World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:5, No:3, 2011

Clustering based Voltage Control Areas for Localized Reactive Power Management in Deregulated Power System

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***Abstract*—**In this paper, a new K-means clustering based approach for identification of voltage control areas is developed. Voltage control areas are important for efficient reactive power management in power systems operating under deregulated environment. Although, voltage control areas are formed using conventional hierarchical clustering based method, but the present paper investigate the capability of K-means clustering for the purpose of forming voltage control areas. The proposed method is tested and compared for IEEE 14 bus and IEEE 30 bus systems. The results show that this K-means based method is competing with conventional hierarchical approach

***Keywords*—**Voltage control areas, reactive power management, K-means clustering algorithm

I. INTRODUCTION

THE power system security of power system is severely affected by reactive power because it affects voltages throughout the system. At key locations in the power system, insufficient reactive power can result in the inability to transfer active power beyond a level. Indeed in the past, many major outages in different countries (e.g. the Canada-US and the Sweden blackouts in 2003) have been ultimately traced to problems with insufficient reactive power support [1]. Providing reactive power by the voltage control ancillary services is becoming a key issue of reactive power management. The Federal Energy Regulatory Commission (FERC 1996, 1997a) recognized the importance of voltage control by including it as an ancillary service in Order 888, Reactive Supply and Voltage Control from Generation Sources [2]. Mainly a problem of *market power* (some of the reactive power producers misusing the situation by giving by extraordinary high prices of their services) may arise while establishing reactive power market for voltage control ancillary services. This problem is caused due to local nature of reactive power and voltage phenomenon in electrical networks [3]-[4]. Therefore, a need of effective design of localized reactive power market considering voltage control areas (VCAs) is realized to overcome the same problem.

Many researchers [4]-[6] have used hierarchical clustering based approach to form VCAs while analysing reactive power management problems such as reactive power pricing, planning and control and congestion management etc. in deregulated power system. This paper presents an application of K-Means clustering algorithm for formation of VCAs in IEEE 14 bus and IEEE 30 bus systems. The results are compared with conventional hierarchical clustering based approach. In section 2, conventional hierarchical clustering and K-means clustering based approach for identification of VCAs are described. Section 3 presents simulation results for IEEE 14 bus and IEEE 30 bus systems. Finally in section 5, conclusion for this work is presented.

Manuscript received February 09, 2011. This work was supported by the University Grant Commission (UGC) of India as a part of major research project on Reactive power pricing.

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II. FORMATION OF VOLTAGE CONTROL AREAS

Formation of VCAs for any electric power system is a process of forming some non overlapping coherent bus groups. These groups are the sets of such buses forming voltage control areas if they are sufficiently uncoupled electrically, from its neighboring areas. Each VCA consists of those buses which have significant electrical couplings (dependencies) among them. A bus voltage profile of each VCA may be effectively controlled by the localized reactive power supports within it and the controls within the area are very less influenced by other areas [7]. In reference [8], a two-stage systematic method is reported for identification of VCAs in the French power system. This method involves determination of electrical distance between the buses in the system, and subsequently hierarchical clustering algorithm is applied to classify the areas and decide the borders of each VCA. In [9], this conventional method is used to analyze “local” voltage stability problems and assess voltage security, while it has been used for examining localized voltage-control services in [10].

A. Conventional hierarchical clustering based approach

Fig.1 presents procedural steps for identification of VCAs using hierarchical clustering based approach. Power flow analysis is performed on power system data and subsequently computing the sensitivity matrix (i.e. $\delta V/\delta Q$ matrix). The normalized electrical distance is computed for the sensitivity matrix. Step-by-step method for the same is given below:

1. Calculate the Jacobian matrix J and hence obtain the sub-matrix J_4, where $J_4 = [\partial \mathbf{Q} / \partial \mathbf{V}]$.
2. Invert J_4. Say, $B = (\partial \mathbf{V} / \partial \mathbf{Q}) = J_4^{-1}$, and the elements of matrix B are written as b_{ij}, where $b_{ij} = \partial V_i / \partial Q_j$.
3. Obtain attenuation matrix, α_{ij} , between all the nodes as follows: $\alpha_{ij} = b_{ij} / b_{jj}$.
4. Calculate electrical distances $D_{ij} = -Log(\alpha_{ij}, \alpha_{ji})$
5. Normalize the electrical distances as follows: $D_{ij} = D_{ji} / \mathrm{Max}(D_{i1}, ..., D_{iN})$

