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Fuzzy Logic Based Power System Contingency Ranking

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Abstract— Voltage stability is a major concern in planning and operations of power systems. It is well known that voltage instability and collapse have led to major system failures. Modern transmission networks are more heavily loaded than ever before to meet the growing demand. One of the major consequences resulted from such a stressed system is voltage collapse or instability. This paper presents maximum loadability identification of a load bus in a power transmission network. In this study, Fast Voltage Stability Index (FVSI) is utilized as the indicator of the maximum loadability termed as Q_{max}. In this technique, reactive power loading will be increased gradually at particular load bus until the FVSI reaches close to unity. Therefore, a critical value of FVSI was set as the maximum loadability point. This value ensures the system from entering voltage-collapse region. The main purpose in the maximum loadability assessment is to plan for the maximum allowable load value to avoid voltage collapse; which is important in power system planning risk assessment.

The most important task in security analysis is the problem of identifying the critical contingencies from a large list of credible contingencies and ranks them according to their severity. The condition of voltage stability in a power system can be characterized by the use of voltage stability indices. This paper presents fuzzy approach for ranking the contingencies using composite-index based on parallel operated fuzzy inference engine. The Line Flow index (L.F) and bus Voltage Magnitude (VM) of the load buses are expressed in fuzzy set notation. Further, they are evaluated using Fuzzy rules to obtain overall Criticality Index. Contingencies are ranked based on decreasing order of Criticality Index and then provides the comparison of ranking obtained with FVSI method.

Index Terms— Contingency Ranking, Fuzzy Sets, Line Flow Index, FVSI, Criticality Index

I. Introduction

Voltage stability has been identified as a crucial issue in power system study and one of the causes that lead to cascading power system blackout in many parts of the world. This phenomenon has made this subject a very relevant issue in power system planning and operation. There are many incidents of power system blackouts, due to voltage collapse, as reported in [1-3]. Thus, it is very important to know the maximum permissible loading of a system so that it can be operated with an adequate voltage stability margin to prevent voltage collapse. Due to the fact that many systems have not expanded their transmission and generation capacity in recent years, many utilities are operating closer to their maximum capacity. For a system with smaller margin, more contingencies are considered as severe contingencies, and the system is exposed to more frequent voltage collapses [4]. Many power systems are now experiencing voltage problems more frequently and voltage studies have gained increasing attention from operating and planning points of views. It is vital, then, for the electric utility planners and operators to know the impact of every contingency on the voltage profile. Ranking all possible contingencies based on their impact on the system voltage profile will help the operators in choosing the most suitable remedial actions before the system moves toward voltage collapse. To maintain the system reliability, it is desirable to study the impact of the contingency on the power system, and to categorize them based on their severities. The change in loading margin to voltage collapse when line outages occur is estimated, a nose curve is computed by continuation to obtain a nominal loading margin. Then linear and quadratic sensitivities of the loading margin to each contingency are computed and used to estimate the resulting change in the loading margin [5]. A Fuzzy Set theory based algorithm is used to identify the weak buses in a power system. Bus voltage and reactive power loss at that bus are represented by membership functions for voltage stability study [6]. Newton optimal power flow is used to identify the weakest bus / area, which is likely to cause voltage collapse. The complex power – voltage curve is examined through Newton optimal power flow. The indicator, which identifies the weakest bus, was obtained by integrating all the marginal costs via Kuhn-Tucker theorem [7]. A Fast Voltage Stability Index is used to estimate the maximum loadability for identification of weak bus. The indicator is derived from the voltage quadratic equation at the receiving bus in a two bus system. The load of a bus, which is to be ranked is increased till maximum value of FVSI is reached and this load value is used as an indicator for ranking the bus [8]. A weak bus-oriented criterion is used to determine the candidate buses for installing new VAR sources in VAR planning problem. Two indices are used to identify weak buses based on power flow Jacobian matrix calculated at the current operating point of the system [9]. A neural network method for the identification of voltage weak buses/areas uses singular value decomposition method. Kohonen neural network is trained to cluster/rank buses in terms of voltage stability [10].

In this paper, analysis of voltage behavior has been approached using static techniques, which have been widely used on voltage stability analysis. An accurate knowledge of how close the actual system's operating point is from the voltage stability limit is crucial to operators. Therefore, to find a voltage stability index has become an important task for many voltage stability studies. These indices provide reliable information about proximity of voltage instability in a power system. Usually, their values change between 0 (no load) and 1 (voltage collapse).

Firstly, FVSI was utilized as the measurement to indicate the voltage stability condition in the maximum loadability identification at several load buses, then Fuzzy logic based algorithm for contingencies ranking is presented. Hence the L.F index and FVSI are used as a static voltage collapse proximity indicators. In order to evaluate the fuzzy logic based algorithm, so results obtained will be compared with FVSI results. The results of contingency analysis and maximum loadability can be used as a guide for controlling and planning of power systems. The approach is tested on IEEE 14 and 30 bus test systems.

