Evaluation Of First Swing Stability Of A Large Power System With Various FACTS Devices

Surabhi Gupta and Surya Prakash

***Abstract*- This paper contains methods of evaluating the first swing stability of a large power system in the presence of flexible ac transmission system (FACTS) device (UPFC). First a unified power flow controller (UPFC) and the associated transmission lines are considered and represented by an equivalent π-circuit model. The above model is then carefully interfaced to the power network to obtain the system reduced admittance matrix which is needed to generate the machine swing curves. The above π-circuit model can also be used to represent other FACTS devices (SSSC and STATCOM) by selecting appropriate values of control parameters of the UPFC. The modified admittance matrix of the π-circuit model is also evaluated during simulation to implement various existing control strategies of FACTS devices and to update the reduced admittance matrix. The effectiveness of the proposed methods of generating dynamic response and hence evaluating first swing stability of a power system on the ten machine, 39-bus New England system.**

Key word- Flexible ac transmission system (FACTS), stability, static compensator (STATCOM), static synchronous series compensator (SSSC), unified power flow controller (UPFC), Matlab.

I. INTRODUCTION

Evaluation of first swing stability (FSS) limit is one of the important aspects in power system planning and operation studies. A first swing stable system may be considered as stable if the system has adequate damping. Lack of damping may cause growing oscillation and ultimately the system may become unstable. The First Swing stability (FSS) limit can be improved by controlling the output power of the severely disturbed machines during transient period.

Flexible ac transmission system device placed at strategic location are found to be very effective in addressing the above issue. There are various forms of FACTS devices. Some of which are connected in series with the line and others are connected in shunt or in combination of series and shunt.

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A unified power flow controller (UPFC) is a member of FACTS family which is connected to a power system in series and shunt combination. It consists of two voltage source converters (series and shunt) coupled through a common dc link as shown in Fig. 1. The dc link provides a path of active power exchange between the converters.

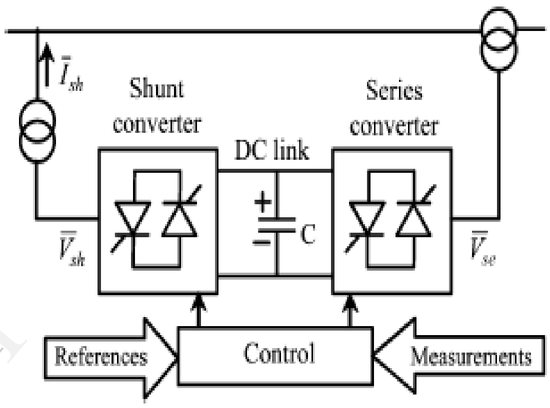

Fig. 1 Schematic diagram of a UPFC

Both the series and shunt converters are capable of generating/absorbing reactive power independently. When the shunt converter is kept inactive, the series converter can exchange reactive power with the system and is called a static synchronous series compensator (SSSC). On the other hand, when the series converter is kept inactive, the shunt converter can operate as a static compensator (STATCOM) and exchange reactive power with the system. In other words, a UPFC is a versatile FACTS device that can also be used as an SSSC or a STATCOM.

The modelling of various FACTS devices is well described in [4], [9], [13], and [14]. There are three types of modelling of various FACTS devices:

i) Electromagnetic models for detailed equipment level investigation;
ii) Dynamic models for stability analysis; and
iii) Steady- state models for steady state operation evaluation.

In this study, dynamic model of FACTS devices is used. In dynamic analysis of a power system, there is an increasing need for appropriate interfacing the models of various FACTS devices to a power network.

In the case of a UPFC, the controller ultimately produces a series injected voltage $\bar{V}_{se}$ and a shunt injected current $\bar{I}_{sh}$, and which are to be interfaced to the power network as shown in Fig. 2.