Once the electrical distances for any couple of nodes in the system are defined, it is possible to trace the boundary of VCAs [10]. There is no unique way to do so. The general idea is to give autonomy and independence, from a reactive power management standpoint, to each area. This is accomplished in different ways depending on the power system. A hierarchical classification algorithm to identify the VCAs according to the electrical distances is applied and reported in [4].

B. *Proposed K-means clustering based approach*

The most popular and well-known partitional clustering method is K-means clustering algorithm. This algorithm is of great interest because of quick convergence [11-12]. As shown in Fig.2, for identifying VCAs, K-means clustering algorithm is applied after performing power flow analysis and subsequent computation of the sensitivity matrix (i.e. $\delta V / \delta Q$ matrix).

K-means algorithm is defined based on the Euclidean distance. The Euclidean distance in a plan is the “ordinary” distance between two points that one would measure with ruler. In N dimension space, the Euclidean distance between two points P and Q is

$$\|P - Q\| = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + ... + (p_n - q_n)^2}$$

where p_i (or q_i) is the coordinate of p (or q) in dimension i .

K-means uses the concept of Euclidean distance to measure the similarity (or dissimilarity) between each point in the database and the centre of the clusters to determine to which cluster the point is better dependent. It tries to separate the data points into an adequate number of clusters in a way that the sum of the Euclidean distances of all points of database to the centriod of their own cluster become minimized (at least locally minimized as mentioned before). This procedure consists of the following steps [11]:

Step 1: Choose K initial cluster centres $z_1(1), z_2(1), . . ., z_k(1)$ arbitrarily.

Step 2: At the r[th] iterative step distributes the samples {X} among the K cluster domains, using the relation,

$$x \in S_j(r) \quad if \quad \|x - z_j(r)\| < \|x - z_i(r)\|$$

For all $i = 1,2,\ldots, K$, $i = j$, where $S_j (r)$ denotes the set of samples whose cluster centre is $z_j (r)$.

Step 3: From the results of Step 2, compute the new cluster centers $z_j(r+1), j = 1, 2, ..., K$, such that the sum of the squared distances from all points in *Sj (r)* to the new cluster centre is minimized. Those cluster centers are considered simply the sample mean of Sj (k).

$$z_j(k+1) = \frac{1}{N} \sum_{X \in S_j(k)} X \qquad j = 1, 2, ..., K$$

where N_j is the number of samples in $S_j(r)$.

Step 4: if $z_j(r+1) = z_j(r)$, For $j = 1, 2, ..., K$, the algorithm has converged and the procedure is terminated. Otherwise go to Step 2.

The behavior of the K-means algorithm is influenced by the number of cluster centres specified, the choice of initial cluster centres, the order in which the samples are taken, and, of course, the geometrical properties of the data.

III. Simulation Results

In this paper, the simulation scheme is divided for two cases studies i.e. for IEEE 14 bus System and IEEE 30 bus system. In both the cases, the disturbances are created by sudden increment in load (real and reactive power) demand. This causes voltage fall at that particular bus below its minimum acceptable limit and poor voltage profile at other buses lying in the same VCA. In order to control voltage profile and bring within their allowable limits, voltage control actions (either by increasing generator voltages or increasing reactive power support of shunt capacitors lying in same VCA). The simulations are carried out and compared for both conventional hierarchical and proposed K-Means clustering based VCAs. The analysis and simulation results are discussed in the following sub section.