II. Static Voltage Stability Indicators

2.1 Fast Voltage Stability Index (FVSI)

Voltage stability index proposed by I.Musirin *et al.* [11] can be conducted on a system by evaluating the voltage stability referred to a line. The voltage stability index referred to a line is formulated from the 2-bus representation of a system. The voltage stability index developed is derived by first obtaining the current equation through a line in a 2-bus system. Representation of the system illustrated in Fig. 1

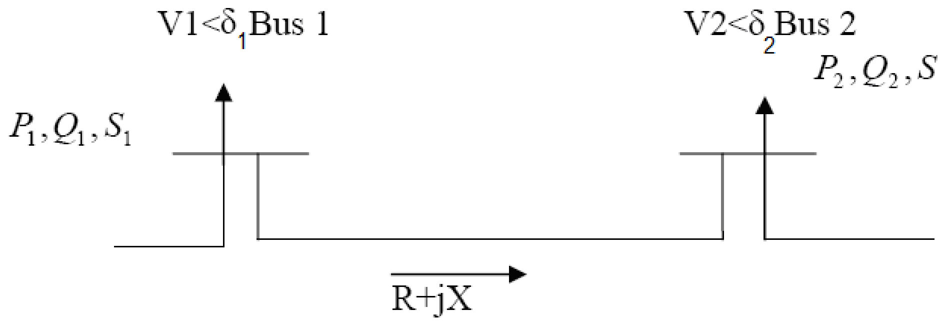

Fig. 1: 2- bus system model

$$FVSI_{ij} = \frac{4 \cdot Z^2 \cdot Q_j}{V_i^2 \cdot X} \quad (1)$$

Where,

Z: line impedance

X: line reactance

Q_j: reactive power at the receiving end

Vi: sending end voltage

2.2 Line Flow Index (L.F)

The Line Flow (L.F) index proposed by M.Moghavvemi *et al.* [12] investigates the stability of each line of the system and they are based on the concept of maximum power transferred through a line as shown in Fig. 2.

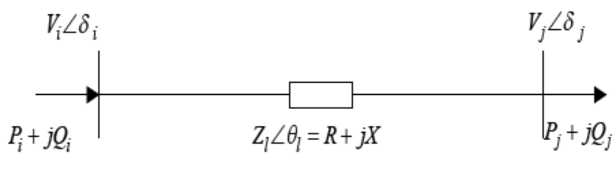

Fig. 2: A transmission line of a power system network

$$L.Findex = \frac{P_R}{P_{R(MAX)}} \quad (2)$$

Where the value of P_R *is* obtained from conventional power flow calculations, and $P_{R(max)}$ is the maximum active that can be transferred through a line. The Line Flow index varies from 0 (no load condition) to 1 (voltage collapse).

$$P_{R(MAX)} = \left(\frac{V_i^2}{2Z_l}\right)\left(\frac{\cos\phi}{1+\cos(\theta_l-\phi)}\right)$$

Where V_i is the voltage magnitude of sending bus of branch i-j, Z_l and θ_l are the magnitude and angle of branch impedance respectively , $\Phi = \arctan(Q_j / P_j)$

III. Determination of Max. Laudability

Maximum loadability identification is important part of the power systems study. It is conducted in power transmission system in order to identify the maximum permissible load that can be sustained by a load bus. Two reliability test system IEEE 14-Bus and IEEE 30-Bus [13] were utilized for this test which involved experiment on several load buses in both test system.

3.1 IEEE-14 case study

In the IEEE 14; three load buses were chosen namely buses 5, 12 and 14 for the tests. These buses were selected mainly due to the types of transmission lines that were connected to them. First, bus 5 was chosen because it represented the few buses connecting the main transmission lines (including the voltage-controlled buses and slack bus) in the system and buses 12 and 14 were chosen randomly among the load buses (distribution buses). Tests were conducted by gradually increasing the reactive power loading at selected bus and the FVSI values for line connected to this bus was calculated accordingly. The reactive power loading at the selected bus was increased in stages until it reaches its voltage stability limit indicated by FVSI value close to unity. The results for the FVSI values and voltage magnitude recorded.

From the table 1, it is observed that the FVSI values at the connecting lines increase accordingly as the reactive power loading at bus 5 was gradually increased. It can be seen that at the maximum reactive power loading of 2.6 p.u., the FVSI values for lines 2, 5, 7 and 10 reach their maximum values of 0.8836, 0.7815, 0.3345 and 0.1363 respectively. At this point, line 2 gives the highest FVSI value of 0.8836. This indicates that this line is close to its voltage stability limit. Further increase in reactive power loading at bus 5 would cause the FVSI value at line 2 to exceed unity. This implies that the line has reached its unstable condition, which may lead to voltage collapse to the entire system. The maximum value of reactive power loading is identified as the maximum loadability of this load bus. Bus 5 is expected to operate at the loading condition less than this point so that secure operation could be maintained. The increase in the reactive power loading at bus 5 has also reduced its voltage to 0.62791p.u. as indicated in the table. The trend of FVSI values at each line connected to bus 5 and the voltage magnitude when reactive power loading at this bus was increased is illustrated in Fig. 3. From the figure, it is observed that FVSI profiles increase accordingly with respect to the reactive power loading increment. On the other hand, voltage reduces with respect to the increment of loading condition. It is also observed that line 2 has the highest FVSI profile indicating the sensitive line

Table 1: Results for FVSI values at the lines connected to bus 5 and voltage magnitude with respect to the increase reactive in power loading

Line No.	Q(p.u)	Line	FVSI	Voltage (p.u)
2	0.75	1-5	0.142	0.97588
10	0.75	6-5	0.0194	
5	0.75	2-5	0.138	
7	0.75	4-5	0.078	
2	1.25	1-5	0.325	0.92015
10	1.25	6-5	0.0186	
5	1.25	2-5	0.295	
7	1.25	4-5	0.113	
2	1.72	1-5	0.5	0.85764
10	1.72	6-5	0.0212	
5	1.72	2-5	0.389	
7	1.72	4-5	0.155	
2	2	1-5	0.6089	0.81238
10	2	6-5	0.0267	
5	2	2-5	0.4785	
7	2	4-5	0.1883	
2	2.3	1-5	0.7307	0.75047
10	2.3	6-5	0.0423	
5	2.3	2-5	0.5921	
7	2.3	4-5	0.2351	
2	2.6	1-5	0.8836	0.62791
10	2.6	6-5	0.1363	
5	2.6	2-5	0.7815	
7	2.6	4-5	0.3345	

