Static and Transient Voltage Stability Assessment of Power System by Proper Placement of UPFC with POD Controller

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Abstract—Optimal Location of FACTS devices are very important for the rapid and successful operation because of high cost and circuit complexities. In this paper best location of UPFC (Unified Power Flow Controller) is obtained both for static and transient voltage stability enhancement of an IEEE 14 bus power system. The simulation is done on PSAT (Power System Analysis Tool-box) in MATLAB and optimal location is found out by Continuation Power Flow (CPF), VCPI (Voltage Collapse Proximity Index) and Fast voltage Stability Index (FVSI). The bus having lowest voltage is the critical bus and the line having largest value of index for maximum permissible load with respect to a bus is the most critical line referred to that bus. It is found that by properly placing UPFC loadability margin of the system has been increased considerably leading to improvement of voltage stability and stability index value decreases at each reactive load with the insertion of the device at right place. Transient stability analysis is also done for an IEEE 14 bus system with a three phase fault created at a bus. It is found from the time domain simulation that proper placement of UPFC increases the transient performance of the system by damping out the power oscillation under large disturbance conditions with less settling time.

Keywords- UPFC, FACTS, CPF, index, stability, PSAT.

I. INTRODUCTION

The successful operation of power system depends on the ability of engineer to give uninterrupted service to the loads. The power system should be operated so that voltage and power should be within acceptable range. Control of active and reactive power flow is very important for the operation of power system. Reactive power imbalance causes voltage instability of the system. Real and reactive losses become very high when the system is operating at peak load. The system in this situation can be made stable by reducing the reactive load or by providing a source of reactive power at the right place before voltage collapse. In case of a disturbance or a fault the basic requirement is to make the synchronous generators to run in synchronism after a disturbance occur in the system. Whenever a perturbation is there in the system the generators tend to lose synchronism and if they re-maintain to run at the same speed the system is said to be stable. If the oscillations after a disturbances are damped and the system comes to new stable operating point hence it is called stable. Due to increased operations which results in making the power system to be highly stressed, the need for dynamic stability is arising. Transient stability assessment is a part of dynamic security assessment of power system which determines the ability of the system to remain in equilibrium when subjected to disturbances.

The revolution of Power Electronics Technology has given opportunities for developing the FACTS devices for stable operation of power system. In the last two decades number of Power Electronic based devices are implemented and known as FACTS (Flexible AC transmission System).These devices are effectively used for voltage control, power flow control, harmonic elimination, damping oscillation and improving transient stability and minimization of losses[10],[12]. Many FACTS devices are widely used like SVC (Static Var Compensator), STATCOM (Static synchronous Compensators), UPFC, TCSC. All these FACTS devices have their own advantages to control active and reactive power for static and dynamic voltage stability. Also whenever a disturbance occurs in the system like load imbalance or any fault, the system loses stability and the generators go out of synchronism.

Proper placement of FACTS devices help in improving the transient stability [1] [8]. To achieve good performance of these devices optimal placement is very important as the cost of these devices is very high. Calculation of Stability indices is very effective method o find out the critical bus a and line of the system. Using power flow these indices can be calculated and the line having maximum value of the index is the most critical line referred to the bus. [7] Various techniques have been implemented in previous research papers to find out the location of these devices using stability indices but they involve numerous complexities in power flow solution and calculations of indices. [11], [13]

In this paper simple and effective method has been implemented for finding the best location of FACTS device based on static, dynamic and transient stability using Continuation Power Flow (CPF), stability index, modal analysis and time domain simulation. Simulations are carried out in PSAT software which is very user friendly. Critical bus is determined using P-V curve and eigenvalue analysis and the Critical line is determined using the voltage stability indicator VCPI (Voltage Collapse Proximity Index) and fast Voltage stability Index(FVSI).The line having maximum value of the index in the most critical line corresponding to that bus. Eigenvalue analysis has been carried out for transient stability. The selection of best possible location of UPFC is carried out both for steady state and transient stability enhancement of a IEEE 14 bus system and it is found that proper placement of UPFC gives the static and transient stability improvement of the power system.

2. Study system

The IEEE 14 bus system modeled in PSAT software is shown in fig 1.It consists of 5 generators, 14 transmission lines, 11 static loads and 4 transformers. Base MVA is taken as 100 and base system voltage is 69KV. Complete system data is shown in Appendix showing complete generator data including transient reactance, inertia constants and time constants.

