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Electric Power Components and Systems

ISSN: 1532-5008 (Print) 1532-5016 (Online) Journal homepage: https://www.tandfonline.com/loi/uemp20

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To cite this article: R. Shivarudraswamy & D. N. Gaonkar (2012) Coordinated Voltage Regulation of Distribution Network with Distributed Generators and Multiple Voltage-control Devices, Electric Power Components and Systems, 40:9, 1072-1088, DOI: 10.1080/15325008.2012.675410

To link to this article: https://doi.org/10.1080/15325008.2012.675410

Electric Power Components and Systems, 40:1072–1088, 2012

ISSN: 1532-5008 print/1532-5016 online
DOI: 10.1080/15325008.2012.675410

Coordinated Voltage Regulation of Distribution Network with Distributed Generators and Multiple Voltage-control Devices

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Abstract *In recent years, there has been a considerable increase in the number of generators connected to distribution networks. While offering a number of benefits and opportunities, increasing penetration of distributed generation systems can cause several technical concerns. One major concern is the rise in steady-state voltage level of a distribution system. This is very important, as distribution networks are traditionally designed to maintain customer voltage constant, within tolerance limit as dictated by statute. The present practice of limiting generation capacity cannot be a solution, as it leads to under-utilization of distributed generation sources. In this article, coordinated voltage regulation of distribution system with distributed generators is presented. The developed method uses the genetic algorithm to determine the optimal operating point for multiple voltage-control devices. The simulated results using the developed method are presented in this article, considering the time-varying load profile. The fuzzy-clustering technique is also employed to obtain the load pattern for the simulation. The reported results show that the method presented is capable of providing the voltage profile within the statute limits.*

Keywords distributed generation, reactive power, voltage control, genetic algorithm, fuzzy clustering

1. Introduction

The need for energy is never ending. This is certainly true of electrical energy, which is a large part of total global energy consumption. But growing in tandem with energy needs are the concerns about sustainable development and environmental issues, such as the movement to reduce greenhouse gas emissions. The result of fulfilling energy needs and meeting environmental and social concerns is the growing interest in reliable distributed generation (DG) sources. It is believed that the future will bring more and more small distributed power generation units connected to the grid [1].

Received 15 September 2011; accepted 9 March 2012.
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The present scenario of deregulation of the power utilities and the competition in the energy markets are further accelerating the growth in parallel operation of DG systems with the utility. Besides offering environmental benefits, integration of modular generating units to a distribution network may bring other significant benefits, such as increased reliability and power quality, loss reduction, and load management. In order to achieve these benefits with a large penetration of DG sources in existing utility networks, several technical problems are to be confronted, such as degradation of system reliability, power quality problems, steady-state voltage rise, islanding, and various other safety issues [1]. The steady-state voltage rise problem is reported as one of the main obstacles for interconnection of large amounts of DG units to the existing radial networks [2].

Distribution networks are designed to keep the customer voltage constant within the tolerance limit as dictated by statute, which has always been a top priority. The range of voltage that must be met under a number of different standards does not exceed $\pm 10\%$, with some standards being even tighter than this [2]. Therefore, the results of some generic studies explaining the voltage rise issue and how it may be overcome are also presented. The various methods have been presented in the literature by using these components in individual control [2–4] or centralized [5] or coordinated control schemes [6]. A cooperative control method using a step voltage regulator (SVR) and a unified power flow controller (UPFC) to regulate the line voltage within the prescribed voltage ranges against steep voltage fluctuations was presented in [7].

In [6], uncoordinated and coordinated voltage control, without and with DG involved in the voltage control, were investigated. The result indicates that involving DG in the voltage control will result in a reduction of the number of on-load tap-changer (OLTC) operations. A comparative study of intelligent distributed voltage and reactive power control and the centralized control scheme in terms of the potential for connecting increased capacities within existing networks was reported in [5]. A method for designing under-load tap-changing (ULTC) parameters with reference to variations in DG output was proposed in [8], and the results reported demonstrate the validity of the proposed method. A coordinated control scheme was presented in [9], where the operation of individual control devices, such as the load ratio control transformer (LRT), SVR, shunt capacitor (SC), shunt reactor, and static VAR compensator (SVC), were determined by using a genetic algorithm (GA).

A method for active management of the distribution system, which makes use of an innovative controller that coordinates the OLTC action with the regulation of reactive exchanges between DG plants and feeders, was presented in [10], considering a realistic radial distribution network. In [11], the coordination of DG, including induction and synchronous generators, and SVR operations for improved distribution system voltage regulation was presented. A voltage-control methodology for interfaced inverters, LRTs, and SVRs, based on information measured in distribution systems using centralized information to calculate the optimal reference value for equipment, was presented in [12]. The feasibility of the concept of a fuzzy controller for voltage regulation was demonstrated, with sensitivities derived through fuzzy clustering of the load profile.

In this article, a coordinated voltage-control method using a GA [13, 14] to determine the schedule for the operation of the voltage control devices in a day is presented. The study presented considers the different loading conditions using a time-varying load curve and a load generated by fuzzy clustering for different case studies. The simulation results using MATLAB (The MathWorks, Natick, Massachusetts, USA) software is presented to validate the method.

2. Voltage Rise in Distribution System with DG

When the generator is connected to the radial feeder, its active power export reduces the power flow from the primary substation. This causes reduction in the voltage drop along the feeder. If the generator's power export is larger than the feeder load, power flows from the generator to the primary substation, and this causes a voltage rise along the feeder. Typically, the worst-case scenarios are (a) no generation and maximum system demand, (b) minimum generation and maximum system demand, and (c) maximum generation and minimum system demand. In the context of the voltage rise effect, minimum load and maximum generation conditions are usually critical for the amount of generation that can be connected [2].