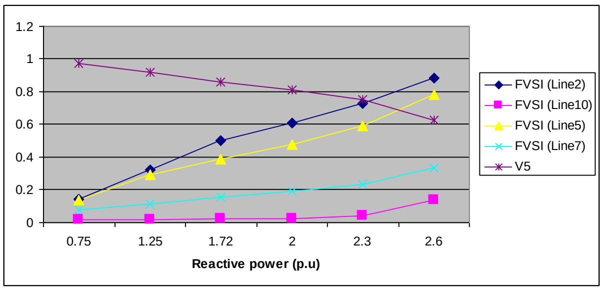

Fig. 3: Effect of Q variation at bus 5 to voltage profile and FVSI evaluated on the lines connected to bus 5

Table 2: Results for FVSI values at the lines connected to bus 12 and voltage magnitude with respect to the increase reactive in power loading

Line No.	Q(p.u)	Line	FVSI	Voltage (p.u)
12	0.2	6-12	0.1485	1.0154
19	0.2	13-12	0.1147	
12	0.35	6-12	0.2626	0.95606
19	0.35	13-12	0.2421	
12	0.45	6-12	0.3532	0.90617
19	0.45	13-12	0.3446	
12	0.565	6-12	0.4876	0.8275
19	0.565	13-12	0.5	
12	0.65	6-12	0.6278	0.74505
19	0.65	13-12	0.6721	
12	0.715	6-12	0.8646	0.60021
19	0.715	13-12	0.9881	

The trend of FVSI values at each line connected to bus 12 and the voltage magnitude when reactive power loading at this bus was increased is illustrated in Fig. 4

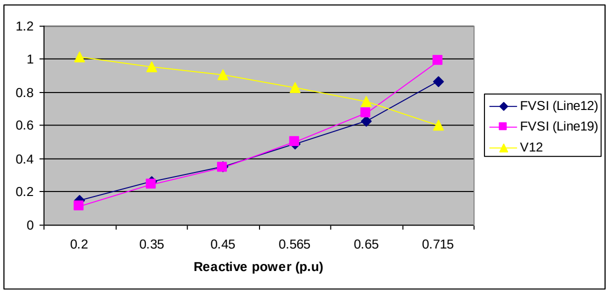

Fig. 4: Effect of Q variation at bus 12 to voltage profile and FVSI evaluated on the lines connected to bus 12

Table 3: Results for FVSI values at the lines connected to bus 14 and voltage magnitude with respect to the increase reactive in power loading

Line No.	Q(p.u)	Line	FVSI	Voltage (p.u)
17	0.1	9-14	0.072	1.025
20	0.1	13-14	0.062	
17	0.2	9-14	0.138	1.0031
20	0.2	13-14	0.136	
17	0.35	9-14	0.262	0.94834
20	0.35	13-14	0.242	
17	0.5	9-14	0.4121	0.87134
20	0.5	13-14	0.3759	
17	0.57	9-14	0.5	0.82192
20	0.57	13-14	0.457	
17	0.65	9-14	0.6274	0.74853
20	0.65	13-14	0.5769	
17	0.727	9-14	0.88034	0.58707
20	0.727	13-14	0.8288	

The trend of FVSI values at each line connected to bus 14 and the voltage magnitude when reactive power loading at this bus was increased is illustrated in Fig. 5

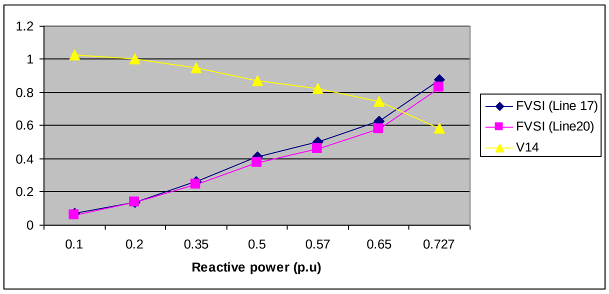

Fig. 5: Effect of Q variation at bus 14 to voltage profile and FVSI evaluated on the lines connected to bus 14

3.2 IEEE-30 case study

In the IEEE 30; four load buses were chosen namely buses 4, 14, 24 and 30 for the tests. Tests were conducted by gradually increasing the reactive power loading at selected bus and the FVSI values for line connected to this bus was calculated accordingly. The reactive power loading at the selected bus was increased in stages until it reaches its voltage stability limit indicated by FVSI value close to unity. The results for the FVSI values and voltage magnitude recorded.