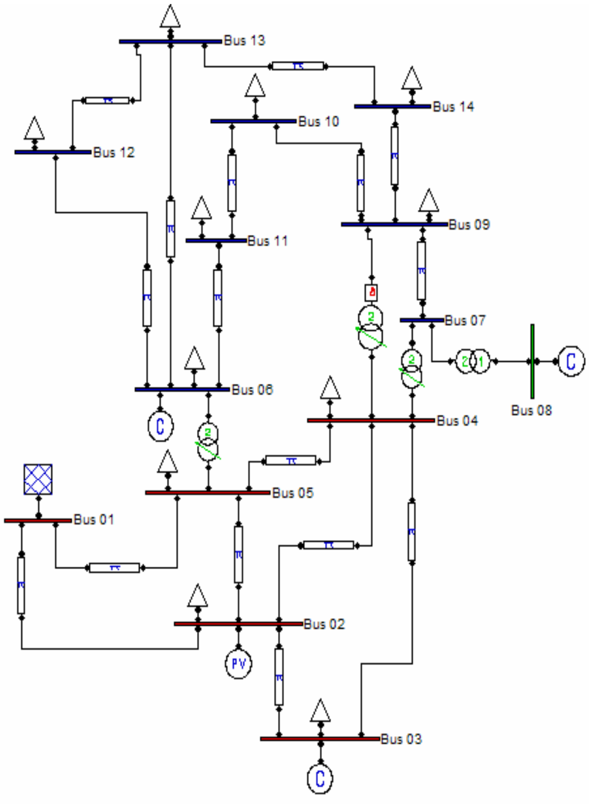


Fig 1 IEEE 14 bus system

3. Methodology

The method used to find the weakest bus and critical line of the system is CPF, Modal analysis and VCPI index.

3.1 Continuation Power Flow

The graph is obtained between the bus voltage and the loading factor λ by Continuation Power Flow is known as P-V curve. It determines the loadability margin i.e. the margin between the voltage collapse point and current operating point.

3.2 Modal Analysis

The eigenvalues of reduced Jacobian matrix are used to find the stability of system. The eigenvectors are calculated for each bus and the bus having maximum value of eigenvector is the weakest bus of the system.

3.3 VCPI (Voltage Collapse Proximity Index)

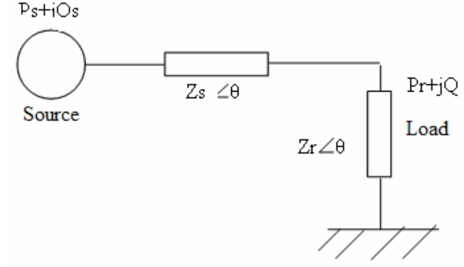


Fig 2

Fig 2 shows a network having a generator, transmission line and load.

$Z_s \angle \theta$ =line impedance

$Z_r \angle \varphi$ =load impedance

$\tan\phi = Q_r / P_r$

With the increase in load, current decreases. This leads to voltage drop at the receiving end

$$I = \frac{V_s}{\sqrt{[(Zs\cos\theta + Zr\cos\phi)^2 + (Zs\sin\theta + Zr\sin\phi)^2]}} \quad (1)$$

$$V_{r=} Z_r I Z_r / Z_s \frac{V_s}{\sqrt{[1+(Z_r/Z_s)^2 + 2(Z_r/Z_s)\cos(\theta-\phi)]}} \quad (2)$$

Power at the receiving end

$$P_r = V_r I \cos\varphi \quad (3)$$

and

$$Q_r = V_r I \sin\varphi \quad (4)$$

Therefore

$$P_r = \frac{V_s^2/Z_s}{1+(Z_r/Z_s)^2 + 2(Z_r/Z_s)\cos(\theta-\phi)} Z_r/Z_s \cos\phi \quad (5)$$

And

$$Q_r = \frac{V_s^2/Z_s}{1+(Z_r/Z_s)^2 + 2(Z_r/Z_s)\cos(\theta-\phi)} Z_r/Z_s \sin\phi \quad (6)$$

The maximum real and reactive powers are given as

$$P_r(\max) = \frac{V_s^2 \cos\phi}{Z_s 4\cos^2(\theta-\phi)/2} \quad (7)$$

$$Q_r(\max) = \frac{V_s^2 \sin\phi}{Z_s 4\cos^2(\theta-\phi)/2} \quad (8)$$

VCPI index is calculated as

VCPI (1) = real power transferred/ Maximum power that can be transferred

VCPI (2) = reactive power transferred/ Maximum reactive power that can be transferred

VCPI (1) and VCPI (2) give the same value for a particular load.

3.4 FVSI (Fast voltage stability Index)

It is calculated as by using reactive power flow as

$$FVSI = 4 Z^2 Q_j / V_i \quad (9)$$

The value of index evaluated close to 1 indicates that the particular line is close to instability point.
The critical bus is determined by finding out the maximum permissible load on the bus. The most critical bus in the system is the bus which can bear smallest maximum load.

3.5 Modeling Of UPFC (Unified Power Flow Controller)

UPFC can be represents by two voltage source representing fundamental components of output voltage waveforms of the two converters and impedances being leakage reactances of the two coupling transformers.

