EMPLOYING FACTS DEVICES (UPFC) FOR TRANSIENT STABILITY IMPROVEMENT

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ABSTRACT

With addition of new captive power plant and increased power transfer, transient stability is much more important for reliable operation. Transient stability evaluation of large scale power systems is an extremely intricate and highly non-linear problem. An important function of transient evaluation is to appraise the capability of the power system to withstand serious contingency in time, so that some emergencies or preventive control can be carried out to prevent system breakdown. In practical operations correct assessment of transient stability for given operating states is necessary and valuable for power system operation.

The damping of power system oscillations after a three phase fault is also analyzed with the introduction of SVC and UPFC on transient stability performance of a power system. A general program for transient stability studies to incorporate FACTS devices is developed using modified partitioned solution approach. The modeling of SVC and UPFC for transient stability evaluation is studied and tested on a 10-Generator, 39 - Bus, New Test System.

Keywords: transient stability

1. INTRODUCTION

A power system is a complex network comprising of numerous generators, transmission lines, variety of loads and transformers. As a consequence of increasing power demand, some transmission lines are more loaded than was planned when they were built. With the increased loading of long transmission lines, the problem of transient stability after
Where stator transients are neglected in parallel with the admittance $Y$ components in the d-axis and q-axis. The rotor mechanical dynamics are represented by the swing equation:

$$2H^*(dS_m / dt) = T_m - T_e - DS_m$$

$$\left( d\delta / dt \right) = S_m^* \omega_s$$  \hspace{1cm} (3) \hspace{1cm} (4)

Where $S_m$ is slip, $\omega_s$ is the base synchronous speed and D is the damping coefficient. $T_m$ is the mechanical torque input, and $T_e$ is electrical torque output and is expressed as:

$$T_e = E_q' i_q + E_d' i_d + (X_d' - X_q') i_d i_q$$  \hspace{1cm} (5)

Stator transients are neglected and the stator reduces to simple impedance with reactance in parallel with the admittance $Y_G$. The $Y_G$ and $I_G$ are defined as:

$$Y_G = 1/(R_G + jX_G')$$  \hspace{1cm} (6)

a major fault can become a transmission limiting factor. Transient stability of a system refers to the stability when subjected to large disturbances such as faults and switching of lines. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power angle relationship. Stability depends upon both the initial operating conditions of the system and the severity of the disturbance. The voltage stability, and steady state and transient stabilities of a complex power system can be effectively improved by the use of FACTS devices.

In this paper dynamics of the system is compared with and without UPFC & SVC. Modeling of UPFC & SVC is carried out and the system stability is analyzed using the above FACTS devices. To achieve the optimum performance of FACTS controllers’ proper placement of these devices in the system is as important as an effective control strategy.

2. MODELING OF POWER SYSTEM AND FACTS DEVICES (UPFC AND SVC)

2.1 Synchronous machine model

Mathematical models of a synchronous machine vary from elementary classical models to more detailed ones. In the detailed models, transient and sub transient phenomena are considered. Here, the transient models are used to represent the machines in the system, according to following equations. To represent transient effects two rotor circuits, one field winding on the d-axis and a hypothetical coil (damper winding) on the q-axis are adequate

$$T_{do} \times (dE_d' / dt) + E_d' = E_{fd} - (X_d - X_d') i_d$$
$$T_{qo} \times (dE_q' / dt) + E_q' = (X_q - X_q') i_q$$  \hspace{1cm} (1) \hspace{1cm} (2)

Where

- is the d-axis open circuit transient time constant
- is the q-axis open circuit transient time constant
- is the field voltage

The rotor mechanical dynamics are represented by the swing equation:

$$2H^*(dS_m / dt) = T_m - T_e - DS_m$$

$$\left( d\delta / dt \right) = S_m^* \omega_s$$  \hspace{1cm} (3) \hspace{1cm} (4)

Where $S_m$ is slip, $\omega_s$ is the base synchronous speed and D is the damping coefficient. $T_m$ is the mechanical torque input, and $T_e$ is electrical torque output and is expressed as:

$$T_e = E_q' i_q + E_d' i_d + (X_d' - X_q') i_d i_q$$  \hspace{1cm} (5)