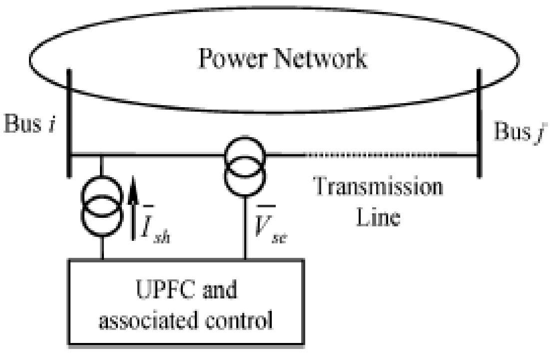

Fig. 2. Interfacing a UPFC to a power network

The above figure can also be used to represent other FACTS devices (SSSC and STATCOM) by selecting proper values of $\bar{V}_{se}$ and $\bar{I}_{sh}$.

II. EVLUATION OF FIRST SWING

A synchronous power system has transient stability if, after a large sudden disturbance, it can regain and maintain synchronism. A sudden large disturbance includes application of faults, clearing of faults, switching on and off the system elements (transmission line, transformers, generators, loads etc.) Usually Transient stability studies carried out over a relatively short time period that will be equal to the period of first swing. Normally, the period will be 1sec or less. The analysis is carried out to determine whether the system loses stability during the first swing or not. In case the power system remains stable, it is assumed that subsequent swings will diminish and that power system remains stable, as usually happens. However, there is a possibility of power system going unstable in some subsequent swing. As said earlier, the power system have rotating synchronous machines, in order to know whether the system is stable or not, is analyzed and solution obtained by swing equation.

The swing equation is represented as

$$M\,(d^2\delta/dt^2) = Ps - Pe \sin\delta \qquad (1)$$

Where, M=Angular Momentum
δ = Load angle
Ps=Input Power
Pe=Output Power
t =Time

The above equation gives the graph of load angle (δ) verses time (t) called swing curve.

This curve is used to determine the stability of the system.

III. MATHEMATICAL MODEL FOR TRANSIENT STABILITY ANALYSIS

This section describes the machine dynamic equations and a simple-circuit model of a UPFC and other FACTS devices.

A. *Machine Dynamic Equations:*

Multimachine equations can be written similar to the one-machine system connected to the infinite bus. To reduce complexity of the transient stability analysis simplifying assumptions are made [15]:

- Each synchronous machine is represented by a constant voltage source behind the direct axis transient reactance.
- The governor's action are neglected and the input powers are assumed to remain constant.
- Using the prefault bus voltages, all loads are converted to equivalent admittances to ground and are assumed to remain constant.
- Damping or asynchronous powers are ignored.
- Mechanical rotor angle of each machine coincides with the angle of the voltage behind the machine reactance.
- Machines belonging to the same station swing together and together are represented by one equivalent machine.

The first step to get the solution of multi-machine system is to solve the initial load flow and determine the initial bus voltage magnitudes and phase angles. The machine currents prior to disturbance are calculated from:

$$I_i = \frac{S_i^*}{V_i^*} = \frac{P_i - jQ_i}{V_i^*},\ i = 1,2,\dots,m \qquad (2)$$

All unknown values are determined from the initial power flow solution. The generator armature resistances are usually neglected and the voltages behind the transient reactance are then obtained:

$$E_i' = V_i + jX_d' I_i \qquad (3)$$

All load are converted to equivalent admittances by using the relation:

$$y_{i0} = \frac{S_i^*}{|V_i|^2} = \frac{P_i - jQ_i}{|V_i|^2} \qquad (4)$$

To include voltages behind transient reactance, m buses are added to the n-bus power system network as shown in Fig.3

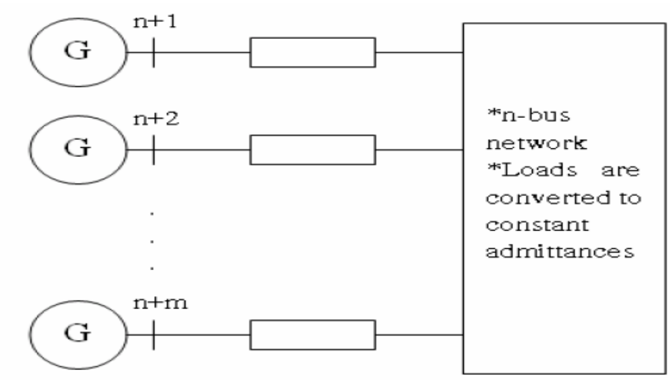

Figure 3. Power system representation for transient stability analysis

Nodes n+1, n+2, . . ., n+m are the internal machine buses, i.e., the buses behind the transient reactances. The node voltage equation with node 0 as reference for this network, is shown in equation (2.4).

