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Voltage Stability Based Formation of Voltage Control Areas Considering Impact of Contingencies

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ABSTRACT

Voltage instability has been considered as a major threat to power system networks since last three decades. Frequent incidences of grid failures caused by voltage instability have been observed in different parts of the world. Fast voltage stability assessment of power system may be done by formation of voltage control areas, clubbing group of buses in geographically compact region having similar voltage instability problem. This paper presents a new approach for formation of voltage control areas (VCAs) based on sensitivity of reactive power generations with respect to reactive power demands, together with bus voltage variations under voltage stability based critical contingencies. The load buses in geographically compact region showing similar sensitivity of reactive power demand to reactive generations have been clubbed together to form voltage control areas. Since, voltage control areas formed should remain valid under change in operating conditions and network topology, the areas formed based on reactive power sensitivities have been modified considering voltage variations at different loadings points under voltage stability based critical contingencies. Voltage stability based Critical contingencies have been selected based on maximum loadability criterion. Case studies have been performed on IEEE 14-bus system. Simulation results performed on IEEE 14-bus system validate VCAs formed even under change in network topology caused by line outages and change in operating conditions caused by variations in real and reactive power demands. The VCAs formed by proposed method have been compared with VCAs formed by few existing approaches. The superiority of proposed approach of voltage control areas formation over few existing approaches has been established on the test system considered.

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1. INTRODUCTION

Power system stability has been recognized as an important problem for its secure operation since 1920s [1],[2]. Traditionally, the problem of stability has been one of maintaining the synchronous operation of generators operating in parallel, known as rotor angle stability. The problem of rotor angle stability is well understood and documented. With continuous increase in power demand, and due to limited expansion of transmission systems, modern power system networks are being operated under highly stressed conditions. This has imposed the threat of maintaining the required bus voltages, and thus the systems have been facing voltage instability problem [3].

Voltage stability is the ability of a power system to maintain voltage magnitudes at all the buses in the system within acceptable range after being subjected to a disturbance from a given initial operating condition [3]. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Due to increase in power demand, modern power system networks are being operated under highly stressed conditions. This has resulted into the difficulty in meeting reactive power requirement, specially under contingencies, and hence maintaining the bus voltages within acceptable limits. Voltage instability in the system, generally, occurs in the form of a progressive decay in voltage magnitude at some of the buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascaded outages and voltage collapse in the system [3],[4]. Voltage collapse is the process by which the sequence of events, accompanying voltage instability, leads to a blackout or abnormally low voltages in a significant part of a power system [4]-[6]. Several incidences of voltage collapse have been observed, in past few decades, in different parts of the world. Some of the incidences of voltage collapse are [6],[7]:

- New York Pool disturbance of September 22, 1970.
- Florida system disturbance of December 28, 1982.
- French system disturbances of December 19, 1978 and January 12, 1987.
- Northern Belgium system disturbance of August 4, 1982.
- Swedish system disturbance of December 27, 1983.
- Japanese system disturbance of July 23, 1983.
- Western Systems Co-ordination Council (WSCC) interconnected system (North America) disturbance of July 2, 1996.
- Sri Lankan Power System disturbance of May 2, 1995.
- Northern grid disturbance in Indian Power System of December 1996.
- Punjab voltage collapse in Indian Power System on June 10, 2007.

The structural weakness of the power system, due to weak transmission boundaries between different groups of buses, has also been considered a reason of voltage instability [8]. These groups of buses, located in geographically compact region, have similar voltage changes for any outside disturbance. The bus clusters so formed are called voltage control areas (VCAs) [8]. Due to weak transmission boundaries, loss of voltage controls within a voltage control area may result in voltage collapse in that area since the voltage controls in other voltage control areas may have relatively less impact in controlling voltages in that area. For any external disturbance, each of the voltage control areas may be reduced to equivalent nodes by some network reduction technique. Localization of voltage controls in critical areas together with reduction of areas to equivalent nodes for external disturbances may be quite helpful in fast voltage stability assessment and control of power system networks.

