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Security Improvement Using Facts Device Placement based on Modal Analysis

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Abstract: Power system security is a major concern in the operation of today's power system. Hence, security analysis becomes an inevitable task in the routine work of the power system operator. The operator has to ensure that the system does not proceed into insecure or extreme states of security, and practice various methods of improving the security of the power system. Security analysis begins with system monitoring and contingency screening. Later depending in the analysis of results, measures to improve security are opted. The Network composite overall severity index (NCOSI) is one of the methods of screening the contingencies to analyze the state of the system. The contingencies are ranked according to their severity based on this index value. NCOSI is computed from three fuzzy variables that depend on line overloading, bus voltage drop limit violation and the voltage stability index.

Keywords: *contingency, modal analysis, voltage stability, security improvement, severity index*

1. Introduction

Power system is a highly capital-intensive network, comprising of crucial equipment like transformers, generators and transmission lines. Damage of any single component effect the system to a very large extent. Hence, maintaining the power system securely is an important part on the operator, taking care of the contingencies that occur in the system. The state of the system during contingencies can be found out exactly only by carrying out detailed analysis on the system parameters. Thus, offline security analysis for different contingencies can help the operator during times of emergencies, and thus reduce the risk of blackouts in power system. Also, the power system needs fast on-line state estimation and security assessment along with control tools that can propose corrective and preventive actions in case the system is vulnerable to instability under contingencies.

Assessing the system security analytically would mean to simulate all the credible contingencies manually and analyze the load flow results, which is tedious. This work will mainly discuss static security assessment of power system as well as means to enhance static security. Security Enhancement deals with implementing control actions to steer the system from Insecure, emergency or restorative states to normal secure state. Placement of FACTS devices is considered to be a possible means of security enhancement. Various types of FACTS devices like series, shunt or combination can be placed in the system using Modal analysis [1]. This method finds the sensitive buses and branches for candidate location of respective types of devices.

Voltage stability at a particular bus depends on load at that bus and its power factor. Voltage stability decreases as load increases, i.e. Voltage stability is maximum at no load and minimum at rated load. Similarly, voltage stability decreases as power factor decreases. Hence, a higher value of power factor indicates a better voltage stability and vice versa. Illustration is done using P-V and Q-V curves [3].

Voltage stability analysis comprises of finding out how close the system is to becoming unstable. The proximity to instability is determined, which if closer indicates the system is nearing instability. The value of this proximity is defined by an index in some literature and depends on parameters like system load limits and reactive power sources available.

2. Voltage Stability Assessment Using L-Index

The assessment of voltage stability using L-index [2] calculated for load buses is a simple method, which uses the information of Y-bus matrix and load flow analysis. The magnitude of this index for the load buses varies from 0 to 1. The value of L-index is 0 during zero load on the system and reaches when the system is at the verge of voltage collapse. The most vulnerable bus for voltage instability will be the bus with the highest value of this index. In order to obtain the formulation of L-index, a system with 'N' buses is considered with 'Ng' number of generators. The system equations can be written in the following form.

$$I_{bus} = Y_{bus}V_{bus}$$

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Using G to represent generator buses, and L to represent load buses, this relation can be expressed separately for G and L as,

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix}$$

where I and V correspond to currents and voltages in generator buses and load buses accordingly.

This equation can now be written as

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix}$$

where $F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}]$

The L-index of the j^{th} node is given by the expression:

$$L_j = \left| 1 - \sum_{i=1}^{N_g} F_{ij} \frac{V_i}{V_j} \angle(\theta_{ij} + \delta_i$$

V_i Voltage magnitude of i^{th} generator.
V_j Voltage magnitude of j^{th} generator.
θ_{ij} Phase angle of the term F_{ij}.
δ_i Voltage phase angle of i^{th} generator unit.
δ_j Voltage phase angle of j^{th} generator unit.
N_g Number of generating units.

L-index is given as

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ij} \frac{V_i}{V_j} \right|$$

where,

j = g+1 to n (load buses)
V_i= voltage at i^{th} bus
g = No. of generator buses
L_j= L-index voltage stability indicator for bus *k*
n = Total no. of buses
$F_{ij} = -[Y_{ll}]^{-1}[Y_{lg}]$

3. Contingency Ranking Using Fuzzy Logic

Scanning for contingencies and ranking them in the order of their severity forms a crucial part of security assessment. This is done with help of a scalar parameter named as Performance Index (PI). The contingencies can be if different types in their severity depending on its effects, whether there is overloading in some of the transmission lines or if there are voltage violations. Therefore, separate indices are required to identify both types of contingencies. Since voltage stability indices can speak of the system state rather than voltage magnitudes alone, these can be considered to assess the security while doing contingency screening. Hence, the ranking and screening of contingencies is done by considering all the influential parameters like line flows, bus voltage magnitudes and voltage stability indices. A new Fuzzy based system is developed for contingency screening to prevail over the masking effect of PI.

