} \bar{I}_{SH} \bar{I}^*_{Line}) \tag{14}$$

It should be noted that there is no need for the iterative procedure to compute the UPFC control parameters. They can be computed directly after a conventional LF solution. Neglecting transformer losses and initializing the active power injected into sending bus to the active power flow controlled on the line, the convergence of the proposed LF algorithm is obtained within one step.

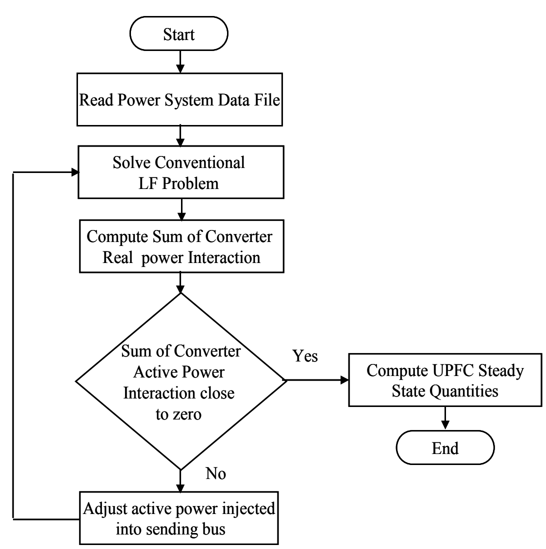


Fig. 4 Load flow algorithm.

B. UPFC dynamic model

For transient stability studies, the DC link dynamics have to be taken into account and can no longer be applied. The DC link capacitor will exchange energy with the system and its voltage will vary [12-13].

The power frequency dynamic model has been implemented in the Power System Analysis Toolbox software (PSAT). The following equation describes this model [10]:

$$CV_{DC}\frac{dV_{DC}}{dt} = (P_{SH} - P_{SE})S_B \tag{15}$$

The system side base values: SB and VB are selected as base power and base voltage, respectively, and all AC variables are normalized using these base quantities.

C. Interfacing the UPFC with the power network

In order to get the network solution (bus voltages and currents) an iterative approach is used. The UPFC sending and receiving bus voltages can be expressed as a function of the generator internal voltages E_G, While, the UPFC Control output determine the UPFC injection voltage magnitudes (V_{SH} and V_{SE}). However, the phase angles of the injected voltages θ_{SE} and θ_{SH} are unknown since they depend on the phase angle of the sending bus voltage θ_S which is the result of the network solution. The algorithm for interfacing the UPFC with the power network is shown, as a flow chat in “Fig. 5,”.

$$\overline{V}_U = L_G\overline{E}_G + L_C\overline{V}_C \tag{16}$$

Where,

$$L_G = (W_U - Y_{UU})^{-1}Y_{UG}$$

$$L_C = -(W_U - Y_{UU})^{-1}W_C$$

$$W_C = \begin{bmatrix} \frac{1}{JX_{SH}} & -\frac{1}{JX_{SE}} \\ 0 & \frac{1}{JX_{SE}} \end{bmatrix}$$

$$W_U = \begin{bmatrix} -\frac{1}{JX_{SE}} & -\frac{1}{JX_{SH}} & \frac{1}{JX_{SE}} \\ \frac{1}{JX_{SE}} & -\frac{1}{JX_{SE}} & \end{bmatrix}$$

$$\overline{V}_U = \begin{bmatrix} \overline{V}_S \\ \overline{V}_R \end{bmatrix}, \quad \overline{V}_C = \begin{bmatrix} \overline{V}_{SH} \\ \overline{V}_{SE} \end{bmatrix}$$

YUU is the admittance matrix connecting with the UPFC currents to the voltages at the UPFC buses.

YUG is the admittance matrix which gives the UPFC currents in terms of generator internal voltages.

However, the shunt and series transformer resistances have been neglected.