A number of methods have been suggested in literature for formation of voltage control areas. Voltage control areas have been determined by eliminating smaller off-diagonal elements of normalized Q-V Jacobian in [8].In order to consider the effect of Q-δ and P-V coupling, which are very much valid under highly stressed conditions, this algorithm has been applied to full load flow Jacobian instead of decoupled Q-V Jacobian in [9]. The methods suggested in [8], [9] requires proper selection of threshold (α) for elimination of smaller off-diagonal elements, which is a difficult task since smaller values of α puts almost all the buses in one cluster, whereas a larger value may make each bus a separate voltage control area. V-Q curve minima based α-selection algorithm has been proposed in [10]. Formation of voltage control areas under contingencies using an electrical distance concept and V-Q sensitivities of power flow Jacobian has been suggested in [11]. Group of coherent buses have been formed in [12] using generator branch reactive power flow sensitivities to reactive power injection at load buses. The buses having similar generator branch sensitivity values within a reasonable limit of 5% have been clubbed to form voltage control areas. Computations of generator branch sensitivities have been done at the base case operating point. However, generator branch sensitivities are not expected to remain same for change in operating condition or network topology. Voltage control areas have been formed based on Jacobian sensitivities together with voltage variations under contingencies [13]. However, formation of voltage control areas has been done at the base case operating point and V-Q curve minima have been used for selection of threshold only, for elimination of weaker off-diagonal elements of Jacobian. In [13], contingencies have been selected randomly and no specific criterion has been proposed for selection of critical contingencies to study voltage variations from the base case value. Voltage control areas have been formed using bus participation factors corresponding to zero eigen value at the nose point of P-V curve [14]. However, eigen analysis is a linear analysis and may not always be suitable at the nose point of P-V curve. Formation of VCAs has been done based on individual critical loading factor (maximum loadability) of various buses in the geographically compact region [15]. In [15], the VCA with lowest range of maximum loading factor of buses has been considered as the most critical area requiring attention, to reduce chances of voltage failures. However, occurrence of contingencies may change individual critical loading factor (maximum loadability) of buses.

Difficulty in supply of reactive power to consumers has been considered as a major cause of voltage instability in power systems. It is extremely vital to determine major reactive power sources supplying reactive power to a group of buses. The exhaustion of reactive reserves of these sources may cause voltage instability in the group of load buses getting mainly reactive power supply from such sources [10]. This paper presents a method that allows easier determination of a group of load buses being dependent on same set of reactive power sources. Such groups of load buses have been clubbed together to form voltage control areas. Sensitivities of reactive power generations to reactive power demands have been computed to determine dependency of group of loads to group of reactive power sources.

Most of the work has concentrated formation of voltage control areas at the base case operating point. Voltage control areas formed at the base case operating point are not expected to remain valid under change in network topology and operating conditions. Very limited effort seems to be made in formation of voltage control areas considering impact of change in network topology and operating conditions. In the present work, the voltage control areas formed based on reactive power sensitivities have been modified by considering bus voltage variations from the case value at different loadings under voltage stability based critical contingencies to consider impact of change in operating conditions and network topology. Voltage stability based critical contingencies have been selected based on maximum loadability criterion. Proposed approach of voltage control areas formation has been tested on IEEE 14-bus system. Voltage control areas formed by proposed method have been compared by areas formed by few existing approaches. It has been observed on the test system that areas formed by proposed approach are more effective compared to considered existing approaches, under change in network topology and operating conditions.

2. RESEARCH METHOD

In this work, voltage control areas have been formed based on sensitivity of reactive power generations to reactive power demands. The sensitivity factor has been derived as per following.

The reactive power balance equation at all the buses ignoring Q-δ coupling can be given by;

$$\begin{bmatrix}\Delta Q_G\\ \Delta Q_L\end{bmatrix} = \begin{bmatrix}\frac{\partial Q_G}{\partial V_L}\\ \frac{\partial Q_L}{\partial V_L}\end{bmatrix}[\Delta V_L] \tag{1}$$

where,

$[\nabla Q_G]$ = Change in reactive power generations

$[\nabla Q_L]$ = Change in reactive power demands

$[\nabla V_L]$ = Change in voltage magnitudes at load buses

Equation (1) may be rewritten as;

$$[\Delta \mathrm{Q_G}]=[\mathrm{S_G}][\Delta \mathrm{V_L}] \tag{2}$$

and,

$$[\Delta \mathrm{Q_L}]=[\mathrm{S_L}][\Delta \mathrm{V_L}] \tag{3}$$

where,

$[S_G] = \left[\frac{\partial Q_G}{\partial V_L}\right]$ = Sensitivity of reactive power generations to voltage magnitudes at load buses

$[S_L] = \left[\frac{\partial Q_L}{\partial V_L}\right]$ = Sensitivity of reactive power demands to voltage magnitudes at load buses

