IET Generation, Transmission & Distribution

Research Article

End-user participation in a collaborative distributed voltage control and demand response programme

ISSN 1751-8687
Received on 30th June 2017
Revised 1st March 2018
Accepted on 20th March 2018
E-First on 17th May 2018
doi: 10.1049/iet-gtd.2017.0975
www.ietdl.org

Ahad Abessi[1], Alireza Zakariazadeh[2], Vahid Vahidinasab[1] ✉, Mohammad Sadegh Ghazizadeh[1], Kamyar Mehran[3]

[1]*Department of Electrical Engineering, Abbaspour School of Engineering, Shahid Beheshti University, Tehran, Iran*
[2]*Department of Electrical and Computer Engineering, University of Science and Technology of Mazandaran, Behshahr, Iran*
[3]*School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK*
✉ *E-mail: v_vahidinasab@sbu.ac.ir*

Abstract: A new generation of electric appliances with controllable reactive power creates an opportunity for operators in distribution systems to be used as a resource for reactive power support. On the other hand, implementing demand response (DR) programmes as an alternative resource to manage the active power demand may also affect the reactive power balance. Collaborative effect of reactive power support devices and the DR programme is investigated in order to control voltage problem in a distribution network. In the first step, distributed voltage (DV) control and DR methods are considered as individual control actions; then, the hybrid DV control with DR (DVDR) method is proposed to improve the voltage profile. The IEEE 33-bus distribution standard test system is chosen for validating the novel method, in which the optimum reactive power injection in the candidate buses and demand curtailment in each area are calculated. The proposed DVDR method can better mitigate the voltage problem and the results showed far desirable performance compared with using just DR or DV methods. The proposed method can also curtail less demand in comparison to the DR method.

1 Introduction

An increase in network peak demand leads to the overload of lines and transformers. Poor voltage profile is also one of the vital problems in today's distribution system where distribution system operator (DSO) must keep the voltage within an acceptable range during different load demand conditions. A number of preventive and corrective control actions to mitigate the voltage problem have been suggested in the literature. However, a majority of them are costly in practice. Few control actions can be found with reasonable cost such as transmission lines switching [1, 2], which employs flexible AC transmission system (FACTS) devices [3–5] and synchronous condensers used in HV/MV substation level. This approach is not yet suitable for the distribution networks.

In the future smart grid, introducing new concepts into end-consumers can bring about comprehensive reactive power control. In [6], a reactive power support method using the capability of end-consumers in providing reactive power is discussed for the smart grid. In [7, 8], few control techniques are investigated for providing reactive power support. In [9–11], the application of end-user reactive power capable devices is discussed for the mitigation of low-voltage problems at the transmission and distribution system levels. The control actions enabled by smart grid technologies are able to maintain voltage profile within acceptable limits. In all mentioned studies, the centralised control action is the main approach failing to consider the advantages of the collaborative effect of demand response (DR) and voltage control. Centralised control actions are essentially not a good candidate for a modern, smart distribution network due to the high communication cost and low network throughput. More importantly, DR programme and its effect on the voltage profile is completely neglected in all conventional approaches.

Reactive power support resource examples are inverters on solar panels, UPS systems, electric vehicles (EVs), lighting, inverter-based home appliances and many other distributed sources [12–15]. To better understand this concept, consider EVs, which can be connected to the electric network in 93% of time. New development in EV charging equipment and power electronics turns EVs as the considerable resources for providing active and reactive power in the grid. With modern bidirectional chargers, EVs are able to produce reactive power while consuming active power [16, 17] and inject the active power into the grid when demanded.

DV control can be one of the best control actions in the smart grid showing low communication cost [18, 19]. For instance, the authors in [18] proposed DV control to improve the voltage profile. In their design, load tap changer and distributed generation's (DG's) reactive rate are used as control variables. However, they have ignored the effects of end-user devices and DR on voltage profile.

The centralised control action, on the other hand, can perform best for voltage mitigation in integrated scenarios. However, the centralised method can cause a low-latency, low-throughput communication network when used in sophisticated grid communication scenarios. DV control, however, is a strong candidate since the sub-systems are independent without any necessary inter-communication links. This results in a massive reduction of the number of data packets normally exchanged between the links. Note that in general voltage mitigation quality in centralised control is relatively higher than the DV control.

Online monitoring of the distribution network is one of the main functions in modern grids. With distribution automation (DA), the DSO can manoeuvre on distribution control variables and use DR as an effective tool for regulating distribution feeders' voltage in normal and emergency conditions. In [19], a centralised support DV control method is proposed in which a DV control as a control action is implemented in each region. In their approach, the centralised control action supports the voltage profile in case of unavailable or insufficient local control centres in the regions. However, DR programmes do not play a role in their design hence the reactive power injection is not controllable using demand and it must be assumed constant. An interested reader can find a complete review on DR and its potential benefits for modern grids in [20] where the current structures for contributing end-consumers and residential loads are studied. In a real-time distribution energy market, a residential DR can save cost for the end-user and reduce the congestion in distribution systems [21]. In [22], the effect of

Table 1 Comparison between different articles

References	Distribution system	Using end users as reactive power support	Using DR as voltage control variable	Using DV control
[6]	—	✓	—	—
[9]	—	✓	—	—
[10]	—	✓	—	—
[11]	✓	✓	—	—
[18]	✓	—	—	✓
[19]	✓	✓	—	✓
[23]	—	—	✓	—
[24]	—	—	✓	—
[25]	—	—	✓	—
[26]	✓	—	—	—
[27]	✓	—	—	—
[28]	—	—	—	✓
[29]	—	—	—	✓
this paper	✓	✓	✓	✓

industrial applications in an ancillary programme is reviewed where the DR is assumed as regulation device and also reserve.