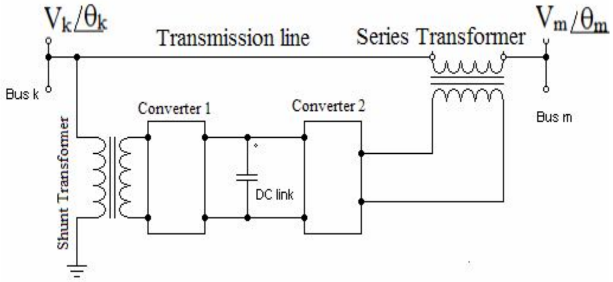


Fig 3 Diagram of UPFC

The active and reactive power equations can be written as
At bus k

$$P_k = V_k^2 G_{kk} + V_k V_m [G_{km}\cos(\theta_k-\theta_m) + B_{km}\sin(\theta_k-\theta_m)] + V_k V_{cr} [G_{km}\cos(\theta_k-\delta_{cr}) + B_{km}\sin(\theta_k-\delta_{cr})] + V_k V_{vr}[G_{vr}\cos(\theta_k-\delta_{vr}) + B_{vr}\sin(\theta_k-\delta_{vr})] \quad (10)$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m [G_{km}\sin(\theta_k-\theta_m) - B_{km}\cos(\theta_k-\theta_m)] + V_k V_{cr}[G_{km}\sin(\theta_k-\delta_{cr}) - B_{km}\cos(\theta_k-\delta_{cr})] + V_k V_{vr}[G_{vr}\sin(\theta_k-\delta_{vr}) + B_{vr}\cos(\theta_k-\delta_{vr})] \quad (11)$$

At bus m

$$Pm = V_m^2 G_{mm} + V_k V_m [G_{mk}\cos(\theta_m-\theta_k) + B_{mk}\sin(\theta_m-\theta_k)] + V_m V_{cr}[G_{mm}\cos(\theta_m-\delta_{vr}) + B_{mm}\sin(\theta_m-\delta_{cr})] \quad (12)$$

$$Qm = -V_m^2 B_{mm} + V_k V_m [G_{mk}\sin(\theta_m-\theta_k) - B_{mk}\cos(\theta_m-\theta_k)] + V_m V_{cr}[G_{mm}\sin(\theta_m-\delta_{vr}) - B_{mm}\cos(\theta_m-\delta_{cr})] \quad (13)$$

Series converter

$$Pcr = V_{cr}^2G_{mm}+VcrVk[G_{km}\cos(\delta_{cr}-\theta_k) + B_{mk}\sin(\delta_{cr}-\theta_k)] +V_mV_{cr}[G_{mm}\cos(\delta_{cr}-\theta_m) +B_{mm}\sin(\delta_{cr}-\theta_m)] \quad (14)$$

$$Qcr = -V_{cr}^2B_{mm} +VcrVk[G_{km}\sin(\delta_{cr}-\theta_k) - B_{mk}\cos(\delta_{cr}-\theta_k)]+V_mV_{cr}[G_{mm}\sin(\delta_{cr}-\theta_m)-B_{mm}\cos(\delta_{cr}-\theta_m)] \quad (15)$$

Shunt converter

$$P_{vr} = -V_{vr}^2G_{vr}+V_{vr}V_k[G_{vr}\cos(\delta_{vr}-\theta_k)+ (B_{vr}\sin(\delta_{vr}-\theta_k)) \quad (16)$$

$$Q_{vc}=V_{vr}^2B_{vr}+V_{vr}V_k[G_{vr}\sin(\delta_{vr}-\theta_k)-B_{vr}\cos(\delta_{vr}-\theta_k)] \quad (17)$$

4 Results and Discussion

4.1 Static voltage stability

4.1.1 P-V curve

The variation of bus voltage with the loading factor λ is obtained for IEEE 14 bus system. Continuation Power Flow has been done in PSAT software and it is found that bus no 14 is the most insecure bus as the voltage at each reactive load of bus 14 is minimum. The figure 4 shows the P-V curve for the lowest three voltage buses without UPFC Fig 5 shows the P-V curve for three lowest voltage buses with UPFC between 9-14. It is clear that the loadability margin has been increased considerably to 50 % with the insertion of UPFC in the system results in the increase in system stability.