$$\begin{bmatrix} I_1 \\ I_2 \\ \cdot \\ \cdot \\ I_n \\ \hline I_{n+1} \\ \cdot \\ \cdot \\ I_{n+m} \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1n} & Y_{1(n+1)} & \cdots & Y_{1(n+m)} \\ Y_{21} & \cdots & Y_{2n} & Y_{2(n+1)} & \cdots & Y_{2(n+m)} \\ \cdot & \cdots & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdots & \cdot & \cdot & \cdots & \cdot \\ Y_{n1} & \cdots & Y_{nn} & Y_{n(n+1)} & \cdots & Y_{n(n+m)} \\ Y_{(n+1)1} & \cdots & Y_{(n+1)n} & Y_{(n+1)(n+1)} & \cdots & Y_{(n+1)(n+m)} \\ \cdot & \cdots & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdots & \cdot & \cdot & \cdots & \cdot \\ Y_{(n+m)1} & \cdots & Y_{(n+m)n} & Y_{(n+m)(n+1)} & \cdots & Y_{(n+m)(n+m)} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ \cdot \\ V_n \\ \hline E'_{n+1} \\ \cdot \\ \cdot \\ E'_{n+m} \end{bmatrix}$$

(5)

$$I_{bus} = Y_{bus} V_{bus} \qquad (6)$$

I_{bus} - vector of the injected bus currents
V_{bus} - vector of bus voltages measured from the reference node.

- The diagonal elements of the bus admittance matrix are the sum of admittances connected to it.
- Off-diagonal elements are equal to the negative of the admittance between the nodes.
- All nodes other than the generator internal nodes are eliminated by Matrix Partitioning.
- To eliminate the load buses, the bus admittance matrix is partitioned such that the n buses to be removed are represented in the upper n rows.
- Since no current enters or leaves the load buses, currents in the n rows are zero. The generator currents are denoted by the vector Im and the generator and load voltages are represented by the vector E'_m and V_n. Then, Equation (5), in terms of submatrices, becomes:

$$\begin{bmatrix} 0 \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nm} \\ Y_{nm}^t & Y_{mm} \end{bmatrix} \begin{bmatrix} V_n \\ E'_m \end{bmatrix} \qquad (7)$$

Now we get the following two sets of equations from

$$0 = Y_{nn} V_n + Y_{nm} E'_m \qquad (8)$$

$$or, \quad V_n = -Y_{nn}^{-1} Y_{nm} E'_m \qquad (9)$$

$$I_m = Y_{nm}^t V_n + Y_{mm} E'_m \qquad (10)$$

Substituting (9) in (10) we get

$$I_m = (Y_{mm} - Y_{nm}^t Y_{nn}^{-1} Y_{nm}) E'_m = Y_{bus}^{red} E'_m \qquad (11)$$

Therefore we obtain the following reduced bus admittance matrix

$$Y_{bus}^{reduced} = Y_{mm} - Y_{mn} Y_{nn}^{-1} Y_{mn}^t \qquad (12)$$

The reduced bus admittance matrix has the dimensions *(m * m)*, where m is the number of generators.
In typical transient stability studies, depending upon the state of system, [Y] will have different entries. The states are pre-fault, faulted and post-fault.under the three conditions, since the configuration of the system changes, the entries of [Y] matrix will be different in each case. However the Y matrix defined in equation (12) includes the generator transient impedance X'_d and the total impedances [15].

$$\text{Let } Y = Y_{ij} = G_{ij} - B_{ij} = Y_{ij} \angle -\theta_{ij} \quad \text{and}$$

$$E_i = |E_i| \angle \delta_i \qquad (13)$$

The electrical power injected at generator node i;

$$S_{ei}^* = E_i^{'*} I_i \qquad or, \qquad P_{ei} = Re(E_i^{'*} I_i) \qquad (14)$$

$$\text{Where,} \qquad I_i = \sum_{j=1}^{m} E'_j Y_{ij} \qquad (15)$$

Substituting the value of I_i in equation (14), result in

$$P_{ei} = \sum_{j=1}^{m} |E'_i||E'_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (16)$$

Prior to disturbance, there is equilibrium between the mechanical power input and the electrical power output, and we have

$$P_{mi} = \sum_{j=1}^{m} |E'_i||E'_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (17)$$

The classical transient stability study is based on the application of a three-phase fault. A solid three-phase fault at bus k in the network results in $V_k = 0$. This is simulated by removing the kth row and column from the prefault bus admittance matrix.

