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Location of UPFC in Electrical Transmission System: Fuzzy Contingency Ranking and Optimal Power Flow

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Abstract*—Increase in electrical power demand due to modernization has led to the increase in the number of power stations and their capacities and consequent increase in the power transmission lines which connect the generating stations to the load centers. So, the operation and planning of large interconnected power systems are becoming increasingly complex. The Fast-Decoupled Load Flow method is performed to estimate post –contingencies of line flows and bus voltages for other contingency cases. Based on system operator's past experience, each post-contingent quantity is assigned a degree of severity according to the potential damage that should be imposed on the power system. Hence human experts tend to use linguistic variables to describe the degree of severity, uncertainty exists in knowledge representation. The objective of contingency screening and ranking is to quickly and accurately select a shortlist of critical contingencies from a large list of potential contingencies and rank them according to their severity. This paper presents an approach for selection of suitable location for Unified Power Flow Controller (UPFC) considering normal and network contingencies. A new approach is considered using Fuzzy Logic Controller (FLC) to evaluate the degree of severity of the considered contingency and to eliminate the masking effect. The purpose of Optimal Power Flow (OPF) is to calculate the recommended set points for power system controls to trade-off between security and economy. The Newton Raphson (NR) method is considered to obtain Optimal Power Flow. It can be obtained either in a preventive or corrective mode. In this paper, a preventive mode of OPF is used to provide suggested improvements for selected contingency cases. The selection of suitable locations for UPFC, use the criteria on the basis of improved system security and Optimized Power flow. The proposed approach is tested on IEEE-14 bus system.

Keywords*— Power Flow Analysis (NRLF and FDLF), FLC, UPFC, OPF.

I. INTRODUCTION

The most comprehensive and flexible device emanated from the Flexible AC Transmission Systems (FACTS) initiative is UPFC. It improves system performance under normal and network contingency conditions. Also UPFC is most expensive thus it is important to ascertain the location for placement of UPFC device suitable for various network contingencies.

The UPFC is an advanced power system device capable of providing simultaneous control of voltage magnitude, active and reactive power flows in an adaptive fashion [1]. It has

- Instantaneous speed of response
- Extended functionality
- Capability to control voltage, line impedance and phase angle in the power system network
- Enhanced power transfer capability
- Ability to decrease generation cost
- Ability to improve security and stability
- Applicability for power flow control, loop flow control, load sharing among parallel corridors [2].

The location of UPFC device in the power system on the basis of static - dynamic performances. There are several methods for finding locations of UPFC in vertically integrated systems, but little attention has been devoted to interconnected power systems under network contingencies. Fuzzy set based reasoning approach has been developed for contingency ranking. The post contingent quantities like line flows and bus voltages are expressed in fuzzy notation and further processed through fuzzy reasoning rules to achieve desired contingency list [3] In this paper for selection of suitable locations of UPFC. The voltage stability index (L-index) of load buses is used as the basis for improved system performance after evaluating the degree of severity of the considered contingency [4]. By Fast-Decoupled Load Flow (FDLF**)** method, the value of L-index is calculated for various contingency cases. The proposed approach for selection of UPFC location has been tested on IEEE 14-bus system [5].

The purpose of Optimal Power Flow (OPF) is to calculate the recommended set points for power system controls that are trade-off between security and economy. The Newton Raphson (NR) method is considered to obtain optimal power flow. The primary task is to find a set of system states within a region defined by the operating constraints such as voltage limits and branch flow limits [11]. The secondary task is to optimize a cost function within this region. Typically, this cost function is defined to include economic dispatch of active power while recognizing the network-operating constraints. The OPF can be obtained either in a preventive or corrective mode [6]. In this paper, the preventive mode is considered to obtain the OPF which is used to provide suggested improvements for selected contingency cases.

II. VOLTAGE STABILITY INDEX (L -INDEX)

Consider a system where n is the total number of buses, with 1,2,.....g generator buses, and g+1,….n, (n-g) load buses. For a given system operating condition, using the load-flow results, the voltage-stability index [6-7] or L - index [7-8] is computed as,

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \quad \text{……..} \quad (1)$$

Where j = g +1,....,n and all the terms within the sigma on the right hand side are complex quantities. The values of F_{ji} are complex and are obtained from the network Y-bus matrix. For a given operating condition,