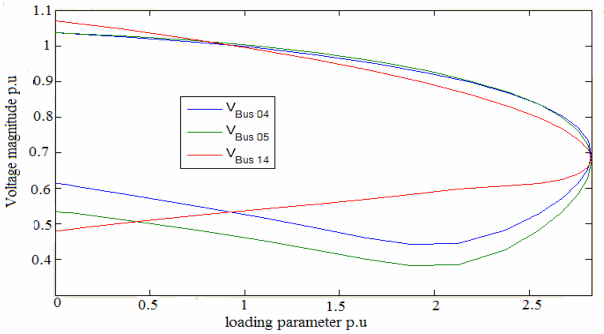


Fig 4 Lowest three bus voltages without FACTS

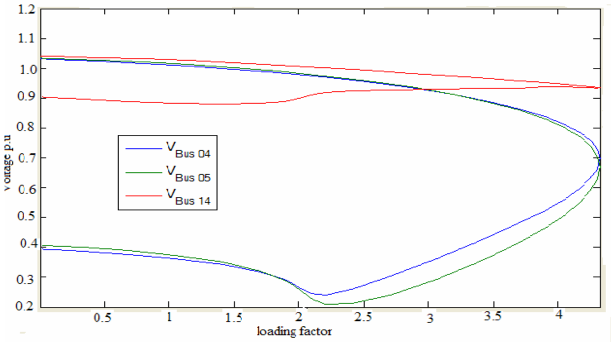


Fig 5 Voltages with UPFC

4.1.2 Modal analysis

Fig 6 shows the eigenvalues of all the buses at a loading factor of 0.5. The bus having highest value of eigenvector is the most unstable bus.

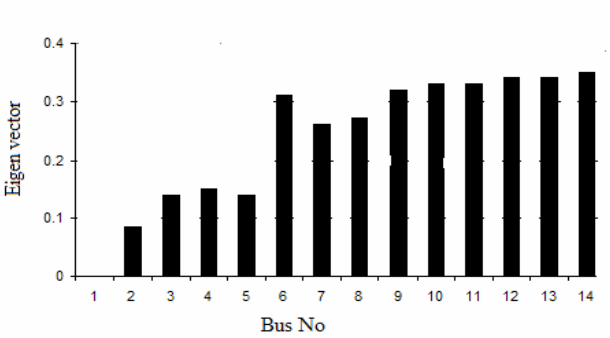


Fig 6 eigenvector

4.1.3 Determination of most critical line with referred to a bus using index

Step1: Reactive load at a bus is gradually increased keeping all other loads constant.

Step2: Load flow is done using PSAT to find out the active and reactive power transmitted at the receiving end for a particular load.

Step3: Maximum Active and reactive power that can be transferred to a particular bus is calculated using the given formula.

Step4: VCPI and FVSI index is calculated at each load knowing power transmitted using load flow.

Step5: This is repeated for each bus and indices are calculated for each line associated with bus.

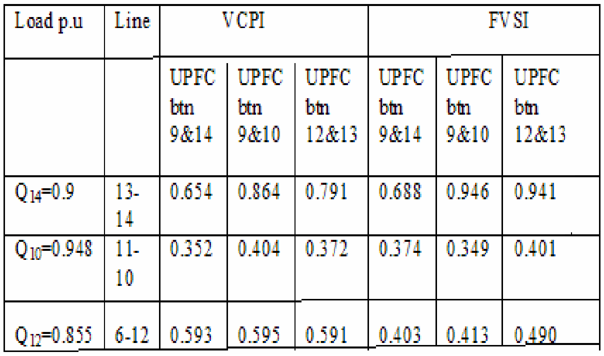
Step6: The line having maximum value of the stability indices at maximum loadability point is the most critical line with respect to that bus.

Table 1 shows the indices value for most stressed lines without UPFC and the results show that the line 13-14 is the most critical line with respect to bus 14 and Table 2 shows the same with UPFC at different locations. It is clear from the table that insertion of UPFC between line 9 -14 reduces the index for each line considerably increasing the loadability margin of each bus.

Table 1(Stability Indices without UPFC)

Load p.u	Line	VCPI(voltage collapse proximity index)	FVSI(Fast voltage stability index)
Q_{14}=0.9	13-14 9-14	0.869 0.746	0.956 0.749
Q_{10}=0.948	11-10 9-10	0.363 0.241	0.389 0.258
Q_{12}=0.855	6-12 13-12	0.598 0.379	0.410 0.431

Table 2(Stability Indices with UPFC)



Load p.u	Line	VCPI			FVSI		
		UPFC btn 9&14	UPFC btn 9&10	UPFC btn 12&13	UPFC btn 9&14	UPFC btn 9&10	UPFC btn 12&13
Q_{14}=0.9	13-14	0.654	0.864	0.791	0.688	0.946	0.941
Q_{10}=0.948	11-10	0.352	0.404	0.372	0.374	0.349	0.401
Q_{12}=0.855	6-12	0.593	0.595	0.591	0.403	0.413	0.490