A. *Case study for IEEE 14 bus System*

For IEEE 14 bus system, two voltage control areas (VCA1 and VCA2) are formed by K-means and hierarchical clustering methods which are represented by dotted lines and hard lines respectively as shown in Fig. 3. In this case study, the disturbances are created at bus no. 4, 7, 9 and 14 by sudden increment in load (real and reactive power demand) till voltage reduced below the specified minimum limit (0.94 p.u.). At the same time, there are also significant voltage fall at other buses lying in same VCA. The simulation result of voltage control actions are analyzed with reference to VCAs formed by K-means clustering method and summarized in Table I.

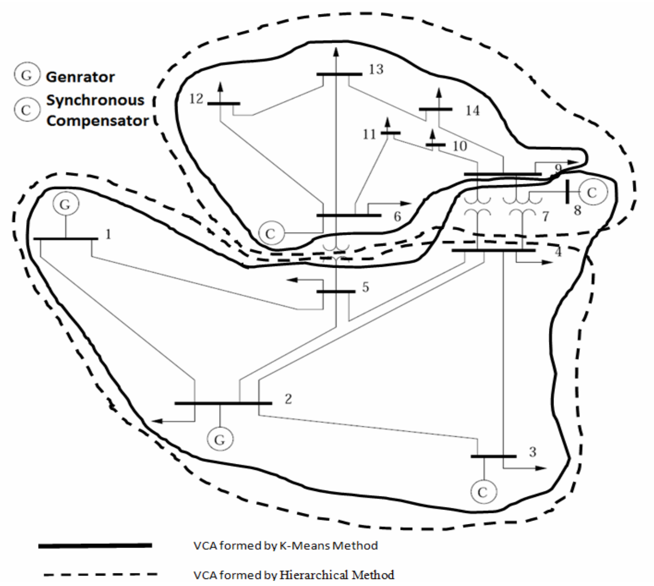
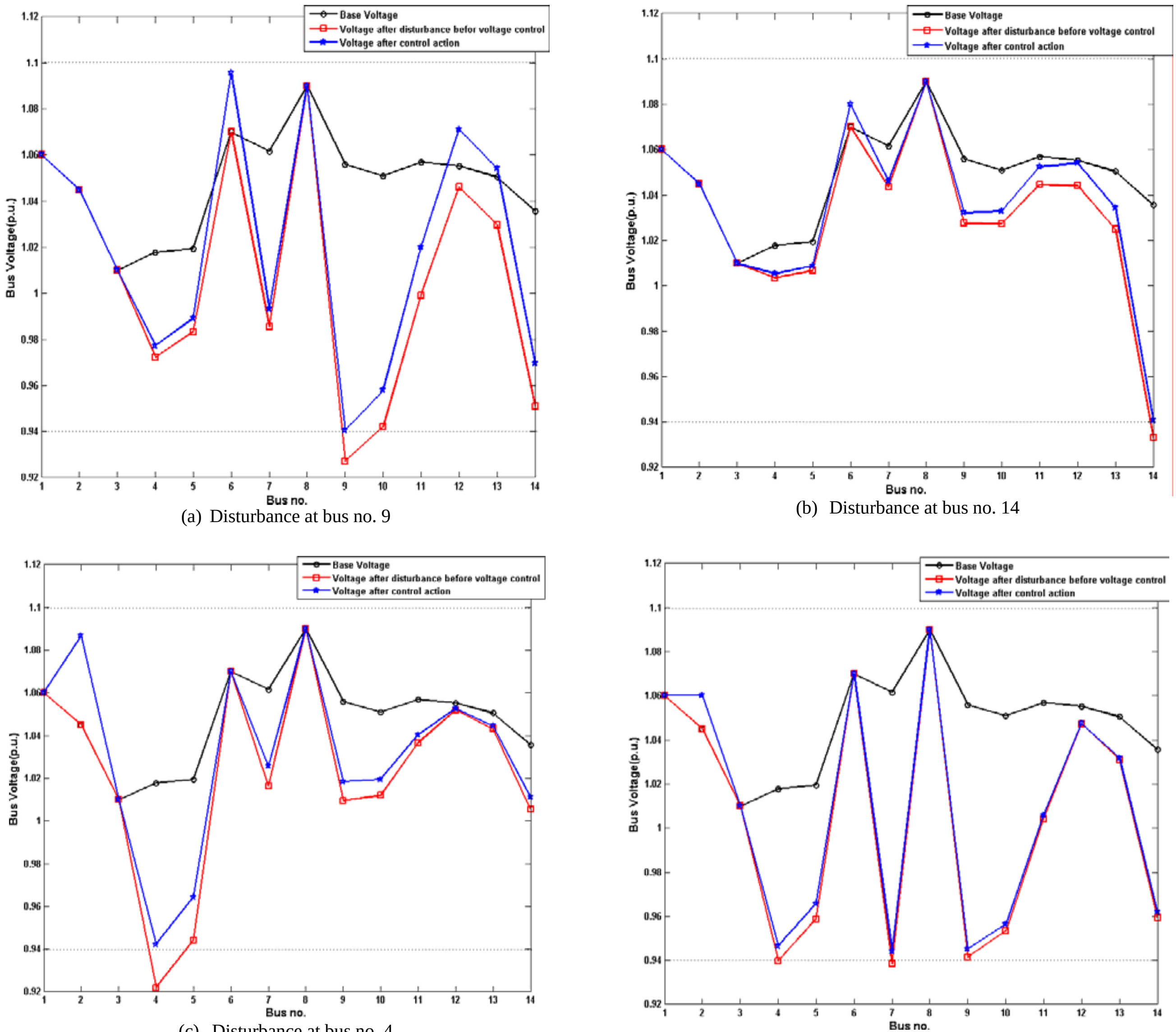