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad \text{………} \quad (2)$$

Where I_G, I_L, V_G, and V_L represent complex current and voltage vectors at the generator nodes and load nodes. [Y_{GG}], [Y_{GL}], [Y_{LL}] and [Y_{LG}] are corresponding partitioned portions of the network Y-bus matrix.
Rearranging, one can obtain

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad \text{………} \quad (3)$$

Where,

$$[F_{LG}] = -[Y_{LL}]^{-1}[Y_{LG}] \quad \text{……….} \quad (4)$$

For stability, the index Lj must not be violated (maximum limit = 1) for any node j. Hence, the global indicator L describing the stability of the complete subsystem is given by L= maximum of Lj , for all j (load buses). An L-Index value away from 1 and close to 0 indicates improved system security. For an unloaded system with generator/load buses voltage 1.0+j0.0 the L indices for load buses are closest to zero, indicating that the system has maximum stability margin. For a given network, as the load/generation increases, the voltage magnitude and angles change near maximum power-transfer condition and the voltage-stability index Lj values for load buses tend to close to unity, indicating that the system is close to voltage collapse. While the different methods give a general picture of the proximity of the system voltage collapse, the L index gives a scalar number to each load bus. Among the various indices for voltage-stability and voltage collapse prediction, the L index gives fairly consistent results. The L indices for given load conditions are computed for all the load buses; and the maximum of the L-indices gives the proximity of the system to voltage collapse.

Algorithm for obtaining voltage stability index:

- Form the network admittance matrix for the system.
- Obtain the elements of F_{LG} by using equation (4).
- Obtain the value of L-index by using the formula specified in the equation (1) by substituting the values of F_{LG} which are determined in step 2

III. IMPLEMENTATION OF FUZZY SET THEORY FOR CONTINGENCY RANKING

The proposed fuzzy approach uses L-index as post contingent quantity in addition to bus voltage profiles to evaluate contingency ranking [3]. The bus voltage profile and L-index values are expressed in fuzzy set notation. The severity indices are also divided into different categories. The fuzzy rules are used to evaluate the severity of each post contingent quantity. The Fuzzy inference structure is tested in MATLAB fuzzy toolbox.

3.1. Bus voltage profiles

The post contingent bus voltage profiles are divided into three categories using fuzzy-set notations: Low Voltage (LV), below 0.95 p.u., Normal Voltage (NV), 0.95-1.05 p.u.., and Over Voltage (OV), above 1.05 p.u. The corresponding membership functions for 3 linguistic variables of bus voltage profiles are shown in Fig.1.

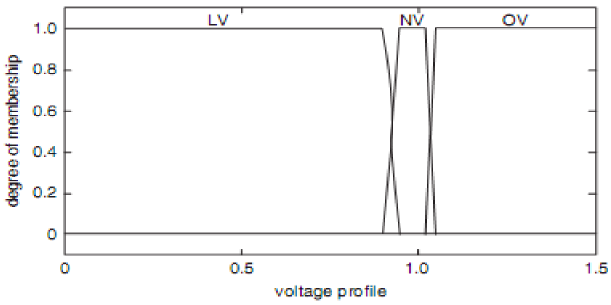

Fig.1. Membership function for 3 linguistic variables of bus voltage profiles

3.2. L-Index

The post contingent L-indices are divided into five categories using fuzzy set notation: Very Small Index (VSI),0-0.1, Small Index (SI), 0.1-0.3, Medium Index (MI), 0.3-0.6, High Index (H), 0.6-0.8, Very High (VHI) 0.8-0.9. The corresponding membership functions for 5 linguistic variables of L-index are shown in Fig. 2.

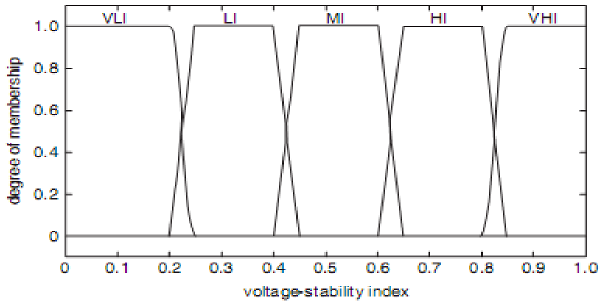

Fig.2.Membershipfunctionsf or5 linguistic variables of L- Index.

3.3 Real Power Loading

Each post-contingent percentage of Real Power Loading is divided into four categories using Fuzzy set notation: Lightly Loaded, 0-50% (LL), Normally Loaded, 50-80% (NL), Fully Loaded 85-100% (FL), and Over Loaded, above 100% (OL). Fig.3 shows the relationship between Real Power Loading and the four linguistic variables which shows the range of loadings as a ratio of actual flow to its rated MVA loading covered by linguistic variables.