Figure 1(a) illustrates the connection of a distributed generator to the distribution network [4]. The active and reactive powers of the generator are P_g and Q_g, respectively. P_L and Q_L represent the active and reactive power of the load connected to the distribution system. I_R is the net current through the line impedance, $Z = R + jX$, and S_R is the net power injected to network. The substation voltage and connection point voltage are V_s and V_g, respectively:

$$S_R = P_R + Q_R = P_g + jQ_g - P_L - jQ_L, \tag{1}$$

$$S_R = V_g I_R^*, \qquad I_R = (P_R - jQ_R)/V_g^*, \tag{2}$$

$$\begin{aligned} V_g &= V_s + I_R Z = V_s + (R + jX)(P_R - jQ_R)/V_g^* \\ &= V_s + (P_R + XQ_R)/V_g^* + j(P_R X - Q_R R)/V_g^*. \end{aligned} \tag{3}$$

Considering the phasor diagram in Figure 1(b),

$$V_g \sin\delta = (P_R X - Q_R R)/V_s. \tag{4}$$

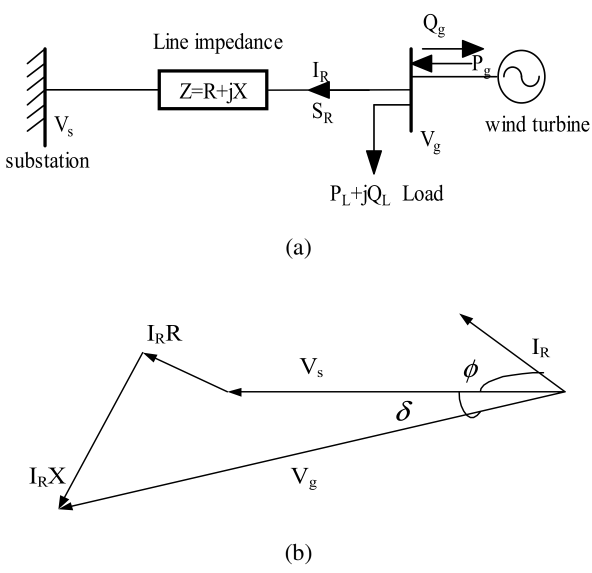


Figure 1. (a) Utility network with DG system and (b) phasor diagram.

Since the voltage angle δ is very small, the term $(P_R X - Q_R R)/V_g^*$ is also very small and can be neglected. The magnitude of voltage rise ΔV is approximately given by

$$\Delta V = (P_R R + X Q_R)/V_g^* = ((P_g - P_L)R - X(Q_g + Q_L))/V_g^*. \tag{5}$$

The active power produced by embedded generators increase the voltage, whereas the reactive power control ability depends upon the type of DG technology. The synchronous generator can generate or absorb reactive power, and a power electronically interfaced DG system can also do a similar function, but the induction generator only consumes reactive power. These outcomes in combination with the system's R/X ratio, distribution network characteristics, and load profiles determine whether or not the voltage level at the connection point is increased by increasing the power production of DG. In general, for a radial system, the voltage level decreases along the feeder, from the supply end to the end of the feeder, and can be determined as given by Eq. (6):

$$\overline{V_{n+1}} = \overline{V_1} - \sum_{k=1}^{n} \frac{(R_k + jX_K)(P_{k+1} - jQ_{k+1})}{\overline{V_{k+1}^*}}. \tag{6}$$

3. Load Profile Generations Using Fuzzy C-means (FCM) Clustering

Fuzzy clustering is an iterative clustering technique that produces an optimal c-partition by minimizing the weighted within-group sum of the squared error objective function [15]. In this work, FCM clustering is used to find a meta-structure of three load profiles (three vectors) from set of hourly load profiles for a day (24 vectors) [16]. The fuzzy-clustering method allows the identification of the centroids or prototypes of the defined clusters and associates a membership value to each load profile. This makes fuzzy clustering more natural than hard clustering. The load profiles along n number of buses can be treated as an n-dimensional vector. In this work, 3 cluster centers are obtained from 24 data-points (each data-point is an n-dimensional vector).

The fuzzy-clustering algorithm starts with an initial guess for the cluster center. Each data-point is allotted a membership function. By iteratively updating the cluster centers and the membership grades for each data-point, the cluster center is moved to the right location within a dataset. The iteration is based on minimizing an objective function that represents the distance from any given data-point to a cluster center weighted by that data-point's membership grade [15]. FCM is a method of clustering that allows one piece of data to belong to two or more clusters. It is based on minimization of the following objective function:

$$J_m = \sum_{i=1}^{N} \sum_{j=1}^{C} u_{ij}^m \|x_i - c_j\|^2, \tag{7}$$

where

m is any real number greater than 1,
u_{ij} is the degree of membership of x_i in cluster j,
x_i is the ith of d-dimensional measured data, and
c_j is the d-dimensional center of the cluster.

Fuzzy partitioning is carried out through an iterative optimization of the objective function shown above, with the update of membership u_{ij} and the c_j cluster centers. The algorithm is composed of the following steps.

1. Initialize $U = [u_{ij}]$ matrix, $U(0)$.
2. At the kth step, calculate the centers vectors $C(k) = [c_j]$ with $U(k)$:

$$C = \frac{\sum_{i=1}^{N} u_{ij}^{m} x_i}{\sum_{i=1}^{N} u_{ij}^{m}}. \tag{8}$$

3. Update $U(k)$, $U(k+1)$:

$$u_{ij} = \frac{1}{\sum_{k=1}^{c} \left(\frac{\|x_i - c_j\|}{\|x_i - c_k\|} \right)^{\frac{2}{m-1}}}. \tag{9}$$

If $\|U(k+1) - U(k)\| < \varepsilon$, then STOP; otherwise, return to Step 2, where ε is a termination criterion between 0 and 1, and k is the iteration step.

4. Results and Discussions

In this work, two case studies are presented: one with a 21-bus and an IEEE 33-bus balanced radial distribution system [9, 17] and the other with an IEEE 13-bus unbalanced radial distribution system [18]. In the above case studies, the upper and lower voltage limits considered are of +6% and −6%, respectively. The Case Study 1 considers the three sample load patterns (low, medium, and high) from a time-varying load profile, shown in Figure 2, and also the three load patterns generated using fuzzy clustering of a 24-hr load profile of the same. Case Study 2 considers the voltage regulation of a three-phase unbalanced distribution system. Two DG systems with reactive power control capability are considered in both case studies. The GA Toolbox of MATLAB [19] is used to obtain the optimal settings of individual control devices, such as the OLTC, LRT, SCs, and SVC, along with the DG. The GA parameters used for generation, population, selection, cross-over, and mutation are 100, 20, stochastic, scattered, and adaptive, respectively. The time required for convergence is 14 sec. The objective function of the GA used for the study is

$$\sum_{m=1}^{n} |V_{mref} - V_m|, \tag{10}$$

V_{mref} is the mth node voltage standard value, and V_m is the mth node voltage. The constraints are $V_{\min} < V_i < V_{\max}$, the reactive power of DG is $Q_{\min} < Q_i < Q_{\max}$, and the tap position is $T_{\min} < T_i < T_{\max}$.