Fig. 3 VCAs formed by K-means and hierarchical clustering methods for IEEE 14 Bus system

From Table I, it is clear that when the load increment at bus no. 7, is (2.0+j0.65) p.u., this results voltage fall at the same bus from base value 1.0615 p.u. to 0.93837 p.u. It is a violation of minimum permissible limit. Therefore, maintaining the voltage within its expected permissible limit, effective voltage control actions are achieved by increasing the voltages of the generator at bus 2 and 8. The best voltage control scenario is achieved in case of disturbance at bus no. 7 is illustrated in Fig.4 (d). In the same manner, the voltage control actions are analysed for subsequent disturbances listed in Table I. Their best voltage control scenarios achieved for different load disturbances are shown in Table I with gray shade and the voltage profiles are shown in Fig.4. From this study, it is clear that bus 7, 2 and 8 have strong electrical coupling so they must be in same VCA. The same VCAs are achieved by K-means clustering method but not by hierarchical clustering method.

TABLE I
SIMULATION RESULTS FOR IEEE- 14 BUS SYSTEM USING K-MEANS CLUSTERING METHOD

Voltage Control Area #1 (1,2,3,4,5,7,8) Voltage Control Area #2 (6,9,10,11,12,13,14)							Other Effected Buses due to disturbance at bus no.7
Voltage Control Area (VCA)			VCA #2		VCA #1		VCA #1
Bus No.			**9**	**14**	**4**	**7**	**4**
Permissible voltage (p.u)		Maximum	1.1	1.1	1.1	1.1	
		Minimum	0.94	0.94	0.94	0.94	-
Base Voltage (p.u.)			1.0559	1.0355	1.0177	1.0615	-
Load Increment (p.u.)	Real power (P)		1.18	0.5215	3.346	2	
	Reactive Power (Q)		0.664	0.175	0.356	0.65	-
Voltage after disturbance before voltage control (p.u.)			0.92717	0.93326	0.92197	0.93837	0.93962
Control With VCA#1	For Gen at bus 1	Increment in Gen. Voltage (p.u.)	0.04	0.04	0.04	***0.04***	***0.04***
		Load bus voltage (p.u.)	0.92994	0.93488	0.92845	***0.9416***	***0.94551***
	For Gen at bus 2	Increment in Gen. Voltage (p.u.)	0.055	***0.055***	***0.0418***	***0.015***	***0.015***
		Load bus voltage (p.u.)	0.93911	***0.94035***	***0.94218***	***0.94412***	***0.94648***
	For Gen at bus 3	Increment in Gen. Voltage (p.u.)	0.09	***0.09***	***0.07***	***0.02***	***0.02***
		Load bus voltage (p.u.)	0.93874	***0.9402***	***0.94106***	***0.94129***	***0.94496***
	For Gen at bus 8	Increment in Gen. Voltage (p.u.)	0.01	0.01	0.01	***0.01***	***0.01***
		Load bus voltage (p.u.)	0.93105	0.93566	0.92311	***0.94386***	***0.94099***
Control with VCA#2	For Gen at bus 6	Increment in Gen. Voltage (p.u.)	***0.0257***	***0.01***	0.03	***0.018***	***0.018***
		Load bus voltage (p.u.)	***0.94037***	***0.94081***	0.92787	***0.94213***	***0.94353***
Remarks			Only Control by VCA #2	Control by both VCA's but effectively control by VCA #2 only	Only Control by VCA #1	Control by both VCA's but effectively control by VCA #1only	Voltage at Bus No.4 is also effectively controlled by VCA #1



