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A new approach for real time voltage control using demand response in an automated distribution system

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HIGHLIGHTS

- We propose a new real time voltage control model usable in emergency conditions.
- This model determines the required load reduction to control the voltage profile.
- This model does not need the generation forecast data to regulate the voltage.
- A novel voltage sensitivity matrix based on demand response program is presented.

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ABSTRACT

The main goal of Distribution Automation (DA) is the real-time operation, usually without operator intervention, of distribution systems as a consequence of load demand or power generation variations and failure conditions in the distribution systems. As real time voltage control is known as a legacy system that can be fully activated by DA equipments, in this paper an analytical study is reported to demonstrate the effects of load curtailments on voltages profile in distribution network. A new method for real time voltage control, based on emergency demand response program, is also proposed. The proposed method uses the real-time measured data collected by RTUs and determines the tap changer condition and load curtailment required in order to maintain the distribution voltage profile. Emergency conditions include outages of generators and lines, and fluctuations due to unpredictable load demand and renewable generation. A novel voltage sensitivity matrix, based on performed voltage sensitivity analysis due to load participation in demand response program, is also proposed. In order to verify the effectiveness and robustness of the proposed control scheme, it is tested on a typical automated distribution network. Simulation results show that the proper selection of load curtailment can improve voltage profile and that, in emergency conditions, demand response is an effective way to keep the voltage in a permissible range.

1. Introduction

In the current and future distribution systems, in which various types of Distributed Energy Resources (DER) are integrated into the network, their operation is a challenging issue, and automatic and intelligent monitoring and control represents an essential tool to overcome this challenge.

In the last decade, online monitoring of distribution network has been a hot topic in power system engineering. New control systems and communication links have been integrated into the power systems in order to help operators to efficiently manage these systems. Distribution Automation (DA) systems provide Supervisory Control and Data Acquisition (SCADA) capabilities throughout the modern distribution system [1]. The communication infrastructure supports measurement and control systems such as remote terminal units (RTU) in distribution substations or feeders [2]. With this wide deployment of DA systems, the distribution system operator (DSO) can switch the distribution tap changer in real time to dynamically maintain buses voltages in an acceptable range. Moreover, with the availability of DA features, the DSO can use demand response as an efficient tool to regulate distribution feeders' voltage in normal and emergency conditions.

Volt/VAr control (VVC) represents an important issue in the daily operation of distribution systems. The proper dispatch of Volt/VAr devices allows, in fact, reducing total power loss and also improving the voltage profile of distribution feeders [3]. As voltage control is one of the Load Tap Changers (LTCs') tasks, in [4], the authors focused on the tasks of substation transformers with LTCs in smart distribution grids. The historic Integrated Volt/VAr Management (IVVM) features and advanced features that will be re-

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quired for full realization of smart grid benefits are discussed in [5]. In [6], the authors proposed the concept of a decentralized non-hierarchal voltage regulation architecture based on intelligent and cooperative smart entities. In [7], the effect of price-based DR has been considered on distribution voltage profile. Consumer behavior modeling was carried out by developing a demand-price elasticity matrix for different types of consumers. The model only considers the price-based DR without using the control option to execute incentive-based DR programs.

In [8] the authors presented a methodology that uses the potential of the smart grids in increasing the efficiency of the voltage control in distribution systems. In [9] the problem of voltage regulation has been well addressed by studying the impacts of DG on the voltage profile and on the operation of step voltage regulators (SVR) and feeder shunt capacitors. In [10], a new approach for voltage regulators function's improvement in multiple feeders including DGs was proposed. This model is based on placing RTUs at each DG unit and each capacitor bus that communicate with each other in a certain order. Data received from RTUs allow the estimation of the maximum and minimum voltages along the feeders and, hence, the voltage regulation of the feeders. In the past, the IEEE P1547 Standard [11] specified that the DG units should not regulate distribution system voltages. An attempt by a DG unit to regulate distribution system voltage, if not properly coordinated, may conflict, in fact, with existing voltage regulation schemes, applied by the utility to regulate the same or a nearby point to a different voltage. Currently, most of the installed DGs are commonly connected to operate at unity power factor in order to avoid interference with the voltage regulation devices connected to the system [12]. However, the recent grid codes of many countries, such as Denmark, Germany, Italy, Ireland and the UK, require that DGs should provide reactive power control capabilities and that network operators may specify power factor or reactive power generation requirement for grid-connected WTs [2,13–17]. In [18], a sustainable energy system including different sub-system has been proposed for a smart grid project in an urban context. The results of an energy analysis showed the effective possibilities of integration aimed at energy saving and environmental sustainability.

