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Enhancement of Voltage stability and Transmission Congestion management with UPFC

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Abstract

In the expanding transmission network, Congestion management and voltage stability are significant issues to be handled. Congestion management can be improved by increasing the power transfer capability or by reducing the system losses. With proper VAR support, the issue of voltage instability can be vanquished. Adaption of Flexible AC Transmission System (FACTS) devices is a techno-commercial manner to overcome the above issues. Unified Power Flow Controller (UPFC) is a pliable FACTS device which can control active power, reactive power and voltage injections concurrently in an efficient manner. In this paper power flow model of UPFC is described, location of UPFC is determined by Line Utilization Factor (LUF) and Line Voltage Stability Index (L_{mn} index) in order to find out the lines which are more vulnerable for congestion and voltage instability. The effectiveness of UPFC is tested on IEEE-14 bus system using MATLAB software. The results are compared with Placement and without placement of FACTS device.

Keywords: *Voltage stability, Congestion, FACTS device, UPFC, security, loss reduction, LMP*

1. Introduction

With the significant increase in power demand in the few past decades, the size of the power transmission network have been improved in vertically integrated environment as well as deregulated power sector. However, the Congestion management and voltage instability problems are challenging issues for the secured and reliable operation of power system.

Congestion in transmission refers to inability of transmission line to deliver power to the desired customer due to simultaneous transactions or insufficient transmission capacity of transmission line [1]. In deregulated power market congestion management is very complex task for system operator when compared to regulated system [2]. The literatures [3-4] have explained different methods and techniques of congestion management. Different problems due to congestion and congestion management by FACTS devices are explained in [5].

We have variant definitions for Voltage stability in literature, as per IEEE/CIGRE voltage stability is defined as ability of a system to take care of voltage in order that once load admittance is raised, load power can increase and that each power and voltage square measure manageable [6]. Voltage instability problem raises due to heavily loads, inability to meet VAR demand, line outages *etc.*, [7]. Voltage stability analysis, assessment techniques and control methods are explained in references [8-10].

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If the transmission system is incapable of handling congestion management and voltage stability it leads to problems of outages, block-outs etc., which dangers the system security and reliability [11]. In order to overcome the above problems FACTS devices are to be allocated in optimal places [12]. M. Esmaili [13] proposed a method for optimal location and sizing of series FACTS device Thyristor Controlled Switched Capacitor (TCSC) based on priority list and Locational Marginal Pricing (LMP).Based on reactive power loss and real power flow performance index TCSC is placed [14]. UPFC have been placed for congestion management based upon Power transmission congestion distribution factor [15], sensitivity analysis and LMP [16]. Voltage stability index also used for congestion management [17] and the voltage stability have been improved by UPFC placement [18]. Based on Newton-Rapshon Optimal Power Flow (NR-OPF) method UPFC have been placed, which enhances the voltage profile and power transfer capability simultaneously[19].

In this paper Line Utilization Factor (LUF) and Line Stability Index (L_{mn}- index) are used for placement of UPFC. Also Voltage Collapse Proximity Index (VCPI) and Active Power Performance Index (APPI) are calculated before and after placement of UPFC in order to observe the performance of UPFC in congestion management and voltage stability. The performance of FACTS device is tested on IEEE-14 bus system for different loading conditions.

2. Placement of UPFC

2.1. Line Utilization Factor (LUF):

Line Utilization Factor (LUF) is an index used to find out the congestion of the transmission lines and it is calculated as,

$$LUF = \frac{MVA_{ij}}{MVA_{ij(max)}} \tag{1}$$

Where,

MVA_{ij} = MVA rating of line connected between buses i, j respectively

$MVA_{ij(max)}$ = maximum MVA rating of line connected between buses i, j respectively

LUF indicates rate or percentage of line utilized and this factor is an effective one to determine the congested line. Higher the LUF, more the line congested.

Different voltage stability indices were compared in reference [20] and L_{mn}- index is used to find the line which has voltage stability of transmission line connected between two buses.

2.2. Line Voltage Stability Index (Lmn- index):

This index is formed based on single-line representation of transmission line shown in Figure 1.