Stator transients are neglected and the stator reduces to simple impedance with reactance components in the d-axis and q-axis. The stator is represented by dependent current source $I_G$ in parallel with the admittance $Y_G$. The $Y_G$ and $I_G$ are defined as:

$$Y_G = 1/(R_G + jX_G')$$  \hspace{1cm} (6)
The differential equation describing the effect of transient saliency is expressed as:

$$T_c \frac{d\psi_c}{dt} = -\Psi_c (X'_c - X'_{qc}) i_q$$  \hspace{1cm} (7)

Where $T_c$ is the time constant of the dummy coil and $\psi_c$ is the voltage correction that accounts for the effect of transient saliency. Thus

$$E'_{dc} = -\Psi_c$$  \hspace{1cm} (8)

The generator armature current and terminal voltage in the q-d reference frame are related to their respective phasor quantities.

$$i_q + j i_d = I_a e^{-j\delta}$$  \hspace{1cm} (9)

$$V_q + jV_d = V e^{-j\delta}$$  \hspace{1cm} (10)

The angle $\delta$ measures the rotor position of the generator relative to the synchronously rotating reference frame, which is implied in the phasor solutions of the network.

Referring to Fig.1, we have

$$I_a = I_c - Y_G V$$  \hspace{1cm} (11)

The generator terminal voltage is expressed as:

$$V_t = |V| = \sqrt{(V_q^2 + V_d^2)}$$  \hspace{1cm} (12)

Using equations (9), (10) equation (11) may be written as:

$$i_q + j i_d = \frac{[E_q + j(X_d - \psi_c)] - (V_q + jV_d)]}{R_a + jX_d}$$  \hspace{1cm} (13)

![Figure-1. Stator representation.](image-url)
2.2 AVR model
The voltage regulator configuration is shown in Figure-2. The AVR equations are

\[
T_A \frac{dE_A}{dt} = -E_A + K_A (V_{ref} - V_t) T_e
\]

\[
E_{fd} = E_A \cdot \text{if } V_{min} < E_A < V_{max}
\]

\[
= V_{min} \cdot \text{if } V_{min} > E_A
\]

\[
= V_{max} \cdot \text{if } V_{max} < E_A
\]

2.3.1 Controller for \( V_{sep} \)
The in phase component of the series injected voltage, \( V_{sep} \) is used to regulate the magnitude of the voltage \( V_2 \). The controller structure is shown in Figure-3. In this \( V_{2ref} \) is the value of the desired magnitude of voltage \( V_2 \) obtained from equation, \( T_{meas} \) is the constant to represent delay in measurements. A simple integral controller is used for the control of \( V_{sep} \). Limits are on the minimum and maximum values of \( V_{sep} \). The gain of the integral controller has to be adjusted so as to prevent frequent hitting of the limits by the controller. It is also assumed that \( V_{sep} \) follows \( V_{2ref} \) without any time delay. During contingency \( V_{2ref} \) can itself be varied. The differential equations relating In-phase Voltage Control are

\[
V_2 = V_R + jL \frac{dV_R}{dt}
\]

\[
\dot{V}_C = (V_2 - V_C) / T_{meas}
\]

\[
\dot{V}_{sep} = K_{il} (V_{2ref} - V_c)
\]
2.3.2 Controller for $V_{\text{seq}}$

$V_{\text{seq}}$ is controlled to meet the real power demand in the line. The controller structure is shown in Figure-5. Referring to Figure-4, $P_{\text{eo}}$ 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, $T_{\text{meas}}$ is the measurement delay and $P_{\text{line}}$ is the actual power flowing in the line. It is assumed that $V_{\text{seq}}$ follows $V_{\text{seq}}^\text{ref}$ without any time delay.

It is necessary to distinguish between the roles of the UPFC as a power flow controller in order to achieve steady state objectives (slow control) and as a device to improve transient performance (requiring fast control). Thus, while real and reactive power references are set from the steady state load flow requirements, the real power reference can also be modulated to improve damping and transient stability. An auxiliary signal ($S_{\text{m}}$) is used to modulate the power reference ($P_{\text{ref}}$) of the UPFC. A washout circuit is provided so as to prevent any steady state bias. The differential equations relating quadrature Voltage Control are

$$\dot{P}_2 = \frac{(P_{\text{line}} - P_2)}{T_{\text{meas}}}$$

$$\dot{V}_{\text{seq}} = K_{r2}(P_{\text{ref}} - P_2)$$

2.3.3 Modeling of UPFC for transient stability evaluation

In Two-port representation of UPFC, the current injections due to UPFC at the two ports are $I_1$ and $I_2$, which have to be determined at every time step of the simulation process.