The impact of residential DR on the voltage profile is studied in [23] where the conventional loads, the demand reduction due to price offers, and the effect of reduction of active load are all considered with ignoring the effect of generating reactive power. The effect of implementing incentive-based DR programme on the voltage profile is studied in [24], where a matrix for calculating the effect of demand curtailment on the voltage profile is suggested. In their approach however only the conventional load is taken into account and the effect of injecting reactive power into end-users is neglected. In [25], a novel DR mechanism is suggested for providing ancillary services, especially the primary voltage control of distribution networks. In their method also only the conventional loads are used and the new concepts in end-consumer reactive power support are not explored. Moreover, the control algorithm is centralised which is not appropriate for future smart grids.

The authors in [26] proposed a novel approach for daily volt/VAR control using DG. However, the reactive power support in end-users and DR effects on voltage problem are not examined in their study. In [27], a new voltage control method for volt/VAR control in distribution system by considering distributed generators (DGs) is proposed. However, the new concept in reactive power support for the end-users and DR and their effect on the voltage control are ignored. In [28], DV control in transmission level is discussed where the FACTS devices perform the voltage control. The decomposition in [27] is carried out in a hierarchical manner using clustering and proximity analysis. Still one cannot find the reactive power support and DR effects on voltage problem.

A centralised method nonetheless can be advantageous in future grid if used for with some specific technologies. We can design hybrid centralised–decentralised methods to utilise the benefits of both worlds with relatively low communication cost in practice. In [29], a model for coordination of EV charging is proposed where a hybrid centralised–decentralised control scheme provides flexible charging choices for customers. In this case, EV owners can either individually choose the charging profile based on their own preferences or assign the charging task to the system controller.

Table 1 shows a comparison study of the suggested approaches in the related literature. As noticed, a group of articles proposed a sort of centralised voltage control method with the use of DR. The other group of studies investigates the effect of DR solely on active load reduction in the voltage control problem and the effect of active power reduction in improving voltage. To the best of our knowledge, there is no investigation about the DR effect on providing more reactive power in end-user appliances for contributing in voltage control problem. This paper proposes a novel concept on DR programmes by providing reactive power services. We investigate the DR effect on providing more reactive power in end-user appliances to contribute to voltage control problem. A hybrid DV control with DR (DVDR) is proposed to control the voltage of the distribution system. This approach achieves the best performance by combining the DR resource and reactive power support of the end-users.

This paper is organised as follows: Section 2 presents DV control. The proposed control algorithm is described in details in Section 3. Section 4 presents the simulations on IEEE 33-bus test system. Finally, conclusions and discussion are presented in Section 5.

2 DV control

According to [18, 19], DV control is one of the best control actions that can be implemented in distribution systems, since the communication burden is low and also the control quality is acceptable. In the DV control, the system must be divided into sub-systems by a decomposition method. In this study, ε-decomposition method is used [18, 30, 31]. The control areas (belong to local sub-systems) essentially work independently and optimise their network locally. Note that few buses may not belong to any control areas. To control voltage by reactive power support of end-users, we must select a set of candidate buses with more influence on the objective function. The methods of finding such candidate buses are different from those of the placement of reactive power resources like capacitors. The algorithm of finding candidate buses in the DV control is well studied in our previous work [19]. In our approach, local control centre in each area is responsible for the control variables such as reactive power injection and load demand reduction.

3 DV control with DR

As mentioned (cf. Sections 1 and 2), in distributed voltage control literature, only reactive power injections and their effect on the voltage profile are investigated. The existing approaches do not use the benefits of the DR and coordination between reactive power injection and DR. We fill this gap by introducing these parameters in our method and show how our hybrid DVDR method will improve the voltage problem.

3.1 Demand response

According to the definition by US Department of Energy (DOE), DR is the changes in electric usage by customers from their normal consumption patterns in response to electricity price or incentive payments designed to encourage less electricity usage at times of high prices or compromise of system reliability. With the features provided by DA in the future grid, DSO as the authority can use DR as an efficient tool to mitigate the voltages of distribution buses. DR is divided into two basic categories: incentive-based programmes and time-based programmes. One of the incentive-based programmes is curtailable service, i.e. distribution utility and consumers have contracts to curtail part of the consumer load whenever needed [32]. In this paper, DR is implemented as a curtailable service programme.

3.2 Combined effect of demand curtailment and reactive power support in DV control

The influence of voltage profile in case of incentive- and price-based DRs has been previously studied [23, 24]. The drawback of the current method is with the implementation of the DR curtailing both active and reactive power. In this paper, we improve such implementation by following these steps.

The capacity of inverter-based appliances (EV, PV) can be used partly by active power and its residue can be used for injecting or absorbing the reactive power (see Fig. 1). The required capacity for injecting reactive power is provided by carefully playing with the active power consumption. This means, a demand curtailment in the reactive controllable devices, in addition to reducing active power, would provide more capacity for injecting reactive power. So, DR as a control action may have different effects on the voltage profile and can play the role of reactive power supplier

