Design and Analysis of Power System Stabilizer and Unified Power Flow Controller for Enhancements of Transient Stability

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Abstract— *Modeling and analysis of AVR, PSS and UPFC in SMIB system for the transient stability enhancement and improvement of power transfer capability have been done in this paper. The effects of UPFC, AVR and PSS controller evaluated under different case studies, namely by step changing reference voltage, infinity bus voltage, mechanical torque and introducing short circuit fault into the system has been made. In all cases the response of rotor angle, slip, excitation voltage, and electrical torque were simulated. The control strategies of UPFC are in phase voltage control, quadrature voltage control, quadrature current control, real current control and phase angle control, but in this paper except phase angle control the leftovers were implemented.*

Key Words*: *SMIB, AVR, PSS, UPFC, Shunt injected current; Series injected Voltage, Transient Stability.

1. INTRODUCTION

The available power generating plants are often placed in distant locations for economic, environmental and safety reasons. Additionally, modern power systems are highly interconnected. Sharing of generation reserves, exploiting load diversity and economy gained from the use of large, efficient units without losing stability, reliability and quality of the system. The stability of the power system implies that all its generators remain in synchronism through normal and abnormal operation conditions. Transient stability arises when a large disturbance such as a loss of generation, load or transmission line takes place in the power system. It is becoming a major factor in planning and day to day operations and there is a need for fast online solutions of transient stability to predict any possible loss of synchronism and to take the necessary measures to restore the stability. Recently varies controller device are designed to damp these oscillations and to improve the system stability, which are found in modern power system, but conventional control and FACTS device still an alternative solution.

The main objectives of excitation system are to control the field currents of synchronous machine. The field current is controlled to regulate the terminal voltage of the machine. And also, the basic functions of power system stabilizer are to add damping to the generator rotor oscillations by controlling its excitations using auxiliary stabilizing signals [12]. To provide damping the stabilizer must produce a component of electrical torque in phase with the rotor speed deviations.

Unified Power Flow Controller (UPFC) is one of the important members of Flexible AC Transmission System(FACTS) family. It is a combination of Static Synchronous Compensator (STATCOM) and Static Series Compensator (SSSC) [2], [6], [10]. These two are coupled via a common DC link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide simultaneous real and reactive series line compensation without an external electric energy source [11]. The schematic of UPFC is shown in Fig-1. The UPFC consists of two branches. The series branch consists of a voltage source converter which injects a voltage in series through a transformer. Since the series branch of the UPFC can inject a voltage with variable magnitude and phase angle it can exchange real power with the transmission line [9]. The shunt branch is required to compensate for any real power drawn/supplied by the series branch and the losses. If the power balance is not maintained, the capacitor cannot remain at a constant voltage.

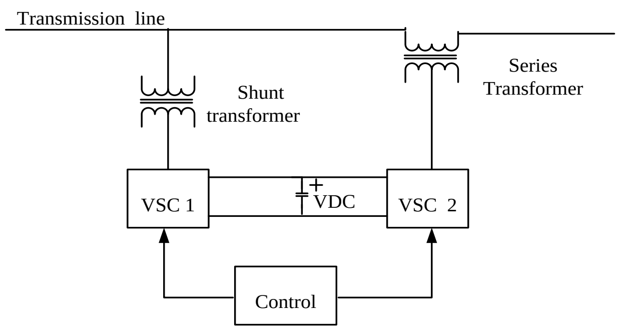


Fig-1: The Schematic diagram of UPFC

As shown in Fig-1 the two converters are operated from a common DC link provided by a DC storage capacitor. VSC2 is used to inject the required series voltage via an injection transformer. The real power exchanged at the terminals of the series transformer is converted by the converter into DC power which appears at the DC link as positive or negative real power demand. This DC link power is converted back to AC and coupled to the transmission line via a shunt transformer by VSC1. Thus, the basic function of VSC1 is to supply or absorb the real power demanded by VSC2 at the common DC link. VSC1 can also generate or absorb controllable reactive power, thus providing shunt compensation for the line independently of the reactive power exchanged by VSC2[6], [7], [10]. The UPFC, thus, functions as an ideal AC-to-AC power converter in which real power can flow freely in either direction between the AC terminals of the two converters and each converter can independently generate or absorb reactive power on its own as output terminal. It can be represented as two port devices with a controllable voltage source V_{inj} in series with the line and a controllable shunt current source I_{sh}. Since the UPFC as a whole does not absorb or generate any real power, the DC capacitor voltage has maintained a constant. This relationship can be expressed mathematically, from figure 2[8].

$$\mathrm{Real}(V_1 I_1 + V_2 I_2) - P_{loss} = 0 \quad (1)$$

UPFC has three controllable parameters: the phase and magnitude of the series injected voltage V_{inj} and the magnitude of the shunt reactive current. These parameters can be controlled in various ways to meet different objectives. It may not even be necessary at times to control all the three parameters [13].

2. MATHEMATICAL MODEL OF POWER SYSTEM WITH PSS, AVR AND UPFC

A classical single machine infinity bus power system as shown in Fig-8 is considered. UPFC is placed in the middle to regulate the bus voltage, to control power flow and to improve the transmission capability.

2.1 Generator equation

The synchronous generator is represented by the detailed model 1.1 comprising of the electromechanical swing equation and the generator internal voltage equation. The differential equations describing the dynamic behavior of the synchronous generator are listed as follows.

- Rotor swings equations

$$\frac{d\delta}{dt} = w_B(S_m - S_{m0}) \quad (2)$$

$$2H\frac{dS_m}{dt} = -D(S_m - S_{m0}) + (T_m - T_e) \quad (3)$$

Where S_m is the slip, w_B is the base synchronous speed and D is the damping [1-4].

- Electrical torque, expressed as

$$T_e = E'_d i_d + E'_q i_q + (X'_d - X'_q) i_d i_q \quad (4)$$

The mechanical torque input Tm is assumed to be constant. The turbine-governor controls are neglected as they have negligible effect on the first swing transient stability [1-4].