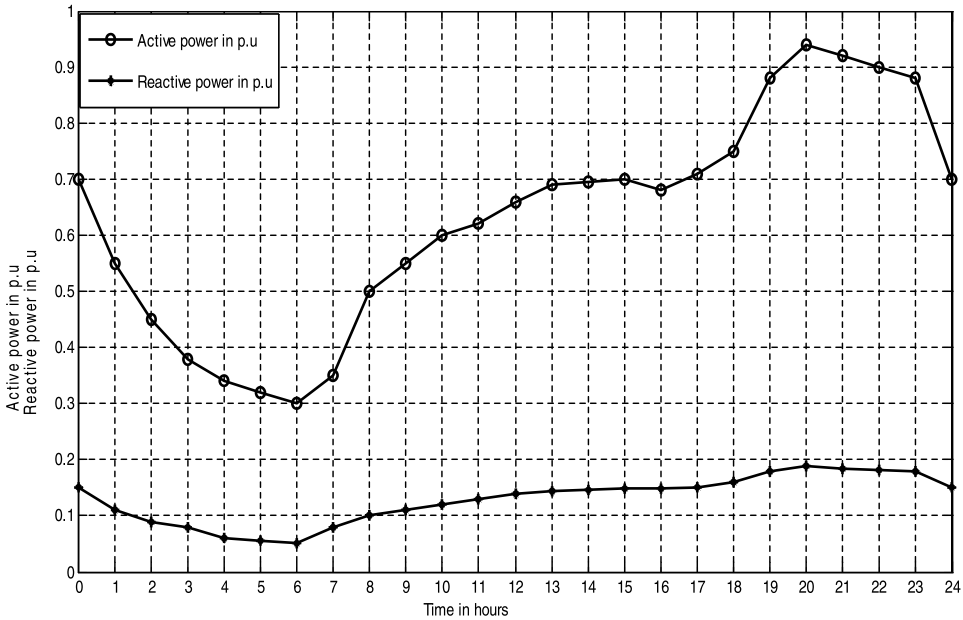


Figure 2. Time-varying load profile for 21-bus system.

4.1. Balanced Radial Distribution Systems

4.1.1. Case Study 1(a). A residential area power distribution system with 21 buses is used for simulation and is shown in Figure 3. The system capacity is 2500 kVA, and the line and load data are given in [9]. The distribution system has two distributed generators, an OLTC, a load ratio transformer, SCs, and an SVC, as shown in Figure 3. The active and reactive power of DG_1 and DG_2 are 0.3 p.u. and 0.14 p.u., respectively; the SCs connected are of 0.05 p.u. value, and the SVC value is 0.1 p.u. The LRT is connected between nodes 7 and 8; it is used to adjust the voltage of the power distribution system.

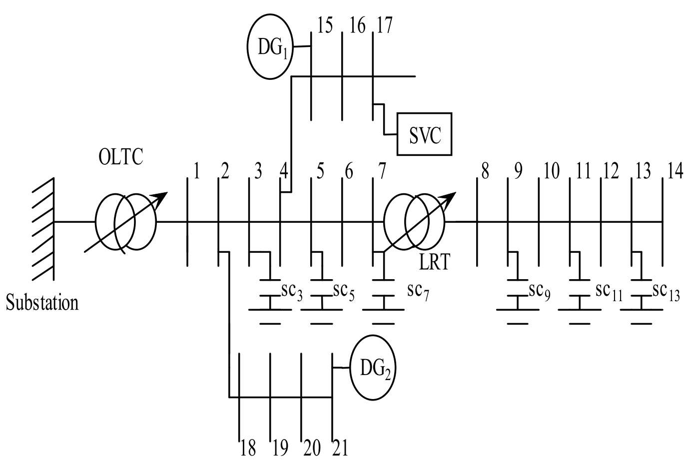


Figure 3. Twenty-one-bus radial distribution system.

The daily load profile of a residential area power distribution system is shown in Figure 2. The system reaches peak load at 8:00 PM. Three types of loads from the load profile are considered for the simulation:

1. light load condition ($P = 0.3$ p.u. and $Q = 0.05$ p.u.) at 6.00 AM,
2. medium load condition ($P = 0.65$ p.u. and $Q = 0.14$ p.u.) at 12:00 PM (noon), and
3. heavy load condition ($P = 0.94$ p.u. and $Q = 0.19$ p.u.) at 8.00 PM.

The assumption is that the active and reactive power at each node is equally divided at the above load conditions. The three sets of voltage control devices are used for the simulation are:

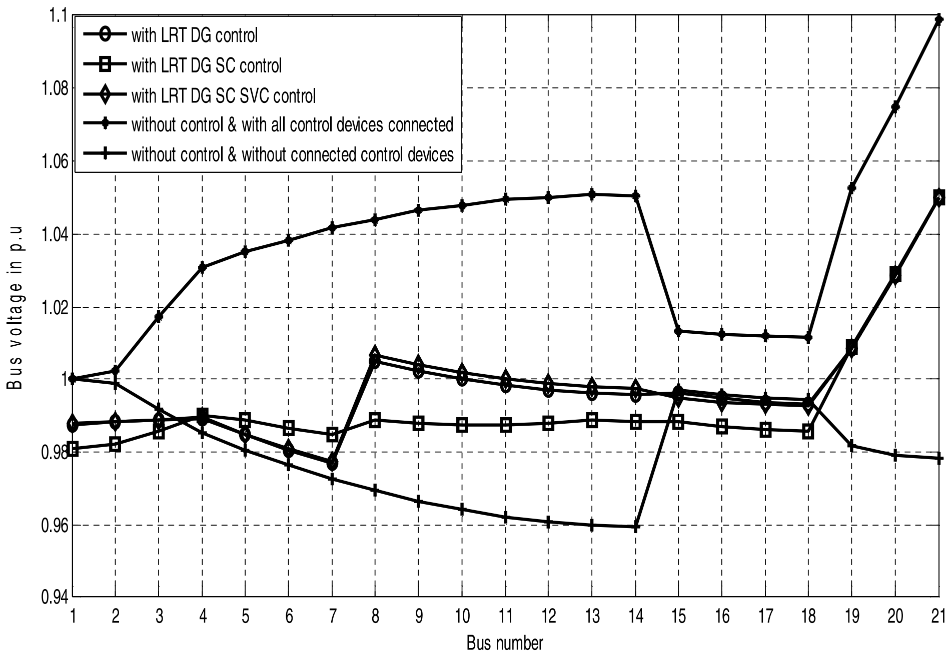
a. with OLTC; LRTs are available with DGs reactive power;
b. with OLTC, LRT, and SCs with DGs reactive power; and
c. with OLTC, LRT, SCs, and SVC with DGs reactive power