(a) Disturbance at bus no. 9

(b) Disturbance at bus no. 14

(c) Disturbance at bus no. 4

(d) Disturbance at bus no. 7

Fig.4. Voltage profiles before and after voltage control actions for IEEE- 14 bus system

B. *Case study for IEEE 30 bus System*

Three voltage control areas (VCA1, VCA2 and VCA3) are formed by K-means and hierarchical clustering methods as shown in Fig. 5. In this case study, the disturbances are created at bus 7, 17, 24 and 30 by sudden increment in load (real and reactive power demand) till voltage reduced below the specified minimum limit (0.94 p.u.). Consequently, there are also significant voltage falls at their corresponding VCA. The simulation result of voltage control actions are analyzed with reference to VCAs formed by K-means clustering method and summarized in Table II.From Table II, it is clear that when the load increment at bus no. 24, is (0.3045+j0.2345) p.u., this results in terms of voltage fall at the same bus from base value 1.0216 p.u. to 0.93701 p.u. It is the violation of minimum permissible limit. Therefore, to maintain the voltage within its permissible limit, voltage control actions are achieved by increasing the voltage of the generator at bus 13. The best voltage control scenario achieved in case of disturbance at bus no. 24 is illustrated in Fig.6 (c). In the same manner, the voltage control actions are analyzed for subsequent disturbances listed in Table II. Their best voltage control scenarios achieved are shown in Table II with gray background and voltage profiles are shown in Fig.6. From this study, it is evident that bus no. 24 and 13 have strong electrical coupling so they must be in same VCA. The same VCAs are achieved by K-means clustering method but not by hierarchical clustering method. It is also clear (see Table II) that if any VCA is formed such that there is no generator lies in the same VCA then voltage fall due to disturbance in this VCA is only controllable by providing reactive power support from local capacitor banks in same VCA. When the load increment at bus 30, is (0.212+j0.038) p.u., this results voltage fall at the same bus and its neighbor bus 29. The best voltage control scenario achieved in case of disturbance at bus no. 30 is illustrated in Fig.6 (d). The detailed analysis of capacitor value for controlling the same is illustrated in Table II.