The new bus admittance matrix is reduced by eliminating all nodes except the internal generator nodes. The generator excitation voltages during the fault and post fault modes are assumed to remain constant.
The electrical power injected at the i^{th} generator in terms of the new reduced bus admittance matrices are obtained from -

$$P_{ei} = \sum_{j=1}^{m} |E'_i||E'_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (18)$$

The swing equation with damping neglected, for machine i becomes:

$$\frac{H_i}{\pi f_0} \frac{d^2 \delta_i}{dt^2} = P_{mi} - \sum_{j=1}^{m} |E'_i||E'_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (19)$$

Y_{ij} - elements of the faulted reduced bus admittance matrix.

H_i - inertia constant of machine i expressed on the common MVA base.

The set of equations is a set of m-coupled non-linear second order differential equations. We introduce here state variables to convert each second order swing equation by two coupled first order differential equation.

$$\frac{d\delta_i}{dt} = \Delta\omega_i \qquad (20)$$

$$\frac{d\Delta\omega_i}{dt} = \frac{\pi f_0}{H_i}(P_{mi} - P_{ei}) \qquad (21)$$

B. UPFC Model

The UPFC and the associated transmission line are separately shown in Fig. 4(a) where the UPFC is represented by a series voltage source $\overline{V}_{se}$ and a shunt current source $\overline{I}_{sh}$. This represents the dynamic model of a UPFC and is used by a large number of researchers for dynamic analysis of a power system. For simplicity, the line is first represented by only its series reactance X. The leakage reactance of the series injection transformer (if any) can be included in X. The voltage source $\overline{V}_{se}$ in series with X can be represented by a current source $\overline{I}_{sh}$ in parallel with X as shown in Fig. 4(b) .

$$I\_se = V\_se \ / \ jX \qquad (22)$$

Without loss of generality, the current source I_{se} between buses i and j can be replaced by two shunt current sources (at buses i and j). Such an equivalent circuit is shown in Fig. 4(c) where

$$I_i = I_{sh} + I_{se} \text{ and } \quad I_j = -I_{se} \qquad (23)$$

Then the shunt current sources is replaced by shunt admittances ($\overline{Y}_i$ and $\overline{Y}_j$) as shown in Fig. 4(d).

$$\overline{Y}_i = \overline{I}_i / \overline{V}_i \quad \text{ and } \quad \overline{Y}_j = \overline{I}_j / \overline{V}_j \qquad (24)$$

Fig. 4(d) represents the π-circuit model of a UPFC and its associated transmission line. Note that the shunt admittances $\overline{Y}_i$ and $\overline{Y}_j$ are not constant but depend on $\overline{V}_{se}$ and $\overline{I}_{sh}$, and hence the control strategy used. The UPFC model can also be used to represent an SSSC or a STATCOM by selecting appropriate values of $\overline{V}_{se}$ and $\overline{I}_{sh}$.

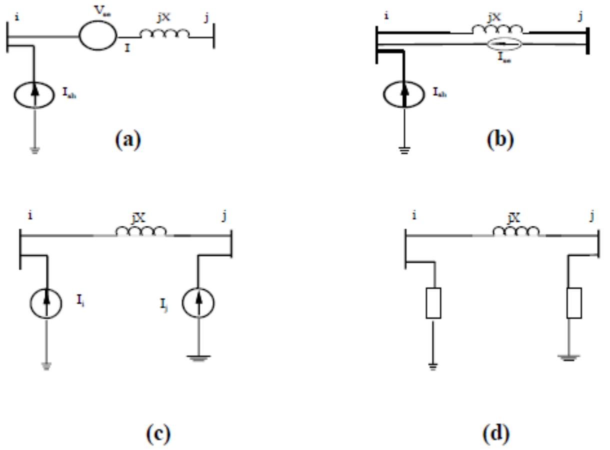

Figure 4. Successive representations of a UPFC and its associated line

C. Line Flow

Consider the line connecting the two buses i and j in figure 5. The line current I_{ij}, measured at bus i and defined positive in the direction $i \rightarrow j$ is given by