Figures 4(a), 4(b) and 4(c) show the voltage profile for the 21-bus system with and without voltage control at light load, medium load, and heavy load conditions, respectively. Figure 4(a) shows the voltage profile with light load condition using three sets of control devices. It can be observed that without voltage control, the voltage profile crosses the upper limit (1.05 p.u.); the peak value of the voltage profile is 1.1 p.u. It can be seen in Figure 4(a) that the voltage has been controlled effectively with the selected set of controlling devices. Figure 4(b) shows the voltage profile with and without voltage control for the medium load at 12:00 PM from the load profile. It is seen that without control, the voltage profile is crossing the upper limit and its peak value is 1.08 p.u. The rise in voltage is regulated by using voltage control devices with optimal setting of reactive power of the DGs. The voltage profile for the system with and without voltage control for heavy load condition is given in Figure 4(c), and the peak value of the uncontrolled voltage value is 1.06 p.u. The optimal setting of the voltage control devices are given in Table 1, and the power loss in the system before and after voltage control is given in Table 2.

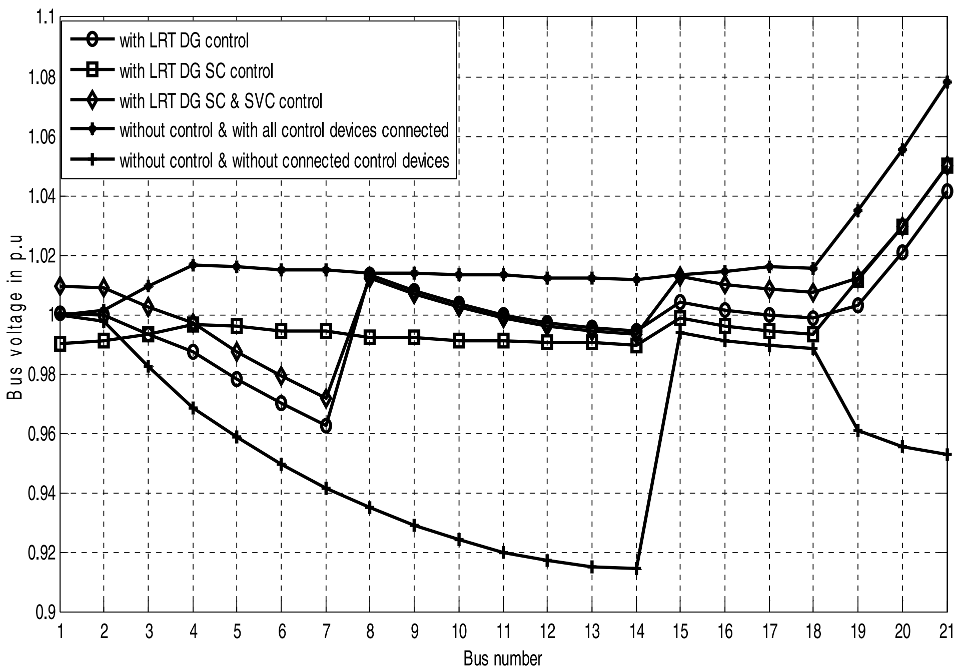
4.1.2. Case Study 1(b). In this case, three sets of fuzzy load patterns are generated using a fuzzy clustering 24-hr load profile for the 21-bus system. In a fuzzy load pattern, each node has a different value of active and reactive power. The three sets of fuzzy load patterns are given in Table 3.

Figures 5(a), 5(b), and 5(c) show the voltage profile for the 21-bus system with and without voltage control using three load patterns generated using fuzzy clustering, as given in Table 3. Figure 5(a) shows the voltage profile for the system with and without voltage control for fuzzy load pattern 1. It can be seen that for the voltage profile without control crossing the upper voltage limit, the observed peak voltage value is 1.062 p.u. The voltage profile for the system with fuzzy load pattern 2 with and without control is given in Figure 5 (b). The peak voltage level achieved in fuzzy load pattern 2 without control is 1.068 p.u., and the voltage has been controlled using multiple controlling devices.

Figure 5(c) shows the voltage profile for fuzzy load pattern 3. Without voltage control, the peak value of the uncontrolled voltage is 1.09 p.u. It can be seen in Figure 5(c) that the voltage has been controlled effectively. The optimal setting values of the controlling devices and SC positions are given in Table 4. The power loss in the system before voltage control is $P_{loss} = 0.00821$ p.u. and $Q_{loss} = 0.0071$ p.u. with fuzzy load

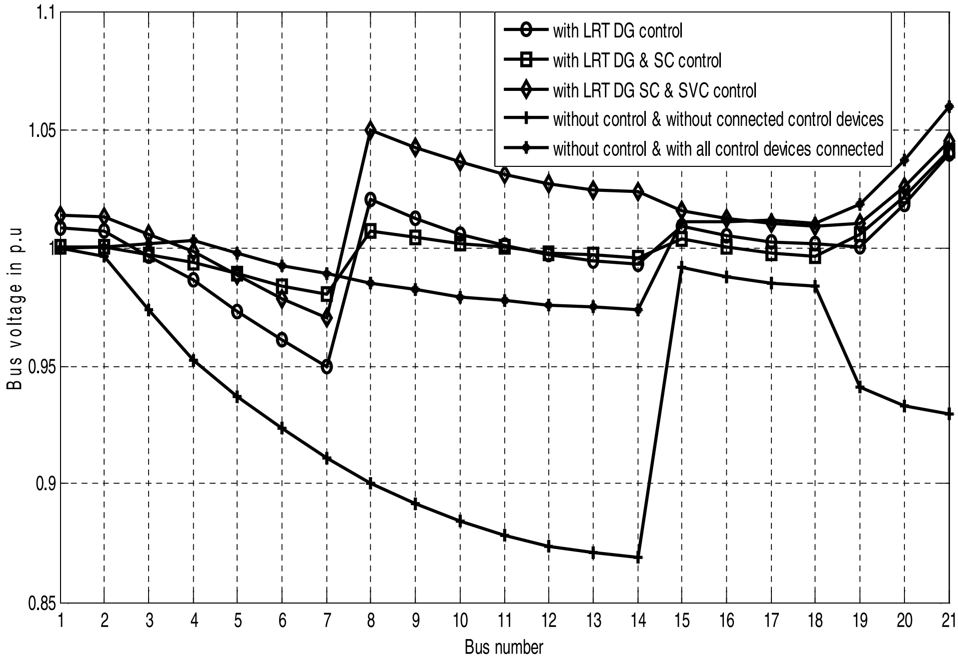


(a)



(b)

Figure 4. Voltage profile for 21-bus system with: (a) light load, (b) medium load, and (c) heavy load. (*continued*)



(c)

Figure 4. (*Continued*).