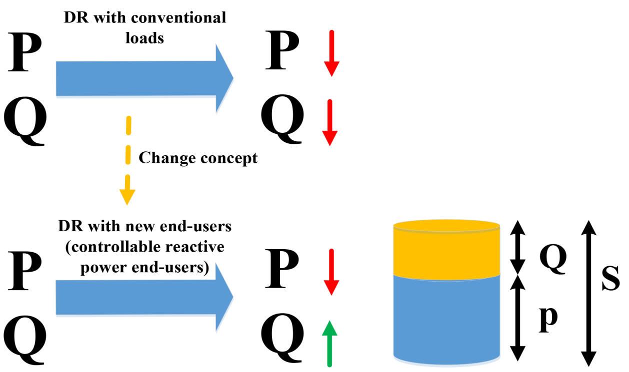

Fig. 1 *New concept in the change of reactive power in future smart grids*

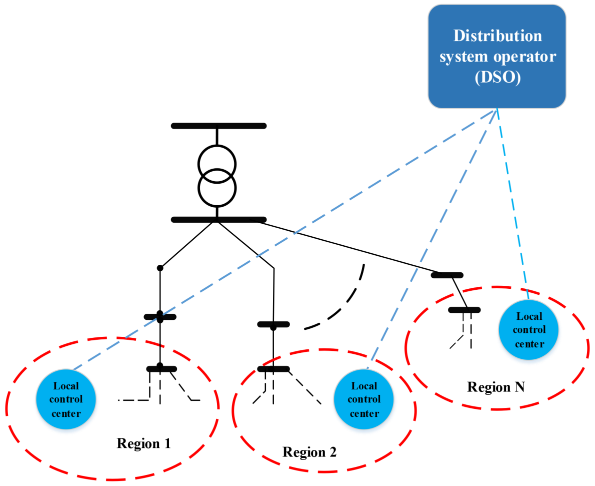

Fig. 2 *General concept of DVDR method*

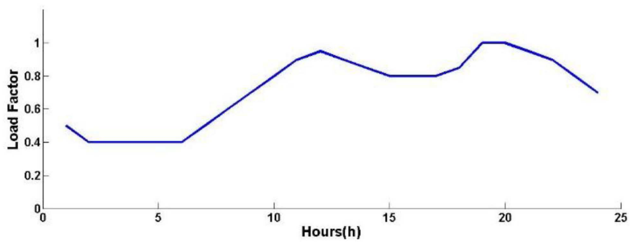

Fig. 3 *Load factor at each time*

while the active power is decreased. In addition to increasing reactive power by the use of DR, reducing active power in DV control is our target. To achieve this target, we develop an optimisation problem and a hybrid DVDR method which will be explained in the following.

3.3 Objective function

Various objective functions can be used for improving voltage profile. We consider reducing the voltage distance from the desired voltage and select the objective function as the minimisation of voltage deviation term for improving voltage profile as

$$f = \sum_{k=1}^{24} \sum_{i=1}^{N_b} [V_{i,k} - V_{\text{ref}}]^2 = \sum_{k=1}^{24} \sum_{i=1}^{N_b} [\eta_{i,k}]^2 \tag{1}$$

$$\eta_{i,k} = V_{i,k} - V_{\text{ref}} \tag{2}$$

In (1) and (2), V_{ref} is the reference voltage level (assumed as unity) and $V_{i,k}$ is the actual bus voltage in time k, N_b is the number of network buses. Function (1) describes the main goal of voltage control. The control is applied by controlling the demand curtailment and the reactive power throughout the system; thus, the reactive power and the demand curtailment amount in each bus are important. Due to high maintenance and operation costs, injecting reactive power and demand curtailment do not come for free. Two terms including the reactive power deviation and the demand curtailment in each bus are embedded in the objective function, cf. equation (3), where $\Delta Q_{j,k}$ is the net reactive power change in bus j and hour k, $\Delta P_{i,k}$ is the demand curtailment in bus i and hour k, M is the number of candidate buses, N_{b} is the number of network buses, α is the penalty factor which limits the reactive power change of each bus and β is the penalty factor for the demand curtailment.

3.4 Optimal DV control considering DR

In this section, the obtained DVDR control in each area using ε-decomposition is described. Reactive power injections in the candidate buses and demand curtailment in the region's buses are the control variables. The general concept of the method is shown in Fig. 2 where DSO provides the local control centres with DR data contracts between DSO and consumers. The local control centres can then determine which contracts can be used. Load factor amount at each period is also shown in Fig. 3.

The goal here is to minimise the objective function described in (1) and (2). The optimisation problem in each area is described as

$$\text{objective} = \min \left(\sum_{k=1}^{24} \left(\sum_{i=1}^{N_b} [V_{i,k} - V_{\text{ref}}]^2 + \alpha \sum_{j=1}^{M} |\Delta Q_{j,k}|^2 + \beta \sum_{i=1}^{N_b} |\Delta P_{i,k}| \right) \right) \tag{3}$$

$$V_{\text{low}} < V_{i,k} < V_{\text{up}}, \quad i = 1, \ldots, N_b, k = 1, \ldots, 24 \tag{4}$$

$$\Delta Q_{j,k} \le Q_{j,k}^{\text{accessable}}, \quad j = 1, \ldots, M, k = 1, \ldots, 24 \tag{5}$$