All the credible contingencies are simulated in order to obtain the post contingent line loadings, voltage magnitudes and voltage stability indices. These quantities are given as inputs to the single input-single output based fuzzy inference system. The outputs of the FLS are known as Overall Severity Indices (OSI), which are computed using the simple set of fuzzy rules. OSI_{LL} indicates the Overall Severity index of all the line loadings, OSI_{VP} indicates the overall severity index of voltage profile of all the buses in the system, and OSI_{VSI} indicates the overall severity index of voltage stability indices of all the buses. The severity indices for all three quantities put together is termed as Network Composite Overall Severity Index (NCOSI) [4]. This index is an indicator of severity in terms of all the quantities considered.

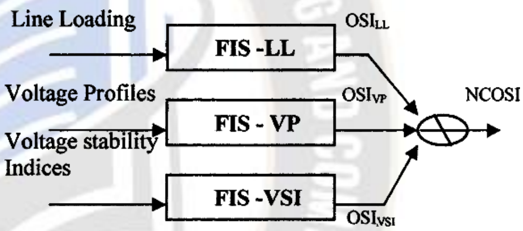

Figure 1. Fuzzy Inference Systems

Based on the range of the obtained quantities, they are classified into membership functions. The severity of that corresponding quantity is considered as output, and accordingly output membership functions are selected. Trapezoidal membership functions are selected in order to have appropriate common and uncommon spaces for various categories considered. Table 1 presents the set of fuzzy rule base for the considered single input-single output based FLS. The severity of the contingency for a particular quantity is categorized on a scale of 1 to 10, where, 10 indicates the maximum severity.

Table 1. Fuzzy rules

Post-contingent quantity	**Input Membership functions**	**Output Membership functions of Critical Severity**
Line Loading	LL, NL, FL, OL, LOL	LC, BC, AC, MC, VMC
Voltage Profile	LV, NV, HV	VLC, LC, BC, AC, MC
Voltage Stability Index	VLI, LI, MI, HI ,VHI	VLC, LC, BC, AC, MC

The first quantity Line loading is split into five categories: Less Load (LL), Normal Load (NL), Full Load (FL), Over

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Load (OL) and Large Over Load (LOL). The ranges of these categories and their corresponding outputs are Less Critical (LC), Below Critical (BC), Above Critical (AC), More Critical (MC) and Very Much Critical (VMC).

The next quantity voltage profile is split into three categories: Low Voltage (LV) Normal Voltage (NV) and High Voltage (HV). The ranges of these categories and their corresponding outputs are Very Less Critical (VLC), Less Critical (LC), Below Critical (BC), Above Critical (AC) and More Critical (MC).

The last quantity voltage stability index is split into five categories: Very Less Index (VLI), Less Index (LI), Medium Index (MI), High Index (HI) and Very High Index (VHI). The ranges of these categories and their corresponding outputs are Very Less Critical (VLC), Less Critical (LC), Below Critical (BC), Above Critical (AC) and More Critical (MC).

The severity indices for various buses and branches of the system are obtained using FLS. These indices aggregated over the number of buses or branches respectively give the Overall Severity indices, and NCOSI is the indicator of severity of any kind. Among the considered contingencies, NCOSI index is used to rank them in the order of their severity. Security improvement of the system is done by determining the location of FACTS device placement for most severe cases, so that less severe cases are automatically taken care of. The list of most severe contingencies in the order of their severity is listed in Table 2.

Table 2. Contingency Ranking List

Rank	**Contingency**	**Fuzzy NCOSI values**
1	5-6	215.33
2	4-9	204.20
3	2-3	192.78
4	6-13	190.18
5	2-4	189.73

4. Security Improvement using Modal Analysis

To obtain required flexibility in power system operation and control, Flexible AC Transmission Systems (FACTS) devices can be used in large power networks. Therefore, FACTS devices can be used for controlling the power flow in a transmission line, or control the voltage magnitude at a bus of interest. As the FACTS devices are intended to be placed in specific locations so as to improve the overall security of the system under any kind of disturbances. Determining the location for placement of FACTS devices is very crucial. It is optimal to place a FACTS device in the weakest bus or weakest branch, depending in the type of device, as suggested by Modal Analysis [5].