Table 4: Results for FVSI values at the lines connected to bus 4 and voltage magnitude with respect to the increase reactive in power loading

Line No.	Q (p.u)	Line	FVSI	Voltage (p.u)
4	0.6	3-4	0.02	0.97675
3	0.6	2-4	0.1208	
7	0.6	6-4	0.0676	
15	0.6	12-4	0.0446	
4	1	3-4	0.0542	0.93596
3	1	2-4	0.212	
7	1	6-4	0.0912	
15	1	12-4	0.0346	
4	2	3-4	0.1883	0.79208
3	2	2-4	0.5	
7	2	6-4	0.1764	
15	2	12-4	0.0598	
4	2.2	3-4	0.2351	0.74672
3	2.2	2-4	0.5889	
7	2.2	6-4	0.2045	
15	2.2	12-4	0.0814	
4	2.43	3-4	0.3496	0.64364
3	2.43	2-4	0.7501	
7	2.43	6-4	0.2651	
15	2.43	12-4	0.1966	

From the table 4, it is observed that the FVSI values at the connecting lines increase accordingly as the reactive power loading at bus 4 was gradually increased. It can be seen that at the maximum reactive power loading of 2.43 p.u., the FVSI values for lines 3, 4, 7 and 15 reach their maximum values of 0.7501, 0.3496, 0.2651 and 0.1966 respectively. At this point, line 3 gives the highest FVSI value of 0.7501 this indicates that this line is close to its voltage stability limit. Further increase in reactive power loading at bus 4 would cause the FVSI value at line 3 to exceed unity. This implies that the line has reached its unstable condition, which may lead to voltage collapse to the entire system. The maximum value of reactive power loading is identified as the maximum loadability of this load bus. Bus 4 is expected to operate at the loading condition less than this point so that secure operation could be maintained. The increase in the reactive power loading at bus 4 has also reduced its voltage to 0.64364 p.u. as indicated in the table. The trend of FVSI values at each line connected to bus 11and the voltage magnitude when reactive power loading at this bus was increased is illustrated in Fig. 6. From the figure, it is observed that FVSI profiles increase accordingly with respect to the reactive power loading increment. On the other hand, voltage reduces with respect to the increment of loading condition. It is also observed that line 3 has the highest FVSI profile indicating the sensitive line.

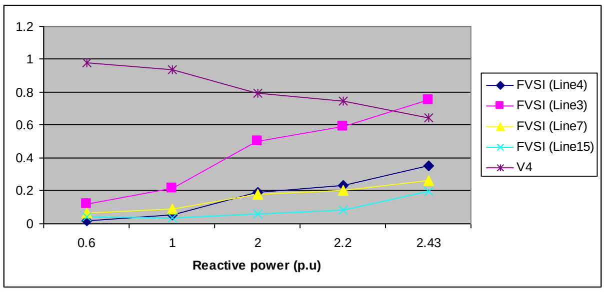

Fig. 6: Effect of Q variation at bus 4 to voltage profile and FVSI evaluated on the lines connected to bus 4

Table 5: Results for FVSI values at the lines connected to bus 14 and voltage magnitude with respect to the increase reactive in power loading

Line No.	Q (p.u)	Line	FVSI	Voltage (p.u)
17	0.2	12-14	0.148	1.003
20	0.2	15-14	0.1238	
17	0.4	12-14	0.3023	0.92612
20	0.4	15-14	0.3067	
17	0.55	12-14	0.4618	0.83414
20	0.55	15-14	0.5	
17	0.65	12-14	0.6149	0.74576
20	0.65	15-14	0.694	
17	0.72	12-14	0.8285	0.61831
20	0.72	15-14	0.9805	

The trend of FVSI values at each line connected to bus 14 and the voltage magnitude when reactive power loading at this bus was increased is illustrated in Fig. 7.

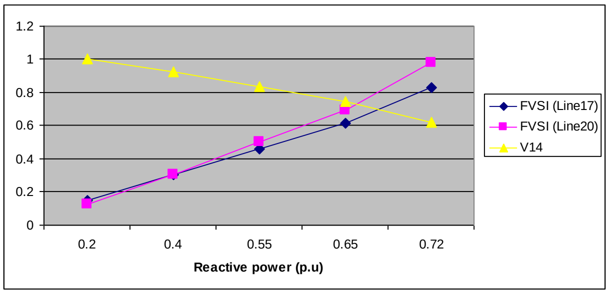

Fig. 7: Effect of Q variation at bus 14 to voltage profile and FVSI evaluated on the lines connected to bus 14

Table 6: Results for FVSI values at the lines connected to bus 24 and voltage magnitude with respect to the increase reactive in power loading

Line No.	Q (p.u)	Line	FVSI	Voltage (p.u)
31	0.4	22-24	0.2131	0.93672
32	0.4	23-24	0.1583	
33	0.4	25-24	0.09	
31	0.55	22-24	0.331	0.86083
32	0.55	23-24	0.2449	
33	0.55	25-24	0.1839	
31	0.695	22-24	0.5	0.75775
32	0.695	23-24	0.3719	
33	0.695	25-24	0.3216	
31	0.75	22-24	0.6	0.69597
32	0.75	23-24	0.4533	
33	0.75	25-24	0.4099	
31	0.79	22-24	0.7831	0.58687
32	0.79	23-24	0.6067	
33	0.79	25-24	0.567	

The trend of FVSI values at each line connected to bus 24 and the voltage magnitude when reactive power loading at this bus was increased is illustrated in Fig. 8.