(see (6))
(see (7))

$$\Delta Q_{i,k} \ge \omega_{i,k} \times Q_{\min} \quad i = 1, \ldots, M, \ k = 1, \ldots, 24 \tag{8}$$

$$Q_{\text{load\_new},i,k} = Q_{\text{load},i,k} - \Delta Q_{i,k} \quad i = 1, \ldots, N_{\text{b}} \ k = 1, \ldots, 24 \tag{9}$$

$$P_{\text{load\_new},i,k} = P_{\text{load},i,k} - \psi_{i,k} \times \Delta P_{i,k}, \quad i = 1, \ldots, N_{\text{b}}, \ k = 1, \ldots, 24 \tag{10}$$

$$\Delta P_{i,k} \le \lambda_i \times \text{load}_{i,k}, \quad i = 1, \ldots, N_{\text{b}} \ k = 1, \ldots, 24 \tag{11}$$

where V_i is the voltage value in each area, V_{ref} is the reference voltage, α is the penalty factor reactive injection, β is the penalty factor for the demand curtailment, $\Delta Q_{j,k}$ represents the reactive power injection at the candidate buses at hour k, $\Delta P_{i,k}$ is the demand curtailment in the region's buses at hour k, and λ_i is the demand curtailment contract in each region's buses (the percentage of curtailed demand). $\theta_{i,k}$ and $\theta_{j,k}$ are phase angle at buses i and j and also hour k. V_{low} and V_{up} are the lower and upper limits of voltage, $P_{i,k}$ and $P_{\text{load\_new},i,k}$ are generation and demand active power in the regions' buses at hour k, $Q_{i,k}$ and $Q_{\text{load\_new},i,k}$ are

$$P_{i,k} - P_{\text{load\_new},i,k} = V_{i,k} \times \sum_{j=1}^{N_b} V_{j,k} \times (G_{i,j} \times \cos(\theta_{i,k} - \theta_{j,k}) + B_{i,j} \times \sin(\theta_{i,k} - \theta_{j,k})) \quad i = 1, \ldots, N_b \quad j = 1, \ldots, N_b \ k = 1, \ldots, 24 \tag{6}$$

Table 2 Load factors in each hour

Hour	1	2	3	4	5	6	7	8
load factor	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.6
hour	9	10	11	12	13	14	15	16
load factor	0.7	0.8	0.9	0.95	0.9	0.85	0.8	0.8
hour	17	18	19	20	21	22	23	24
load factor	0.8	0.8	1	1	0.95	0.9	0.8	0.7

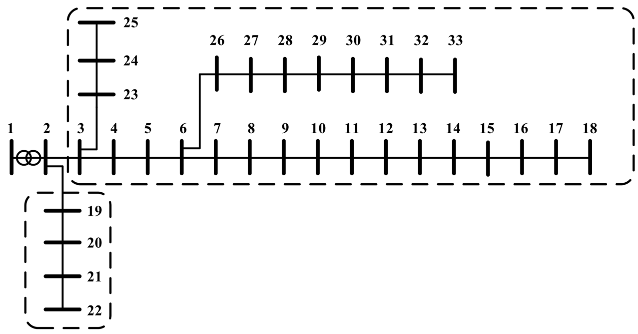

Fig. 4 *Regions in the 33-bus distribution system*

generation and demand reactive power in the regions' buses, $Q_{\min}$ is minimum reactive power for injection, $G_{i,j}$ and $B_{i,j}$ are real and image parts of Y bus, $\omega_{i,k}$ and $\psi_{i,k}$ are binary variables in bus i and hour k, $\text{load}_{i,k}$ is load profile at bus i and hour k, and $Q_{j,k}^{\text{accessable}}$ is the accessible reactive power (for injecting) in each candidate bus at hour k.

To understand how the proposed method affects the voltage problem, accessible reactive power in each candidate bus is assumed as

$$Q_{j,k}^{\text{accessable}} = \sqrt{S_{j,k}^2 - P_{j,k}^2}, \quad j = 1, \ldots, M, \quad k = 1, \ldots, 24 \tag{12}$$

where $P_{j,k}$ and $S_{j,k}$ are active and apparent load demands of candidate buses, respectively. Note that all buses in each control areas have the ability to participate in voltage control. However, only candidate buses in each control areas can inject reactive power to improve voltage profile. GAMS software is used to run the distribution load flow and optimise the reactive power injection into candidate buses and demand curtailment in the control areas. The computation time for the proposed method is 90 s using a computing power of 5-Core 2.50 GHz CPU and 4 GB RAM.

4 Simulation results

The proposed method is tested using the standard IEEE 33-bus distribution test systems [33, 34] and candidate buses are selected based on [19]. The case study is chosen as a 24-h period where the load factors at each hour are given in Fig. 3 and Table 2. The 33-bus distribution system is radial and concludes one main feeder and three lateral feeders. It consists of 32 sections and 33 buses, as shown in Fig. 4. Data of feeders' line and loads is obtained from [30, 31]. The voltage and the power buses are assumed as 12.66 kV and 100 MVA. A set of buses (11, 12, 13, 14, 15, 16, 17, 18, 31, 32, and 33) of the 33-bus distribution system has low voltages ∼0.9 p.u. Applying ε-decomposition algorithm with ε is chosen as 0.00005 results in two sub-networks (see Fig. 4).

We use three methods for the voltage control analysis in DV control:

- *Method 1*: DV control method in a network without the DR participation (DV method). In this way, candidate buses have the capability for injecting reactive power.
- *Method 2*: DV control method by just using demand curtailment in the buses of control areas (DR method). Candidate buses do not have the capability for reactive power injection.
- *Method 3*: DV control in the test system considering the DR (DVDR method). In this way, both reactive power injection and demand curtailment are used.

Evaluating the influence of the level of demand curtailment on the voltage control, we use two scenarios for the demand curtailment:

1–20% of load in the sub-network buses can be curtailed ($\lambda_i = 0.2$).
2–30% of load in the sub-network buses can be curtailed ($\lambda_i = 0.3$).