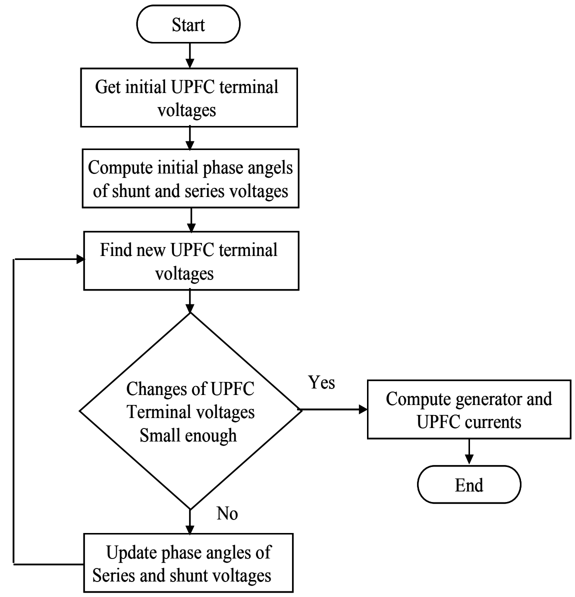


Fig. 5 interfacing of UPFC with the power network algorithm

IV. Numerical Simulations

The Unified Power Flow Controller (UPFC) is used to control the power flow in a 500 kV transmission system. The UPFC located at the left end of the 75-km line L2, between the 500 kV buses B1 and B2 is used to control the active and reactive power flowing through bus B2 while the controlling voltage at bus B1 as shown in “Fig. 1,” It consists of two 100-MVA, three-level, 48-pulse GTO-based converters, one connected in shunt at bus B1 and another one connected in series between buses B1 and B2. The shunt and series converters can exchange power through a DC bus. The series converter can inject a maximum of 10% of nominal line-to-ground voltage (28.87 kV) in series with line L2.

Initially, Pref = +8.7 pu /100MVA (+870 MW) and Qref = -0.6 pu /100MVA (-60 MVAR). At t=0.25 sec. Pref is changed to +10 pu (+1000MW). Then, at t=0.5 sec, Qref is changed to +0.7 pu (+70 MVAR). The reference voltage of the shunt converter will be kept constant at Vref=1 pu during the whole simulation.

“Fig. 6,” shows that the active power steady state is reached (P=+8.7 pu) after a transient period lasting approximately 0.15 sec. Also it can be seen that P is ramped to the new settings (P=+10 pu) after changing the reference value at t=0.25 sec. It can be seen from “Fig. 7,” at t=0.5 sec, the reference value for reactive power has been changed to 0.7 pu and the value of Q has ramped to the new value after 0.15 sec. So, the active power has a small changes around its steady state value due to the changes in the reactive power and vice verse due to the changes of the active power at t = 0.25 sec and there is a small change in the reactive power.

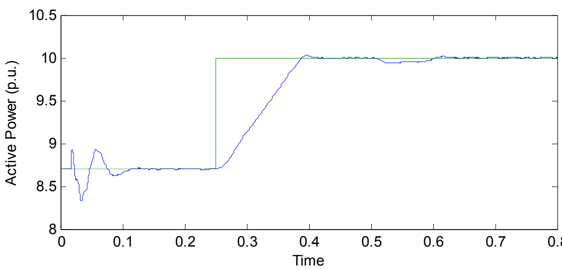


Fig. 6 UPFC responses for changing active power

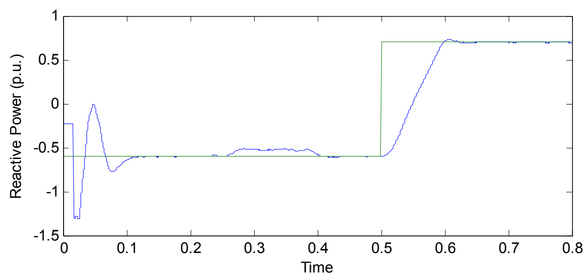


Fig. 7 UPFC responses for changing reactive power

This control of the reactive power is obtained by varying the magnitude of the secondary voltage Vs generated by the shunt converter while keeping it in phase with the bus B1 voltage Vp as shown in “Fig. 8,” that Vs started to appear at t = 0.5 sec due to changing the value of the reactive power. Also it can be seen from “Fig. 9,” that the Vdc increases from 17.5 kV to 21 kV due to the increasing of the reactive power which will have an effect on the connected DG through the DC link, So, it is recommended in the future research to determine the kind and size of the connected DG and study the effect on its performance and stability due to the voltage deviation.

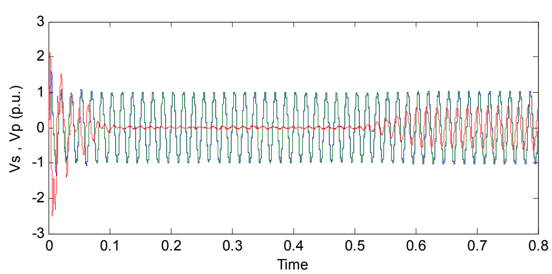


Fig. 8 Series and Parallel injected voltages

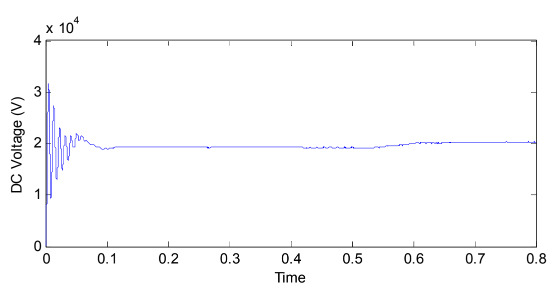


Fig. 9 DC voltage

V. CASE STUDY

The performance of the UPFC is tested on a two-area–four-generator system (test system) as shown in “Fig. 10,”. Data for this system can be found in appendix 1.The two areas are identical to one another and interconnected with two parallel 230-km tie lines that carry about 400 MW from area 1 (generators 1 and 2) to area 2 (generators 3 and 4) during normal operating conditions [14]. The UPFC is placed at the beginning of the lower parallel line between buses 101 and 13 to control the power flow through that line as well as to regulate voltage level.