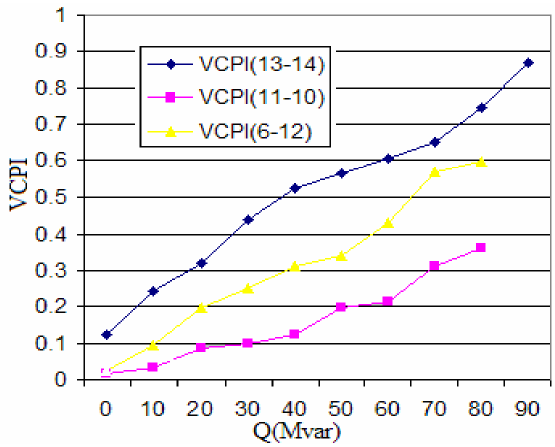


Fig 7 Variation of VCPI with reactive load for highly stressed lines without FACTS controller

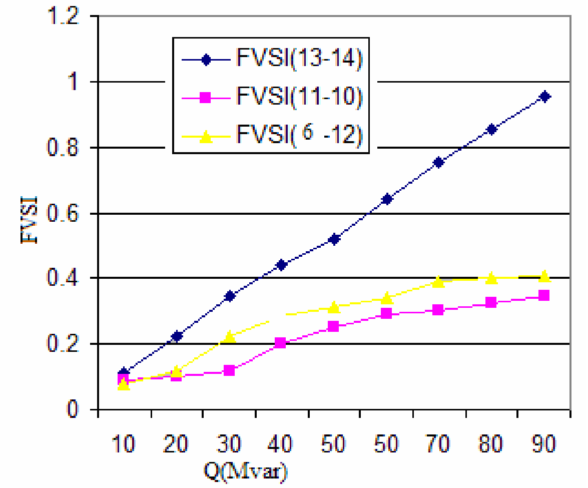


Fig 8 Variation of FVSI with reactive load for highly stressed lines without FACTS controller

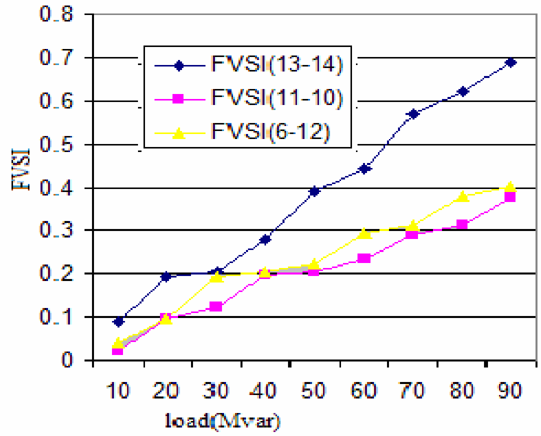


Fig 9 Variation of FVSI with reactive load for highly stressed lines with FACTS controller

Fig 7&8 shows the variation of VCPI and FVSI indices for three stressed lines without UPFC and fig.9 &10 shows the indices with the device. It is clear that from the figure the value of index decreases at each reactive load when the device is placed optimally between 9& 14 increasing the system stability. With the insertion of UPFC at the right location maximum load handling capability of each bus is increased considerably.

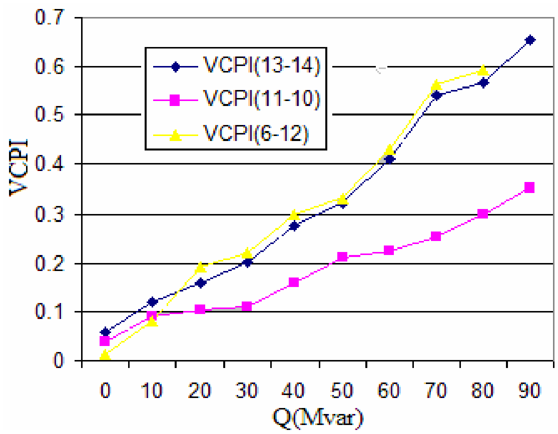


Fig 10 Variation of VCPI with reactive load for highly stressed lines with FACTS controller

4.2 Transient stability

4.2.1 Time Domain Simulation

Eigenvalue analysis is performed using PSAT to find the stability of the system and to determine the optimal placement of UPFC. The fault is created at bus 5 and UPFC is placed at different locations and eigenvalues are calculated using PSAT software. Table 3 shows the results of eigenvalue analysis. It is evident from the figure that dynamic order and negative eigenvalues of the system increases after the insertion of UPFC leads to dynamic system stability. When UPFC is placed between 1-5 the damping is more as compared to other locations hence it is chosen as the best location to improve transient stability.