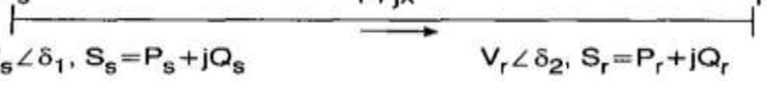

Figure 1. Single-line Representation of Transmission Line

L_{mn}- index is calculated as shown below [21],

$$L_{mn}=\frac{4XQ_r}{\left[V_s\sin(\theta-\delta)\right]^2} \tag{2}$$

Where

X = Reactance of the transmission line considered

Q_r = Reactive power at receiving end

V_s, V_r = Voltages of buses at sending end and receiving end respectively

θ = Impedance angle of the line

$\delta=\delta_1-\delta_2$

$\delta_1,\ \delta_2$ = Load angles at sending end and receiving end respectively

If L_{mn}- index reaches or nearing to unity, it indicates that the line is losing its stability and voltage collapse will occurs.

2.3. Voltage Collapse Proximity Index (VCPI):

As per comparison of different voltage stability indices [20], VCPI is used to determine voltage stability situation of buses. VCPI for kth bus is obtained by,

$$\mathrm{VCPI}=\left|\frac{1-\sum\limits_{\substack{m=1\\m\neq k}}^{N}V_m}{V_k}\right| \tag{3}$$

Where V_k= Voltage magnitude of kth bus in p.u

VCPI ranges from 0 to 1. If it reaches unity, it indicates that voltage collapse condition.

2.4. Active Power Performance Index (APPI):

Active power performance index otherwise known as Real power performance index or severity index is used to check the limitations or violations of MW power flows [22]. This APPI is evaluated as

$$\mathrm{APPI}=\sum_{k=1}^{L}\left(\frac{w}{2n}\right)\left[\frac{P_k}{P_k^{max}}\right]^{2n} \tag{4}$$

Where

P_k = Real Power flow of kth line in MW

P_k^{max} = MW capacity of kth line

w = real non-negative weighing factor (here w = 1)

n = exponent of penalty function (here n = 1)

This index values are below unity and above unity indicates whether the line loading is within the limits are exceeding. Higher the value indicates that line loading is more.

In this paper LUF is calculated for every line and most congested line is find out from these values *i.e.*, the line with highest LUF. Also L_{mn}- index for each line is calculated and the line nearing to voltage collapse *i.e.*, with highest value is determined. In first case UPFC is placed in the most congested line and again both the indices are calculated for comparison. Similarly, in second case UPFC is placed in the line with highest L_{mn}- index and again the indices are calculated. For both the cases APPI and VCPI are calculated without UPFC placement and with UPFC placement in order to test the ability in Congestion alleviation and voltage stability improvement respectively. The above steps are performed at different loading conditions.

3. Power Flow Model of UPFC:

3.1. Power Flow Equations:

The fundamental ideas regarding topology, working principle, controlling is available in literature [23-24]. It consists of two voltage source converters one is connected in series to line, the other is connected in shunt and both the converters are coupled by a dc-link. An UPFC can work as shunt reactive power compensator, series reactive power compensator as well as phase shift transformer. It has control over real and reactive power flows, voltage injection magnitudes and dc link voltage.

Through a coupling transformer the output voltage of series converter is injected into the line, which acts as series voltage source and control the sending end voltage. Hence the active power and reactive power supply is controlled by this series voltage source. The shunt converter maintains the balancing of reactive power and so that it controls the ac voltage magnitudes also. The equivalent circuit of UPFC is shown in following Figure 2. The power flow equations *i.e.*, active power (P) and reactive power (Q) equations are deduced based on this equivalent circuit.