A three phase fault is applied at bus number 3, area 1 at t = 1s. The fault is cleared at t = 1.05s by opening breaker at bus 101 on upper line from bus 03 to bus 101. A comparison of the simulation results for the test system without the UPFC and with the UPFC.

“Fig. 11,” shows that the rotor speed swings are better damped in the case of the system with UPFC and it can be noticed that, the system recovers quickly after the fault is cleared and reaches the desired power flow in approximately 14 sec. though the power flow control has positive effect on the first swing transient in the system. In the case of the system without the UPFC, there is no damping for the rotor angle swings which mean that the system will not recover an acceptable state and “Fig. 11,” shows the divergence of the rotor speed. So the system will loose the stability.

On the other, in the case of the system without the UPFC the voltage fluctuations has going away the accepted limits as shown in “Fig. 12,”. Also, it can be seen that, the UPFC is operated to keep the bus voltage at the accepted limits.

VI. CONCLUSION AND OUTLOOK

The system proposed in this paper has the functions of improving power quality and ensuring the continuity of electricity supply, the UPFC has been proposed to control simultaneously real and reactive power flows in the transmission line as well as to regulate the voltage bus using the FACTS. This device creates a tremendous impact on power system stability enhancement and loading of transmission lines close to their thermal limits. Thus, the device gives power system operators much needed flexibility to satisfy the demands that the deregulated power system imposes.

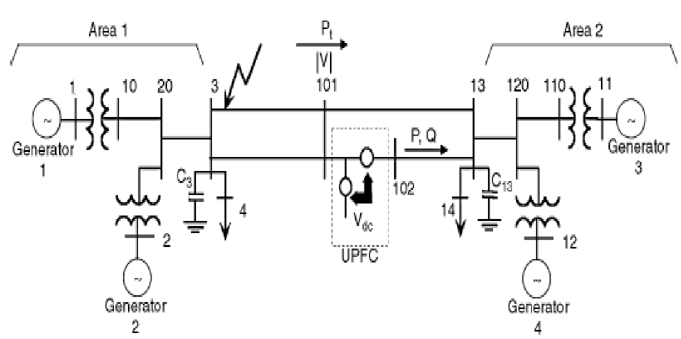
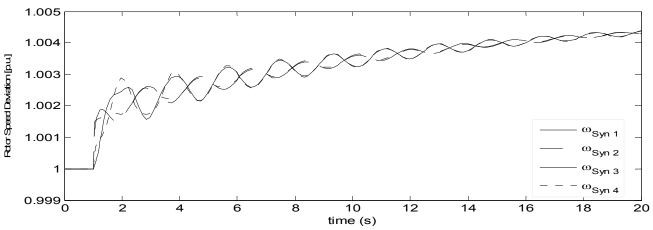
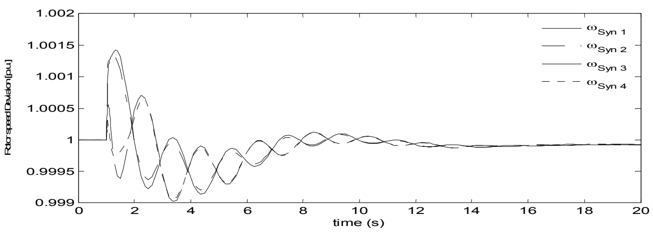


Fig. 10 Two-area–four-generator test system.



(a) Without UPFC

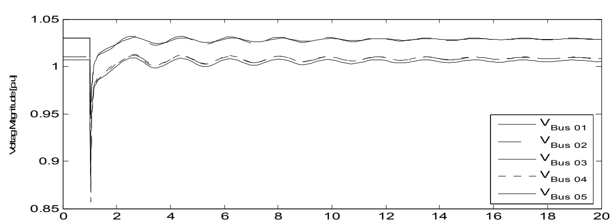


(b) With UPFC

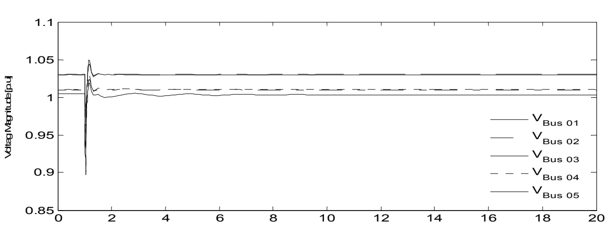
Fig. 11 Rotor speed deviation

Simulation results have shown that the UPFC is capable of controlling the line power flow and supporting the voltage level in extreme operating conditions and tracking the step changes in active and reactive power flow reference values.