In this paper, a real time voltage control approach is presented that uses load curtailment as a part of demand response programs to keep the distribution feeders' voltages within their specified ranges. Since renewable generation and load demand unpredictable changes, as well as contingencies in the distribution network, may usually determine voltage violations at some buses, the proposed real time voltage control is performed if voltage violations at some buses occur. It is supposed that, in a normal condition, the voltage control is performed based on a pre-scheduling voltage control program carried out during the day ahead operational scheduling program.

The innovative contributions of this paper are highlighted as follows:

- unlike most previous work, the basis of the proposed approach is the contribution of DR programs to the real time voltage control;
- an analytical study to integrate demand response with the conventional voltage control model in a novel matrix based sensitivity analysis approach is presented;
- the proposed model is not dependent on consumers' load demand and renewable generation forecasted data.

This paper is organized as follows. In Section 2, the relation between demand response concept and voltage control action is described. Section 3 explains the proposed voltage control model. Section 4 reports some simulation results, and finally conclusions are given in Section 5.

2. Emergency demand response and voltage control

Voltage control can be provided at any level of a power system (generation, transmission, distribution) by means of shunt capacitors, tap changers, distributed generation and demand reduction. When some consumers agree to reduce their load demand, the active and reactive power flow through the feeders decrease, and as a result, the voltage drop in the distribution network can also be compensated in such a way that the voltages at buses respect voltage constraints.

Two general types of DR can be highlighted: program and event DR. Program type focuses on the economical aspect, while event type DR is related to emergency conditions.

Emergency demand response programs, many of which have been developed in the last decade [19], provide incentive payments to customers for reducing their loads during reliability-triggered events. The level of the payment is typically specified beforehand; while a contingency occurs in the grid, the system operator calls committed customers to reduce their load and the response duration depends on the nature of the event.

In this paper, an emergency demand response program is assumed for emergency load reduction in the proposed real time voltage control model to counteract DGs outage or renewable generation and load demand uncertainties.

3. Proposed model for real time voltage control

In this section, the proposed distribution system configuration as well as the real time voltage control algorithm is presented. The assumptions used in proposed real time voltage control model are:

- responsive loads have already signed their participation contracts, and only their selection is done in real time by the DSO. According to emergency demand response program, the level of the payment is typically specified beforehand and the loads do not offer price for their demand reduction, but a uniform price is defined by the system operator or regulator that is mentioned in the contract signed by the customer [19];
- control of the main transformer tap changer and demand curtailment are considered in order to regulate the voltages at buses. Even if the effect of other voltage control devices such as switched capacitor and DGs, can be taken into account, the main aim of the proposed method is that of evaluating the effectiveness of demand response in the voltage regulation action.

3.1. Voltage estimation between DG buses

Voltage levels at some buses on a feeder may violate allowable constraints due to both variations of load power demand and of power injections from one or multiple DGs. In these cases, the maximum and minimum voltage estimations through the feeder are required by the voltage regulator.

In a typical distribution system, the maximum voltage may occur at the substation bus, DG buses or capacitor buses. However, the point with the lowest voltage magnitude may be placed at end buses or between DG buses [10]. Minimum voltage points can usually take place only at the end of the feeder as well as in between any DG connecting buses. The voltage of the end points can be read by RTU or it can be estimated with the minimum voltage point estimation between the DG units' buses.

For the minimum voltage point estimation, it is assumed that the load between two DG units is concentrated halfway between them. Based on this assumption, the value of the minimum voltage point between DG1 and DG2, if exists, as calculated by DG unit 2 ($V_{est,DG2,DG1}$) can be given as (see Fig. 1) [10,20]:

$$V_{est,DG2,DG1} = V_{DG2} - \left(P_{2,1}\frac{r}{2} + Q_{2,1}\frac{x}{2}\right) \tag{1}$$

where V_{DG2} is the bus voltage of the DG unit 2. Also $P_{2,1}$ and $Q_{2,1}$ are the injected active and reactive powers from bus 2. The resistance and reactance of the feeder between buses 1 and 2 where DG unites are connected are denoted by r and x. The value of the assumed minimum voltage point calculated by DG unit 1 is given by:

$$V_{est,DG1,DG2} = V_{DG1} - \left(P_{1,2}\frac{r}{2} + Q_{1,2}\frac{x}{2}\right) \tag{2}$$

A better estimation is achieved by averaging these two values:

$$V_{est} = \frac{V_{est,DG1,DG2} + V_{est,DG2,DG1}}{2} \tag{3}$$

where V_{est} is the estimation of the voltage between two DG buses.