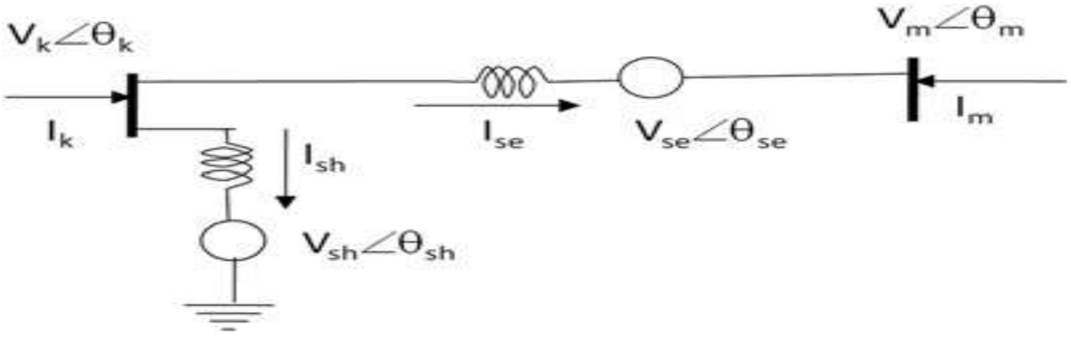

Figure 2. Equivalent Circuit of UPFC

At node k,

$$P_k = V_k^2 G_{kk} + V_k V_m \left(G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_k - \theta_m)\right) + V_k V_{se}\left(G_{km}\cos(\theta_k - \theta_{se}) + B_{km}\sin(\theta_k - \theta_{se})\right) + V_k V_{sh}\left(G_{sh}\cos(\theta_k - \theta_{sh}) + B_{sh}\sin(\theta_k - \theta_{sh})\right) \tag{5}$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m \left(G_{km}\sin(\theta_k - \theta_m) - B_{km}\cos(\theta_k - \theta_m)\right) + V_k V_{se}\left(G_{km}\sin(\theta_k - \theta_{se}) - B_{km}\cos(\theta_k - \theta_{se})\right) + V_k V_{sh}\left(G_{sh}\sin(\theta_k - \theta_{sh}) - B_{sh}\cos(\theta_k - \theta_{sh})\right) \tag{6}$$

At node m,

$$P_m = V_m^2 G_{mm} + V_k V_m \left(G_{mk}\cos(\theta_m - \theta_k) + B_{mk}\sin(\theta_m - \theta_k)\right) + V_k V_{se}\left(G_{mm}\sin(\theta_{se} - \theta_k) - B_{mm}\cos(\theta_{se} - \theta_k)\right) \tag{7}$$

$$Q_m = -V_m^2 B_{mm} + V_k V_m \left(G_{mk}\sin(\theta_m - \theta_k) - B_{mk}\cos(\theta_m - \theta_k)\right) + V_k V_{se}\left(G_{mk}\sin(\theta_m - \theta_{se}) - B_{km}\cos(\theta_m - \theta_{se})\right) \tag{8}$$

3.2. Initial Conditions:

The initial parameters selection will impact the convergence of load flow calculation. Hence the initial conditions are to be determined before the load flow calculation. Here we assume lossless UPFC, coupling transformers and null voltage angles in equations 4-7, so that we get the best initial estimations [25].

The initial conditions for the series source are,

$$\theta_{se} = \arctan\left(\frac{P_{mref}}{|C_1|}\right) \tag{9}$$

$$V_{se} = \left(\frac{X_{se}}{V_m^0}\right)\sqrt{P_{mref}^0 + C_1^2} \tag{10}$$

Where

$$C_1 = Q_{mref} - \left(\frac{V_m^0}{X_{se}}\right)\left(V_m^0 - V_k^0\right), \text{ if } V_m^0 \neq V_k^0 \tag{11}$$

$$C_1 = Q_{mref} \text{ , if } V_m^0 = V_k^0 \tag{12}$$

Where X_{se} = Reactance of series source

The initial conditions for the shunt source are,

$$\theta_{sh} = -\arcsin\left(\frac{\left(V_k^0 - V_m^0\right)V_{se}^0 X_{sh} \sin\left(\theta_{se}^0\right)}{V_{sh}^0 V_k^0 X_{se}}\right) \tag{13}$$

Where

X_{sh} = Reactance of shunt source

To make the shunt converter as a voltage regulator, the voltage magnitudes of the shunt source are to be fixed for initial target values and to be updated for every load flow iteration.