$$V_{\text{seq}} = V_2 - V_1$$

$$I_{\text{sh}} = I_1 + I_2$$
The magnitudes of the components of the series injected voltage, \( V_{sep} \) and \( V_{seq} \) at the two ports of the UPFC, when the external network is represented by its Thevenin’s equivalent at the two ports, can be written as:

\[
I_{shp} = \text{Re} \left( \frac{a_1 I_2^*}{V_1} \right)
\]

(21)

\( V_{oc1} \) and \( V_{oc2} \) are the open circuit voltages across port1 and port2 respectively and \( Z_{eq} \) is the open circuit impedance (Thevenin’s impedance) matrix of the external network at the two ports.

To solve the network equation \( I = YV \), the current injections \( I_1 \) and \( I_2 \) have to be calculated where the UPFC is placed. Therefore the objective, when UPFC is incorporated in the transient stability algorithm, is to evaluate these current injection at those particular buses.

3.1 Partitioned-Solution approach for transient stability equations

The transient stability problem is defined by a set of non-linear differential equations (DAEs).

\[
[\dot{Y}] = [f([Y],[X],t)]
\]

(23)

\[
0 = [g([y],[x])] \quad (24)
\]

Equation (23) describes machine dynamics including their control circuits, and equation (24) describes the network static behavior including steady state models of loads and algebraic equations of machines.

4. TRANSIENT STABILITY EVALUATION WITH AND WITHOUT UPFC AND/OR SVC

The transient stability program developed can take care of 3-phase symmetrical fault at a bus with an option of with line and without line outage. The stability of the system is observed with and without the UPFC.

4.1 Solution steps

The algorithm for the transient stability studies with FACTS devices involves the following steps:
1. Reads the line data. It includes the data for lines, transformers and shunt capacitors.
2. Form admittance matrix, \( Y_{BUS} \).
3. Reads generator data (\( R_a, X_a, X_d, X_q, X_{d*}, X_{q*}, H, D \) etc).
4. Reads steady state bus data from the load flow results. (\( V, [\delta], [P_{load}], [Q_{load}], [P_{gen}], [Q_{gen}] \)).
5. Calculates the number of steps for different conditions such as fault existing time, line outage time before auto-reclosing, simulation time etc
6. Modify $Y_{\text{BUS}}$ by adding the generator and load admittances.
7. Calculate fault impedance and modify the bus impedance matrix when there is any line outage following the fault.
8. Calculate the initial conditions and constants needed in solving the DAEs of generators, AVR etc.
9. Solves the network equation iteratively in each time step.
10. For $X_d$-$X_q$ models calculates $V_d$-$V_q$ using the obtained voltages and rotor angles.
11. Calculates the generator electric power outputs
12. The time step is advanced by the current time step.
13. Solves the generator swing equations using trapezoidal rule of integration keeping generator mechanical power output as constant.
14. Solves the AVR equations
15. Solves the UPFC and SVC. The bus current injection vector is modified with UPFC and SVC injection currents. Then network equation is again solved using $[Y_{\text{BUS}}][V]=[I_{\text{inj}}]$.

5. CASE STUDY

Case studies are conducted, to evaluate the performance of the controller, on 10-Generator, 39-Bus, New Test System:

For this system, generator #9 is severely disturbed, so swing curves of generator #9 are only observed. Both Classical and Detailed models are considered for this study. A three-phase fault at any bus with a clearing time of 60ms is considered to observe both transient stability and damping of power oscillations.

![Diagram of 10-Generator, 39-Bus, New Test System](image)

**Figure 5** - Bus, New Test System

The following cases are considered:
(i) Fault at bus #26, no line cleared, UPFC in line 29-26. (ii) Fault at bus #26, line cleared 26-28, UPFC in line 29-26
(iii) Fault at bus #26, no line cleared, UPFC in line 15-14
(iv) Fault at bus #26, no line cleared, UPFC in line 29-26 and SVC at 28 bus.
(v) Fault at bus #26, line cleared 26-28, UPFC in line 29-26 and SVC at 28 bus.
(vi) Fault at bus #26, no line cleared, UPFC in line 15-14 and SVC at 28 bus.