Table 3 Eigenvalues

	No UPFC	UPFC Between			
		2&5	1&5	3&4	2&3
Σ(max)	-40.24	-79.7	-82.36	-78.53	-81.2
Dynamic order	55	56	56	56	56
Pos. Eigen	0	0	0	0	0
Neg. Eigen	54	55	55	55	55
Complex pair	11	9	8	9	8
Zero eigen	1	1	1	1	1

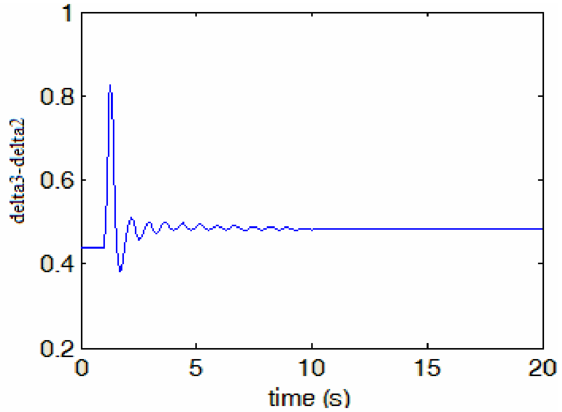


Fig 11 Variation of relative rotor angles 32

A three phase to ground fault is created at bus 5 and time domain simulation is done using PSAT software. Fig.11-15 shows the plots of relative rotor angles, angular speeds and lowest voltages. It is clear that without UPFC oscillations are damped out after a considerable period of time.

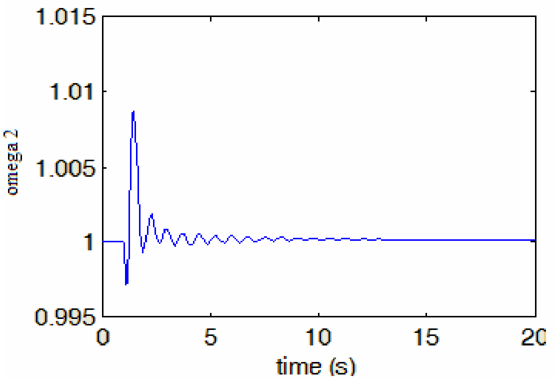


Fig 12 Variation of angular speed 2

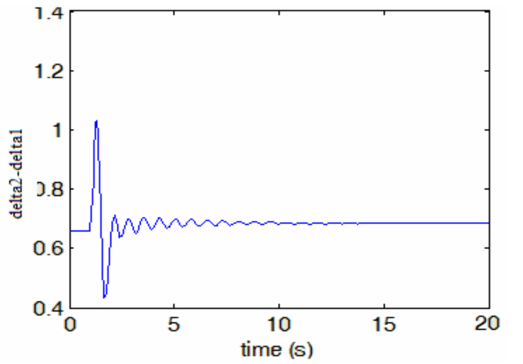


Fig 13 Variation of relative rotor angles 21

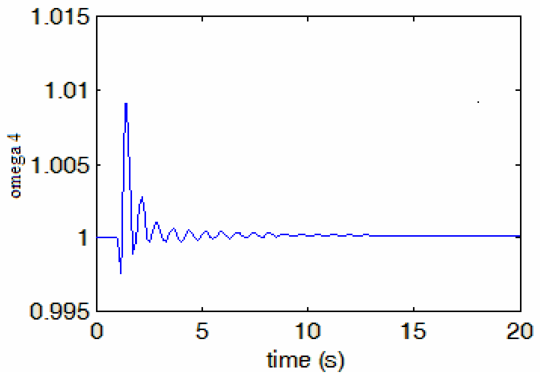


Fig 14 Variation of angular speed 4

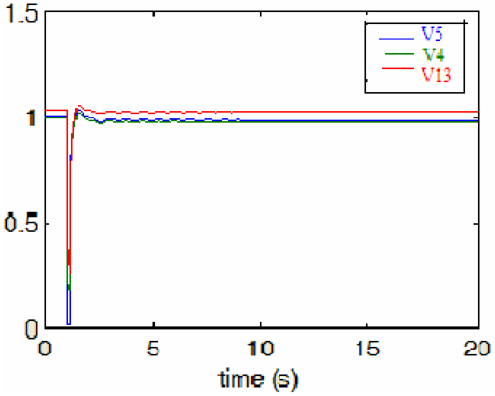


Fig 15 Variation of three lowest voltages

Fig (11-15) Graphs without FACTS device

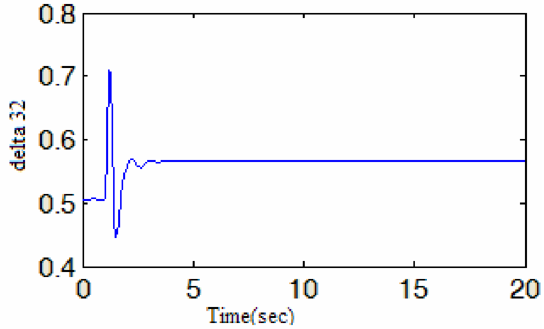


Fig 16 Variation of relative rotor angles 32

UPFC is placed at various locations with POD controller near to the bus where fault is located and time domain simulation is done for each location. UPFC is placed at various locations with POD controller near to bus where fault is located and the time domain simulations is done for each location. It is clear from the voltage graphs that transients in the voltages of the buses die out rapidly with the insertion of UPFC at proper location.