4. Results and Discussions

The proposed method is carried out on MATLAB software, the performance of UPFC have been tested on IEEE-14 bus system with normal loading or 100% loading, 110% loading and 130% loading conditions. It consists of 14 buses in which bus no: 1 is Slack bus, four buses are Generator buses numbered 2, 3, 6, 8 and remaining Nine buses are load buses. It consists of 20 transmission lines. We are considering only load buses for the placement of UPFC.

For each loading condition LUF, L_{mn}-index at each line VCPI at each bus, APPI and power losses are calculated. Based upon LUF and L_{mn}-index the critical line is identified *i.e.*, the line with highest values of these indices and in that line UPFC is placed and again the above parameters are calculated.

4.1. At 100% Loading or Normal Loading Conditions:

The LUF values and L_{mn}-index for all lines are calculated with and without placement of UPFC these values are presented in Table 1. From these values we infer that line 4-5 is the most congested line with LUF 1.3400 and line 13-14 is the critical line for voltage stability with L_{mn}-index 0.0824. Even though line 7-8 is exhibiting highest L_{mn}-index of 0.1417, being a lossless line it is not considered as critical line. Hence UPFC is to be placed in line 4-5 for congestion management and in line 7-8 for voltage stability.

Then APPI, system losses, VCPI for all buses and Voltage profile without UPFC and with UPFC are presented in Table 2, Figure 3 and Figure 4 respectively.

Table 1. Line Utilization Factors and L_{mn}- Index Without and with Placement of UPFC with Normal Loading

Line no:	Line connected between buses (From-To)	LUF without UPFC	LUF with UPFC		L_{mn}-index without UPFC	L_{mn}-index with UPFC	
			Placed in line 4-5	Placed in line 13-14		Placed in line 4-5	Placed in line 13-14
1	1-2	1.3200	1.3500	1.3500	0.0733	0.0775	0.776
2	1-5	1.1640	1.0400	1.2100	0.0091	0.0063	0.0033
3	2-3	1.2300	1.1370	1.1310	0.0145	0.0403	0.0404
4	2-4	0.8607	0.7337	0.7340	0.0031	0.0021	0.0026
5	2-5	0.8366	0.7160	0.7180	0.0287	0.0177	0.0166
6	3-4	0.0950	0.1410	0.1420	0.0560	0.0700	0.0110
7	4-5	**1.3400**	1.1200	1.1310	0.0181	0.0128	0.0127
8	4-7	0.4978	0.5040	0.4980	0.0461	0.0450	0.0309
9	4-9	0.4950	0.5010	0.5080	0.0481	0.0503	0.0470
10	5-6	1.0500	0.9890	1.0310	0.0684	0.0654	0.0652
11	6-11	0.7200	0.6630	0.6970	0.7090	0.7040	0.7055
12	6-12	0.2690	0.2710	0.2720	0.0359	0.0367	0.0361
13	6-13	0.6520	0.6480	0.6510	0.0590	0.0593	0.0613
14	7-8	0.6360	0.6310	0.6880	0.1417	0.1406	0.1358
15	7-9	0.9640	0.9570	0.9470	0.0583	0.0578	0.0522
16	9-10	0.1520	0.1401	0.1530	0.0035	0.0061	0.0038
17	9-14	0.2780	0.2710	0.2740	0.0070	0.0067	0.0061
18	10-11	0.6790	0.6680	0.6180	0.0602	0.0609	0.0420
19	12-13	0.1930	0.1960	0.2016	0.0236	0.0239	0.0222
20	13-14	0.6850	0.6321	0.4154	**0.0824**	0.0819	0.0614

Table 2. APPI and System Losses Comparision without and with Placement of UPFC under Normal Loading Conditions

S no:	UPFC location	APPI	MW Losses	MVAR Losses
1	Without UPFC	0.0897	13.5929	31.0093
2	UPFC placed in line 4-5	0.0812	12.6102	28.1176
3	UPFC placed in line 13-14	0.0835	13.0969	29.8166