**Generator:**
\[ \begin{align*}
X_d &= 1.5, \quad X_d' = 0.31, \quad T_d = 6.0, \quad X_q = 1.54, \\
X_q' &= 0.31, \quad T_{qo} = 0.43, \quad H = 5.0, \quad f_B = 60 \text{ Hz}
\end{align*} \]

**Network:**
\[ \begin{align*}
X_{tr}' &= 0.1, \quad X_{L1} = X_{L2} = 0.2, \quad X_b = 0.1
\end{align*} \]

**AVR:**
\[ \begin{align*}
K_A &= 200, \quad T_A = 0.05, \quad E_{fdmin} = -6.0, \quad E_{fdmax} = 6.0
\end{align*} \]

**Initial Operating Point:**
\[ \begin{align*}
V &= 1.05, \quad P_g = 0.75, \quad E_b = 1.0
\end{align*} \]

**UPFC:** The limits on both \( V_{sep} \) and \( V_{seq} \) = 0.35 pu

The swing curves for all the ten generators represented by classical models are shown in Fig8.

A three-phase symmetrical fault at bus 26 with a clearing time of 60 ms, for no line outage, is considered for the study. It is observed from the Figure-6 that only generator #9 is severely disturbed, and so swing curves of generator #9 are only considered for the investigation of the effect of UPFC on the system.

### 5.1. Effect of UPFC’s location
Figure 8.- Swing curves: Fault at bus#26, no line cleared, UPFC in line 26-29

Figure 9- Swing curves –Fault at bus #26, line cleared 26-28, UPFC in line 26-29

Figure-10. Swing curves- Classical model: Fault at bus # 26, no line cleared, SVC at bus # 28
For this case study, only control of $V_{\text{seq}}$ is considered. $V_{\text{sep}}$ is assumed to be zero at all instants. Hence, the UPFC behaves as a SSSC. The Fig.13 shows the swing curves of generator #9 for case (i) with and without UPFC. In this case a three-phase fault at bus 26, which is cleared after three cycles without any line outage is considered. The UPFC is connected in the line 26-29, at the end of the line close to bus 26.

Figure-10 shows the swing curve of generator 9, which separates from the rest of the generators when the system is unstable, for a fault at bus 26. Comparing the curves with and without the UPFC, it can be observed that the power controller helps in damping the power oscillations and also improves the transient stability by reducing the first swing. This is because in multi-machine systems there are many modes of oscillations and the control signal may not be effective in damping all the modes. Figure-9 shows the plot of the series injected voltage of the UPFC. UPFC is injecting leading voltage to damp oscillations. Several other cases are tested. It is observed that the effect of UPFC is more pronounced when it is placed near heavily disturbed generator rather than placed at remote location. This can be observed by comparing Figure-10 and Figure-12, where in Figure-12 the swing curves shown for case (iii), in which UPFC is placed between lines 15-14. It is also observed that the effect of UPFC is more pronounced when the controller is placed near the faulted bus rather than placed at remote locations.

5.2 Effect on critical clearing time with no line outage

Table-1. New Test System: Fault at 26, No line outage, UPFC is in line 29-26, closed to 29
Table-2. New Test System: Fault at #26, line cleared 26-28 UPFC is in line 29-26, close to 29

![Table-2](image)

The effect of UPFC on transient stability of multi-machine system can be observed by observing critical clearing time ($t_{cr}$). Tables 1 and 2 gives critical clearing time for different cases and for different machine models. From these tables it is observed that:

- The UPFC improves transient stability by improving critical clearing time
- Improvement in $t_{cr}$ is more pronounced when the controllers are placed near the heavily disturbed generator.

6. CONCLUSIONS

UPFC is modeled as dependent current injection model. Calculation of injected currents has been carried in such a way that it simplifies the inclusion of UPFC in generalized transient stability program. The transient stability and damping of power oscillations are evaluated with UPFC and SVC. Dynamics of the system is compared with and without presence of UPFC and SVC in the system. It is clear from the results that there is considerable improvement in the system performance with the presence of SVC and UPFC.

The effect of UPFC is dominant when the controller is placed near heavily disturbed generator.

- The effect of UPFC is more effective when the controller is placed near faulted bus rather than placed at remote locations.
- UPFC helps in improving transient stability by improving critical clearing time.
- The transient stability is improved by decreasing first swing with UPFC and SVC.
- SVC helps in improving transient stability by improving critical clearing time

REFERENCES