In each scenario, a few analyses must be followed:

1. To consider the effect of load profile on voltage control algorithm, the improved voltage profile during two periods, i.e. hour 2 (minimum load) and hour 20 (maximum load profile), is studied.
2. To consider the voltage control in the 24 h time period, voltage profile of bus 18 (the worst bus as voltage profile) at 24 h is taken into account.
3. To evaluate the effect of demand curtailment on voltage control, the demand curtailment at hours 20 (maximum load factor), 9 (medium load factor), and 4 (minimum load factor) is considered.
4. To evaluate the demand curtailment in 24 h time period, the demand curtailment at 24 h in three different buses (18, 33, and 28) is considered.

Note: values of α in region 1 (the larger region) and region 2 (the smaller region) are assumed 5×10^{-5} and 5×10^{-7}, respectively. The value of β is assumed 0.005 for both regions.

4.1 Scenario 1

The candidate buses with potential for injecting reactive power are chosen based on the algorithm described in [19]. The candidate buses are usually the end buses in each region (see Table 3). Using DV control with the DR, it is visible that the voltage is substantially improved at hour 20:00 (see Fig. 5*a*). As shown, end buses with voltage problem and their voltage deviation higher than the one in other buses, have better voltage improvement. This improvement helps the reactive power injection and the demand curtailment to be mainly occurred in the buses reducing the voltage drops. In this case, the voltage mitigation by implementing the DR programme is better than the one without it (see Fig. 5*a*). Furthermore, the voltage improvement by DR method is worse than the voltage profile using DV method. This means that with 20% of the load for the DR programme, DR method shows a less effect on the voltage profile compared to the DV method.

$$Q_{i,k} - Q_{\text{load\_new},i,k} = V_{i,k} \times \sum_{j=1}^{N_b} V_{j,k} \times (G_{i,j} \times \sin(\theta_{i,k} - \theta_{j,k}) - B_{i,j} \times \cos(\theta_{i,k} - \theta_{j,k})) \tag{7}$$
$$i = 1, \ldots, N_b \quad j = 1, \ldots, N_b \; k = 1, \ldots, 24$$

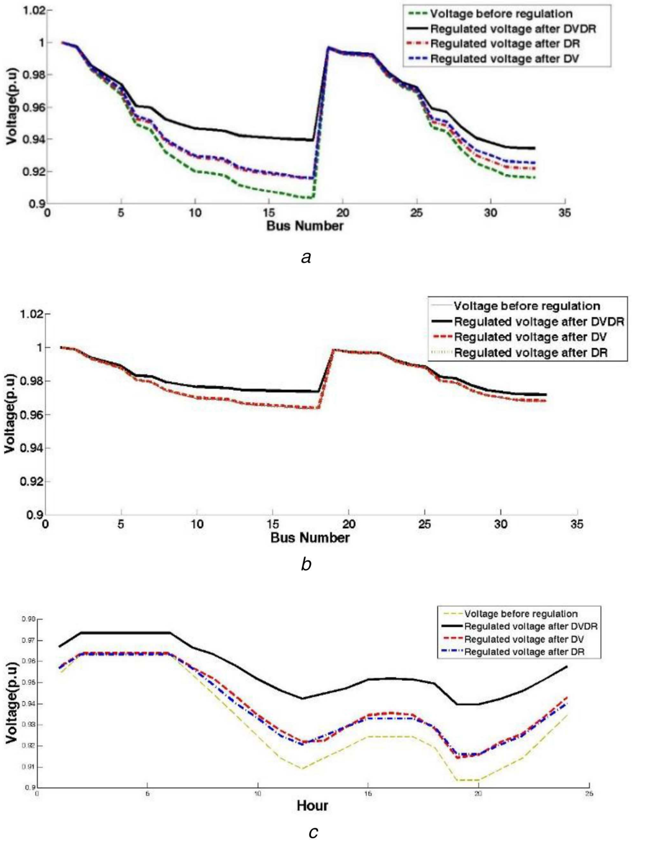

Fig. 5 *Voltage amount before and after voltage regulation at hour 20 (maximum load factor), hour 2 (minimum load factor) and 24 h in Scenario 1*
(a) Hour 20 (maximum load factor), ***(b)*** Hour 2 (minimum load factor), ***(c)*** 24 h

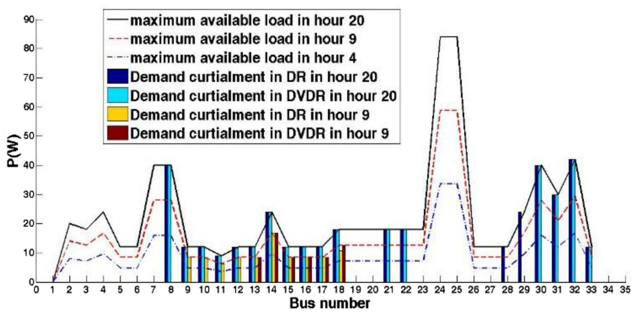

Fig. 6 *Demand curtailment using DR and DVDR methods in Scenario 1*

The voltage improvement at hour 2:00 is shown in Fig. 5*b*, where such an improvement occurs mainly at the buses with the voltage problem and the individual use of DR and DV methods does not have any effect on the voltage profile. Only our DVDR method improves the voltage profile.

The voltage improvement at 24 h in bus 18 is also shown in Fig. 5*c* where it is evident that the proposed hybrid DVDR performs better than using DV or DR individually.

The level of demand curtailment by DR and DVDR methods is shown in Fig. 6 where the demand curtailment by DR method is more than DVDR method at both hours 20:00 and 9:00 (Table 4). This means that DSO must pay more money when using only DR programme compared with DVDR. In both DR and DVDR methods however the demand curtailment at hour 4:00 is zero and the demand curtailment usually happens in the end buses due to the voltage problem (see Fig. 6).