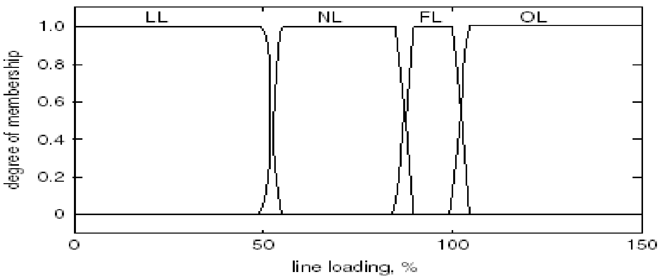

Fig .3 Membership functions for 4 linguistic variables of line loading

3.4. Reactive Power Loading

Each post-contingent percentage of Reactive Power Loading is divided into four categories using Fuzzy set notation: Lightly Loaded, 0-50% (LL), Normally Loaded, 50-80% (NL), Fully Loaded 85-100% (FL), and Over Loaded, above 100% (OL). Fig.4 shows the relationship between Reactive Power Loading and the four linguistic variables which shows the range of loadings as a ratio of actual flow to its rated MVAr loading covered by **l**inguistic variables.

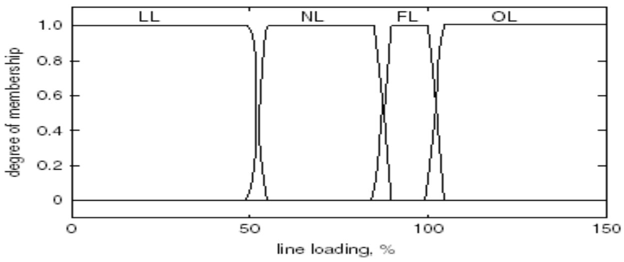

Fig. 4. Membership functions for 4 linguistic variables of reactive power loading

The fuzzy rules are used for evaluation of severity index of post contingent quantities like bus voltage profiles, L-index, Real and Reactive power loadings are tabulated in table 1.

Table 1: Fuzzy rules

Post- contingent quantity.	Severity Index
LV,NV,OV	MS, BS, MS
VLI, LI, MI, HI,VHI	VLS, LS,BS,AS,MS
LL, NL,FL,OL	LS,BS,AS,MS
LL,NL,FL,OL	LS,BS,AS,MS.

Where: VLS- very less severe; LS- less severe;
BS- below severe,; AS – above severe ; MS – more severe.

After obtaining the Severity Index (SI) of all the bus-voltage profiles, voltage-stability index, Real and Reactive power loadings, by using Fuzzy approach, the overall-severity index (OSI) for a particular line outage are obtained using the expressions:

$$OSI_{VP} = \sum W_{VP} * SI_{VP}$$
$$OSI_{VSI} = \sum W_{VSI} * SI_{VSI}$$
$$OSI_{LP} = \sum W_{LP} * SI_{LP}$$
$$OSI_{LQ} = \sum W_{LQ} * SI_{LQ}$$

Where- W_{VP},$W_{VSI,}$ W_{LP} and W_{LQ} are the weighing coefficients for severity indexes of, voltage profile, voltage-stability index, Real and Reactive power ladings respectively.
SI_{VP}, $SI_{VS,I}$, SI_{LP} and SI_{LQ} are the severity index of post-contingent Voltage profile, voltage stability index Real and Reactive power ladings respectively.

The effect of these weighing coefficients is that the Overall severity index is first dominated by the severity index MS, and next by the severity indexes AS, BS, LS, and VLS, respectively. Thus the overall severity index reflects the actual severity of the system for a contingency.

IV. SYSTEM OVERALL-SEVERITY INDEX(SOSI)

The network composite System Overall Severity Index is obtained by adding the four Overall Severity Indices as Shown in Fig.5 which is called Parallel Operated Fuzzy Inference System (FIS). When the Overall Severity Index for each Contingency in the contingency list is obtained, the overall Severity indices for those contingency cases with a severity Index exceeding a pre-specified value are listed, and ranked According to the network composite Overall Severity Index.