- Internal voltage equations expressed as

$$\frac{dE'_q}{dt} = \left(\frac{1}{T'_{do}}\right)[-E'_q + (X_d - X'_d)i_d + E_{fd}] \quad (5)$$

$$\frac{dE'_d}{dt} = \left(\frac{1}{T'_{qo}}\right)[-E'_d - (X_q - X'_d)i_q] \quad (6)$$

2.2 Automatic voltage regulator model

The excitation systems of the generators are using the AVR for maintaining the magnitude of the terminal voltage of the synchronous generators at the desired level. AVR in power systems also plays another important role of controlling the reactive power to help in enhancing system stability [2-4].

In short, automatic voltage regulator is provided in the excitation systems for improving power system stability. The excitation system affects stability under both transient and steady state conditions. Fig-2 shows the block diagrams of a static automatic voltage regulator [1].

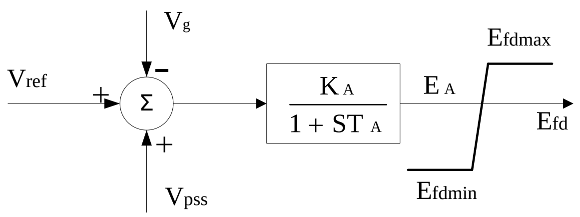


Fig-2: Block diagram of AVR

Equations described statics automatic voltage regulator are,

$$V_{ref} = \frac{E_{fd}}{K_A} + V_g \quad (7)$$

$$\mathrm{error} = V_{ref} - V_g \quad (8)$$

$$\frac{dE_A}{dt} = \left(\frac{1}{T_A}\right)[-E_A + K_A(V_{ref} - V_g)] \quad (9)$$

Output of static automatic voltage regulator is given by

$$\left.\begin{aligned} E_{fd} &= E_A \ (E_{fdmin} < E_A < E_{fdmax}) \\ &= E_{fdmin} \ (E_A < E_{fdmin}) \\ &= E_{fdmax} \ (E_A > E_{fdmax}) \end{aligned}\right\} \quad (10)$$

2.3. Power system stabilizer model

The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped for generator rotor oscillation to maintain the system stability. So, it is controlled by using a Power system stabilizer, the output signal of the PSS is used as an additional input to the Excitation System. The Power System Stabilizer is modeled by the following nonlinear system [1-3]:

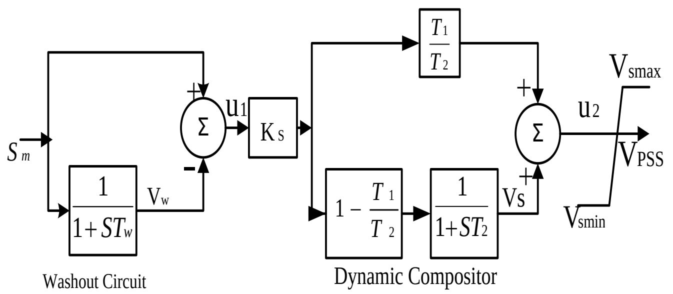


Fig- 3: State variables Block diagram of PSS

Wash out circuit is provided to eliminate steady state bias in the output of PSS. The time constant T_1 and T_2 are chosen depending on the compensation required for damping. It is to be noted that a single lead-lag compensator is adequate with a static exciter.

Dynamic compensator transfer function expressed as

$$T(s) = K_s (1 + sT_1)/(1 + sT_2)$$

Equation described PSS are derived from both washout and dynamic compensator circuit

$$\frac{dV_w}{dt} = \left(\frac{1}{T_w}\right)(-V_w + S_m) \quad (11)$$

$$u_1 = S_m - V_w \quad (12)$$

$$\frac{dV_s}{dt} = \left(\frac{1}{T_2}\right)\left[-V_s + K_s\left(1 - \frac{T_1}{T_2}\right)u_1\right] \quad (13)$$

$$u_2 = V_s + K_s\left(\frac{T_1}{T_2}\right)u_1 \quad (14)$$

Where V_w and V_s are state variables corresponding to wash out circuit and dynamic compensator. The outputs of PSS are given by

$$\left.\begin{aligned} V_{pss} &= u_2 (V_{Smin} < u_2 < V_{Smax}) \\ &= V_{Smin} \ (u_2 < V_{Smin}) \\ &= V_{Smax} \ (u_2 > V_{Smax}) \end{aligned}\right\} \quad (15)$$

2.4 Unified Power Flow Controller(UPFC) model

The UPFC can perform the function of STATCOM and SSSC and phase angle regulator. Besides that, the UPFC also provides an additional flexibility by combining some of the functions above. UPFC has also a unique capability to control real and reactive power flow simultaneously on a transmission system as well as to regulate the voltage on the bus where it's connected. At the same time the UPFC also can increase the security system by increases the limit of transient stability, fault and the overload demand [14].
The UPFC allows us three degrees of freedom such as magnitude of series injected voltage, the magnitude of the shunt reactive current and phase angle. Mainly UPFC has two main control strategies.

2.4.1 Series injected voltage control

To achieve real and reactive power flow control, it need to inject a series voltage of the appropriate magnitude and angle. The injected voltage can be split into two components which are in phase or real voltage and in quadrature or reactive voltage to the line current. This can be controlled active power flow using the reactive voltage and the reactive power controlled by using a real voltage of the injected voltage [6], [7].

To design series injected voltage control using one of the two methods:

(i) Power flow control using reactive voltage.
(ii) UPFC port 2 voltage control using real voltage.

2.4.2 Shunt Current Control

It is well known that shunt reactive current injection can be used to control bus voltage. It is split into real and reactive current. The reactive current reference is set by a bus voltage magnitude regulator (for port 1 of the UPFC) [1].

To design Shunt converter voltage control by using one of the three methods,

(i) Closed loop current (real and reactive) control.
(ii) UPFC port 1 voltage control using reactive current.
(iii) Capacitor voltage regulation using real current.
Control of UPFC

UPFC is a combination of shunt and series controllers. The shunt current I_{sh} is split into two components: a reactive current I_{shd} in quadrature with bus voltage V_1 and a real current I_{shq} in phase with V_1. The reactive current I_{shd} is controlled to regulate the voltage magnitude at port 1 of the UPFC as proposed for the STATCOM by Schauder and Mehta [3]. The voltage reference of the voltage regulator can be varied slowly to meet steady state reactive power requirements. The reference value for the shunt real current I_{shq} is set so that the capacitor voltage is regulated, which implies power balance. The series injected voltage can be controlled to meet a required real and reactive power demand in the line [6].