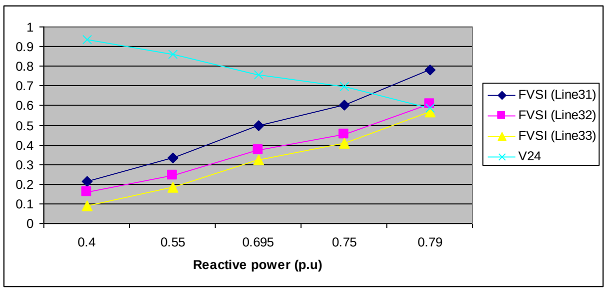

Fig. 8: Effect of Q variation at bus 24 to voltage profile and FVSI evaluated on the lines connected to bus 24

Table 7: Results for FVSI values at the lines connected to bus 30 and voltage magnitude with respect to the increase reactive in power loading

Line No.	Q (p.u)	Line	FVSI	Voltage (p.u)
38	0.05	27-30	0.0959	0.97
39	0.05	29-30	0.0431	
38	0.15	27-30	0.3	0.88641
39	0.15	29-30	0.1597	
38	0.235	27-30	0.5	0.79213
39	0.235	29-30	0.2968	
38	0.3	27-30	0.7282	0.68139
39	0.3	29-30	0.4661	
38	0.326	27-30	0.9408	0.54206
39	0.326	29-30	0.6808	

The trend of FVSI values at each line connected to bus 30 and the voltage magnitude when reactive power loading at this bus was increased is illustrated in Fig. 9.

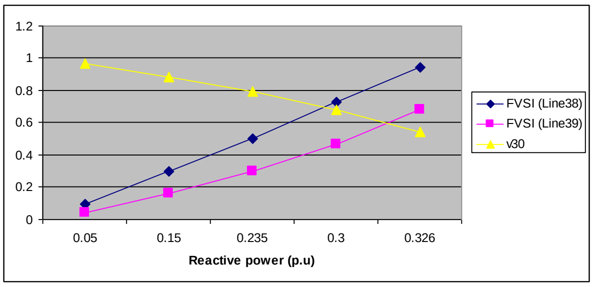

Fig. 9: Effect of Q variation at bus 30 to voltage profile and FVSI evaluated on the lines connected to bus 30

IV. Fuzzy Inference System

In this formulation, L.F index values, which are linearly normalized into a [0,1] range with the largest (L.F) having a value of 1 and the smallest having a value of 0, along with load bus Voltage magnitudes are the inputs to the fuzzy system that determines the severity indices of line flow and voltage profile by fuzzy inferencing. In fuzzy logic based approaches, the decisions are made by forming a series of rules that relate the input variables to the output variables using if-then statements. A set of multiple-antecedent fuzzy rules are established for determining the severity index of voltage profile (SI_{VP}) and severity index for line flow ($SI_{L.F}$), the input to the rules (L.F) and (VM) and the output consequent is ($SI_{L.F}$) and (SI_{VP}) respectively. The rules are summarized in the fuzzy decision matrix in table 8. Having related the input variables to the output variable, the fuzzy results are defuzzified through what is called a defuzzification process, to achieve a crisp numerical value. The most commonly used centroid or centre of gravity defuzzification strategy [14, 15] is adopted. The fuzzy inference structure is tested in MATLAB R2008a fuzzy toolbox. The ranking obtained using fuzzy approach is verified with (FVSI).

4.1 Bus voltage profiles (selected Fuzzy input)

The voltage profile at load buses is described using the linguistic variables as Low Voltage (LV), Normal Voltage (NV) and Over Voltage (OV) as shown in Fig. 10.

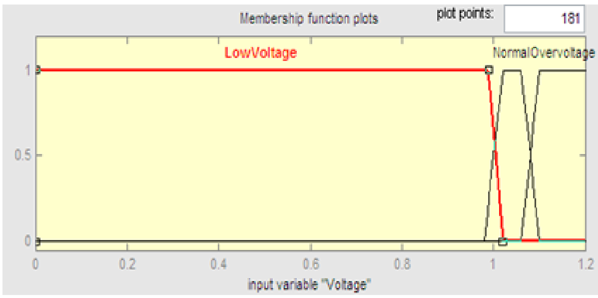

Fig. 10: Voltage profiles membership function

4.2 Line Flow Index (selected Fuzzy input)

The Line Flow index is divided into five categories using Fuzzy Set notations: Very Small (VS), Small (S), Medium (M), High (H) and Very High (VH) as shown in Fig. 11.

Fig. 12 and Fig. 13 show membership function chosen for linguistic output variables.

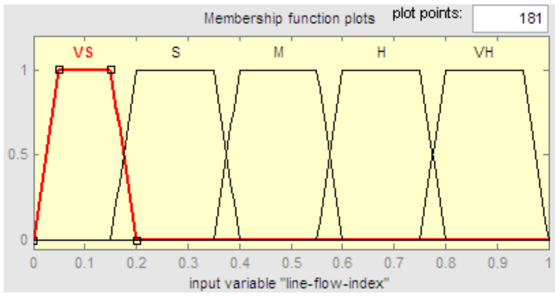

Fig. 11: Line flow index membership function

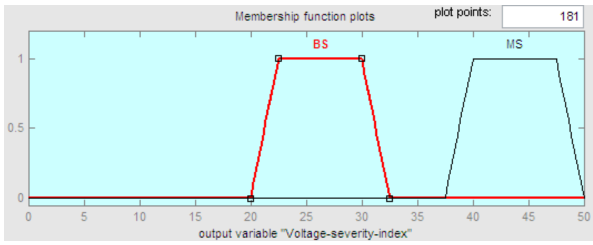

Fig. 12: Severity index for voltage profile

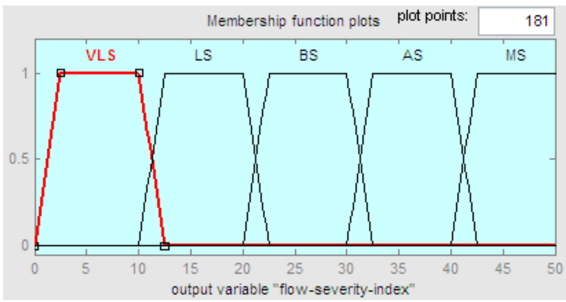

Fig. 13: Severity index for Line Flow

4.3 Fuzzy Rules

The fuzzy rules, which are used for evaluation of severity indices of bus voltage profiles and line flow indices, are given in table 8.