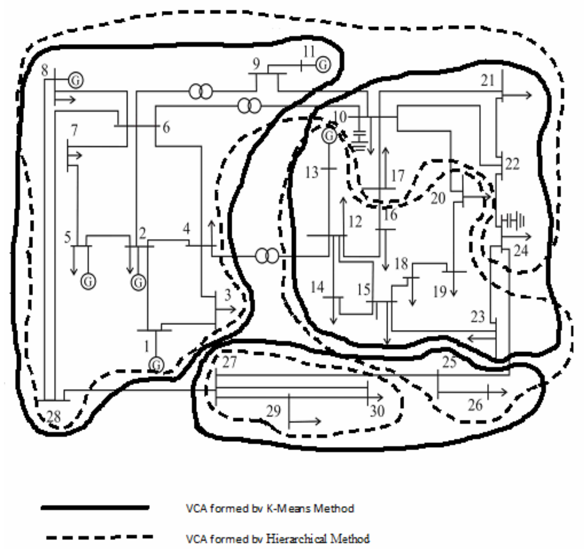
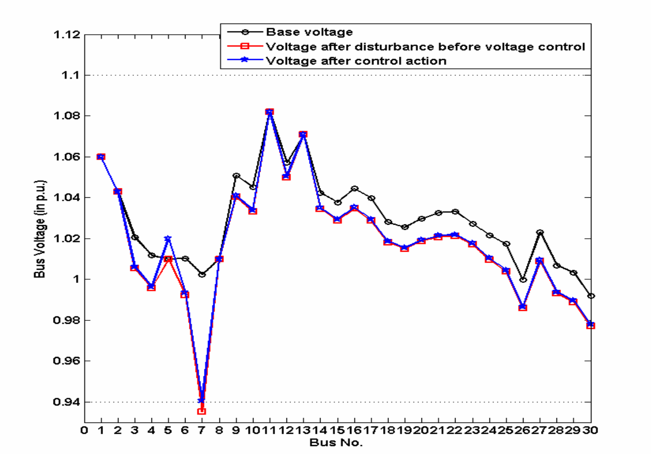


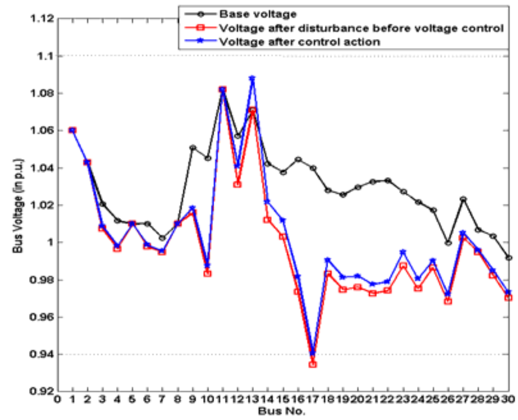
Fig. 5 VCAs formed by K-means and hierarchical clustering methods for IEEE 30 bus system