Modal analysis is performed using the Jacobian matrix. Also, the Q-V relation at a bus influences the voltage stability of a system. The Q-V sensitivity, if positive the system has better voltage stability, or else unstable if the sensitivity is not positive for at least on bus. The system equations can be expressed as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}$$

where, ΔP - Incremental Change in Bus Real Power
ΔQ - Incremental Change in Bus Reactive Power
$\Delta\theta$ - Incremental Change in Bus Voltage Angle
ΔV - Incremental Change in Bus Voltage Magnitude

In presence of FACTS devices, the system Jacobian matrix is incorporated with the following changes. There is effect of both P and Q on voltage stability of the system. the value of P is held constant and the effect of Q-V relation is deduced by changing Q and observing V [6].

If $\Delta P = 0$,

$$\begin{bmatrix} \mathbf{0} \\ \Delta \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J_{P\theta}} & \boldsymbol{J_{PV}} \\ \boldsymbol{J_{Q\theta}} & \boldsymbol{J_{QV}} \end{bmatrix}$$

$$\Delta \boldsymbol{Q} = \boldsymbol{J_R} \Delta \boldsymbol{V}$$

$$\Delta \boldsymbol{V} = \boldsymbol{J_R^{-1}}\, \Delta \boldsymbol{Q}$$

where, J_R is known as reduced Jacobian matrix of the system, that quantifies the relation between voltage magnitude and bus reactive power injection. This formulation helps in simplifying computations and observing Q-V relation keenly.

The power system is considered to be having better voltage stability if the eigen values of the Jacobian matrix are greater than zero, not negative, and the Jacobian matrix is positive definite. Therefore, Q-V sensitivity values are also positive inferring that the voltage stability of the power system is intact. The eigen values tend to become small or zero and even negative if the system gets stressed up. The proximity to voltage instability in terms of loading in MW can be determined by incremental loading and application of modal analysis at every step.

The critical buses with respect to voltage instability are also found by identifying the buses and branches that are part of every mode.

The participation factor of bus k to mode is defined as,

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$$P_{ki} = \xi_{ki}\eta_{ki}$$

P_{ki} indicates the contribution of the i^th eigen value to the Q

The flow chart for modal analysis is presented in Figure 2.

The vector of modal reactive power variations, q corresponding to mode I, if all of its elements are zero except the i^th, which equals to 1, then the bus reactive power variations is given as [7, 8],

$$\Delta Q^{(I)} = \eta^{-1} q = \xi q = \xi_I$$

where

ξ_i is the i^{th} right eigenvector of J_R

The vector of bus voltage variations is

$$\Delta V^{(i)} = \frac{1}{\lambda_i} \Delta Q^{(i)}$$

The corresponding vector of bus angle variations is

$$\Delta \theta^{(i)} = -J_{P\delta}^{-1} J_{PV} \Delta V^{(i)}$$

For every mode, Branch participation factor indicates the amount of reactive power drawn to an incremental increase in reactive load. Weak branches can be identified as the branches with high participation factor.

The relative participation of branch *j* in mode *i* is given by the participation factor

$$P_{ji} = \frac{\Delta Q_{loss} \text{ for branch}}{\text{maximum } \Delta Q_{loss} \text{ for all branches}}$$