Table 8: Fuzzy rules

Input Variable	Output Variable
Voltage	SI_{VP}
LV NV OV	MS BS MS
L.F index	$SI_{L.F}$
VS S M H VH	VLS LS BS AS MS

Where,

VLS: Very Low Severe, LS: Low Severe, BS: Below Severe, AS: Above Severe, MS: More Severe.

4.4 Fuzzy output (Composite Index)

The overall severity index (Composite index) for a particular line outage is given by $\mathbf{CI = \Sigma SI_{LF} + \Sigma SI_{vp}}$ [16] as shown in Fig. 14; Where, $\mathbf{\Sigma SI_{LF}}$ is the severity index of all Line flow index and $\mathbf{\Sigma SI_{vp}}$ is severity index of all load bus voltage profiles for selected contingencies. Thus, the overall severity index indicates the actual severity of the system for a contingency.

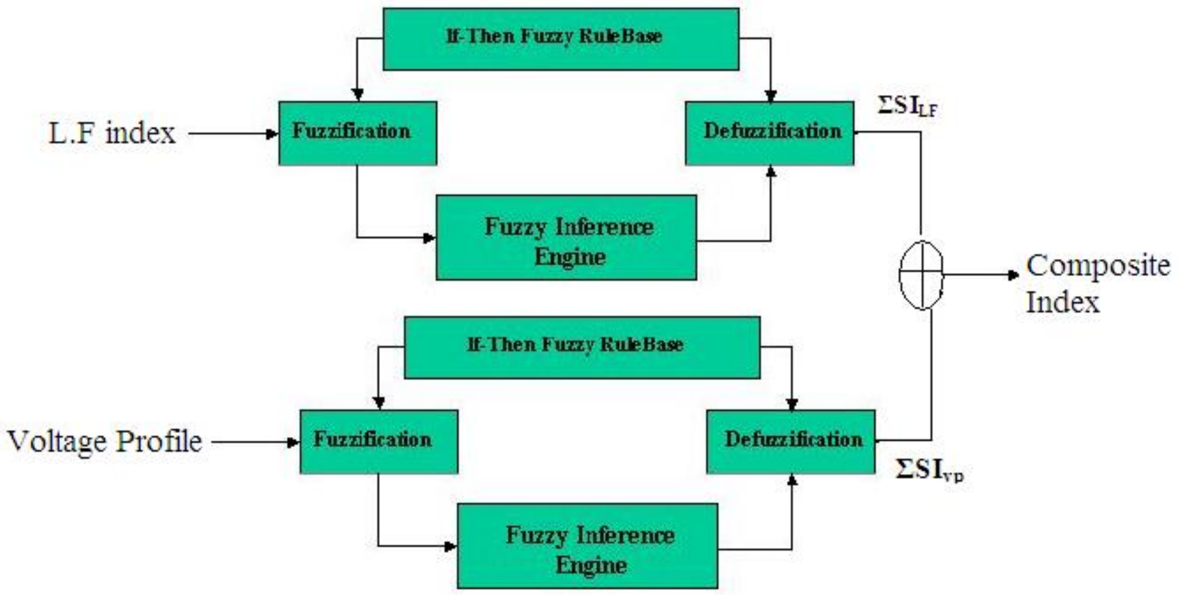

Fig. 14: Fuzzy output (Composite Index)

V. Simulation Results

5.1 IEEE-14 bus system

The fuzzy logic approach is tested on IEEE-14 bus system. The line outages considered for ranking are listed in table 9.

Table 9: List of selected Contingencies

Contingency No.	Type of Contingency	From	to
1	Line Outage	10	11
2	Line Outage	4	9
3	Line Outage	5	6
4	Line Outage	12	13
5	Double Line outage	9	10
		13	14

Contingency No.1 analysis:

Tables 10 and table 11 show severity index for voltage profiles and line flow index calculated using fuzzy rules

Table 10: Severity indices for voltage profiles

Bus No.	Voltage (p.u)	SI_{vp}
Bus 4	1.0169	28.3
Bus 5	1.0193	27.6
Bus 7	1.0596	26.3
Bus 9	1.0524	26.3
Bus 10	1.0449	26.3
Bus 11	1.0635	28
Bus 12	1.055	26.3
Bus 13	1.0497	26.3
Bus 14	1.0332	26.3

$\mathbf{\Sigma SIvp = 241.7}$

Table 11: Severity Indices for L.F index

Line	From	to	L.F index	SI_{LF}
1	1	2	0.195553	15.3
2	1	5	0.358289	18
3	2	3	0.320033	16.3
4	2	4	0.235641	
5	2	5	0.185067	13.2
6	4	3	0.097943	6.25
7	5	4	0.059059	6.25
8	4	7	0.083447	6.25
9	4	9	0.168847	10.1
10	5	6	0.246067	16.3
11	6	11	0.027215	6.25
12	6	12	0.068677	6.25
13	6	13	0.08762	6.25
15	7	9	0.072067	6.25
16	9	10	0.031477	6.25
17	9	14	0.08226	6.25
19	12	13	0.020885	6.25
20	13	14	0.081216	6.25

ΣSI_{LF} = 174.25
CI = $\Sigma SI_{LF} + \Sigma SI_{vp}$ = 415.95

Contingency No.2 analysis

Table 12 and table 13 shows severity index for voltage profiles and line flow index calculated using fuzzy rules shown in table 8.