Fig 16-23 shows various graphs of relative angular positions, angular speeds of individual generators and voltages. It is clear from the result that with the insertion of UPFC at the proper location oscillations die out rapidly hence transient behavior is improved. So when fault is located at bus 5, the best location of UPFC is between lines 1-5.

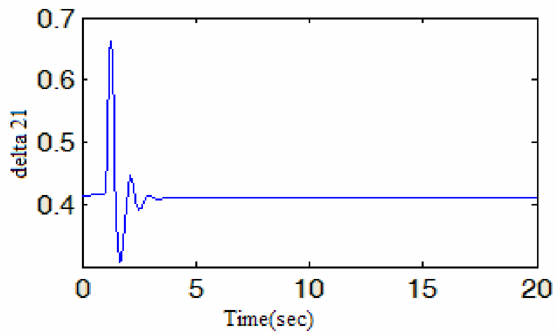


Fig 17 Variation of relative rotor angles 21

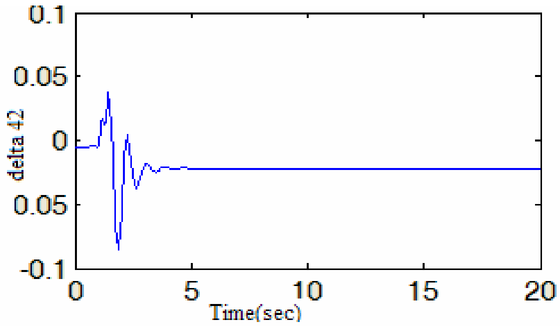


Fig 18 Variation of relative rotor angles 42

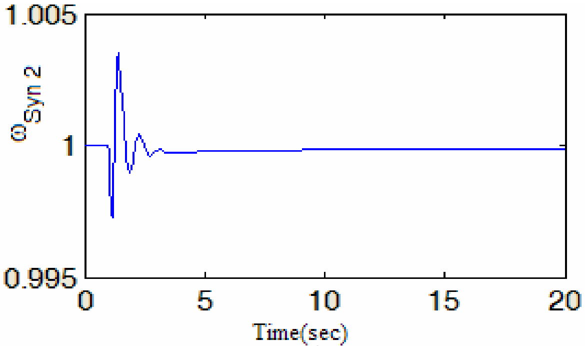


Fig 19 Variation of angular speed 2

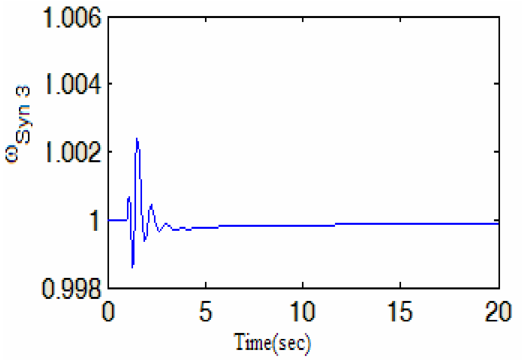


Fig 20 Variation of angular speed 3

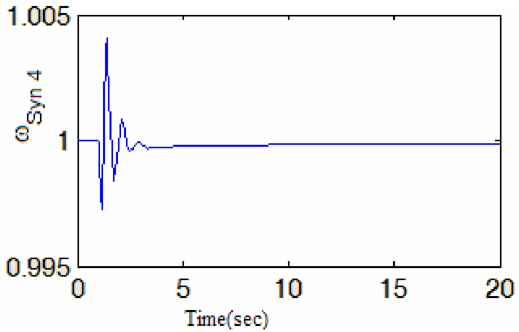


Fig 21 Variation of angular speed 4

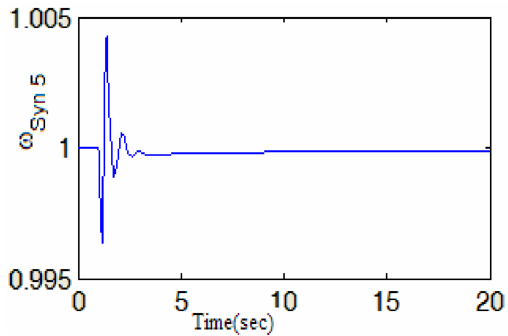


Fig 22 Variation of angular speed 5

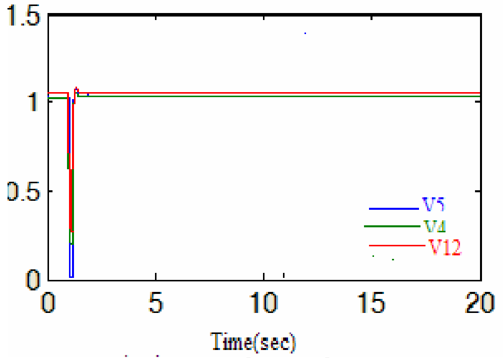


Fig 23 Voltages Plots

5 Conclusion

Static and Transient stability enhancement of IEEE 14 bus system is done with the help of UPFC. Simulation is carried out in PSAT software and critical line and weakest bus is determined using CPF and stability index. Dynamic stability analysis is done using eigenvalue analysis .Proper placement of UPFC enhances the steady state, dynamic and transient stability of the system. Time Domain simulation is done by creating fault at a bus and the results show that by properly placing UPFC, settling time of the system can be reduced considerably making the system stable with fewer oscillations.

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Appendix

IEEE-14 BUS DATA

Generator	1	2	3	4	5
MVA	615	60	60	25	25
Xl(p.u)	0.2396	0.00	0.00	0.134	0.134
Ra(p.u)	0.00	0.0031	0.031	0.0014	0.0041
Xd(p.u)	0.8979	1.05	1.05	1.25	1.25