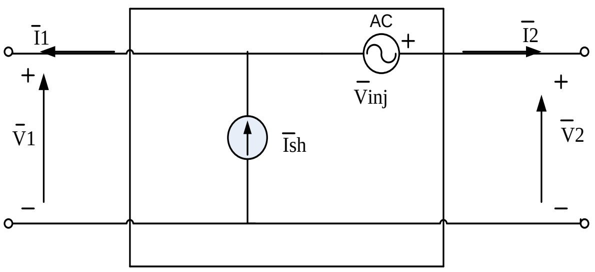


Fig- 4: UPFC equivalent circuit

The series injected voltage V_{inj} can be split into two components: one component of magnitude V_{inj1} in phase with the line current and another component of magnitude V_{inj2} in quadrature with the current. The controller is designed to control the magnitudes of the two components of the injected voltage independently to meet the real and reactive power requirements [7-11].
The line with the UPFC is shown in Fig.-4.

Injecting a voltage in quadrature with the line current is equivalent to inserting a reactance in series in the line. Since the line current varies, injecting a constant voltage in quadrature, actually introduces a variable reactance. However, a series voltage injected in phase with the current is not exactly analogous to a variable resistance inserted in series with the line. If a resistor is inserted in a lossless line, the sending end power will have to supply the receiving end power and the loss in the resistor.

2.4.3 Controller structure

A) Controller for V_{inj1}

The in-phase component is used to regulate the magnitude of voltage $\overline{V}_2$. The controller structure is as shown in Fig-5. In the figure $V_{s2ref}$is the value of the desired magnitude of voltage $\overline{V}_2$ obtained from Eq. (31). $T_{mm}$is the time constant to represent a delay in measurements, A simple integral controller is used for the control of V_{inj1}. Limits are placed on the minimum and maximum values of V_{s2ref}. The gain of the integral controller has to be adjusted so as to prevent frequent hitting of the limits by the controller. It is assumed that V_{inj1}follows $V^{ref}{}_{inj1}$ without any time delay. During a contingency, V_{s2ref} can itself be varied.

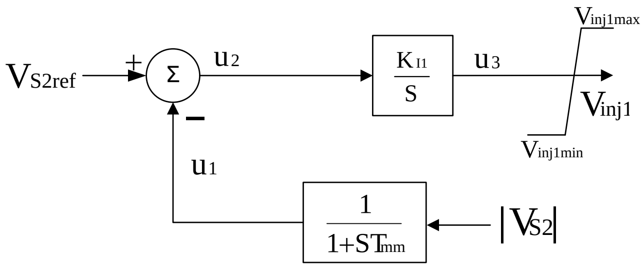


Fig- 5: Block diagram for V_{inj1}Controller

The block diagrams of V_{inj1} controller can be expressed mathematically:

$$\frac{dU1}{dt} = \frac{1}{Tmm}(V_{s2} - U1) \quad (16)$$

$$U2 = V_{s2ref} - U1 \quad (17)$$

$$\frac{dU3}{dt} = K_{I1}U2 \quad (18)$$

$$\left.\begin{aligned} V_{inj1} &= U_3(V_{inj1min} < U_3 < V_{inj1max}) \\ &= V_{inj1min}\ (U_3 < V_{inj1min}) \\ &= V_{inj1max}\ (U_3 > V_{inj1max}) \end{aligned}\right\} \quad (19)$$

B) Controller for V_{inj2}

V_{inj2} is controlled to meet the real power demand in the line. Referring to Fig-6, P_{eo} is the steady-state power, D_C and K_C are constants to provide damping and synchronizing powers in the line, S_m is the generator slip, T_{mm} Is the measured delay and P_{line} is the actual power flowing in the line. Setting of D_C and K_C to zero results in a constant power controller where the injected voltage is controlled so as to maintain the line power atP_{eo}. The two components of the series injected voltage can be controlled independently. If V_{inj1} is assumed to be zero at all times, then the UPFC behaves like a Static Synchronous Series Compensator (SSSC), in which case, only the component V_{inj2} is controlled as described above. In this case, VSC1 in figur1can be eliminated as no exchange of real power takes place. It is assumed that V_{inj2} follows $V^{ref}{}_{inj2}$without any time delay [6].

From the controller orders,V_{inj1} andV_{inj2},be able to compute the magnitude of the series voltage to be injected as,

$$\overline{V}_{inj} = \sqrt{V_{inj1}{}^2 + V_{inj2}{}^2} \quad (20)$$

This voltage is injected with an angle of 90^0 lead over the angle of the line current (Ø), given by

$$\angle V_{inj} = \tan^{-1}\left(\frac{V_{inj2}}{V_{inj1}}\right) = \emptyset + 90^0 \quad (21)$$

A phase-locked loop is required to attain synchronization with the line current.

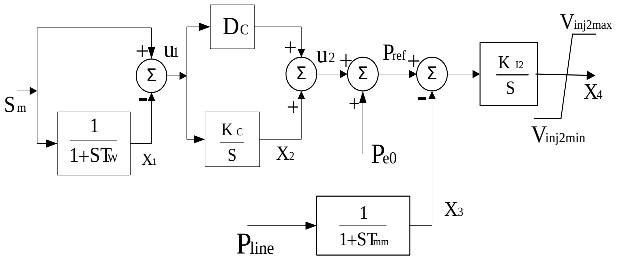


Fig- 6: Transfer functions, representation of controller

$$\frac{dX_1}{dt} = \frac{1}{T_w}(S_m - X_1) \quad (22)$$
$$y_1 = S_m + x_1 \quad (23)$$
$$\frac{dx_2}{dt} = K_C y_1 \quad (24)$$
$$y_2 = D_C y_1 + x_2 \quad (25)$$
$$P_{ref} = P_{eo} + y_2 \quad (26)$$
$$\frac{dx_3}{dt} = \frac{1}{T_{mm}}[P_{line} - x_3] \quad (27)$$
$$P_{err} = P_{ref} - x_3 \quad (28)$$
$$\frac{dx_4}{dt} = P_{err} K_{I2}$$
$$\left.\begin{aligned} V_{inj2} &= x_4(V_{inj2min} < x_4 < V_{inj2max}) \\ &= V_{inj2min}(x_4 < V_{inj1min}) \\ &= V_{inj2max}(x_4 < V_{inj1max}) \end{aligned}\right\} \quad (29)$$

C) Shunt Injected Current

The shunt current $I_{sh}$is split in to two components: a reactive currentI_{shd} in quadrature with bus voltage V_1 and a real current I_{shq} in phase with V_1. The reactive current I_{shd} is controlled to regulate the voltage magnitude at port 1 of the UPFC as proposed for the STATCOM by Schauder and Mehta [3]. The voltage reference of the voltage regulator can be varied slowly to meet steady state reactive power requirements. The reference value for the shunt real current I_{shq} is set so that the capacitor voltage is regulated which implies power balance.