Table 12: Severity indices for voltage profiles

Bus No.	Voltage (p.u)	SI_{vp}
Bus 4	1.0171	28.2
Bus 5	1.0186	27.2
Bus 7	1.0599	26.3
Bus 9	1.0538	26.3
Bus 10	1.049	26.3
Bus 11	1.0557	26.3
Bus 12	1.0552	26.3
Bus 13	1.0499	26.3
Bus 14	1.034	26.3

$\Sigma SIvp$ = 239.5

Table 13: Severity Indices for L.F index

Line	From	to	L.F index	SI_{LF}
1	1	2	0.19507	15.2
2	1	5	0.36104	18.6
3	2	3	0.31879	16.3
4	2	4	0.23283	16.3
5	2	5	0.18877	13.9
6	4	3	0.0996	6.25
7	5	4	0.052	6.25
8	4	7	0.11649	6.25
10	5	6	0.27828	16.3
11	6	11	0.06843	6.25
12	6	12	0.0688	6.25
13	6	13	0.08833	6.25
15	7	9	0.08634	6.25
16	9	10	0.01814	6.25
17	9	14	0.08144	6.25
18	11	10	0.03931	6.25
19	12	13	0.02133	6.25
20	13	14	0.08371	6.25

ΣSI_{LF} = 171.6
CI = $\Sigma SI_{LF} + \Sigma SI_{vp}$ = 411.1

Contingency No.3 analysis

ΣSI_{vp} = 275.6
ΣSI_{LF} = 183.98
CI = $\Sigma SI_{LF} + \Sigma SI_{vp}$ = 459.58

Contingency No.4 analysis

ΣSI_{vp} = 239.3
ΣSI_{LF} = 171.66
CI = $\Sigma SI_{LF} + \Sigma SI_{vp}$ = 410.96

Contingency No.5 analysis

ΣSI_{vp} = 239.5
ΣSI_{LF} = 164.36
CI = $\Sigma SI_{LF} + \Sigma SI_{vp}$ = 403.86

5.2 IEEE-30 bus system

The fuzzy logic approach is tested on IEEE-30 bus system. The system consists of 6 generators, 2 shunt capacitors and 41 transmission lines. Contingency Screening is based on all the heavily loaded line, the line outages considered for ranking are listed in table 14

Table 14: List of selected Contingencies

Contingency No.	Type of Contingency	From	to
1	Line Outage	2	5
2	Line Outage	16	17
3	Line Outage	5	7
4	Double Line outage	8	28
		6	28
5	Double Line outage	14	15
		18	19

Contingency No.1 analysis

Table 15 and table 16 shows severity index for voltage profiles and line flow index calculated using fuzzy rules

Table 15: Severity indices for voltage profiles

Bus No.	Voltage (p.u)	SI_{vp}
Bus3	0.99505	37.9
Bus4	0.98118	43.2
Bus6	0.97038	43.8
Bus7	0.92842	43.8
Bus9	1.0238	26.3
Bus10	1.0171	28.2
Bus12	1.0411	26.3
Bus14	1.0244	26.3
Bus15	1.0178	27.7
Bus16	1.0228	26.3
Bus17	1.0138	30.1
Bus18	1.0051	34.1
Bus19	1.0008	35.8
Bus20	1.004	34.5
Bus21	1.0043	34.4
Bus22	1.0049	34.2
Bus23	1.0034	34.8
Bus24	0.99286	38.7
Bus25	0.98311	42.3
Bus26	0.96479	43.8
Bus27	0.98594	41.1
Bus28	0.96758	43.8
Bus29	0.96527	43.8
Bus30	0.95331	43.8

$\Sigma SI_{vp} = 865$

Table 16: Severity Indices for LF index

From	To	L.F index	SI_{LF}
1	2	0.212443	16.3
1	3	0.42102	26.3
2	4	0.338385	16.3
3	4	0.109873	6.25
2	6	0.433222	26.3
4	6	0.124829	6.25
7	5	0.323465	16.3
6	7	0.296271	16.3
6	8	0.027194	6.25
6	9	0.062973	6.25
6	10	0.137157	6.25
9	10	0.068137	6.25
4	12	0.269247	16.3
12	14	0.077079	6.25
12	15	0.100466	6.25
12	16	0.07644	6.25
14	15	0.026142	6.25
16	17	0.041595	6.25
15	18	0.059468	6.25
18	19	0.02022	6.25
20	19	0.01551	6.25
10	20	0.061961	6.25
10	17	0.01404	6.25
10	21	0.054117	6.25
10	22	0.051897	6.25
22	21	0.002316	6.25
15	23	0.060376	6.25
22	24	0.05018	6.25
23	24	0.044053	6.25
25	24	0.003431	6.25
25	26	0.076142	6.25
27	25	0.023568	6.25
28	27	0.169291	10.2
27	29	0.10137	6.25
27	30	0.161603	8.68
29	30	0.06504	6.25
28	8	0.004531	6.25
6	28	0.029831	6.25

$\Sigma SI_{LF} = 334.23$

$CI = \Sigma SI_{LF} + \Sigma SI_{vp} = 1199.23$

Contingency No.2 analysis

Table 17 and table 18 shows severity index for voltage profiles and line flow index