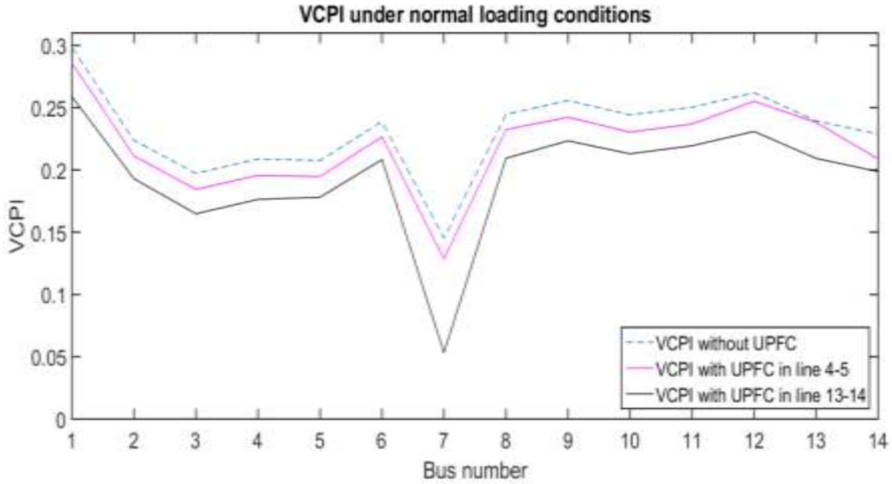

Figure 3. VCPI Under Normal Loading Condition

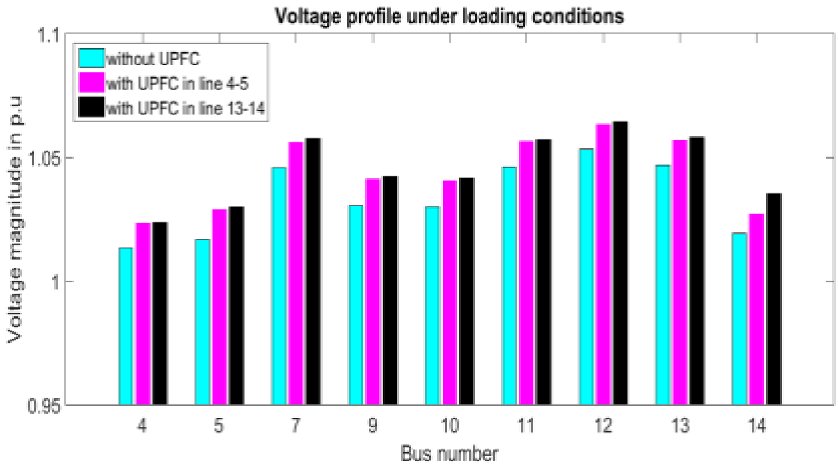

Figure 4. Voltage Profile under Normal Loading Condition

From Table I we observe that after placement of UPFC in line 4-5, LUF decreased to 1.12 from 1.34 L_{mn}-index also decreased 0.127 to 0.181. If UPFC is placed in line 13-14, LUF decreased to 0.4154 from 0.6850 and L_{mn}-index decreased to 0.0614 from 0.0824. The comparison of LUF values and L_{mn}-index values of each line with and without placement of UPFC has been presented in Table I. It can be observed that LUF values of more congested lines are decreased and least congested are increased i.e., redistribution of power flow can be observed. But this is in effective manner if UPFC is placed in line 4-5 than in line 13-14. Besides this L_{mn}-index values are decreased for most of the lines if UPFC is in line 4-5 and these values are decreased for all lines if it is in line 13-14.

We can notice that UPFC is providing good voltage stability as well as congestion relief, but Congestion relief performance is better when UPFC is placed in line 4-5 than line 13-14 as well as Voltage stability improvement is good if UPFC is in line 13-14 than in line 4-5.

This can be better understood by observing Table III, Figure 3 and Figure 4. In Table III, APPI is reducing with placement of UPFC, but APPI is smaller when UPFC in line 4-5 than in line 13-14. This is due to reduction of system losses are more which can be compared, indicating congestion relief. If we observe the VCPI and voltage profile in Figure 3 and Figure 4 respectively, VCPI have been decreased and the voltage profile of load buses have been improved with placement of UPFC but it is better when UPFC is placed in 13-14.