From (2) and (3),

$$[\Delta \mathrm{Q_G}] = [\mathrm{S}][\Delta \mathrm{Q_L}] \tag{4}$$

where,

$$[S] = [\mathrm{S_G}][\mathrm{S_L}]^{-1} \tag{5}$$

Elements of matrix [S] represent sensitivity of reactive power generations to reactive power demands, and can be calculated using full Q-V Jacobian sub-matrix of Newton Raphson Load Flow. Load buses having closer sensitivities to a group of generators are expected to have similar voltage instability problem since hitting of reactive power limit of such generators will result in difficulty in meeting reactive power demands of these load buses. Therefore, load buses having closer reactive power sensitivity values have been clubbed together to form voltage control areas. However, voltage control areas so formed are not expected to remain same with change in network topology and operating conditions. Therefore, voltage control areas formed based on sensitivity of reactive power generations to reactive power demands have been modified considering voltage variations from the base case value under critical contingencies at different loading conditions. Critical contingencies have been obtained based on post-contingency saddle-node-bifurcation points (maximum loadability points). For obtaining post-contingency saddle-node-bifurcation points, real power output of generators (*PG)*, real power demand *(PD)* and reactive power demand *(QD)* have been varied using:

$$PG_j = PG_j^0 (1+\lambda) \quad (6)$$

$$PD_j = PD_j^0 (1+\lambda) \quad (7)$$

$$QD_j = QD_j^0 (1+\lambda) \quad (8)$$

where,λ represents system loading factor common to all the buses and, PG_j^0, PD_j^0, QD_j^0 are real power output of generator and real and reactive power loads at bus-j at a base operating point (*λ=0.0*).

3. RESULTS AND ANALYSIS

The proposed method of formation of voltage control areas has been applied to IEEE 14-bus system (shown in Figure-1) [16]. IEEE 14-bus system has 5 generators with 20 transmission lines (including 2 transformers and one phase shifting transformer). Loads have been connected at 11 buses including two generator buses.

The sensitivity of reactive power generations to reactive power demands were calculated using (5) at the base case operating point with the help of elements of Newton Raphson Load Flow Jacobian matrix. The sensitivity values between different generator buses and load buses have been shown in Table-1. The senstivity values shown in Table-1 represent dependency of load buses to reactive power sorces. If a group of load buses (say Group-A) has high and similar dependency on a group of reactive power sources (say Group-B), hitting of reactive power generation limit of generators in Group-B is expected to result in voltage instability at all the load buses in Group-A. Therefore, all the load buses in Group-A are expected to face similar voltage instability problem. Voltage control areas were formed clubbing load buses having closer reactive power sensitivities to generators. The voltage control areas so formed have been shown in Table-2 and Figure-1.

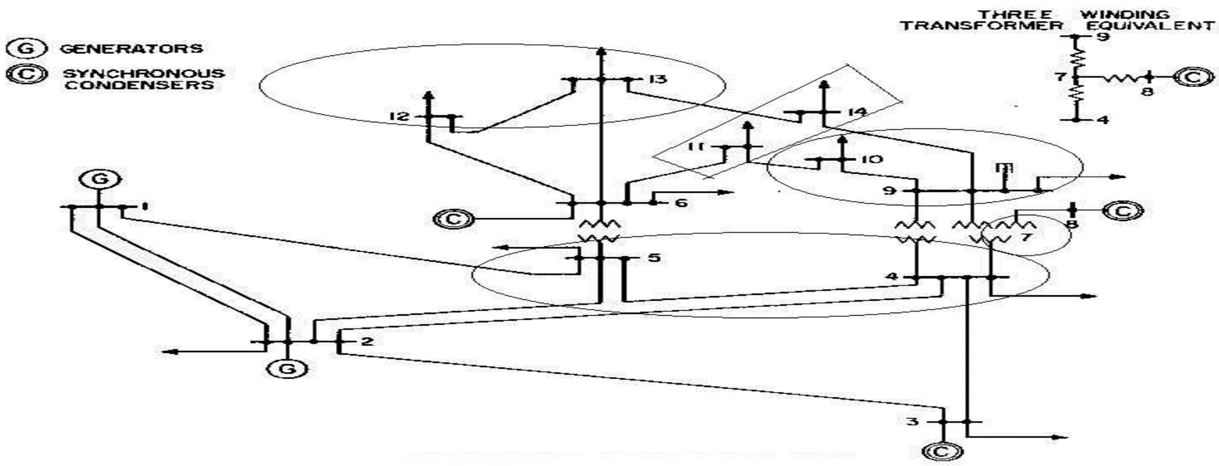

Figure-1. VCAs for IEEE 14-bus system based on reactive power sensitivities

Table 1. Sensitivity of Reactive Power Generations to Reactive Power Demands (S_{ij}) - 14-Bus System