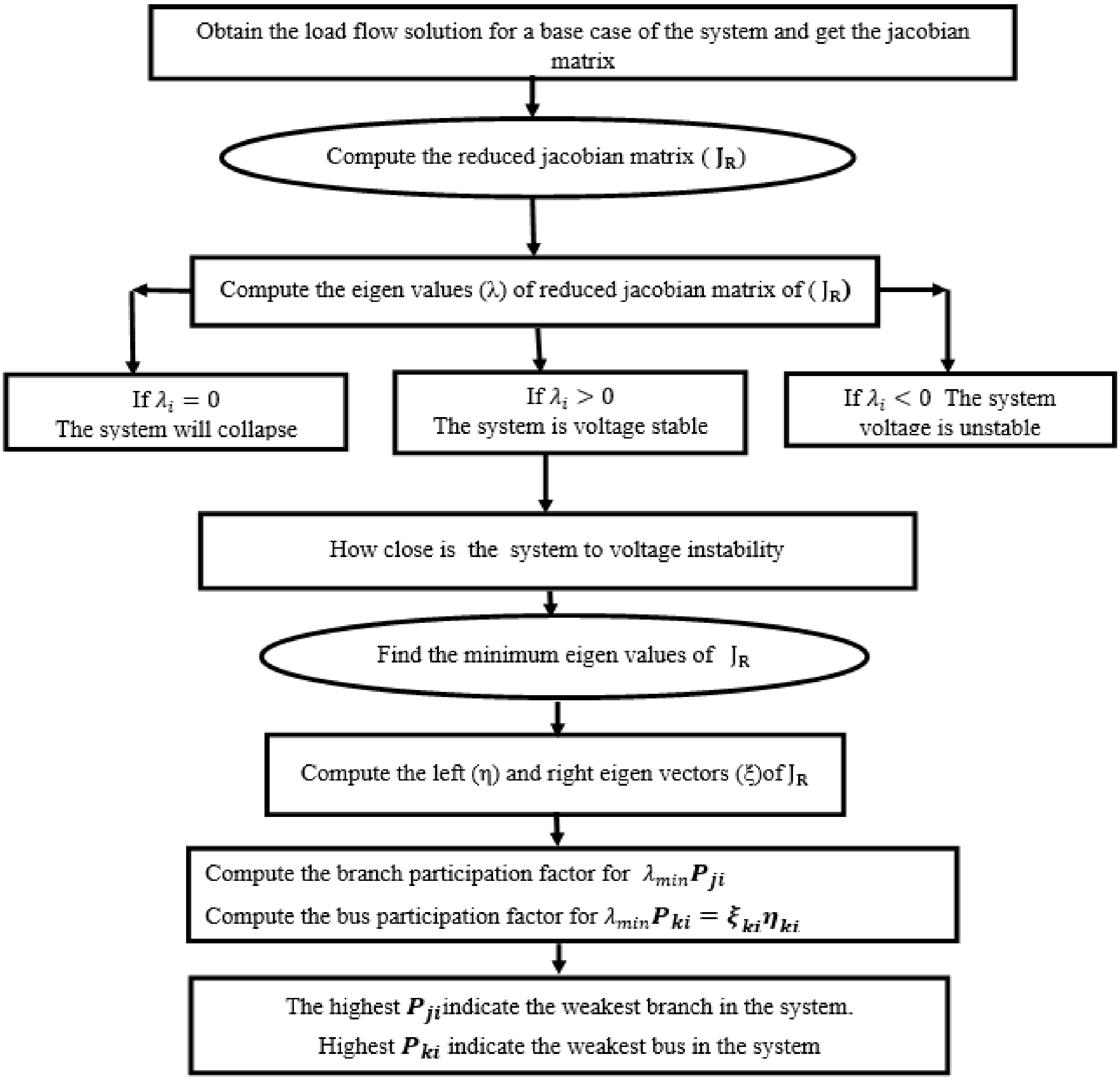

Figure 2. Flow Chart of Modal Analysis

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5. Case Study and Results

IEEE-14 bus system contains 14 buses and 20 lines. Modal analysis is utilized for determining the weakest bus and weakest branch in the system, in order to place series FACTS device.

From the Jacobian matrix, reduced Jacobian matrix (J_R) is formed. Eigen values of reduced Jacobian matrix for minimum eigen value mode (i) are used to calculate the participation factors. The bus having the maximum value of this factor is considered to be the weakest bus in system. In the same way, the branch having the maximum value of this factor is considered to be the weakest branch in the system.

Table 3. Weakest bus and weakest branch for 14 bus system

S NO	LINE OUTAGE	WEAKEST BUS	WEAKEST BRANCH
1	Base case	14	9-14
2	1-2	14	10-11
3	1-5	14	10-11
4	2-3	14	10-11
5	2-4	14	10-11
6	2-5	14	10-11
7	3-4	14	10-11
8	4-5	14	7-9
9	4-7	14	10-11
10	4-9	14	10-11
11	5-6	14	10-11
12	6-11	11	4-7
13	6-12	12	4-9
14	6-13	13	9-14
15	7-8	--	--
16	7-9	9	10-11
17	9-10	14	10-11
18	9-14	14	13-14
19	10-11	11	9-14
20	12-13	12	13-14
21	13-14	14	10-11

After calculating the weakest bus and weakest branch, TCSC with 50% compensation is chosen to be placed in the weakest branch for the corresponding contingency. The NCOSI values for different contingencies and values are presented in Table 4.