The proposed control and stabilization methodology constitute more recommended method for interconnection of dispersed storage and renewable energy sources (e.g. solar energy, fuel cell and wind energy e.t.c.) to the utility to formulate the smart grid. So, it is recommended in the future work to design a hybrid solar/fuel cells/wind farm as a Static Synchronous compensator (STATCOM) to regulate the voltage profile and the power flow in the distribution network, also study the best location of the utility to connect the excess renewable energy sources with respect to power quality, voltage profile enhancement and dynamic stability.



(a) Without UPFC



(b) With UPFC

Fig. 12 Bus Voltage Magnitudes

REFERENCES

[1] K. C. Kalaitzakis and G. J. Vachtsevanos, "On the Control ans Stability of Grid Connected Photovoltaic Sources", IEEE Transactions on Energy Conversion, Vol. EC-2, No. 4, December 1987.

[2] Prechanon Kumkratug, "Application of UPFC to Increase Transient Stability of Inter-Area Power System", Journal of Computers, Kasetsart University Sriracha Campus, Chonburi, Thailand, Vol. 4, No. 4, April 2009.

[3] M. R. Patel, "Wind and Solar Power Systems Handbook ", CRC Press LLC, 1999.

[4] N. Tambey and M.L. Kothari, "Damping of power system oscillations with unified power flow controller (UPFC)", IEE Proc.-Gener. Trans. Distrib, Vol. 150, No. 2, March 2003.

[5] Xiao-Ping Zhang, Christian Rehtanz and Bikash Pal, "Flexible AC Transmission Systems Modeling and Control", Germany, 2006.

[6] Marcelo C. Cavalcanti, Gustavo M.S.Azevedo, Bruno A.Amaral and Francisco A.S.Neves, "Unified Power Quality Conditioner in a Grid Connected Photovoltaic System", Electrical Power Quality and Utilization, Journal Vol. No.2, 2006.

[7] J.David Irwin, "The Power Electronic Handbook", CRC Press LLC, 2002.

[8] S.Tara Kalyani, G.Tulasiram Das, "Simulation of Real and Reactive Power Flow Control with UPFC Connected to a Transmission Line", Journal of Theoretical and Applied Information Technology, 2008.

[9] Sidhartha Panda, Ramnarayan N. Patel, "Improving Power System Transient Stability with an Off–Center Location of Shunt Facts Devices", Journal of Electrical Engineering, Vol. 57, No. 6, 2006.

[10] Karl Schoder, Azra Hasanovic, and Ali Feliachi, "Load-Flow and Dynamic Model of the Unified Power Flow Controller (UPFC) within the Power System Toolbox (PST)", proc. 43rd IEEE Midwest Symp. on Circuts and Systems, Lansing MI, Aug 8-11.20000-7803-6475-9/M), 2000.

[11] Valerijs Knazkins, "Stability of Power Systems with Large Amounts of Distributed Generation", Stockholm, 2004.

[12] SHENG Kun, KONG Li and PEI Wei, "Small Signal Stability Analysis of Stand Alone Power System with Distributed Generation", 19th International Conference on Electricity Distribution, Vienna, 21-24 May 2007.

[13] Wang Yi-Bo, Wu Chun-Sheng, Liao Hua and Xu Hong-Hua, "Steady-State Model and Power Flow Analysis of Grid-Connected Photovoltaic Power System", 978-1-4244-1706-3/08/2008 IEEE.

[14] P.Kundur, "Power System Stability and Control Handbook", McGraw-Hil1, lnc., 2000.

APPENDIX 1

The generator parameters in per unit are as follows:

Xd= 1.8 Xq = 1.7 X'd = 0.3 X'q = 0.55
Ra = 0.0025 Xl = 0.2 T'd0 = 8s T'q0 = 0.4s
H = 6.5 (for G1 and G2) H = 6.175 (for G3 and G4) Dw = 0

The exciter parameters in per unit are as follows:

$K_A = 20$ $T_A = 0.055$ $T_E = 0.36$ $K_E = 0$
$K_F = 0.125$ $T_F = 1.8$ $A_{ex} = 0.0056$ $B_{ex} = 1.075$
$T_R = 0.05$

The UPFC parameters in per unit are as follows:

$r_{max} = 0.09$ $\gamma = 90^0$ $S_s = 0.4$ $I_q = 0$ $K_\gamma = 2$
$T_\gamma = 0.2$ $K_r = 0.02$ $T_r = 0.02$