Table 1
Optimal setting values of the voltage control devices for Case Study 1(a)

Different sets of controls	Controlling devices	Light load	Medium load	Heavy load
First set	LRT tap setting (p.u.)	1.03	1.05	1.08
	OLTC tap setting (p.u.)	0.98	1.0	1.0
	DG reactive power (p.u.):			
	DG_1	0.14	0.038	0.022
	DG_2	0.02	0.044	0.085
Second set	LRT tap setting (p.u.)	1.01	1.0	1.03
	OLTC tap setting (p.u.)	0.98	0.99	1.0
	DG reactive power (p.u.):			
	DG_1	0.10	0.072	0.043
	DG_2	0.025	0.022	0.022
	SC position	Six SCs off	Six SCs on	Six SCs on
Third set	LRT tap setting (p.u.)	1.02	1.05	1.09
	OLTC tap setting (p.u.)	0.98	1.0	1.01
	DG reactive power (p.u.):			
	DG_1	0.03	0.022	0.022
	DG_2	0.026	0.025	0.025
	SC position	Six SCs off	Six SCs off	Three SCs on, three SCs off
	SVC setting value	−0.02	−0.01	0.01

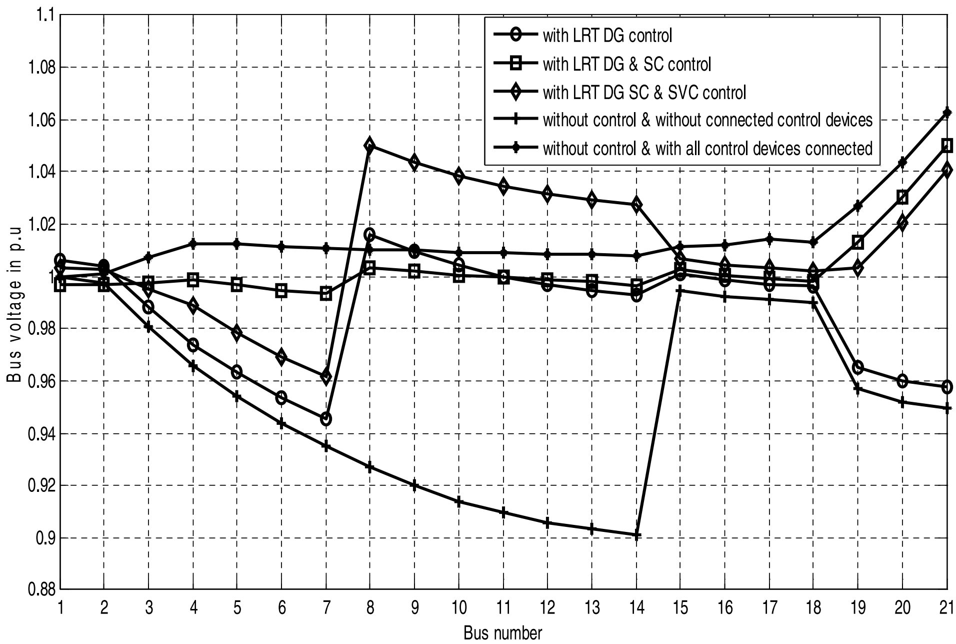
Table 2
Power loss in 21-bus system for Case Study 1(a)

Load conditions	Before voltage control		After voltage control	
	P_{loss} (p.u.)	Q_{loss} (p.u.)	P_{loss} (p.u.)	Q_{loss} (p.u.)
Low load	0.00445	0.0069	0.0044	0.0065
Medium load	0.0045	0.0072	0.0044	0.0071
Heavy load	0.0046	0.0073	0.0045	0.0072

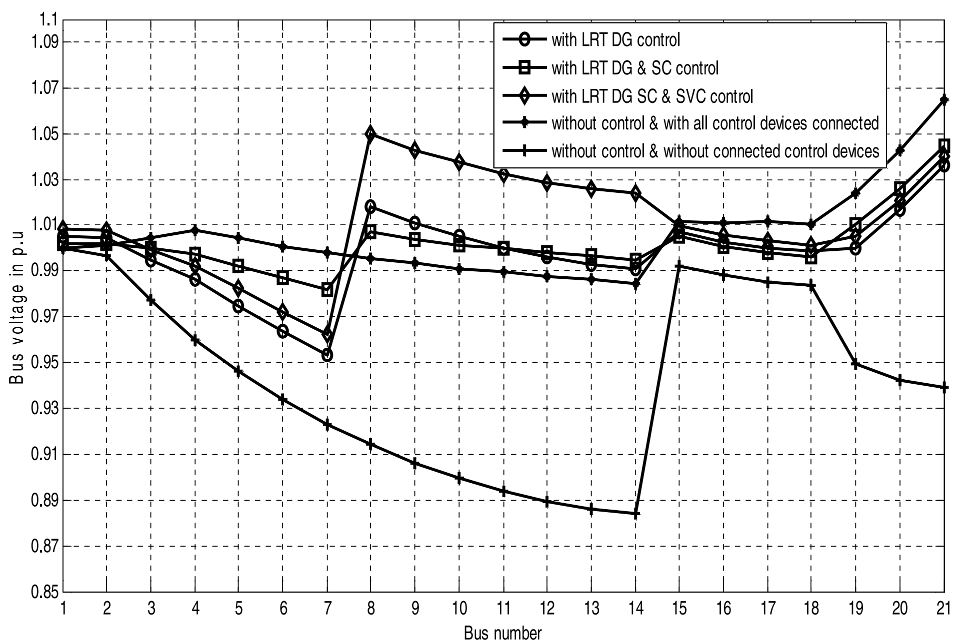
pattern 1; $P_{loss} = 0.00445$ p.u. and $Q_{loss} = 0.0067$ p.u. with fuzzy load pattern 2, and $P_{loss} = 0.00446$ p.u. and $Q_{loss} = 0.0056$ p.u. with fuzzy load pattern 3. Similarly, the power loss after voltage control is $P_{loss} = 0.0079$ p.u. and $Q_{loss} = 0.0068$ p.u. with fuzzy load pattern 1, $P_{loss} = 0.00434$ p.u. and $Q_{loss} = 0.0056$ p.u. with fuzzy load pattern 2, and $P_{loss} = 0.00445$ p.u. and $Q_{loss} = 0.0054$ p.u. with fuzzy load pattern 3. It can be observed from these results that there is a decrease in the power loss after the voltage control.