$$I_{ij} = I_l + I_i = y_{ij}\left(V_i - V_j\right) + y_i V_i \qquad (25)$$

Similarly, the line current I_{ij} measured at bus j and defined positive in the direction $j \rightarrow i$ is given by [H. Saadat]

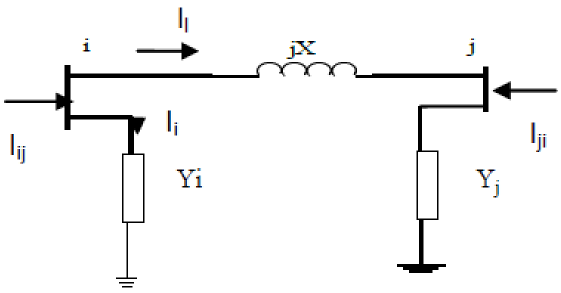

Figure 5. Transmission line model for calculating line flow.

$$I_{ji} = I_l + I_j = y_{ij}\left(V_j - V_i\right) + y_j V_j \qquad (26)$$

The complex power S_{ij} from bus i to j and S_{ji} from bus j to i are -

$$S_{ij} = V_i I_{ij}^* \qquad (27)$$

$$S_{ji} = V_j I_{ji}^* \qquad (28)$$

Bus i is taken as generator (PV) bus and bus j as load bus. Initial value of V_i and V_j are taken from load flow and after interfacing UPFC in power system V_j is computed from equation 29 [16].

$$V_j^{(1)} = \frac{\frac{P_j - jQ_j}{V_j^{*(0)}} + y_{ij} V_i}{y_{ij} + y_j} \qquad (29)$$

D. Interfacing the UPFC model to Power Network

Consider that a UPFC is placed in one of the transmission lines connected between buses i *and* j of a general power system as shown in Fig. 6(a). The objective is to find the overall reduced admittance matrix $\overline{Y}_{red}$ (with the UPFC) to evaluate the dynamic equations. First replace the loads by constant shunt admittances and then eliminate all physical buses of the system except the UPFC end buses (i *and* j). The partially reduced system consists of only machine internal buses and two physical buses (i *and* j) as shown in Fig. 6(b). The corresponding partially reduced admittance matrix is represented by $\overline{Y}_{red}^{partial}$ and thus

$$\begin{bmatrix} \overline{I}_g \\ 0 \\ 0 \end{bmatrix} = \left[\overline{Y}_{red}^{partial}\right] \begin{bmatrix} \overline{E}_g' \\ \overline{V}_i \\ \overline{V}_j \end{bmatrix} \qquad (30)$$

Here $\overline{E}_g'$ *and* $\overline{I}_g$ are the vectors of generator complex internal voltage and current, respectively.

The UPFC and the associated transmission line are now replaced by the proposed π–circuit model (Fig. 6(d)) and is shown in Fig. 6(c). For a given operating condition of the UPFC, the shunt admittances of the π-circuit model can be incorporated into the ith and jth diagonal elements of $\bar{Y}_{red}^{partial}$. Afterward, buses i and j can also be eliminated to obtain $\bar{Y}_{red}$ as shown in Fig. 6(d). Thus, the system equation becomes