Load bus no.	Generator bus no.				
	1	2	3	6	8
4	-0.12038	-0.38004	-0.21604	-0.17201	-0.12044
5	-0.19713	-0.37703	-0.12872	-0.22221	-0.07176
7	-0.05366	-0.16941	-0.09630	-0.22054	-0.49275
9	-0.05211	-0.16451	-0.09352	-0.38568	-0.34688
10	-0.04380	-0.13829	-0.07861	-0.49828	-0.29159
11	-0.02265	-0.07152	-0.04066	-0.74709	-0.15080
12	-0.00335	-0.01057	-0.00601	-0.98826	-0.02228
13	-0.00809	-0.02555	-0.01452	-0.94007	-0.05386
14	-0.03442	-0.10868	-0.06178	-0.64634	-0.22916

Table 2. VCAs Formed Using S_{ij} Values (IEEE 14-Bus System)

VCA no.	Buses present

1	12, 13
2	11, 14
3	9, 10
4	4, 5
5	7

Voltage control areas shown in Figure-1 and Table-2 represent areas for the intact system. The load buses within the areas so formed are expected to have similar voltage instability problem. However, voltage control areas so formed are expected to change under change in network topology and operating conditions, since the sensitivity values are expected to change under change in network topology and operating conditions. In order to consider impact of change in network topology and operating conditions, the voltage control areas formed based on reactive power sensitivities were modified based on bus voltage variations under voltage stability based critical contingencies at large number of new real and reactive power demands. Voltage stability based most severe contingencies were selected based on post-contingency saddle-node-bifurcation points (maximum loadability points) using continuation power flow based software package UWPFLOW [17]. Voltage stability based contingency ranking has been shown in Table-3. Voltage magnitude at all the load buses were calculated at the base case operating point, nose point (maximum loadability point) and some of the intermediate loading points, under critical contingencies. The change in voltage magnitude from the base case operating point value, of all the load buses, at some of the post-contingency loadings have been shown in Table-4. The voltage control areas formed using reactive power sensitivities (shown inTable-2 and Figure-1) were modified based on post-contingency voltage variations from the case operating value, under different loadings. Modified voltage control areas have been shown in Table-5 and Figure-2.

Table 3. Voltage Stability Based Contingency Ranking (IEEE 14-bus System)

Line outage	Maximum loading factor (λ_{max})	Contingency ranking
2-3	1.2747	1
5-6	1.3059	2
2-4	2.1463	3
6-13	2.2427	4
2-5	2.2465	5
12-13	2.2775	6
13-14	2.2799	7
1-5	2.4536	8
4-7	2.4978	9
7-9	2.7485	10

Table 4. Voltage Variations of Load Buses under Few Critical Contingencies with Increased Demands (IEEE 14-bus System)

Line	Loading	Change in voltage magnitude (p.u.) from the base case operating point value of load buses								
outage	factor	Bus-4	Bus-5	Bus-7	Bus-9	Bus-10	Bus-11	Bus-12	Bus-13	Bus-14
2-3	**1.2747***	-0.193	-0.179	-0.107	-0.127	-0.111	-0.025	-0.002	-0.011	-0.109
5-6	**1.3059***	-0.136	-0.109	-0.143	-0.170	-0.168	-0.096	-0.016	-0.037	-0.179
2-4	**2.1463***	-0.284	-0.312	-0.180	-0.222	-0.200	-0.096	-0.022	-0.052	-0.205
6-13	**2.2427***	-0.175	-0.177	-0.186	-0.280	-0.250	-0.123	-0.233	-0.491	-0.481
2-5	1.4750	-0.084	-0.093	-0.061	-0.082	-0.075	-0.028	+0.001	-0.014	-0.085
12-13	**2.2775***	-0.056	-0.054	-0.183	-0.072	-0.066	-0.024	+0.017	-0.020	-0.082
13-14	**2.2799***	-0.161	-0.156	-0.183	-0.284	-0.256	-0.127	+0.001	-0.001	-0.500
1-5	1.4144	-0.076	-0.079	-0.056	-0.075	-0.068	-0.025	+0.002	-0.011	-0.078
4-7	1.5335	-0.074	-0.075	-0.050	-0.098	-0.091	-0.040	-0.002	-0.020	-0.100
7-9	**2.7485***	-0.289	-0.341	-0.119	-0.620	-0.543	-0.282	-0.067	-0.138	-0.504