The series and shunt VSIs are represented by controllable voltage sources V_{inj} and V_{sh}, respectively. R_{sh} and L_{sh} represent the resistance and leakage reactance of the shunt transformer [6].

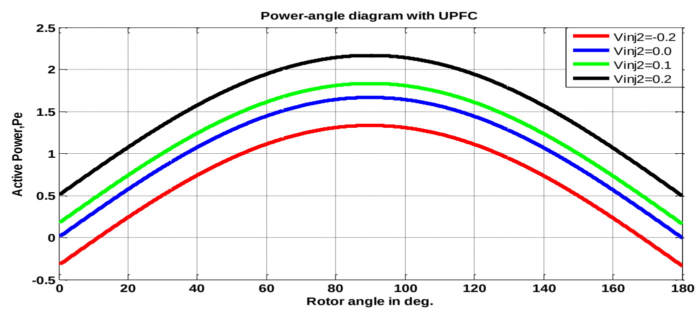
$$\frac{di_{shd}}{dt} = -\frac{R_{sh}}{L_{sh}} i_{shd} + \omega i_{shq} + \frac{1}{L_{sh}}(V_{sd} - V_{shd}) \quad (30)$$
$$\frac{di_{shq}}{dt} = -\frac{R_{sh}}{L_{sh}} i_{shq} - \omega i_{shd} + \frac{1}{L_{sh}}(V_{sq} - V_{shq}) \quad (31)$$

2.5 Power angle curve with UPFC

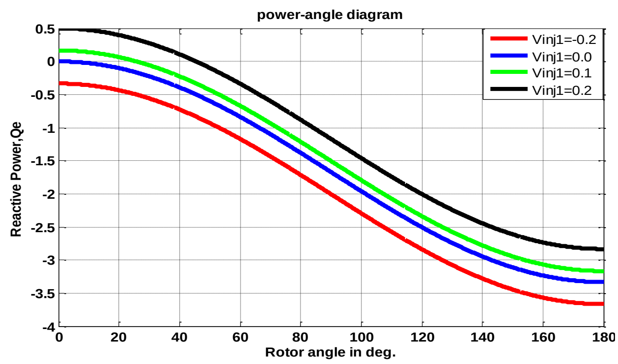
The steady-state power angle curves for the system of Fig-8: are shown in Fig-7a and b.

Fig-7a: shows the power angle curve for fixed values of generator voltage and infinity bus voltages and V_{inj1}, for different values of V_{inj2}. It can be seen that when the injected voltage is capacitive, the power angle curve is higher than when it is zero. From the figure, it can be observed that as the magnitude of V_{inj2} injected increases, the angle at which maximum power transfer takes place increases and it mainly affect the actual powers of the system.

Fig- 7b: plots the power angle curve with fixed values of V_{inj2}, generator and infinitive bus voltages, for different values of V_{inj1}. It is interesting to observe that the effect of injecting a negative resistive voltage in series is to increase the reactive power transfer in varies values of δ. With an increase in the magnitude of V_{inj1}, the angle at which maximum reactive power transfer takes place also increases.



(a) Fixed value of V_{inj1} ($V_{inj1} = 0.1, E'_q = E_b = 1$)



(b) Fixed value of V_{inj2} ($V_{inj2} = 0.1, E'_q = E_b = 1$)

Fig- 7: Power angle curve with UPFC: (a) Fixed value of V_{inj1} ($V_{inj1} = 0.1, E'_q = E_b = 1$),(b) Fixed value of V_{inj2} ($V_{inj2} = 0.1, E'_q = E_b = 1$)

Referring to Fig -7: if the power demand at the receiving end (P_R and Q_R) and the receiving end voltage V_R are specified the current required to meet this power demand and the voltage V_2 can be computed from

$$V_R I^*_L = P_R + j * Q_R \quad (32)$$
$$\bar{V}_2 = \bar{V}_R + I_L(R_L + j * X_L) \quad (33)$$

The magnitude of the in-phase component (V_{inj1}), is controlled to maintain the magnitude of V_2 at the value obtained from Eq. (33). That means, it is possible to control indirectly the reactive power by changing the voltage reference value for port 2. The magnitude of the quadrature component (V_{inj2}), is controlled to meet the real power demand P_R and the magnitude of the real component (V_{inj1}), is controlled to meet the reactive power demand Q_R. Hence, the power flow in the line has to be suitably modulated to maintain stability and damp the oscillations.

3. MODELLING OF UPFC FOR TRANSIENT STABILITY

In transient stability programs, the network has to be solved for the bus voltages. The admittance form of representing the network has gained widespread application due to the simplicity of data preparation and the sparsely of the bus admittance matrix.

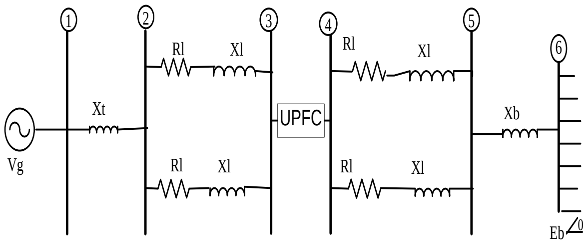


Fig- 8: SMIB with UPFC system

In this representation, the bus voltages are solved from:

$$[\bar{I}] = [\bar{Y}][\bar{V}] \quad (34)$$

Where $[\bar{V}]$ is the vector of bus voltages, $[\bar{I}]$ is the vector of current injections and $[\bar{Y}]$ is the bus admittance matrix. The current injection at any bus is the sum of injections due to generators, nonlinear loads and other devices connected to the bus. The UPFC can be modeled as dependent current sources and the current injections due to the UPFC can be computed and used in Eq. (34) along with other current injections to solve the bus voltages, as explained below.