Table 4. Fuzzy Indices after placement of TCSC

S No	Line Outage	%Line Loading Index	Voltage Profile Index	Voltage Stability Index	NCOSI (With TCSC)
1	Base case	82.34	60.67	36.25	179.26
2	1-2	74.61	60.67	36.25	171.53
3	1-5	86.36	60.67	36.25	183.29
4	2-3	84.63	60.67	36.25	181.55
5	2-4	85.33	60.67	36.25	182.25
6	2-5	81.40	60.67	36.25	178.32
7	3-4	78.21	60.67	36.25	175.13
8	4-5	88.58	60.67	36.25	185.50

9	4-7	87.24	60.67	36.89	184.80
10	4-9	83.31	60.67	36.25	180.23
11	5-6	102.86	60.67	44.55	208.08
12	6-11	80.01	60.67	36.25	176.93
13	6-12	83.96	60.67	36.25	180.88
14	6-13	84.93	60.67	36.25	181.25
15	7-8	--	--	--	--
16	7-9	88.45	60.67	36.25	183.37
17	9-10	80.47	60.67	36.25	177.39
18	9-14	81.91	60.67	36.25	178.84
19	10-11	76.96	60.67	36.25	173.88
20	12-13	81.80	60.67	36.25	178.72
21	13-14	78.73	60.67	36.25	175.65

Table 5. NCOSI Values Before and After Placing TCSC

S NO	Line Outage	NCOSI	NCOSI (with TCSC)
1	Base case	181.56	179.26
2	1-2	182.07	171.53
3	1-5	187.77	183.29
4	2-3	192.78	181.55
5	2-4	189.73	182.25
6	2-5	184.55	178.32
7	3-4	178.99	175.13
8	4-5	185.90	185.50
9	4-7	185.07	184.80
10	4-9	204.20	180.23
11	5-6	215.33	208.08
12	6-11	185.10	176.93
13	6-12	186.19	180.88
14	6-13	190.18	181.85
15	7-8	--	--
16	7-9	184.78	183.37
17	9-10	182.21	177.39
18	9-14	185.16	178.84
19	10-11	184.59	173.88
20	12-13	183.16	178.72
21	13-14	186.98	175.65

It can be observed from the above table that NCOSI value that indicates the overall severity is decreased after placing the TCSC. The decrease in this value is the increase in security of the system. Since the compensation offered by the TCSC is chosen arbitrarily to be 50%, the following analysis shown in Table 6 explains the value of compensation of TCSC that would exactly be suitable for a selected contingency.

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Table 6. NCOSI values for various degrees of compensation of TCSC

S No	Most Severe Contingencies	NCOSI without TCSC	Weakest Line for including TCSC	NCOSI with TCSC Compensation			
				20%	40%	50%	60%
1	5-6	215.33	10-11	206.64	**206.27**	208.08	207.89
2	4-9	204.20	10-11	180.38	180.29	180.23	**180.18**
3	2-3	192.78	10-11	**181.55**	183.55	181.55	183.55
4	6-13	190.18	9-14	182.43	181.85	**181.72**	181.87
5	2-4	189.73	10-11	**182.25**	182.25	182.25	182.26

For the listed most severe contingencies in the given order, the above table indicates that the insertion of series FACTS device helps in reducing the NCOSI values, indicating that the security of the system has been improved. Instead of optimally selecting the compensation to be offered by TCSC, it is simulated for various probable values and concludes that different compensations of TCSC are suitable for different contingency cases. Hence the value of TCSC compensation can be changed and implemented accordingly.

Conclusion

Security improvement of the system is implemented by placing series and shunt type of FACTS devices. The security is intended to be improved for most severe contingencies that occur in the system. Most severe contingencies result in large overloads or large voltage violations and pose threat to system security. The most severe contingencies are identified for the considered test system and ranked in order based on Network Composite Overall Performance Index (NCOSI). This index is a combination of Overall Severity Indices of loadings of all lines, Voltage profiles of all buses and their voltage stability indices.

FACTS device placement is done based on Modal Analysis of the system which gives the weakest bus and weakest branch of the system depending on the eigen values and eigen vectors of the reduced Jacobian matrix of the system. Security improvement is realized in terms of reduced NCOSI values before and after placement of series type FACTS device (TCSC) for the IEEE 14-bus system.

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