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Power System Contingency Ranking using Fuzzy Logic Based Approach

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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 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 provide the comparison of ranking obtained with Fast Voltage Stability Index (FVSI) method.*

Keywords: *Contingency Ranking, Fuzzy Sets, Line Flow Index, Fuzzy Inference System.*

1. 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].

Also the energy function is used for voltage stability assessment of multi-machine power system [11]. The formulated energy function provides an excellent indicator of the system vulnerability to voltage collapse. It is, also, used to rank the system buses according to their contributions to voltage collapse. Also, a multi-layer feed-forward ANN with error back-propagation learning algorithm is proposed for calculation of voltage stability margins (VSM).

This paper is organized as follows; section 2 explains the static voltage stability indicators which provide reliable information about proximity of voltage instability in a power system. Usually, their values change between 0 (no load) and 1 (voltage collapse).

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Section 3 illustrates the Fuzzy Inference System (FIS) which formulating the mapping from selected inputs to outputs through fuzzy decision rules; Section 4 shows the numerical results of applying the algorithm to IEEE-14 and IEEE-30 bus test systems and provides performance comparison by comparing results obtained from fuzzy based algorithm to FVSI method. Finally the conclusion is given in Section 5.

2. Static Voltage Stability Indicators

2.1. Fast Voltage Stability Index

Voltage stability index proposed by [12] 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.

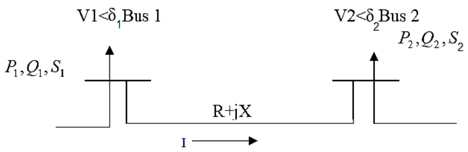

Figure 1. 2- Bus system model

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

where,
Z: line impedance
X: line reactance
Qj: reactive power at the receiving end
Vi: sending end voltage

2.2. Line Flow Index

The Line Flow (L.F) index proposed by [13] 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.

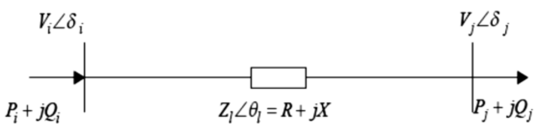

Figure 2. A transmission line of a power system network.

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

Where the value of PR is obtained from conventional power flow calculations, and PR(max) is the maximum active that can be transferred through a line see (Equation 3). The Line Flow index varies from 0 (no load condition) to 1 (voltage collapse).

$$P_{R(MAX)} = \left(\frac{V_i^2}{2Z_l}\right)\left(\frac{\cos\phi}{1+\cos(\theta_l - \phi)}\right) \tag{3}$$

Where Vi is the voltage magnitude of sending bus of branch i-j, Zl and θl are the magnitude and angle of branch impedance respectively , Φ = arctan (Qj / Pj)

3. 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 (SIVP) and severity index for line flow (SIL.F), the input to the rules (L.F) and (VM) and the output consequent is (SIL.F) and (SIVP) 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).

3.1. Bus Voltage Profile (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. 3.

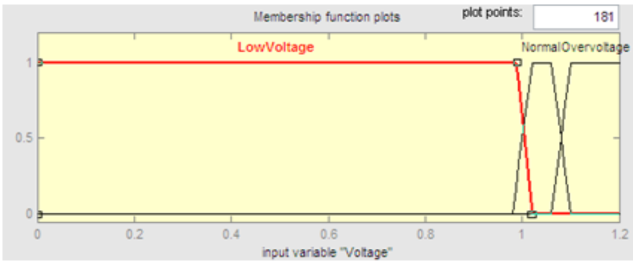

Figure 3. Voltage profiles membership function

3.2. 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. 4. Fig. 5 and Fig. 6 show membership function chosen for linguistic output variables.