3.2. Proposed system configuration

SCADA solutions for DA and Distribution Management Systems (DMS) deliver comprehensive benefits for monitoring and control tasks. Modern SCADA provides proper monitoring of equipments to maintain operations at an optimal level by identifying and correcting problems before they turn into significant system failures.

A SCADA system is made up of a number of remote terminal units (RTUs) collecting field data and sending data back to a master station via a communications link. The RTU provides an interface to the field analog and digital sensors situated at each remote site. The master station displays the acquired data and also permits the operator to perform remote control tasks [2,21].

In the proposed Volt/VAr control model, the distribution system must be equipped with a communication link and RTUs installed at DGs and capacitors buses. The measured data by RTUs as well as load demand curtailment notification should be transferred by a communication link such as Power Line Carrier (PLC) or GPRS to a distribution energy management system. This information and communication infrastructure is available in an automated distribution system like the considered distribution system. However, the implementation of the proposed voltage control method is possible in every conventional distribution system endowed with a communication system as well as installed RTUs at DGs or capacitor buses.

A block diagram presenting how the real time voltage control carried out by the DMS is linked to the LTC and responsive loads in the modern distribution grid is shown in Fig. 2. Volt/VAr optimization software is one part of the DMS that processes customer voltage level for implementing electric reliability, voltage and volt-ampere reactive optimization procedures. The Volt/VAr optimization software is responsible for day-ahead voltage and reactive power scheduling, as well as real time voltage control. This paper focuses on real time Volt/VAr control implementation. The DMS receives required data from SCADA master that collects data from RTUs, geographic information systems (GIS), and Customer Information Systems (CIS). Also the current operation states of

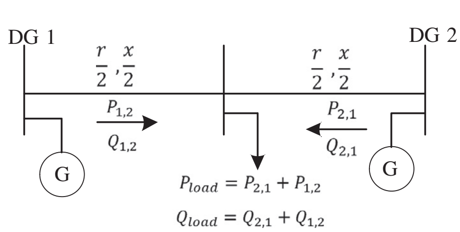

Fig. 1. Part of a distribution system.

equipments like DGs, tap changers and switched capacitors are required as input information for the DMS in order to carry out the required control actions.

Starting with the RTU, the measurement and internal calculations are done by each RTU, and the specified parameters are sent to the next RTU. This procedure continues until the data are delivered to the SCADA master data management system. These data received from RTUs are sent to the DMS. At this stage, the proposed algorithm is run to determine the load reduction required to improve the voltage profile. After that, the output results of the real time voltage control software are sent to the SCADA master. Finally, the SCADA master sends the request for load reduction through a communication link to customers that have been selected in order to curtail their consumption. The proposed system structure is shown in Fig. 3.

In this system, one RTU is assumed to be installed at each bus where a DG is installed. The communication contact between RTUs has been also presented in Fig. 3. In the proposed model, each RTU measures some local parameters, as shown in Fig. 4, and performs some simple calculations. The local parameters measured by the RTUs are the voltages at buses and the active and reactive power flows through lines.

3.3. Voltage estimation based on RTUs' measurement

Maximum and minimum voltages are calculated by each RTU and the output results are sent to the next RTU as an input data. For clarification, let RTU_n be the RTU connected to a specific DG and define RTU_{n-1} as the upstream RTU, i.e., the RTU connected to the DG upstream from the first DG. Also, define RTU_{n+1} as the downstream RTU. According to Fig. 5, the algorithm can be clarified as follows: RTU_n, by performing local measurements, estimates the voltage between RTU_{n+1} and its node using Eq. (2) that is given as follows:

$$V_{est,n,n+1} = V_n - \left(P_{n,n+1}\cdot\frac{r_{n,n+1}}{2} + Q_{n,n+1}\cdot\frac{x_{n,n+1}}{2}\right) \tag{4}$$

where $V_{est,n,n+1}$ is the estimation of voltage between the buses related to RTU_n and RTU_{n+1} as calculated by RTU_n, and V_n is the voltage of the DG bus n at which RTU_n is connected. The active and reactive power flows from the bus related to RTU_n to the bus related to RTU_{n+1} are indicated as $P_{n,n+1}$ and $Q_{n,n+1}$, respectively. Also $r_{n,n+1}$ and $x_{n,n+1}$ are the resistance and reactance of the lines between the buses related to RTU_n and RTU_{n+1}, respectively.