Table 3
Load patterns obtained from FCM clustering for 21-bus system

Fuzzy load pattern 1		Fuzzy load pattern 2		Fuzzy load pattern 3	
P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)
0.03845	0.002471	0.03571	0.002019	0.02136	0.002025
0.04473	0.001229	0.02196	0.003304	0.03464	0.002572
0.03801	0.004653	0.03468	0.003701	0.01901	0.002422
0.03687	0.003465	0.03970	0.002645	0.03995	0.001986
0.02198	0.002602	0.03893	0.001960	0.05032	0.003727
0.05971	0.002346	0.02694	0.002245	0.02069	0.001240
0.01261	0.005620	0.09091	0.001454	0.01042	0.003128
0.03772	0.003293	0.01805	0.002023	0.02684	0.001678
0.02495	0.006720	0.04603	0.002681	0.03767	0.004912
0.04429	0.009500	0.03903	0.002660	0.04295	0.003026
0.03152	0.002803	0.04234	0.002841	0.01321	0.002703
0.03984	0.001131	0.03099	0.003935	0.05238	0.003907
0.02659	0.003744	0.04951	0.001668	0.01262	0.002084
0.06961	0.003945	0.08211	0.003366	0.01696	0.001668
0.02820	0.003917	0.02793	0.003461	0.02171	0.002822
0.02803	0.001164	0.05244	0.002835	0.01010	0.003434
0.02594	0.003316	0.04552	0.003244	0.02069	0.001245
0.03151	0.002641	0.07286	0.02289	0.03088	0.000440
0.03877	0.004392	0.04054	0.001998	0.00351	0.001105
0.03384	0.003397	0.04262	0.004023	0.01996	0.000839
0.02972	0.003832	0.04268	0.002269	0.02142	0.003021

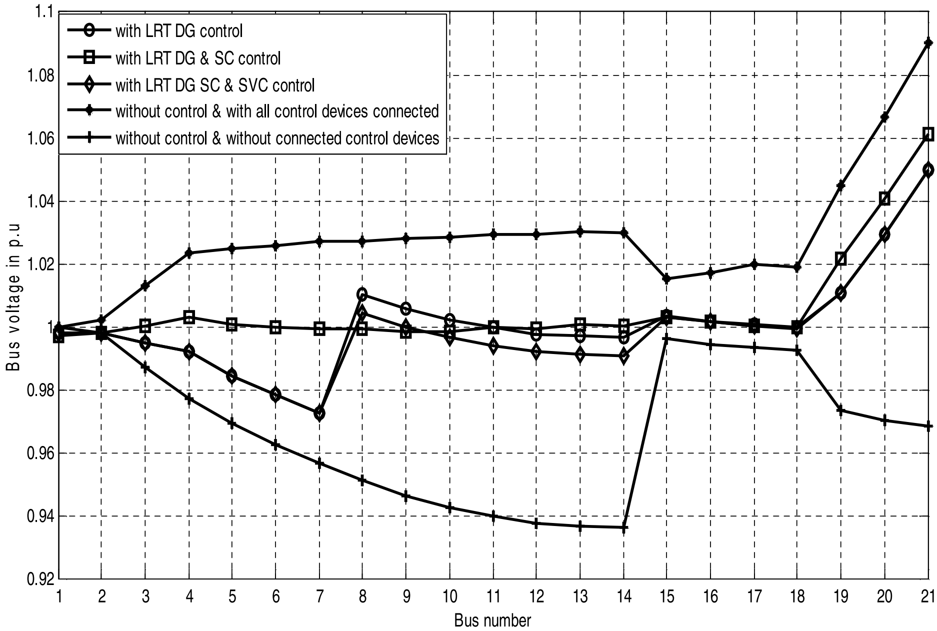


(a)



(b)

Figure 5. Voltage profile of 21-bus system with: (a) fuzzy load pattern 1, (b) fuzzy load pattern 2, and (c) fuzzy load pattern 3. (*continued*)



(c)

Figure 5. (*Continued*).

Table 4
Optimal setting values of voltage control devices for Case Study 1(b)

Different sets of controls	Controlling devices	Fuzzy cluster load 1	Fuzzy cluster load 2	Fuzzy cluster load 3
First set	LRT tap setting (p.u.)	1.07	1.07	1.04
	OLTC tap setting (p.u.)	1.01	1.0	0.99
	DG reactive power (p.u.):			
	DG_1	0.14	0.023	0.022
	DG_2	0.025	0.043	0.022
Second set	LRT tap setting (p.u.)	1.03	1.03	1.01
	OLTC tap setting (p.u.)	0.99	1.0	0.99
	DG reactive power (p.u.):			
	DG_1	0.025	0.047	0.102
	DG_2	0.033	0.022	0.023
	SC position	Four SCs on, two SCs off	Five SCs on, one SC off	Two SCs on, four SCs off
Third set	LRT tap setting (p.u.)	1.08	1.09	1.04
	OLTC tap setting (p.u.)	1.0	1.01	0.99
	DG reactive power (p.u.):			
	DG_1	0.022	0.022	0.022
	DG_2	0.026	0.023	0.023
	SC position	One SC on, five SCs off	One SC on, five SCs off	One SC on, five SCs off
	SVC setting value	−0.06	−0.004	0.003