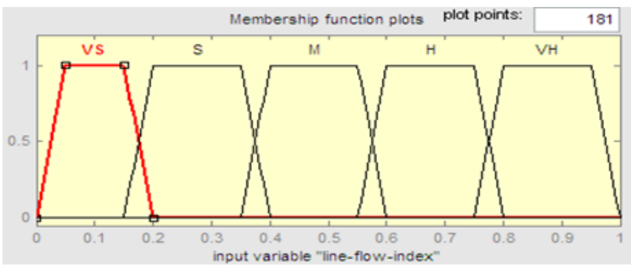

Figure 4. Line flow index membership function

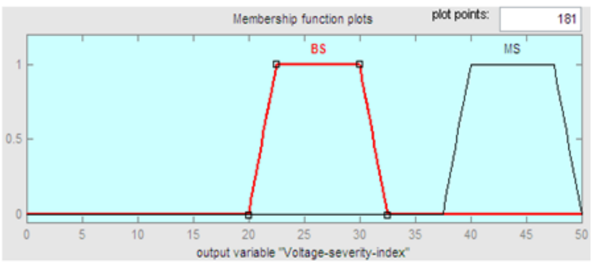

Figure 5. Severity index for Voltage Profile

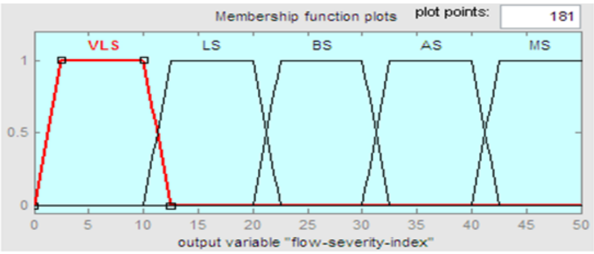

Figure 6. Severity index for line flow

3.3. 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 1.

Table 1. 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

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

3.4. Fuzzy Output (Composite Index)

The overall severity index (Composite index) for a particular line outage is given by CI = ΣSILF + ΣSIvp [16] as shown in Fig. 7; where, ΣSILF is the severity index of all line flow index and ΣSIvp 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.

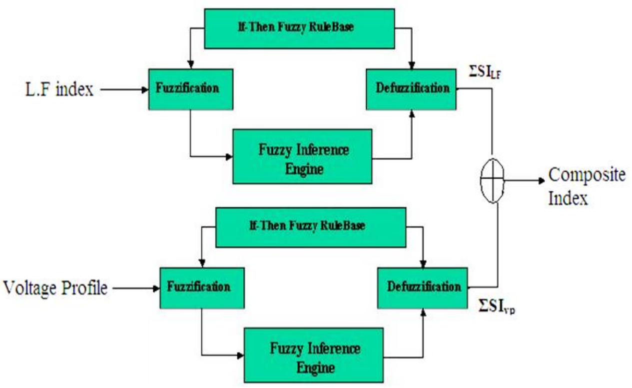

Figure 6. Severity index for line flow

4. Results and Discussion

4.1. IEEE 14 Bus Test System

The fuzzy logic approach is tested on IEEE-14 bus system. The line outages considered for ranking are listed in Table 2.

Table 2. List of selected contingencies

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

4.1.1. Contingency No.1 Analysis

Tables 3 and Table 4 show severity index for voltage profiles and line flow index calculated using fuzzy rules

Table 3. 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

ΣSIvp = 241.7

Table 4. 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	16.3
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

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

4.1.2. Contingency No.2 Analysis

ΣSIvp = 239.5
ΣSILF = 171.6
$CI = \Sigma SI_{LF} + \Sigma SIvp = 411.1$

4.1.3. Contingency No.3 Analysis

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

4.1.4. Contingency No.4 Analysis

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

4.1.5. Contingency No.5 analysis

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

4.2. IEEE 30 Bus Test 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. The line outages considered for ranking are listed in Table 5.

Table 5. List of selected contingencies

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

4.2.1. Contingency No.1 Analysis

Table 6 and Table 7 shows severity index for voltage profiles and line flow index calculated using fuzzy rules

Table 6. Severity indices for voltage profiles

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

$\Sigma SI_{vp} = 865$

Table 7. Severity indices for L.F index

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

$\Sigma SI_{LF} = 334.23$
$CI = \Sigma SI_{LF} + \Sigma SI_{vp} = 1199.23$

4.2.2. . Contingency No.2 Analysis

$\Sigma SIvp = 691.7$
$\Sigma SILF = 307.15$
$CI = \Sigma SILF + \Sigma SIvp = 998.85$

4.2.3. Contingency No.3 Analysis

$\Sigma SIvp = 701.6$
$\Sigma SILF = 310.55$
$CI = \Sigma SILF + \Sigma SIvp = 1012.15$

4.2.4. Contingency No.4 Analysis

$\Sigma SIvp = 793$
$\Sigma SILF = 314.15$
$CI = \Sigma SILF + \Sigma SIvp = 1107.15$

4.2.5. Contingency No.5 analysis

$\Sigma SIvp = 691.6$
$\Sigma SILF = 299.75$
$CI = \Sigma SILF + \Sigma SIvp = 991.35$

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 8 and Table 9 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 8. 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 9. 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

5. Conclusions

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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