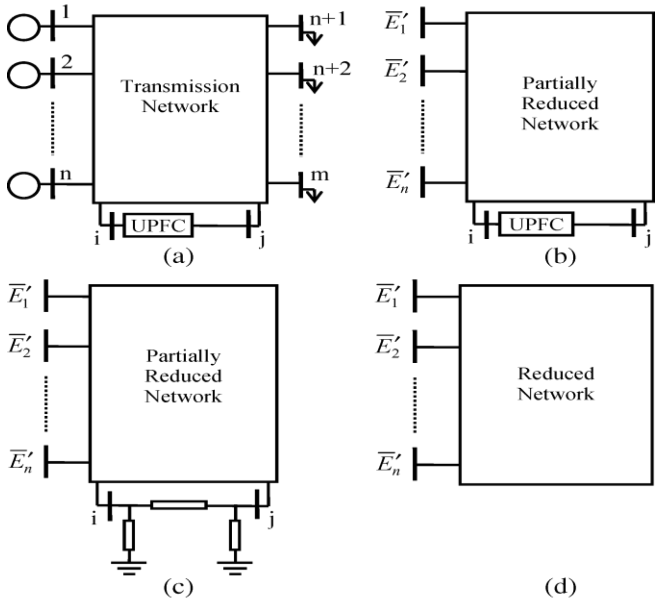

Fig. 6 Successive representation of a general power system with a UPFC

$$[\bar{I}_g] = [\bar{Y}_{red}][\bar{E}_g'] \qquad (31)$$

The above technique of interfacing the π-circuit model of a UPFC to a power network is also applicable for other FACTS devices (SSSC and STATCOM) [7].

Note that during transient period, the shunt admittance of the π-circuit model are not constant but depend on *Vse* and *Ish* which in turn depend on the control strategy used. Thus, $\bar{Y}_{red}$ is to be updated in each integration step.

IV. CONTROL STRATEGIES

There are numerous control strategies of FACTS devices are available. Most of the control strategies used some information (directly or indirectly), such as bus voltage magnitude, angle, line current, line active/reactive power flow, etc. as input signals to the controller. The above information can easily be obtained from the complex voltage at two end buses (i and j) of the π–circuit model. The controller ultimately produces a series injected voltage V_{se} and/or a shunt injected current I_{sh}. Once V_{se} and I_{sh} are known, the parameters of the corresponding π–circuit model can easily be determined. Note that different controllers may produce different values of V_{se} and I_{sh}, and thus generate different system responses. However, the technique of generating the response remains the same. The objective of this study is to obtain the system response or determine the FSS of a large power system in the presence of various FACTS devices using some existing control strategies. Thus, the effectiveness or limitations of various control strategies, or the coordination between the controllers of various FACTS devices has not been investigated.

The improvement of transient stability and damping of a power system by operating the series converter of a UPFC is done in three different modes: impedance control mode, perpendicular voltage control mode, and voltage angle control mode. Detailed analysis revealed that the perpendicular voltage control mode is the simplest and most practical mode of operation of a UPFC. It can maintain the control sensitivity for a wide operating region. In this study, the perpendicular voltage control mode of the series converter of a UPFC and a combination of full and continuous control as described in [22] and [24] are used. For such a mode of operation, there is no active power exchange between the series and shunt converters of the UPFC.

V. ALGORITHM OF TRANSIENT STABILITY EVALUATION WITH AND WITHOUT UPFC

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.

A. Analysis of transient stability without UPFC:

- Reads the line data. It includes the data for lines, transformers and shunt capacitors.
- Form admittance matrix, Y_{BUS} Reads generator data (R_a, X_d, X_q, X_d', X_q', H, D etc).
- Reads steady state bus data from the load flow results. ([V], [δ], [P_{load}], [Q_{load}], [P_{gen}], [Q_{gen}]).
- Calculates the number of steps for different conditions such as fault existing time, line outage time before auto-reclosing, simulation time etc.
- Modify Y_{BUS} by adding the generator and load admittances.
- Calculate fault impedance and modify the bus impedance matrix when there is any line outage following the fault.
- Calculate the initial conditions and constants needed in solving the DAEs of generators.
- Calculates the generator electric power outputs.
- The time step is advanced by the current time step.
- Solves the generator swing equations [17].