From UPFC equivalent circuit (Fig. 4), the current injections due to the UPFC at the two ports are $\bar{I}_1$ and $\bar{I}_2$ which have to be determined at every time step of the simulation process [6]. From the figure we can write,

$$\bar{I}_{sh} = (\bar{I}_1 + \bar{I}_2) \quad (35)$$
$$\bar{V}_{inj} = (\bar{V}_2 - \bar{V}_1) \quad (36)$$

It is to be noted here that the shunt current is the sum of the two components $\bar{I}_{shd}$ and $\bar{I}_{shq}$ and the series injected voltage is the sum of the components whose magnitudes are V_{inj1} and V_{inj2}. The magnitude of the shunt real current $\bar{I}_{shd}$ is determined from power balance requirements as

$$|\bar{I}_{shd}| = \left(\frac{\bar{V}_{inj} * \bar{I}_2}{|\bar{V}_1|}\right) \quad (37)$$

The magnitudes of the components of the series injected voltage, V_{inj1} and V_{inj2}, and the magnitude of the shunt reactive current $\bar{I}_{shq}$ are obtained as output of controllers. With the external network represent by its Thevenin equivalent at the two ports of the UPFC the two-port network equation can be written as

$$\begin{bmatrix} \bar{V}_{oc1} \\ \bar{V}_{oc2} \end{bmatrix} = -[\bar{Z}_{eq}] \begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \end{bmatrix} + \begin{bmatrix} \bar{V}_1 \\ \bar{V}_2 \end{bmatrix} \quad (38)$$

In the above equation $\bar{V}_{oc1}$ is the open circuit voltage across port 1 and $\bar{V}_{oc2}$ is the open circuit voltage across port 2. $\bar{Z}_{eq}$ is the open circuit impedance matrix of the external network at the two ports. At every time step of the simulation, the UPFC current injections are computed as follows:

1. Compute $\bar{Z}_{eq}$, the open circuit impedance matrix of the external network at the two ports. This has to be computed only at the instants of the network undergoing a change.
2. Compute the open circuit voltages $\bar{V}_{oc1}$ and $\bar{V}_{oc2}$ at the two ports. This is obtained by solving Eq.(34) with UPFC current injections $\bar{I}_1$ and $\bar{I}_2$ set to zero.
3. It is important to note here that at a given time step, only the magnitudes of the components of the series injected voltage and the shunt reactive current are obtained from the controller. The angle of the series injected voltage is with reference to the series $\bar{I}_2$ and the angle of the shunt current source $\bar{I}_{sh}$ depends on $\bar{V}_1$ (Fig. 2). Hence, an iterative scheme will have to be used to solve the network. At any kth iteration of the solution, noting

that we know the values of $\overline{V}_1^{k-1}$, $\overline{V}_2^{k-1}$, $\bar{I}_1^{k-1}$, $\bar{I}_2^{k-1}$ solve as follows:

(i) Fix the angle of with $\overline{V}_{inj}^{k-1}$ respect to $\bar{I}_2^{k-1}$.

(ii) Compute the magnitude of, $\bar{I}_{shq}^{k}$ using Eq. (37) as

$$|\overline{I}_{shq}^{k}| = Real\left(\frac{\overline{V}_{inj}^{k} * \bar{I}_2^{k-1}}{|\overline{V}_1^{k-1}|}\right) \quad (39)$$

iii) Compute

$$\bar{I}_{sh}^{k} = (\bar{I}_{shd}^{k} + j\bar{I}_{shq}^{k}) \quad (40)$$

(iv) From Eq. (35) have $\bar{I}_2 = (\bar{I}_{sh} - \bar{I}_1)$ and $\overline{V}_{inj} = (\overline{V}_2 - \overline{V}_1)$ from Eq. (36). Substituting these two relations, Eq. (38) is written as

$$[\overline{V}_{oc1} \quad -\overline{V}_{oc2}] = [-1 \quad 1][\overline{Z}_{eq}]\begin{bmatrix}\bar{I}^k{}_1 \\ -\bar{I}^k{}_1 + \bar{I}^k{}_{sh}\end{bmatrix} + [\overline{-V}_{inj}^{k}] \quad (41)$$

Solve the above equation for $\bar{I}^k{}_1$ and compute

$$\bar{I}_2^{k} = (-\bar{I}^k{}_1 + \bar{I}^k{}_{sh}) \quad (42)$$

(v) Substitute $\bar{I}_1^{k}$ and $\bar{I}_2^{k}$ in Eq. (34) with the other current injections and solve for the bus voltages.

(vi) Go to step (i) and iterate until

$$\left|\bar{I}_1^{k} - \bar{I}_1^{k-1}\right| \le \epsilon \qquad |\bar{I}_2^{k} - \bar{I}_2^{k-1}| \le \epsilon \quad (43)$$

It is important to note here that the iterations have to be carried out at every time step of the solution [4-6]. The algorithm for the solution of bus voltages with the UPFC converged in three to five iterations in the case studies presented below. Hence, the model can be used effectively for transient stability studies.

4. CASE STUDIES

4.1 Description

The case studies are carried out on the single machine infinity bus system through a double circuit transmission line with intermediate buses to evaluate the transient stability of the system under different case studies. The system is considered as shown Fig-8 The data are given in Appendix. In the figure, Z_b and $E_b \angle 0$ represents the Thevenins impedance and Thevenins voltage of the external network.

The UPFC is connected at the middle of the transmission line. The initial operating points are obtained by the UPFC does not inject any voltage and current into the system. The component V_{inj1} is controlled so as to maintain the voltage of bus four at its steady state value which is equal to the value of the infinite bus in this case study. V_{inj2} is varied to control the power flow in the line. UPFC port one voltage control using shunt reactive current I_{shd} and real components of shut injected current I_{shq} used to regulate capacitor voltage for maintaining power balance. The magnitude of each of the two components of the UPFC is restricted to ± 0.35 per unit.

To study the performance of the controller the following case studies are carried out.