4.2 Scenario 2

Fig. 7*a* shows that voltage improvement by the demand curtailment is better than the case without and using the DR method is better than just using DV method. In fact, by increasing the level of demand curtailment, voltage improvement becomes better than the one using DV method. In both scenarios, the combined voltage control strategies show better results.

As shown in Fig. 7*b*, similar to previous cases, the voltage improvement is mainly in the end buses with the voltage problem and the individual use of DR method or DV method cannot improve the voltage profile. However, we can see improvements

Table 3 Candidate buses

	Candidate buses									
20 buses	7	8	9	10	11	12	13	14	15	16
	17	18	22	24	25	29	30	31	32	33

Table 4 DR amount in 24 h in Scenario 1

	Time	1	2–6	7	8	9	10	11	12	13	14
Bus 18	DR	9	0	9	10.8	12.6	14.4	16.2	17.1	16.2	15.3
	DVDR	0	0	0	10.8	12.6	14.4	16.2	17.1	16.2	15.3
	time	15	16	17	18	19	20	21	22	23	24
	DR	14.4	14.4	14.4	15.3	18	18	17.1	16.2	14.4	12.6
	DVDR	14.4	14.4	14.4	15.3	18	18	17.1	16.2	14.4	12.6
	time	1	2–6	7	8	9	10	11	12	13	14
Bus 33	DR	0	0	0	0	0	9.6	10.8	11.4	10.8	10.2
	DVDR	0	0	0	0	0	0	10.8	11.4	10.8	0
	time	15	16	17	18	19	20	21	22	23	24
	DR	9.6	9.6	9.6	10.2	12	12	11.4	10.8	9.6	0
	DVDR	0	0	0	0	12	12	11.4	10.8	0	0
	time	1	2–6	7	8	9	10	11	12	13	14
Bus 28	DR	0	0	0	0	0	0	0	11.4	0	0
	DVDR	0	0	0	0	0	0	0	0	0	0
	time	15	16	17	18	19	20	21	22	23	24
	DR	0	0	0	0	12	12	11.4	0	0	0
	DVDR	0	0	0	0	0	0	0	0	0	0

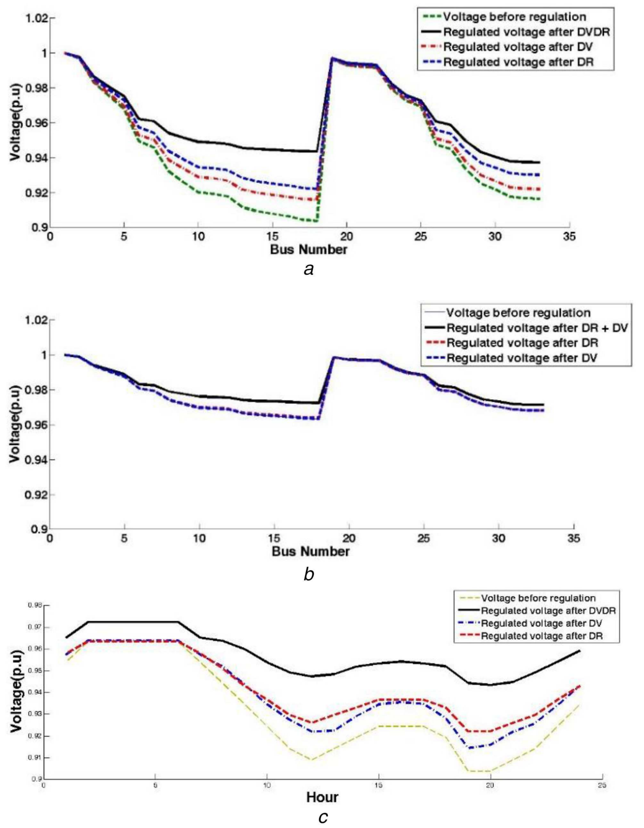

Fig. 7 *Voltage amount before and after voltage regulation at hour 20 (maximum load factor), 2 (minimum load factor) and 24 h in Scenario 2*
(a) Hour 20 (maximum load factor), ***(b)*** Hour 2 (minimum load factor), ***(c)*** 24 h

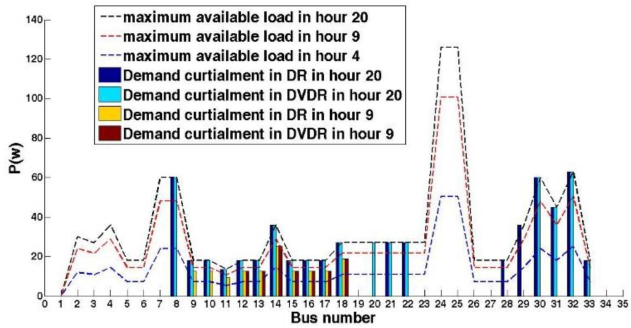

Fig. 8 *Demand curtailment using DR and DVDR methods in Scenario 2*

Table 5 DR amount in 24 h in Scenario 2

	Time	1	2–6	7	8	9	10	11	12	13	14
Bus 18	DR	13.5	0	13.5	16.2	18.9	21.6	24.3	25.65	24.3	22.95
	DVDR	0	0	0	16.2	18.9	21.6	24.3	25.65	24.3	22.95
	time	15	16	17	18	19	20	21	22	23	24
	DR	21.6	21.6	21.6	22.95	27	27	25.65	24.3	21.6	18.9
	DVDR	21.6	21.6	21.6	22.95	27	27	25.65	24.3	21.6	18.9
	time	1	2–6	7	8	9	10	11	12	13	14
Bus 33	DR	0	0	0	0	0	14.4	16.2	17.1	16.2	15.3
	DVDR	0	0	0	0	0	0	0	17.1		0
	time	15	16	17	18	19	20	21	22	23	24
	DR	14.4	14.4	14.4	15.3	18	18	17.1	16.2	14.4	0
	DVDR	0	0	0	0	18	18	17.1	0	0	0
	time	1	2–6	7	8	9	10	11	12	13	14
Bus 28	DR	0	0	0	0	0	0	0	0	0	0
	DVDR	0	0	0	0	0	0	0	0	0	0
	time	15	16	17	18	19	20	21	22	23	24
	DR	0	0	0	0	18	18	0	0	0	0
	DVDR	0	0	0	0	0	0	0	0	0	0