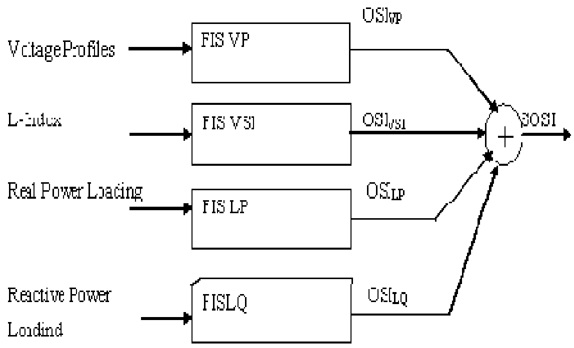

Fig.5. Parallel Operated Fuzzy Inference System

4.1 Approach for the Location of UPFC Based on Contingency Ranking

It is proposed to improve the performance of the system by selecting suitable locations for UPFC. Computations are carried out with UPFC in three locations for each contingency case. A contingency may involve a line having UPFC, and thus two locations for UPFC are selected based on the best performance of the system. These two locations of UPFCs can take care of severe network contingencies for the system studied.

Computational steps involved in the approach for selection of UPFC location under a given network contingency are:

Step1: Obtain the contingency ranking by using F.A.
Step2: Select a few transmission lines at suitable Locations for each network contingency.
Step3: Perform the power-flow analysis with UPFC Connected in the selected line for a given network Contingency.
Step4: Compute the power loss at each and every location of UPFC for each contingency and tabulate the results.
Step5: From the results, one can identify the most suitable location for UPFC, which gives a minimum value for power loss.

V. TESTING OF ON IEEE 14-BUS SYSTEM

In order to effectively investigate the impact of UPFC device on transmission systems, the implementation has been tested on IEEE 14-Bus system [12], which consists of Five Synchronous machines, three of which are Synchronous compensators used for reactive power Support and another two of which one is considered as generator bus and another one is considered as a slack bus, which is also called as reference bus and three Tap changing Transformers and one tertiary winding Transformer. There are shunt reactors also connected at various buses for transient-over voltage protection. In this system there are 20 lines and 12 loads. The system totaling is 270.2 MW and 73.5 MVAr, the corresponding p.u. values with base quantities 100 MVA would be 2.702 p.u and 0.735 p.u respectively.

5.1. Contingency ranking

In this section the Fuzzy set based reasoning approach has been developed for contingency ranking of the system to eliminate the "Masking Effect". The contingency analysis is carried out using FDLF method.
The simulated program is tested in MATLAB environment and the convergence obtained in five iterations with a tolerance of 0.0001, the corresponding voltage complexes, L-indexes, **of** a pre-outage case are given in Table 1.

Table: 1 Voltages, angles, L-indices, under normal Condition

Bus No	Voltage (V)	Angle(Deg)	L-index
1	1.0600	0.0000	-
2	1.0397	0.0000	-
3	1.0100	-17.1798	0.0374
4	0.9765	-13.1586	0.0749
5	0.9833	-10.7984	0.0664
6	1.0700	-22.3712	0.0369
7	1.0158	-20.7474	0.0671
8	1.0900	-20.7474	0.0055
9	0.9844	-23.4799	0.1069
10	0.9848	-23.8356	0.1100
11	1.0199	-23.3092	0.0796
12	1.0373	-24.0158	0.0680
13	1.0235	-24.1051	0.0811
14	0.9654	-25.8353	0.1363

For finding the Severity Index, the heuristic rules are to be used**.** The system consists of 20 lines and each line is removed as a single line outage (contingency) to obtain contingency ranking based on the severity index. The System Overall Severity Index (SOSI) is obtained by adding the four overall Severity Indices as shown in Fig 4 and the Overall Severity Index for each contingency in the contingency list is obtained, the Overall Severity Indices for those contingency cases with a Severity Index exceeding the pre-specified value are listed out and ranked according to System Overall Severity Index. The top ten contingencies are arrived based on the System Overall Severity Index obtained by using Fuzzy Approach and corresponding results are tabulated in Table 2.

Table: 2 The Overall Severity ranking based on FLC

Line between buses	**OSI_{VP}**	**OSI_{VSI}**	**OSI_{LP}**	**OSI_{LQ}**	**SOSI**	**RANk**
2-3	561.315	26.504	1332.837	1567.779	3488.435	1
6-11	651.181	26.504	1190.699	1424.349	3292.733	2
10-11	687.145	26.504	1214.870	1337.027	3265.54	3
1-5	609.681	26.504	1074.614	1531.482	3242.282	4
2-5	613.744	26.504	1109.367	1485.216	3234.832	5
2-4	565.165	26.504	1259.983	1374.429	3226.081	6
1-2	555.481	26.504	1075.087	1409.786	3066.859	7
4-7	563.873	26.504	1234.325	1230.910	3055.612	8
9-14	626.883	27.149	1061.337	1304.403	3019.772	9
13-14	638.976	28.068	1061.267	1215.457	2943.76	10

The proposed approach can provide the user that may cause immediate loss of load or islanding at certain bus. This kind of information in which is a very helpful to system operators, an Overall Severity Index is given for which outage case.