* **Nose point**
\+ **Voltage rise**
\- **Voltage drop**

Table 5. VCAs Formed Based on S_{ij} Values Together with Bus Voltages Variations under Critical Contingencies (IEEE 14-Bus System)

VCA no.	Buses present
1	12, 13
2	11
3	9, 10
4	4, 5
5	7
6	14

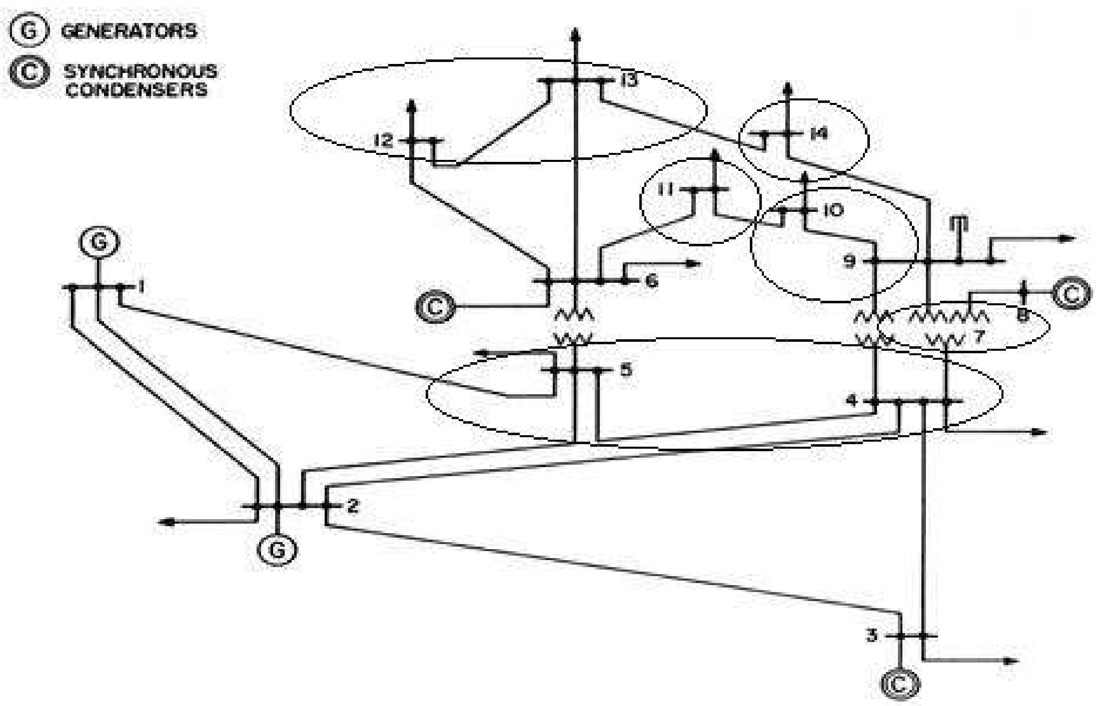

Figure-2. VCAs formed by proposed method (IEEE 14-bus System)

The maximum change in voltage from the base case operating point (considered as A in present work) with bus number having maximum change in voltage, the minimum change in voltage from the base case operating point (considered as B in present work) with bus number having minimum change in voltage, and absolute value of difference between A and B (considered as C in present work), have been shown in Table-6 for different voltage control areas under few critical contingencies at some of the loadings. It is observed from Table-6 that voltage control areas formed by proposed approach consist of buses having very small range of voltage variations with change in network topology caused by line outages and change in operating conditions caused by change in demands.