Case I: By step changing the reference voltage, V_{ref}
Case II: By step changing the mechanical torque, T_m
Case III: By step changing the infinity bus voltage, E_b
Case IV: A three phase fault at the sending end of one of the circuits of the transmission line followed by clearing at the end of 4 cycles. The fault is happing in between buses two and three. Then, the switch is tripped a single transmission line to clear the fault.

4.2 Result and discussion

In order to observe the effects of both conventional and FACTS device controllers on power system four cases have been made. In all cases the response of rotor angle, variation of slip, variation of excitation voltage, variation of electrical torque, variation of terminal voltage and the terminal current in d-q axis has done. But, in this paper the first three consecutive system parameters were plotted and discussed. The responses without controller are not included. The response with automatic voltage regulator, power system stabilizer and unified power flow controller shown with read line, blue line and green line with legend 'AVR','PSS', and 'UPFC'; respectively. The following cases are considered:

Case -I: By step changing the reference voltage (V_{ref})

In this case, the simulation has done the changing of V_{ref} by 0.1 in each step in the system. As shown in Fig- (12a-12c) the systems are unstable with an AVR controller. But, with PSS and UPFC controllers the systems are stable. When the reference voltage increases the response of rotor angle is reduced from a steady state value or initial value. Fig-12a shows, the response of the rotor angle controlled by the UPFC has been a little bit higher than the response of the rotor angle controlled by PSS. The response of the system with UPFC is more stable than AVR and to a certain extent stable than PSS controller. The PSS and UPFC controllers could damp the oscillation within two seconds. The electrical torque and slip with PSS and UPFCS increases initially and settles down to the previous value by neglecting the superimposed oscillations. The field voltage hits the ceiling initially and settles down (neglecting oscillations) to initial operating value as the demagnetizing current is reduced on account of the decrease in the rotor angle.

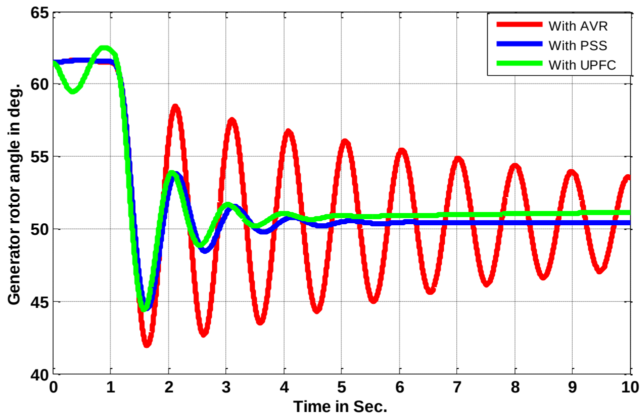


Fig- 12a: Variation of rotor angle (δ)

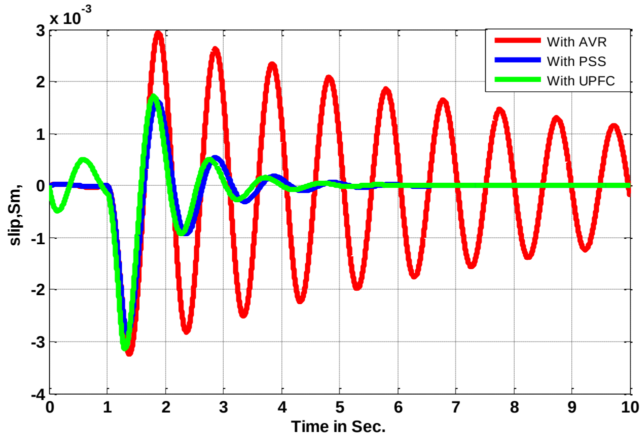


Fig- 12b: Variation of slip, S_m

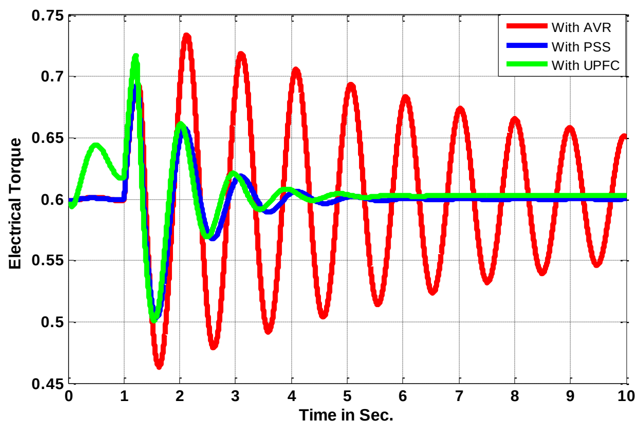


Fig- 12c: Variation of electrical torque, T_e

Case -II: By step changing the mechanical torque (T_m)

Step increasing of mechanical torque in the system occurs for 10 seconds. The plot of the variations of rotor angle, slip, filed voltage, and electrical torque is given in Fig-(13a-13c). The system result shows that, the system with AVR is unstable and the oscillations and their magnitude continual increased. As shown the figure, the system with power system stabilizers and a unified power flow controller is the oscillation fully cleared after two cycles. The response rotor angle is increased beyond to a steady state value as the mechanical torque is increased. The response of the electrical torque increased beyond to a steady state value. But, as shown Fig-13c the system controlled by the power system stabilizer have got high electrical torque responses than the system controlled by UPFC. The responses of slip slightly rise and settles down to the initial operating value by neglecting oscillation within 1.5 second, when the T_m Changed continuously from 0.1. The field voltage, highly increases initially and settles down to initial operating value and the oscillations are cleared beyond to two cycles.