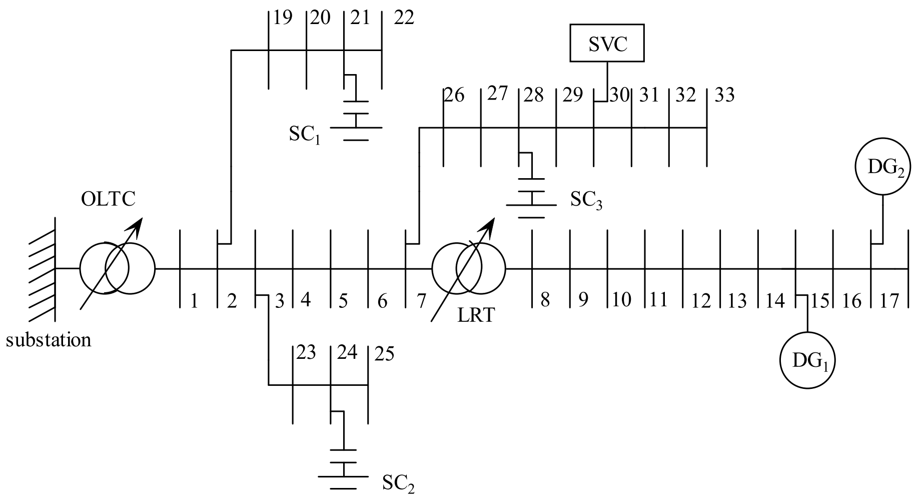


Figure 6. IEEE 33-bus distribution system.

4.1.3. *Case Study 1(c).* In this section, the GA has been implemented to solve the voltage control on the IEEE 33-bus test feeder, the one-line diagram of which is given in Figure 6. It is a balanced 3-phase system that consists of 33 buses operating at 11-kV voltage level. The system has total real and reactive power loads of 3.72 MW and 2.29 MVAr, respectively. The feeder lines and load data are taken from [17]. There are 2 generators, with active power 0.3 p.u. and reactive power 0.14 p.u., connected at buses 15 and 17; 3 SCs connected at buses 21, 24, and 28 with capacity of 0.05 p.u. each; and 1 SVC connected at bus 30 with 0.1 p.u. capacity. An LRT is connected between buses 7 and 8.

Figure 7 shows the voltage profile of the 33-bus system with and without voltage control. It can be seen that when DGs are connected to the system, the voltage crosses the upper limit at 1.05 p.u. at bus 17. The peak voltage has been controlled successfully using all connected voltage regulators and the DG reactive powers supply. In this case, it has been observed that the power loss decreased ($0.00368 + j0.00284$) after the voltage control compared to power loss ($0.00636 + j0.00432$) without voltage control.

4.2. *Unbalanced Radial Distribution System*

4.2.1. *Case Study 2.* In this study, the standard 4.16-kV IEEE 13-bus 3-phase unbalanced radial distribution system is used for the simulation. The line and load data are given in [18]. The base voltage and base MVA chosen are 4.16 kV and 100 MVA, respectively. The voltage-regulating devices, LRT, SCs, and SVC are connected with two DGs, as shown in Figure 8. The active and reactive power ratings of the DG systems are 0.14 p.u. and 0.06 p.u., respectively. The SC and SVC rating considered are 0.05 p.u. and 0.1 p.u., respectively

Figure 9(a) shows the voltage profiles for the 3-phase 13-bus system without voltage control. It can be seen that the voltage profiles of phases A and C are within the upper and lower limits, 1.05 p.u. and 0.95 p.u., respectively. The voltage profile of phase B

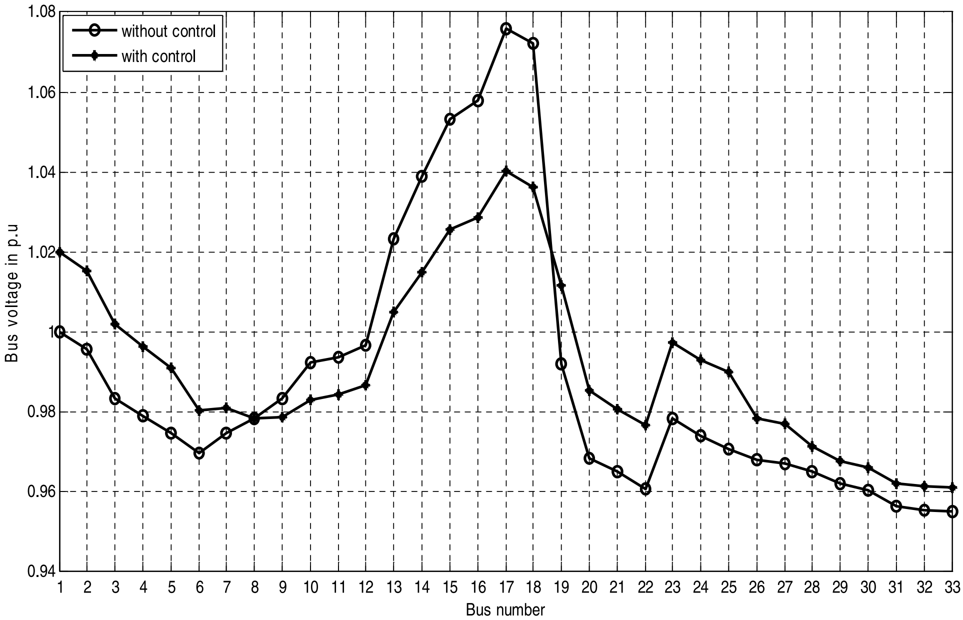


Figure 7. Voltage profile of IEEE 33-bus system with and without voltage control.

crosses the upper voltage limit with peak value 1.068 p.u. The rise in voltage is controlled by using voltage control devices with their optimal setting. The voltage profile of the system with control is shown in Figure 9(b). The optimal setting values of the various control devices in phases *a*, *b*, *c* are LRT: 0.98, 0.96, and 0.98; SVC: 0.09, 0.05, and 0.05; DG_1: 0.06, 0.06, and 0.03; and DG_2: 0.017, 0.017, and 0.045, respectively.