Table 17: Severity indices for voltage profiles

Bus No.	Voltage (p.u)	SI_{vp}
Bus3	1.0209	26.3
Bus4	1.012	31
Bus6	1.0101	31.9
Bus7	1.0023	35.2
Bus9	1.0495	26.3
Bus10	1.0426	26.3
Bus12	1.0586	26.3
Bus14	1.0435	26.3
Bus15	1.0381	26.3
Bus16	1.0521	26.3
Bus17	1.035	26.3
Bus18	1.0275	26.3
Bus19	1.0244	26.3
Bus20	1.0281	26.3
Bus21	1.0304	26.3
Bus22	1.031	26.3
Bus23	1.0269	26.3
Bus24	1.0204	26.3
Bus25	1.0165	28.5
Bus26	0.99884	36.5
Bus27	1.0227	26.3
Bus28	1.0066	33.5
Bus29	1.0029	35
Bus30	0.99139	39.3

$\mathbf{\Sigma SI_{vp} = 691.7}$

Contingency No.3 analysis

$\mathbf{\Sigma SI_{vp} = 701.6}$
$\mathbf{\Sigma SI_{LF} = 310.55}$
$\mathbf{CI = \Sigma SI_{LF} + \Sigma SI_{vp} = 1012.15}$

Contingency No.4 analysis

$\mathbf{\Sigma SI_{vp} = 793}$
$\mathbf{\Sigma SI_{LF} = 314.15}$
$\mathbf{CI = \Sigma SI_{LF} + \Sigma SI_{vp} = 1107.15}$

Contingency No.5 analysis

$\mathbf{\Sigma SI_{vp} = 691.6}$
$\mathbf{\Sigma SI_{LF} = 299.75}$
$\mathbf{CI = \Sigma SI_{LF} + \Sigma SI_{vp} = 991.35}$

Table 18: Severity Indices for LF index

From	To	L.F index	SI_{LF}
1	2	0.210229	16.3
1	3	0.318498	16.3
2	4	0.202954	16.3
3	4	0.079472	6.25
2	5	0.345205	16.3
2	6	0.257821	16.3
4	6	0.066233	6.25
7	5	0.033011	6.25
6	7	0.079489	6.25
6	8	0.026472	6.25
6	9	0.085544	6.25
6	10	0.171276	10.5
9	10	0.07127	6.25
4	12	0.263275	16.3
12	14	0.070888	6.25
12	15	0.09048	6.25
12	16	0.027741	6.25
14	15	0.021505	6.25
15	18	0.052596	6.25
18	19	0.016665	6.25
20	19	0.016384	6.25
10	20	0.06362	6.25
10	17	0.032211	6.25
10	21	0.050409	6.25
10	22	0.047943	6.25
22	21	0.002559	6.25
15	23	0.048524	6.25
22	24	0.042711	6.25
23	24	0.029169	6.25
25	24	0.00975	6.25
25	26	0.071222	6.25
27	25	0.034026	6.25
28	27	0.175092	11.3
27	29	0.094104	6.25
27	30	0.150227	6.3
29	30	0.060236	6.25
8	28	0.004276	6.25
6	28	0.030325	6.25

$\mathbf{\Sigma SI_{LF} = 307.15}$
$\mathbf{CI = \Sigma SI_{LF} + \Sigma SI_{vp} = 998.85}$

VI. Performance COMPARISON

In order to evaluate the fuzzy logic based algorithm, so results obtained will be compared with FVSI results by calculation of FVSI value for every line in the system using equation (1). Firstly the corresponding line which gives the highest FVSI must be identified. During these contingencies No. (1, 2, 3, 4, 5) at IEEE-14 bus case study, line connected between bus 7 to bus 8 demonstrates the highest FVSI with values 0.1084, 0.1074, 0.1298, 0.1022 and 0.0955 respectively.

At IEEE-30 bus case study, line connected between bus 9 to bus 11 demonstrates the highest FVSI with values 0.167, 0.1162, 0.1168, 0.1316 and 0.1139 respectively.

Table 19 and table 20 provide the comparison of ranking obtained from Fuzzy logic based algorithm and FVSI method. The rankings obtained from fuzzy logic method are matched to the results obtained using FVSI method.

Table 19: Comparison of Contingency Ranking Using Fuzzy logic and FVSI Method at IEEE-14 bus

Contingency No.	$CI = \Sigma SI_{LF} + \Sigma SI_{vp}$	Rank	FVSI	Rank
1	415.95	2	0.1084	2
2	411.1	3	0.1074	3
3	459.58	1	0.1298	1
4	410.96	4	0.1022	4
5	403.86	5	0.0955	5

Table 20: Comparison of Contingency Ranking Using Fuzzy logic and FVSI Method at IEEE-30 bus

Contingency No.	$CI = \Sigma SI_{LF} + \Sigma SI_{vp}$	Rank	FVSI	Rank
1	1199.23	1	0.167	1
2	998.85	4	0.1162	4
3	1012.15	3	0.1168	3
4	1107.15	2	0.1316	2
5	991.35	5	0.1139	5

The comparative study shows that there is a close agreement in the results between Fuzzy algorithm method and FVSI indicating that this technique is possible to be implemented practically.

VII. Conclusion

Simultaneous load increase at the selected load buses was conducted in order to identify the appropriate loading condition before a system started to lose its stability, then the contingencies ranked using composite index provides very useful information about the impact of the contingency on the system as a whole and helps in taking necessary control measures to reduce the severity of the contingency. The fuzzy logic based algorithm is efficient, simple and effectively ranks the contingencies. Based on composite index, suitable location for installing FACTS or any other corrective actions such as load shedding can be identified to avoid voltage collapse.

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