B. Interfacing of UPFC in Power System:

- Replace the loads by constant shunt admittances and eliminate all physical buses of the system except the two end buses (i and j) of the π-circuit model of the FACTS device to get $\bar{Y}_{red}^{partial}$.
- Select a suitable control strategy of the FACTs device. Use of different control strategy may provide different value of $\bar{V}_{se}$ and I_{sh}.
- Evaluate $\bar{V}_i$ and $\bar{V}_j$.
- Using the selected control strategy, evaluate $\bar{V}_{se}$ and I_{sh}, and then find $\bar{Y}_i$and $\bar{Y}_j$.
- Incorporate $\bar{Y}_i$and $\bar{Y}_j$into $\bar{Y}_{red}^{partial}$ and then eliminate buses i and j to get $\bar{Y}_{red}$.

- Evaluate the machine angles and speeds through (1) and (2) using $\overline{Y}_{red}$.
- Repeat steps (2–5) for the next integration step until the maximum period of study is reached.

VI. SIMULATION RESULTS

The proposed method of determining the FSS of a power system in the presence of various FACTS devices is tested on the ten-machine, 39-bus New England system. The simulation results obtained in the above system is briefly described in the following Sections.

New England System

The single line diagram of the ten-machine, 39-bus New England system is shown in Fig. 5.1. Related data are given in the table which contains load data, transformer data, line data, generation data and machine data. Data tables are given in reference [3]. First a three-phase fault near bus 26 cleared by opening the line 26–29 is considered. The critical clearing time (CCT) of the fault, without any FACTS device, is found as 63-64 ms. A UPFC is then placed in line 26–28 near bus 28. The CCT is increased to 64–65 ms a when the UPFC operates as STATCOM with I_{se} = 2.0 pu. On the other hand, when the UPFC operates as SSSC with V_{sh} =0.2 pu, the CCT is increased to 67-68 ms.

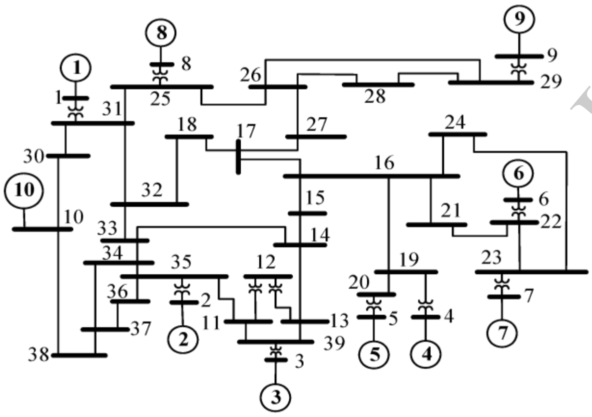

Fig. 7. Single line diagram of the New England system

However, when the device operate as UPFC, the CCT is further increased to 69-70 ms (with I_{se} = 2.0 and V_{sh} = 0.2). This is obvious because the UPFC exploits the benefits of both SSSC and STATCOM. The figures below show the CCT of all machines with and without FACTS devices.

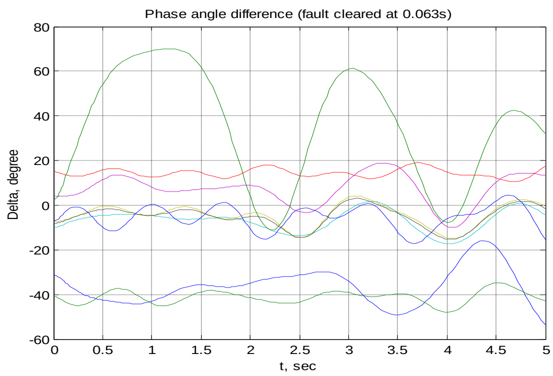

Figure 8. Swing curves of all machines of the New England system for a three-phase fault near bus 26 without FACTs device.

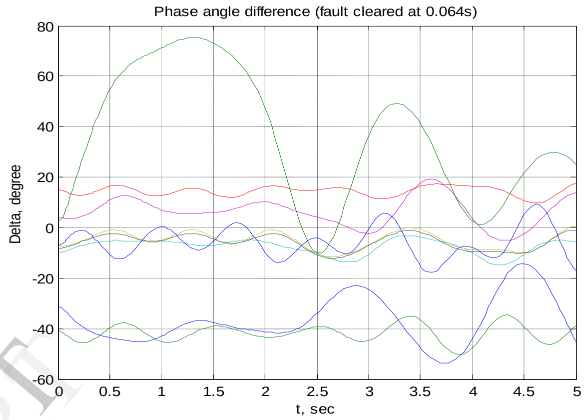

Figure 9. Swing curves of all machines of the New England system for a three-phase fault near bus 26 when the device acts as STATCOM.