TABLE II
SIMULATION RESULTS FOR IEEE 30 BUS SYSTEM USING K-MEANS CLUSTERING METHOD

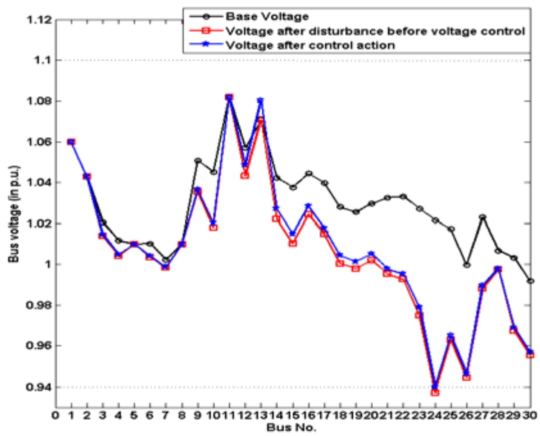
Voltage Control Area #1 (***1***,***2***,3,4,5,6,***7***,8,9,11,28) Voltage Control Area #2 (10,12,13,14,15,16,17,18,19,20,21,22,23) Voltage Control Area #3 (25,26,27,29,30)								Other Effected Buses due to disturbance at bus no.30
Voltage Control Area (VCA)				VCA #1	VCA #2		VCA #3	VCA #3
Bus No.				**7**	**17**	**24**	**30**	**29**
permissible voltage (p.u)			Maximum	1.06	1.06	1.06	1.06	-
			Minimum	0.94	0.94	0.94	0.94	
Pre disturbance Voltage(p.u.)				1.0024	1.0399	1.0216	0.99191	
Load Increment (p.u.)		Real power (P)		1.2540	0.63	0.3045	0.212	-
		Reactive Power (Q)		0.5995	0.406	0.2345	0.038	
Post disturbance Voltage(p.u.)				0.93532	0.93446	0.93701	0.87107	0.91819
Control With VCA #1	For Gen. at bus 1	Increment in Gen. Voltage (p.u.)		0.04	0.04	0.04	0.04	0.04
		Load bus voltage (p.u.)		0.93723	0.9373	0.9391	0.87421	0.92115
	For Gen. at bus 2	Increment in Gen. Voltage (p.u.)		***0.0365***	***0.0417***	***0.0313***	0.057	0.057
		Load bus voltage (p.u.)		***0.94018***	***0.94098***	***0.94195***	0.8825	0.92896
	For Gen. at bus 5	Increment in Gen. Voltage (p.u.)		***0.0101***	***0.0859***	***0.0606***	0.09	0.09
		Load bus voltage (p.u.)		***0.94048***	***0.94002***	***0.94108***	0.87969	0.92632
	For Gen at bus 8	Increment in Gen. Voltage (p.u.)		***0.0151***	***0.0202***	***0.0101***	0.09	***0.09***
		Load bus voltage (p.u.)		***0.94076***	***0.94185***	***0.94125***	0.93468	***0.97834***
	For Gen. at bus11	Increment in Gen. Voltage (p.u.)		0.018	0.018	***0.018***	0.018	0.018
		Load bus voltage (p.u.)		0.93594	0.93953	***0.94116***	0.8737	0.92068
Control with VCA #2	For Gen. at bus 13	Increment in Gen. Voltage (p.u.)		0.029	***0.0171***	***0.0093***	0.029	0.029
		Load bus voltage (p.u.)		0.9363	***0.94035***	***0.94002***	0.87658	0.92339
Control with VCA #3	At bus 25	Capacitor provided(MVAR)		-	-	-	21	***21***
		Load bus voltage (p.u.)		-	-	-	0.93522	***0.97886***
	At bus 26	Capacitor provided(MVAR)		-	-	-	10	***10***
		Load bus voltage (p.u.)		-	-	-	0.90141	***0.94682***
	At bus 27	Capacitor provided(MVAR)		-	-	-	***18***	***18***
		Load bus voltage (p.u.)		-	-	-	***0.94375***	***0.98696***
	At bus 29	Capacitor provided(MVAR)		-	-	-	***12***	***12***
		Load bus voltage (p.u.)		-	-	-	***0.94036***	***0.99907***
	At bus 30	Capacitor provided(MVAR)		-	-	-	***10***	***10***
		Load bus voltage (p.u.)		-	-	-	***0.94331***	***0.96959***
Remarks				Only Control by VCA#1	Control by both VCA but effectively by VCA#2	Control by both VCA but effectively by VCA#2	Control by only VCA #3	Voltage at Bus No. 29 also effectively controlled by VCA #3



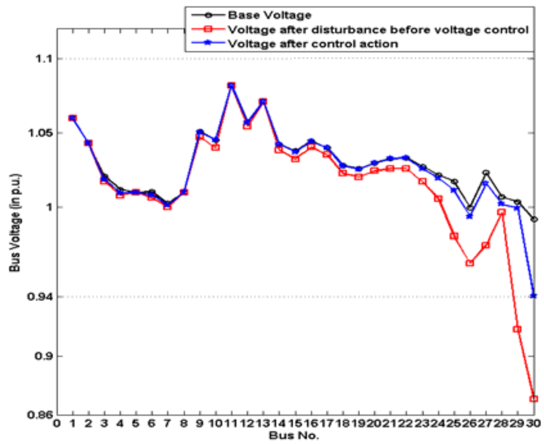
(a) Disturbance at bus no. 7



(b) Disturbance at bus no. 17



(c) Disturbance at bus no. 24



(d) Disturbance at bus no. 30

Fig. 6 Voltage profiles before and after voltage control actions for IEEE 30 bus system

IV. Conclusion

This paper attempts to develop an alternative approach for forming VCAs for reactive power management and voltage control based on K-means clustering algorithm. The proposed K-means approach has demonstrated good performance for different load disturbances taken in both case studies. The results and subsequent discussions presented in previous section show that K-mean clustering based method is also a well deserved approach for identifying VCAs effectively and compete with conventional hierarchical clustering approach.

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