X'd(p.u)	0.2995	0.1850	0.1850	0.232	0.232
X''d(p.u)	0.23	0.13	0.13	0.12	0.12
Tdo'(p.u)	7.4	6.1	6.1	4.75	4.75
Tdo''(p.u)	0.03	0.04	0.04	0.06	0.06
Xq(p.u)	0.646	0.98	0.98	1.22	1.22
Xq(p.u)	0.646	0.36	0.36	0.715	0.715
xq''(p.u)	0.4	0.13	0.13	0.12	0.12
Tqo'(p.u)	0.00	0.3	0.3	1.5	1.5
Tqo''(p.u)	0.033	0.099	0.099	0.21	0.21
H	5.148	6.54	6.54	5.06	5.06
D	2.0	2.0	2.0	2.0	2.0

BUS DATA

Qmin	Bus no	P(p.u)	Q(p.u)	P(load)	Q(load)	Bus type	Qmax
-10.0	1	2.32	0.00	0.00	0.00	2	10.0
-0.4	2	0.4	-0.424	0.1270	0.1270	1	0.5
0.00	3	0.00	0.00	0.9420	0.1900	2	0.4
0.00	4	0.00	0.00	0.4780	0.00	3	0.00
0.00	5	0.00	0.00	0.0760	0.0160	3	0.00
-0.06	6	0.00	0.00	0.1120	0.0750	2	0.24

0.00	7	0.00	0.00	0.00	0.00	3	0.00
-0.06	8	0.00	0.00	0.00	0.00	2	0.24
0.00	9	0.00	0.00	6.2950	0.1660	3	0.00
0.00	10	0.00	0.00	0.0900	0.0580	3	0.00
0.00	11	0.00	0.00	0.0350	0.0180	3	0.00
0.00	12	0.00	0.00	0.0610	0.0160	3	0.00
0.00	13	0.00	0.00	0.1350	0.0580	3	0.00
0.00	14	0.00	0.00	0.1490	0.0500	3	0.00

LINE DATA

From bus	To bus	R(p.u)	X(p.u)	Line charging(p.u)	Lap Ratio
1	2	0.01938	0.05917	0.0528	1
1	5	0.05403	0.22304	0.0492	1
2	3	0.04699	0.19797	0.0438	1
2	4	0.05811	0.17632	0.0374	1
2	5	0.05695	0.17388	0.034	1
3	4	0.06701	0.17103	0.0346	1
4	5	0.01335	0.04211	0.0128	1
4	7	0.00	0.20912	0.00	0.978
4	9	0.00	0.55618	0.00	0.969
5	6	0.00	0.25202	0.00	0.932
6	11	0.09498	0.1989	0.00	1
6	12	0.12291	0.25581	0.00	1
6	13	0.06615	0.13027	0.00	1
7	8	0.00	0.17615	0.00	1
7	9	0.00	0.11001	0.00	1
9	10	0.03181	0.0845	0.00	1
9	14	0.1271	0.27038	0.00	1
10	11	0.08205	0.19207	0.00	1
12	13	0.2209	0.19988	0.00	1
13	14	0.17093	0.34802	0.00	1

UPFC parameters
Series Compensation-30%
Gain and time constant-75 and 0.005

POD controller parameters
Gain K_w and time constant T_w=-0.577and 10
T1, T2,T3,T4= 0.3187, 0.1928,0.3187, 0.1928