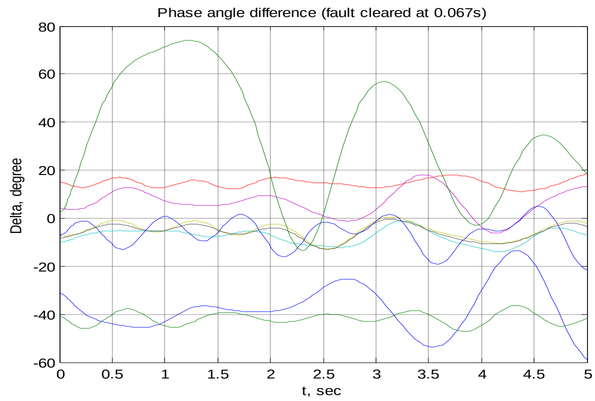

Figure 10. Swing curves of all machines of the New England system for a three-phase fault near bus 26 when the device acts as SSSC.

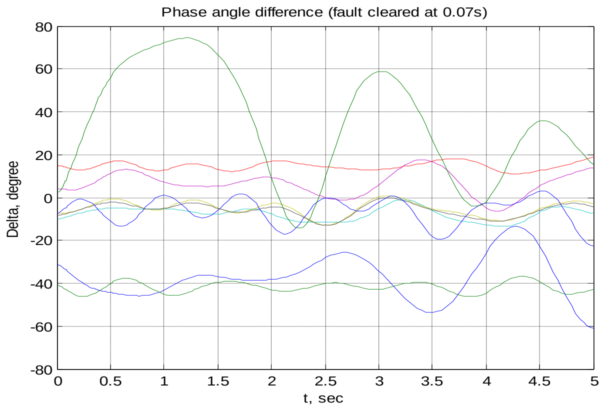

Figure 11. Swing curves of all machines of the New England system for a three-phase fault near bus 26 when the device acts as UPFC.

The figure 12. shows the comparison of swing curve of most disturbed machines at a fault clearing time of 60 ms with and without FACTs devices.

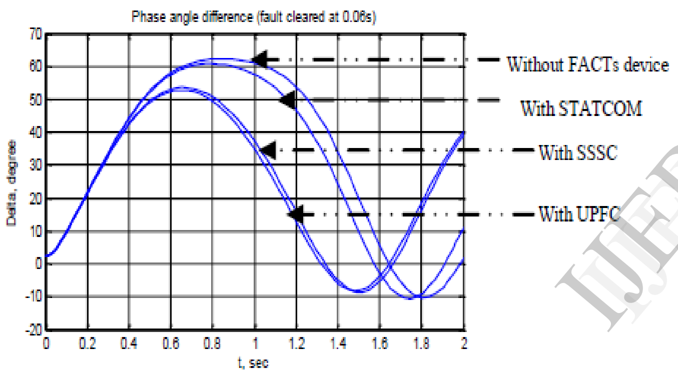

Figure 12. Comparison of swing curve of most disturbed machine with various FACTs devices.

VII. CONCLUSIONS

A simple and general method of generating the dynamic response and hence determining the first swing stability of a large power system in the presence of various FACTS devices is presented. First a UPFC and its associated transmission line are considered and represented by an equivalent π- circuit model where the shunt admittances depend on control parameters of the UPFC. The parameters of the π-circuit model are then carefully evaluated based on the control strategy used and interfaced to the power network. The above the π-circuit model can also be used to represent a STATCOM or an SSSC by choosing proper values of control parameters of the UPFC. The complex voltages at two end buses of the π-circuit model are also evaluated during simulation so that various existing control strategies of FACTS devices can easily be implemented. The effectiveness of the proposed method is tested on the ten –machine New England system and the 20-machine IEEE test system using two different control strategies and consistent result arefound. The proposed method of generating the system response is very general and can easily be applied to a large power system with various FACTS devices using different control strategies.

VIII. ACKNOWLEDGMENT

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