The voltage control areas formed by proposed approach were compared with the methods of voltage control areas formation suggested in Ref. [10], Ref. [13] and Ref. [15], respectively, based on lowest maximum C value between all the voltage control areas formed. Table-7 shows maximum C for different approaches under voltage stability based critical contingencies at some of the loading values. It is observed from Table-7 that voltage control areas formed by proposed approach have lowest maximum C values compared to voltage control areas formed using methods suggested in Ref. [10], Ref. [13] and Ref. [15], under critical contingencies at different loadings, for most of the cases. Therefore, VCAs formed by proposed approach remains valid under critical contingencies at different loadings. Due to lowest voltage variations compared to three existing approaches, under voltage stability based critical contingencies at a set of real and reactive power demands, the areas formed by proposed approach may be more efficient in voltage stability assessment under change in operating conditions and network topology.

4. CONCLUSION

A modified method for formation of voltage control areas has been presented in this paper. Proposed method of VCAs formation first clubs load buses based on closer sensitivity of reactive power generations to reactive power demands. The VCAs so formed have been modified based on voltage variations of load buses under voltage stability based critical contingencies at a set of new loadings. Voltage stability based critical contingencies have been obtained based on maximum loadability criterion. Proposed method of VCAs formation has been tested on IEEE 14-bus system. Results obtained on the test system considered establish better suitability of VCAs formation over some of the existing approaches under change in operating conditions and network topology. Voltage control areas formed by proposed approach may be quite effective in fast voltage stability assessment and control of power system networks. Since VCAs have been formed to study voltage stability phenomenon, generator buses have not been considered for clustering in the present work.

Table 6. Voltage Variations at Buses within VCAs Formed by the Proposed Approach (IEEE 14-bus System)

Line outage	Loading factor	VCA no.	Maximum and minimum change in voltage magnitude (p.u.) from the base case operating point at buses within VCAs, and absolute value of difference (p.u.) between maximum voltage change and minimum voltage change at buses within VCAs		
			A	B	C
1-5	1.4144	1	+0.002 (bus-12)	-0.011 (bus-13)	**0.013****
		2	Contain only one load bus		
		3	-0.075 (bus-9)	-0.068 (bus-10)	0.007
		4	-0.079 (bus-5)	-0.076	0.003
		5	Contain only one load bus		
		6	Contain only one load bus		
2-3	**1.2747***	1	-0.011 (bus-13)	--0.002 (bus-12)	0.009
		2	Contain only one load bus		
		3	-0.127 (bus-9)	-0.111 (bus-10)	0.006
		4	-0.192 (bus-4)	-0.179 (bus-5)	**0.013****
		5	Contain only one load bus		
		6	Contain only one load bus		
6-13	**2.2427***	1	-0.491 (bus-13)	-0.233 (bus-12)	**0.258****
		2	Contain only one load bus		
		3	-0.280 (bus-9)	-0.250 (bus-10)	0.030
		4	-0.177 (bus-5)	-0.175 (bus-4)	0.002
		5	Contain only one load bus		
		6	Contain only one load bus		
12-13	**2.2775***	1	-0.020 (bus-13)	+0.017 (bus-12)	**0.037****
		2	Contain only one load bus		
		3	-0.072 (bus-9)	-0.066 (bus-10)	0.006
		4	-0.056 (bus-4)	-0.054 (bus-5)	0.002
		5	Contain only one load bus		
		6	Contain only one load bus		

*** Nose point**
**** Maximum value of C between all the VCAs formed by the proposed method**
+ Voltage rise
- Voltage drop
A = Maximum change in voltage (in p.u.) from the base case operating point value occurring at one of the bus within VCA
B = Minimum change in voltage (in p.u.) from the base case operating point value occurring at one of the bus within VCA
C = Absolute value of difference between A and B

Table 7. Comparison of VCAs formed by different approaches

Line outage	Loading Factor	Maximum value of C between different VCAs fomed

		VCAs formed by method suggested in Ref. [10]	VCAs formed by method suggested in Ref. [13]	VCAs formed by method suggested in Ref. [15]	**VCAs formed by proposed method**
2-3	**1.2747***	0.091	0.109	0.175	**0.013****
5-6	**1.3059***	0.191	0.143	0.143	**0.021****
2-4	**2.1463***	0.153	0.183	0.231	**0.030****
6-13	**2.2427***	**0.110****	0.257	0.313	0.257
2-5	1.4750	0.071	0.085	**0.008****	0.014
12-13	1.4862	0.062	0.062	0.062	**0.037****
13-14	**2.2799***	0.499	0.499	0.340	**0.028****
1-5	1.4144	0.068	0.078	0.067	**0.013****
4-7	1.5335	0.079	0.099	0.077	**0.020****
7-9	**2.7485***	0.365	0.501	0.501	**0.077****

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