4.2. At 110% Loading Conditions:

On increasing the load, real power losses, reactive power losses increases and the voltage magnitudes will decreases. Placement of UPFC have improved active power flow performance and reduced the system losses which can be observed from the Table 3. Significant improvement of voltage profile and voltage stability can be observed from the results presented in Figure 5 and Figure 6 showing the voltage profile and VCPI variations under 110% loading condition.

Table 3. APPI and System Losses Comparison without and with Placement of UPFC under 110% Loading Conditions

S no:	UPFC location	APPI	MW Losses	MVAR Losses
1	Without UPFC	0.1152	17.0474	45.3861
2	UPFC placed in line 4-5	0.1041	15.0124	40.367
3	UPFC placed in line 13-14	0.1097	16.6927	41.2617

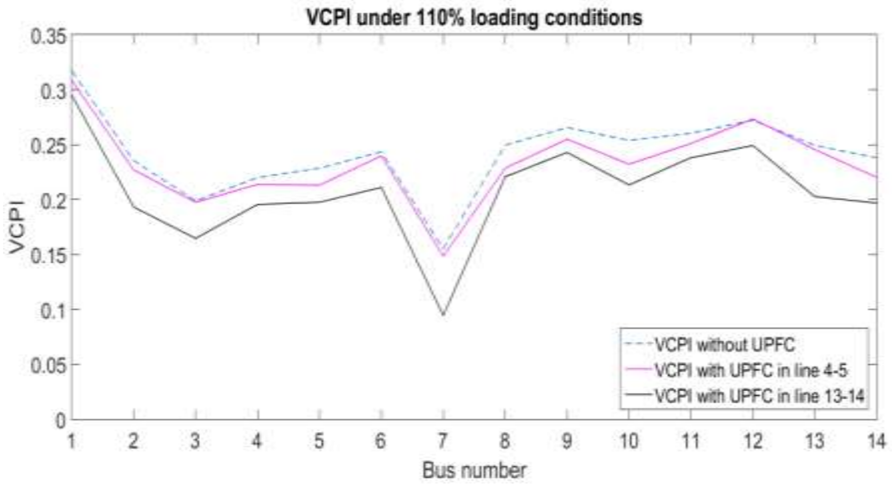

Figure 5. VCPI under 110% Loading Condition

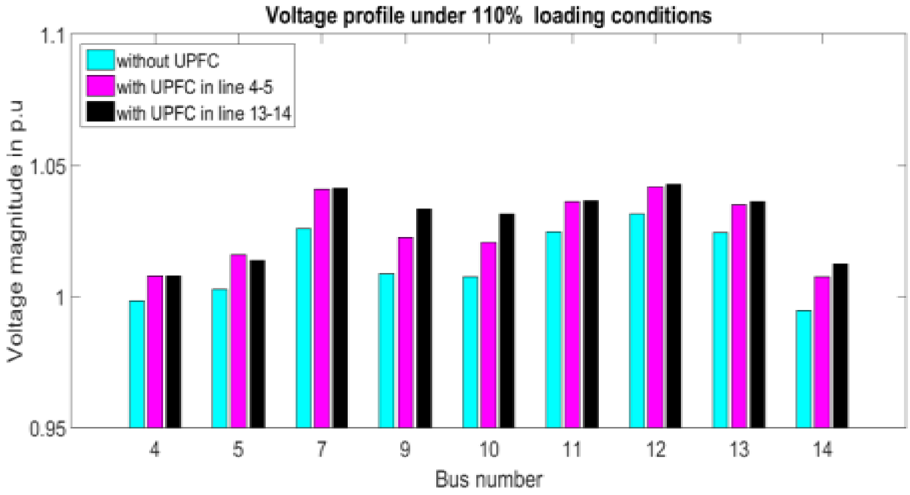

Figure 6. Voltage Profile Under 110% Loading Condition

4.3. At 130% Loading Conditions:

The results under 130% loading conditions are shown in Table 4, Figure 7 and Figure 8. With the UPFC placement, APPI values and reduction of system losses indicates the better congestion relief whereas improvement in voltage profile and reduction VCPI values indicates the better voltage stability.