5.2 Location of UPFC for OPF

Most of the contingencies may not pose threat to the System performance. Those contingencies that pose serious system performance are selected. A set of most severe contingencies, in the order of severity, is identified which needs additional supporting devices. Based on the above set of network contingencies, a few transmission lines are considered for placement of UPFC device for each contingency. The selection of UPFC location under network contingency is carried out by using Fuzzy approach of composite rule, out of which for illustration purpose, top three contingency ranks are considered and the corresponding results are tabulated in Tables 3 to 5

Table 3: Rank1 Contingency (Line outage 2-3)

S.No	**Line**	**Total power loss (p.u.)**
1	2-5	0.1393
2	3-4	0.1564

From the Table 3, it is observed that the possible locations of UPFC under this rank- 1 contingency are 2-5 and 3-4. When UPFC is placed between 2-5 gives minimum power loss as compared to the position of 3-4.

Table 4: Rank2 Contingency **(line outage 6-11)**

S.No	**Line**	**Total power loss (p.u.)**
1	6-5	0.1629
2	11-10	0.1869

From the Table 4, it is observed that the possible locations of UPFC under this rank 2 contingency are 6-5 and 11-10. When UPFC is placed between 6-5 gives minimum power loss as compared to the position of 11-10.

Table 5: Rank3 Contingency (line outage 10-11)

S.No	Line	Total power loss (p.u.)
1	9-10	0.1417
2	6-11	0.1490

From the Table 5, it can be observed that the possible locations of UPFC under this rank 3 contingency are 9-10 and 6-11.When UPFC is placed between 9-10 gives minimum power loss as compared to the position of 6-11.

From the above results, for contingency 2-3, when UPFC is placed between buses 2-5 gives minimum power loss and significant improvement in Voltage profiles and Power profiles. So the line 2-5 is selected as best location of UPFC to achieve Optimal Power Flow (OPF). This is summarized in Table 10

VI. TEST RESULTS WITH OPTIMAL POWER FLOW

The Optimal Power Flow (OPF) is to calculate the recommended set points for power system controls to trade-off between security and economy by using N-R method [8- 9-10]. It can be obtained either in a preventive or corrective mode. For contingencies found to cause over loads, voltage limit violations are the stability problems, hence preventive actions are required. In this paper**,** a preventive mode of OPF is considered, and test results are carried out with and without UPFC device which is presented in the following sections.

6.1. Test Results without UPFC

The system is simulated on Matlab Environment, the Voltage profile at each bus of the system is given Table. 6 and the Power flow profile of the each line of the system is given in Table7.

Table 6: Voltage profile

Bus code	Voltage(p.u)	Angle(deg)
1	1.060000	0.000000
2	0.954157	4.725332
3	0.861736	10.311505
4	0.844637	8.753683
5	0.832320	7.599271
6	0.868774	12.237421
7	0.868180	11.830225
8	0.868180	11.830225
9	0.881651	12.907436
10	0.885748	13.008747
11	0.880336	12.731503
12	0.881265	12.912938
13	0.885347	12.981765
14	0.898076	13.678048

Table 7 Power flow profile without UPFC

Line No.	Bus No.	Real power(p.u)	Reactive power(p.u)	Loss(p.u)
1	1-2	0.693648	2.151743	0.136903
2	1-5	0.489303	0.501066	0.057349
3	2-3	0.506506	-0.154066	0.022396
4	2-4	0.402241	-0.090213	0.011125
5	2-5	0.287793	-0.068980	0.016416
6	3-4	-0.173764	0.017535	0.029642
7	4-5	-0.509925	0.127629	0.003811
8	4-7	0.259911	-0.104998	0.016610
9	4-9	0.133635	-0.061348	0.012156
10	5-6	0.321103	-0.129087	0.031281
11	6-11	0.060009	-0.030366	0.000961
12	6-12	0.058646	-0.021281	0.001064
13	6-13	0.135667	-0.060028	0.003098
14	7-8	0.000000	0.000000	0.000000
15	7-9	0.179505	-0.122994	0.005025
16	9-10	0.036072	-0.036425	0.000223
17	9-14	0.068039	-0.030323	0.001558
18	10-11	-0.033304	0.015025	0.000260
19	12-13	0.013363	-0.006284	0.000061
20	13-14	0.045420	-0.015331	0.000831