employing the proposed hybrid DVDR where the voltage improvement in the off-peak load profile is less than the one in the peak load profile. This is because the voltage condition in the off-peak load is better than the one in the peak load. Fig. 7*c* shows that using DVDR method results in better voltage improvement at 24 h in bus 18 compared to just using DV or DR method. In contrast to scenario 1, the voltage improvement at all the hours using DR method is better that the one using DV method. This is due to the fact that when the demand curtailment increases, DR method has more influence on voltage profile than DV.

The level of demand curtailment using DR and DVDR methods are shown in Fig. 8. It can be seen that the demand curtailment with DR is more than the one using DVDR method at both hours 20:00 and 9:00. This means that DSO must pay more money in case of using just DR method. The demand curtailment at hour 4:00 in both DR and DVDR methods is zero and it usually occurs in end buses due to the voltage problem (see Fig. 8).

To evaluate the effect of demand curtailment on the voltage profile at 24 h, the levels of demand curtailment at 24 h in buses 18, 33, and 28 are given in Table 5. It can be seen that the levels of demand curtailment in the DVDR method are less than the one using DR. In bus 18 using DR method, the demand curtails at hours 1:00 and 7:00. However, at these hours, the demand does not curtail using DVDR. In bus 33 using DR method, the demand curtails at hours 10:00, 11:00, 12:00–18:00, 22:00, and 23:00. Again, at these hours, the demand does not curtail using DVDR method. In bus 28 using DR method, demand curtails only at hours 19:00 and 20:00. However, the demand curtailment is zero at all the hours. This means that in the off-peak periods, the reduction in the number of buses participating in DR programme using the DVDR method is more than the one in the peak load profile. Note that the reduction in the number of buses for participating in DR program in DVDR method is more than the case in Scenario 1. This is due to the fact that when the amount of demand curtailment in Scenario 2 increases, voltage control centre has more capacity to control and curtail the demand in the lower number of buses with respect to Scenario 1.

5 Conclusion

Taking advantage of the novel technologies recently introduced in the modern grid such as controllable reactive power support and the DR resources, this paper investigated reactive power support and control voltage problem in distributed scenarios using the combined data of end-users and DR. The proposed hybrid DVDR method is designed to control the demand curtailment in the buses associated with a region and the reactive power injection in the candidate buses. The DVDR method suggests a novel but the practical approach to the integration of the DR in a DV control system. The results prove considerable improvement in the voltage profile when compared to just using DR or DV methods. Using DVDR method, the demand curtailment also becomes less than DR methods which means DSO can pay less money for consumer participation in DR. The results further showed that using DVDR method, the reduction in the number of the buses participating in DR in the off-peak load period is more than the one in the peak load periods.

6 Acknowledgment

This work was supported by the EPSRC Global Challenge Research Fund, Institutional Sponsorship to Queen Mary University of London, Grant No. EP/R512709/1.

7 References

[1] Hedman, K.W., O'Neill, R.P., Fisher, E.B., *et al.*: 'Optimal transmission switching with contingency analysis', *IEEE Trans. Power Syst.*, 2009, **24**, (3), pp. 1577–1586

[2] Mazi, A., Wollenberg, B., Hesse, M.: 'Corrective control of power system flows by line and bus-bar switching', *IEEE. Trans. Power Syst.*, 1986, **1**, (3), pp. 258–264

[3] Ma, K., Mutale, J.: 'Risk and reliability worth assessment of power systems under corrective control'. Proc. North American Power Symp. (NAPS), Starkville, MS, USA, October 2009, pp. 1–6

[4] Shao, W., Vittal, V.: 'LP-based OPF for corrective FACTS control to relieve overloads and voltage violations', *IEEE. Trans. Power Syst.*, 2006, **21**, (4), pp. 1832–1839

[5] Hingorani, N.G..: 'Flexible AC transmission', *Proc. IEEE Spectrum*, 1993, **30**, (4), pp. 40–45

[6] Recio, C.J.: 'The utilization of power converters in consumer products for distributed reactive power support', M.Sc. Thesis, Department of Electrical Engineering, University of Illinois at Urbana-Champaign, IL, 2012

[7] Sefa, I., Atlin, N., Ozdemir, S.: 'An implementation of grid interactive inverter with reactive power support capability for renewable energy sources'. Proc. IEEE POWERENG, Malaga, Spain, May 2011, pp. 1–6

[8] Dominguez-Garcia, A.D., Hadjicostis, C.N., Krein, P.T.*, et al.*: 'Small inverter-interfaced distributed energy resources for reactive power support'. Proc. IEEE Applied Power Electronics Conf. (APEC), Fort Worth, TX, USA, March 2011, pp. 1616–1621

[9] Rogers, K.M., Klump, R., Khurana, H.*, et al.*: 'An authenticated control framework for distributed voltage support on the smart grid', *IEEE Trans. Smart Grid.*, 2010, **1**, (4), pp. 40–47