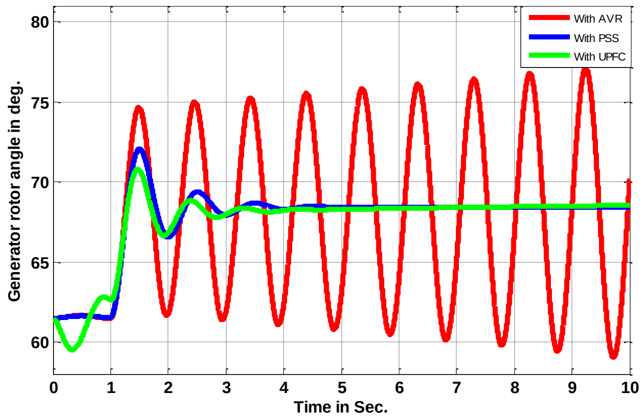


Fig- 13a: Variation of rotor angle, δ

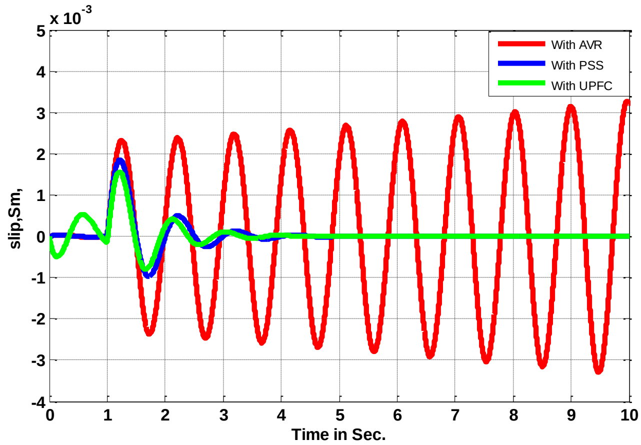


Fig- 13b: Variation of sleep, S_m

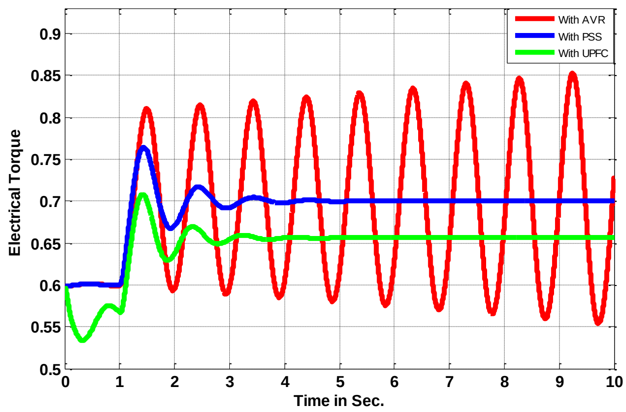


Fig- 13c: Variation of electrical torque, T_e

Case-III: By step changing the infinity bus voltage, E_b

The third case is concentrated on step changing infinity bus voltage E_b in to the system. As shown in the Fig- (14a-14c), the system with automatic voltage regulator is unstable and has more oscillations, but the system controlled by power system stabilizer and unified power flow control the system become stable after two cycles. The response of the rotor angle increased ahead of to initial value and also the system controlled by the power system stabilizer give high over shoot compared to the system controlled by a unifying power flow control. The slip response is initially rising and settles down to a slightly lower value than the initial operating value in both controllers. The response electrical torque is a slightly lower value compared to the steady state value as the infinity bus voltage is increased. Whereas, as shown Fig-14c the system controlled by the unified power flow control have high electrical torque responses than the system controlled by power system stabilizer. The oscillations are cleared at almost in to two second. In this case the response of electrical torque with unified power flow control had more over shoot than the response with power system stabilizer.

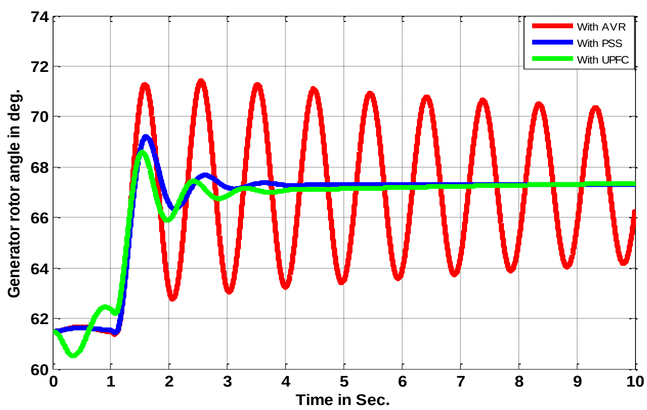


Fig- 14a: Variation of rotor angle (δ)

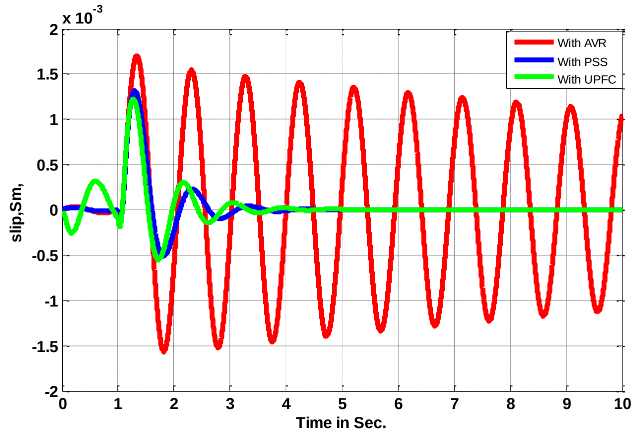


Fig- 14b: Variation of slip, S_m

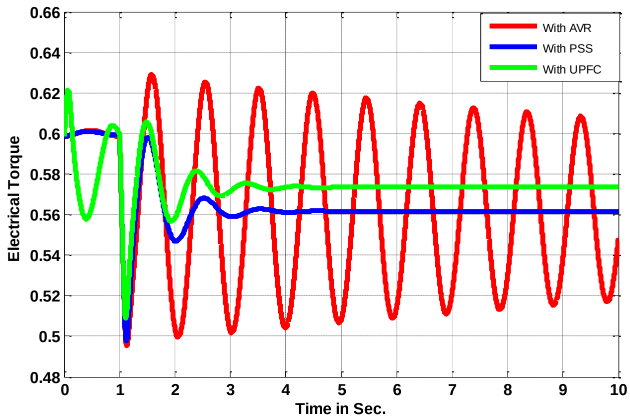


Fig- 14c: Variation of electrical torque, T_e

Case IV: In this case, three phase short circuit fault is happened in between bus two and three, and this line is disconnected for the sake of clearing fault from the system. The plot of the variations of rotor angle, slip, and electrical torque is given in Fig- (15a-15c).