6.2. Test Results with UPFC

The UPFC is connected between the 2-5 based on the (contingency) severity of the system, the sample test results are tabulated. The voltage profile at each bus of the system is given in Table 8 and the Power flow profile of the each line of the system is given in Table 9

Table.8 Voltage profile

Bus No	**Voltage (p.u)**	**Angle (deg)**
1	1.060000	0.000000
2	0.970344	3.632111
3	1.027969	6.749644
4	1.024513	5.971632
5	1.005439	5.433918
6	1.038769	8.014333
7	1.042393	7.686850
8	1.042393	7.686850
9	1.052448	8.314296
10	1.055150	8.388034
11	1.049456	8.259904
12	1.049103	8.404171
13	1.052622	8.434328
14	1.064534	8.808441

Table.9: Power flow profile

Line No.	Bus No.	Real Power(p.u)	Reactive power(p.u)	Loss(p.u)
1	1-2	0.509111	1.778144	0.060840
2	1-5	0.363171	0.341113	0.012881
3	2-3	0.321194	-0.219371	0.007120
4	2-4	0.294833	-0.212249	0.007742
5	2-5	0.216437	-0.138473	0.003736
6	3-4	-0.079733	-0.016667	0.000409
7	4-5	-0.342601	0.356542	0.003110
8	4-7	0.152857	-0.085307	0.000000
9	4-9	0.079245	-0.049837	0.000000
10	5-6	0.186578	-0.128769	0.000000
11	6-11	0.040814	-0.036276	0.000262
12	6-12	0.039891	-0.022699	0.000240
13	6-13	0.093419	-0.062805	0.000777
14	7-8	0.000000	0.000000	0.000000
15	7-9	0.109206	-0.094680	0.000000
16	9-10	0.025906	-0.023889	0.000036
17	9-14	0.047322	-0.024644	0.000327
18	10-11	-0.022209	0.021807	0.000071
19	12-13	0.010498	-0.006868	0.000032
20	13-14	0.031167	-0.020653	0.000216

Table 10: Summary of results with and without UPFC for Optimal Power Flow

S.No	**Bus No.**	**Parameter**	**Without UPFC (p.u)**	**With UPFC (p.u.)**
1	2	Voltage Magnitude	0.954157	0.970344
2	5	Voltage Magnitude	0.832320	1.005439
3	2-5	Power loss	0.016416	0.003736
4	Total power loss of the system		0.3507	0.1393

From the results when UPFC is placed between line 2-5 the power loss is reduced from 0.016416p.u. to 0.003740 p.u. and at the same time the voltage magnitudes at the corresponding buses increased from 0.954157p.u (bus no 2) to 0.970344p.u (bus no 2), and from 0.83232 (bus no 5) p.u. to 1.0054390p.u (bus no 5) respectively. Similarly the voltage magnitudes at all buses are increased and are in limits according to statutory act, total power loss of the system reduced from 0.3507p.u (35.07 MW) to 0.1393 p.u (13.93MW) by placing the UPFC at specified location. From the above results the most severe contingencies are selected based on severity by using Fuzzy Approach, and the voltage profile, power flow through the lines increases and power loss at those severe contingencies and in overall system also reduced by placing the UPFC which are the main objective of OPF.

VII. CONCLUSIONS

In this paper, bus voltages and the voltage stability indices at the load buses are also used as the post-contingent quantities to evaluate the network composite contingency ranking. The fuzzy contingency ranking method eliminates the masking effect of other methods of contingency ranking effectively. The selection of UPFC location under contingencies is obtained in the order of system severity. A set of most severe contingencies, based on the severity, is identified which needs additional supporting devices. Based on the above set of network contingencies, a few transmission lines are considered for placement of UPFC devices. For each contingency, analyses are carried out with placement of UPFC in different transmission lines.

From the results the most severe contingencies are selected based on severity by using fuzzy, and the voltage profile, power flow through the lines increases and power loss at those severe contingencies also reduces by placing the Unified Power Flow Controller (UPFC). The proposed approach for UPFC location and Optimal Power Flow (OPF) can be tested for any bus system.

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