[10] Rogers, K.M., Klump, R., Khurana, H.*, et al.*: 'Smart-grid-enabled load and distributed generation as a reactive resource'. Proc. IEEE PES Innovative Smart Grid Technology, Gaithersburg, MD, USA, 2010

[11] Aquino-Lugo, A.A., Klump, R., Overbye, T.J.: 'A control framework for the smart grid for voltage support using agent-based technologies', *IEEE Trans. Smart Grid*, 2011, **2**, (1), pp. 173–180

[12] Logue, D.L., Krein, P.T.: 'Utility distributed reactive power control using correlation techniques'. Proc. Applied Power Electronics Conf. (APEC), Anaheim, CA, USA, March 2001, pp. 1294–1300

[13] Begović, M., Pregelj, A., Rohatgi, A.*, et al.*: Impact of renewable distributed generation on power systems'. Proc. Hawaii Int. Conf. System Sciences, Maui, HI, USA, January 2001, pp. 654–663

[14] Hu, K., Liaw, C.: 'On a bidirectional adapter with G2B charging and B2X emergency discharging functions', *IEEE Trans. Ind. Electron.*, 2014, **61**, (1), pp. 243–257

[15] Chang, C., Lin, Y., Chen, Y.*, et al.*: 'Simplified reactive power control for single-phase grid-connected photovoltaic inverters', *IEEE Trans. Ind. Electron.*, 2014, **61**, (5), pp. 2286–2296

[16] Kisacikoglu, M., Kesker, M., Tolbert, M.: 'Single-phase on-board bidirectional PEV charger for V2G reactive power operation', *IEEE Trans. Smart Grid*, 2015, **6**, (2), pp. 767–775

[17] Yilmaz, M., Krein, P.: 'Review of battery charger topologies. Charging power levels, and infrastructure for plug-in electric and hybrid vehicles', *IEEE Trans. Power Electron.*, 2013, **28**, (5), pp. 767–775

[18] Yu, L., Czarkowski, D., León, F.D.: 'Optimal distributed voltage regulation for secondary networks with DGs', *IEEE Trans. Smart Grid*, 2012, **3**, (2), pp. 959–967

[19] Abessi, A., Vahidinasab, V., Ghazizadeh, M.S.: 'Centralized support distributed voltage control by using end-users as reactive power support', *IEEE Trans. Smart Grid*, 2015, **1**, (1), pp. 178–188

[20] Siano, P.: 'Demand response and smart grids—a survey', *Renew. Sustain. Energy Rev.*, 2014, **30**, pp. 461–478

[21] Siano, P., Sarno, D.: 'Assessing the benefits of residential demand response in a real time distribution energy market', *Appl. Energy*, 2016, **161**, pp. 533–551

[22] Shoreh, M.H., Siano, P., Shafie-khah, M.*, et al.*: 'A survey of industrial applications of demand response', *Electric. Power Syst. Res.*, 2016, **141**, pp. 31–49

[23] Venkatesan, N., Solanki, J., Solanki, S.K.: 'Residential demand response model and impact on voltage profile and losses of an electric distribution network', *Appl. Energy*, 2012, **96**, pp. 84–91

[24] Zakariazadeh, A., Homaee, O., Jadid, S.*, et al.*: 'A new approach for real time voltage control using demand response in an automated distribution system', *Appl. Energy*, 2014, **117**, pp. 157–166

[25] Rabiee, A., Soroudi, A., Mohammadi-Ivatloo, B.*, et al.*: 'Corrective voltage control scheme considering demand response and stochastic wind power', *IEEE Trans. Power Syst.*, 2015, **29**, (6), pp. 2965–2973

[26] Niknam, T., Firouzi, B.B., Ostadi, A.: 'A new fuzzy adaptive particle swarm optimization for daily volt/Var control in distribution networks considering distributed generators', *Appl. Energy*, 2010, **87**, (6), pp. 1919–1928

[27] Tanaka, K., Oshiro, M., Toma, S.*, et al.*: 'Decentralised control of voltage in distribution systems by distributed generators', *IET Gener. Transm. Distrib.*, 2010, **4**, (11), pp. 1251–1260

[28] Dodo Amadou, M., Mehrjerdi, H., Lefebvre, S.*, et al.*: 'Area voltage control analysis in transmission systems based on clustering technique', *IET Gener. Trans. Distrib.*, 2014, **12**, (1), pp. 2134–2143

[29] Wang, R., Xiao, G., Wang, P.: 'Hybrid centralized-decentralized (HCD) charging control of electric vehicles', *IEEE Trans. Veh. Tech.*, 2017, **66**, (8), pp. 6728–6741

[30] Amano, M., Zecevic, A., Siljak, D.: 'An improved block-parallel Newton method via epsilon decompositions for load-flow calculations', *IEEE Trans. Power Syst.*, 1996, **11**, (3), pp. 1519–1527

[31] Sezer, M., Šiljak, D.: 'Nested ε-decompositions and clustering of complex systems', *Automatica*, 1986, **22**, (3), pp. 321–331

[32] FERC, Staff Report: 'Assessment of demand response and advanced metering', 2006, AD06e2

[33] Babu, P.R., Rakesh, C., Kumar, M.N.*, et al.*: 'A novel approach for solving distribution networks'. Proc. IEEE INDICON, Gujarat, India, December 2009, pp. 1–5

[34] Sarma, A.K., Rafi, K.M.: 'Optimal selection of capacitors for radial distribution systems using plant growth simulation algorithm', *Int. J. Adv. Sci. Technol.*, 2011, **2**, pp. 43–54