The system result shows that, the system with automatic voltage regulator is unstable and the oscillations and their magnitude continual increased. As shown the figure, the system with power system stabilizers and a unified power flow controller is the oscillation cleared after four cycles. The response electrical torque and rotor angle is increased beyond to a steady state or initial operating value. The response of rotor angle is increased beyond to a steady state value in both controllers, when infinity bus voltage increased but the oscillations are damping at four seconds. The responses of slip initially rise and settles down to the initial operating value or steady state value by neglecting oscillation.

The field voltage, highly increases initially and settles down to initial operating value and the oscillations are cleared at 1.5 second. Fig -15c show, the response of the electrical torque controlled by the power system stabilizer has been higher than the response of the electrical torque controlled by unified power flow control. As shown in Fig-15c, the response of electrical torque has more settling time than the remain cases.

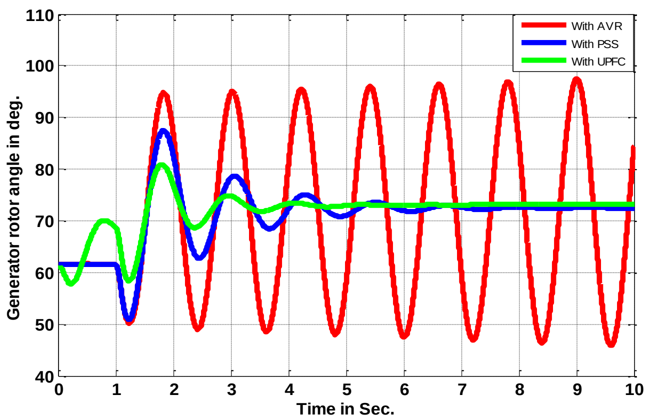


Fig- 15a: Variation of rotor angle (δ)

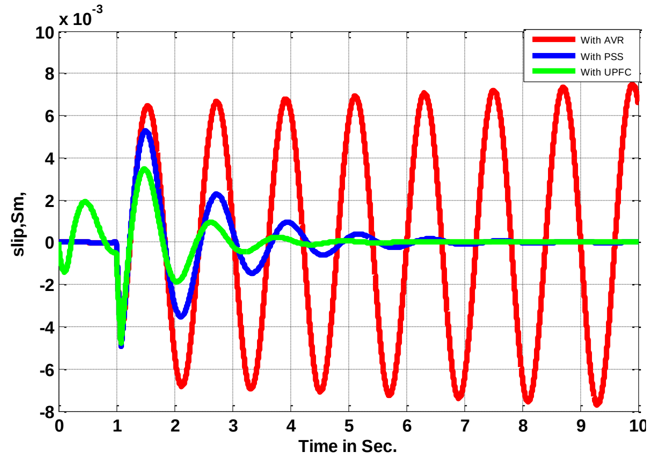


Fig- 15b: Variation of slip, S_m

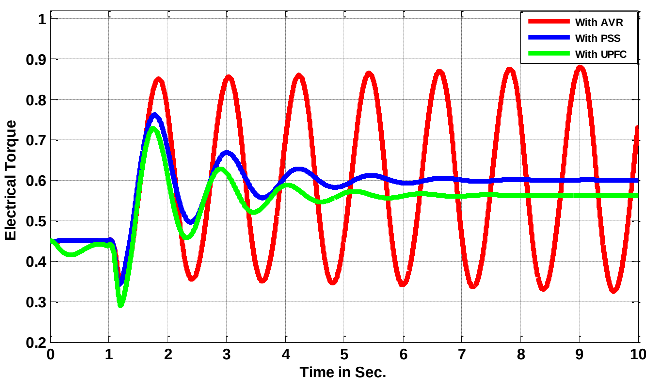


Fig- 15c: Variation of electrical torque, T_e

5. CONCLUSION

In this paper, the effects of different controllers namely AVR, PSS and UPFC have been studied under four different case studies for transient stability improvement of a SMIB power system. The UPFC being a very versatile device can be used for fast controller of active and reactive power in the transmission line. PSS helps in improving transient stability of the system without degrading the system's performance in case of faults or transients. As shown from the results, there is a considerable improvement in the system performance with the presence of UPFC and PSS.

It is clear from the simulation results that, the system with automatic voltage regulation is marginally unstable and the oscillations continue increasing in all cases. The response rotor angle decreases as the reference voltage is increased. But, the rotor angle response is increasing as the infinity bus voltage and mechanical torque increased. The responses of slip initially rise and settles down to the initial operating value by neglecting oscillation. The excitation voltage hits the ceiling initially and settles down to a slightly lower value compared to the initial operating value. The system result shows after clearing the short circuit fault and during increment of mechanical torque the magnitude of the electrical torque controlled by the power system stabilizer has been higher than the magnitude of the electrical torque controlled by UPFC. But, equal to and lower than the initial operation value where reference voltage and the infinity bus voltage is increased, respectively.

ACKNOWLEDGEMENT

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APPENDIX

A single line diagram of the system is shown in Fig.8. The system data one 1000 MVA base are given below.
Generator:$R_a = 0.00327$,$X_d = 1.7572$,$X_q = 1.5845 X_d{}' = 0.4245$,$X_q{}' = 1.0245$ $T'_{d0} = 6.66$, $T'_{q0} = 0.44$, H = 3.542, $f_B =$ 50 Hz.
Transformer: $R_t = 0.0 X_t = 0.1364$
Transmission line: (per circuit): R_L= 0.08593, X_l= 0.8125, B_C= 0.1184 (These parameters are representative of a 400 kV, 400 km long line with 50% shunt compensation)
Excitation System:$K_A = 400$, $T_A = 0.025$,$E_{fdmin} = -6.0$, $E_{fdmax} = 6.0$
Operating Data $E_b = 1$, $P_t = 0.6$, $Q_t = 0.02224$, $V_t = 1.05$, θ =21.65°, Z_b= 0.13636
Power system stabilizer data: $T_1 = 0.75$,$T_2 = 0.3$, $T_w = 10$, $K_S = 4$, $V_{Smin} = -0.05$, $V_{Smax} = 0.05$
UPFC data:$K_{I1} = 0.001$, $K_{I2} = 50$, $D_C = 500$, $K_C = 100$, $T_{means} = 10$, $P_{e0} = 0.75$,$V_{S2ref} = 1.0$,
$V_{inj1max} = 0.35$,$V_{inj2max} = 0.25$,
$V_{inj1min} = -0.35$,$V_{inj2max} = -0.25$,

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