Table 3. APPI and System Losses Comparison without and with Placement of UPFC under 130% Loading Conditions

S no:	UPFC location	APPI	MW Losses	MVAR Losses
1	Without UPFC	0.1815	25.7549	81.0093
2	UPFC placed in line 4-5	0.1632	23.8102	75.1176
3	UPFC placed in line 13-14	0.1737	24.8969	77.8166

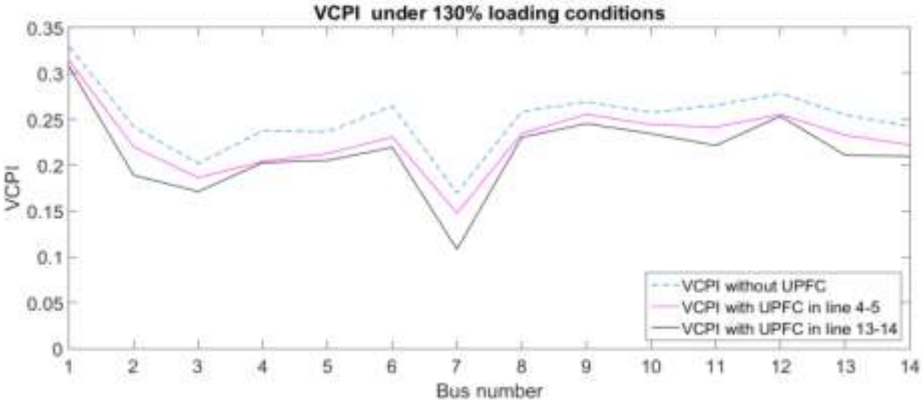

Figure 7. VCPI under 130% Loading Condition

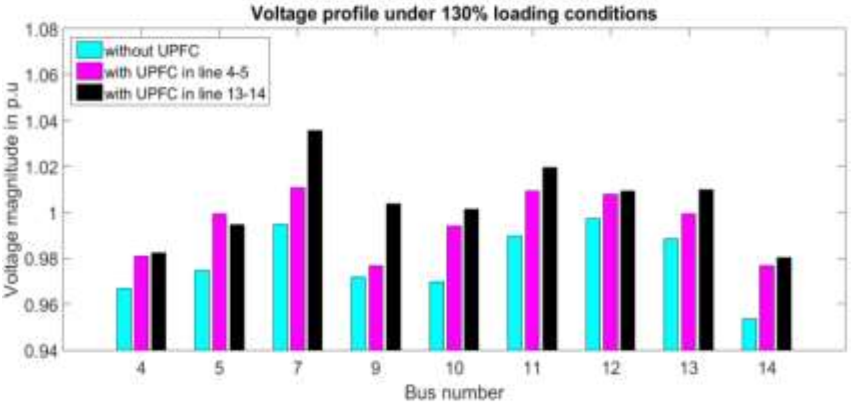

Figure 8. Voltage Profile under 130% Loading Condition

5. Conclusion

In this paper to address the congestion management and voltage stability issues, a handy FACTS device named Unified Power Flow Conditioner (UPFC) is used. We have placed the UPFC based upon line burden and voltage stability indices namely Line Utilization Factor (LUF) and L_{mn}-index. The impact of UPFC in congestion relief and Voltage stability improvement are assayed through Active Power Performance Index (APPI) and Voltage Collapse Proximity Indicator (VCPI). We can observe significant reduction in system losses and better improvement in voltage profile. The work is carried out on IEEE-14 bus system with different loading conditions and the MATLAB results shows the better congestion relief and improvement in Voltage stability.

6. Future Scope

In this paper UPFC is placed without tuning of its parameters, also two different locations are identified for its placement. The work is carried out on constant load, increased loads and without any contingency condition. Also it is more suitable in vertically integrated system. By using a suitable optimization algorithm with well-defined objective functions we can have optimal placement and tuning of UPFC which can give better results by identifying a single location for optimal placement, suitable parameters of UPFC, the security of the system also be improved in contingency condition and by defining selective capacity of FACTS device, it can be executed in economic manner. Here we examined with simple model of UPFC, so complex models of UPFC can be considered in further study.

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