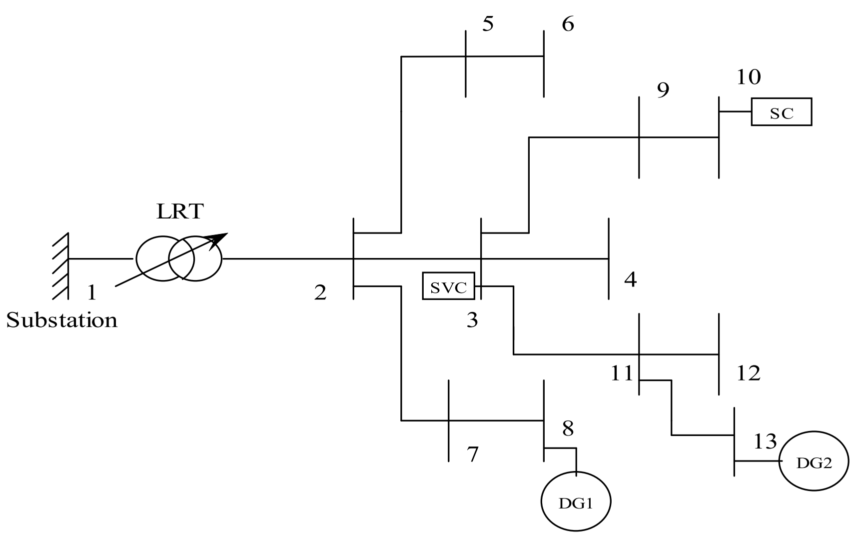
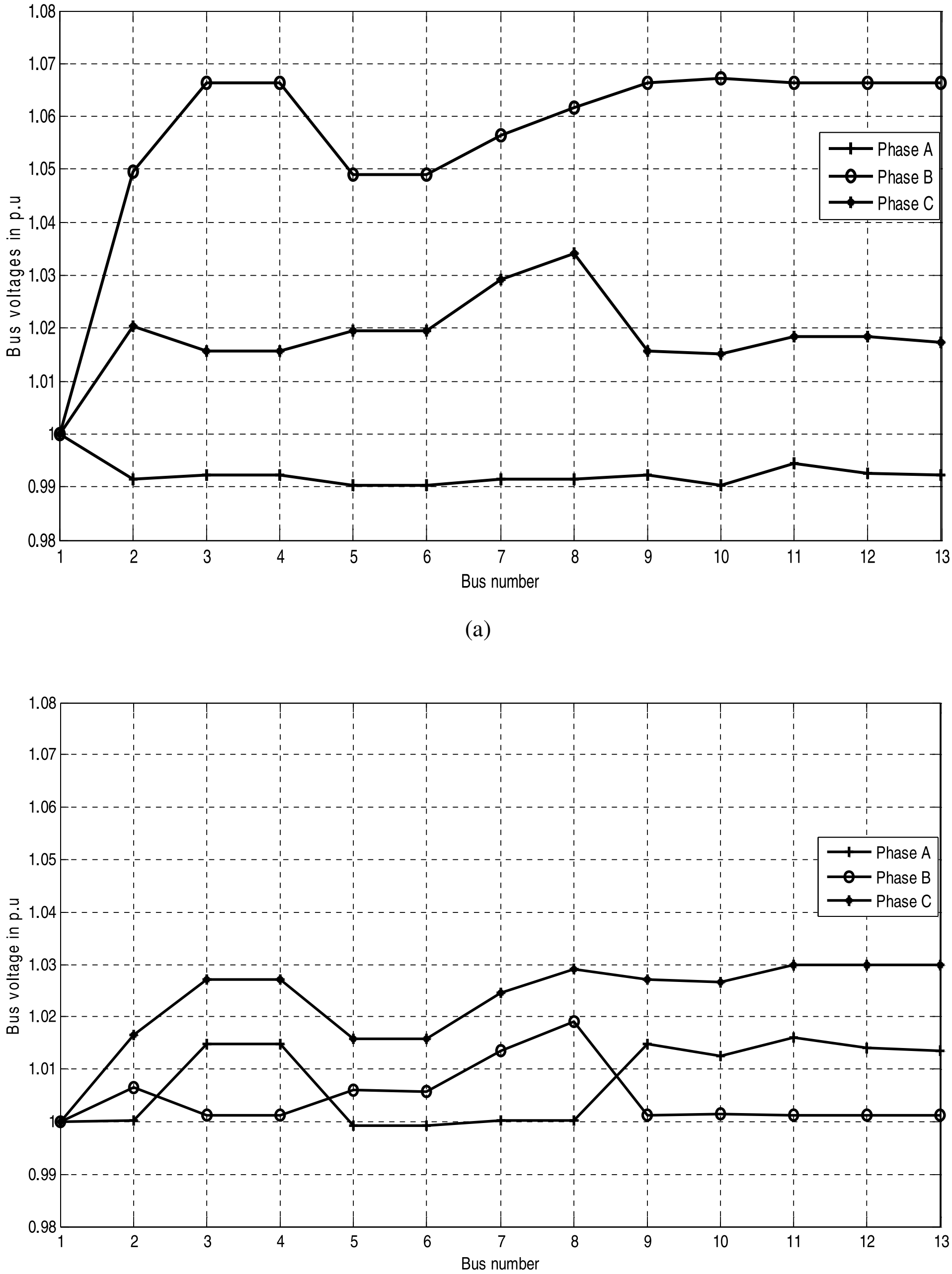


Figure 8. Three-phase unbalanced IEEE 13-bus distribution system [18].



(a)

(b)

Figure 9. Voltage profile of 13-bus unbalanced system: (a) without voltage control and (b) with voltage control.

5. Conclusions

In this article, coordinated voltage regulation of a distribution system with distributed generators using a GA has been presented with two case studies. Multiple voltage regulators such as OLTC, LRT, SCs, and SVC, are considered along with the reactive power control of two DG systems. The simulation results reported show the performance of the developed method using two kinds of load patterns: one with three sample load conditions directly obtained from the 24-hr load profile and another with generating three load profiles using FCM clustering considering 24-hr load variations. It has been observed that obtaining the load profile through fuzzy clustering can represent the more realistic case compared to considering the sample load conditions from the load profile. In this work, voltage regulation of both balanced and unbalanced distribution system is analyzed through simulation using case studies. The results presented through the case studies show that by optimally setting the values and having various voltage control devices through the GA, the distribution system voltage can be regulated well within the statute limits and power loss can also be reduced. The study also shows that involving DG systems and SCs in the coordinated voltage control will result in the reduction of the number of OLTC and LRT operations. The presented method of coordinating various voltage-control devices in a distribution system can help in effective integration of a large number of DG systems to the utility network.

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