The final estimated voltage for the distance between the buses related to RTU_n and RTU_{n+1} is calculated by means of the above estimated voltage and the similar estimated voltage by RTU_{n+1} for this distance (see also Eq. (1)), using the following equation:

$$V^F_{est,n,n+1} = \frac{V_{est,n,n+1} + V_{est,n+1,n}}{2} \tag{5}$$

where $V^F_{est,n,n+1}$ is the final estimated voltage for the lines between the buses related to RTU_{n+1} and RTU_n.

In the next stage, the voltage between RTU_n and RTU_{n-1} is estimated with Eq. (6) (see also Eq. (1)):

$$V_{est,n,n-1} = V_n - \left(P_{n,n-1}\cdot\frac{r_{n,n-1}}{2} + Q_{n,n-1}\cdot\frac{x_{n,n-1}}{2}\right) \tag{6}$$

Finally, the voltages V_n, $V^F_{est,n,n+1}$ and $V_{est,n,n-1}$ are sent to the upstream RTU (RTU_{n-1}).

As some of the calculations are carried out by each RTU, the transferred data and the calculation time is reduced if compared with common SCADA, thus the proposed model exhibits a faster reaction to voltage variation.

After calculation of the voltages at each section of the feeder, the voltage regulator controller calculates the maximum and min-

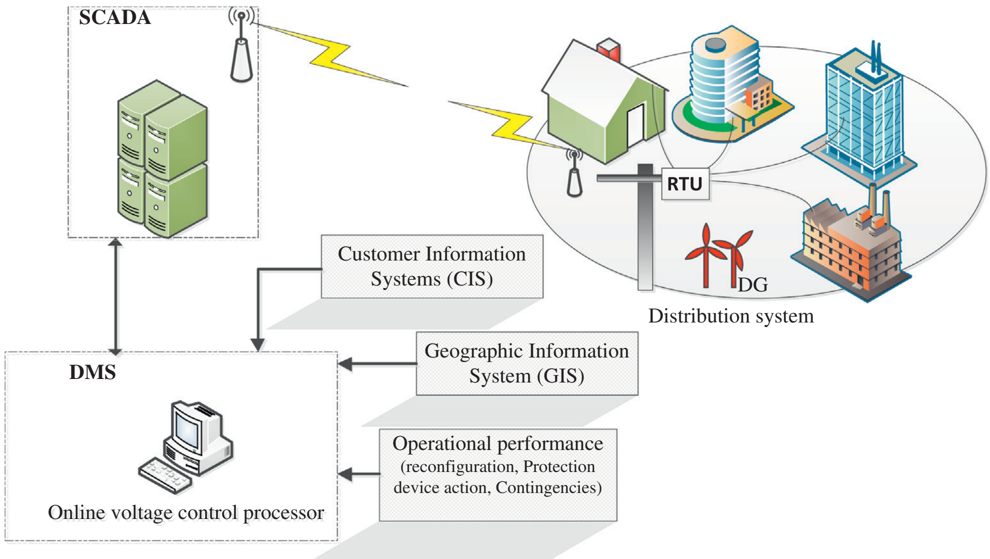

Fig. 2. DMS, SCADA and RTU configuration.

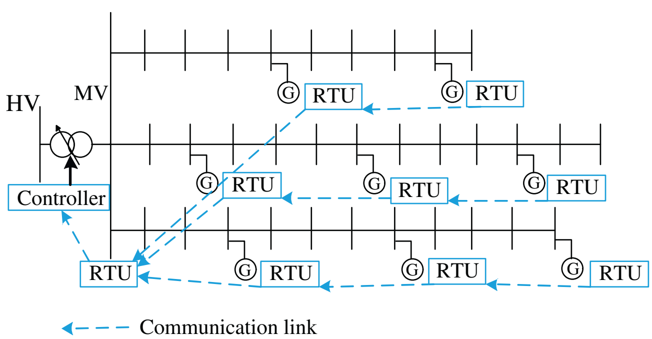

Fig. 3. The structure and position of equipments in the proposed approach.

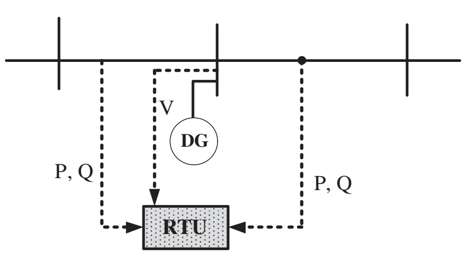

Fig. 4. Details of RTU measurements.

imum voltages of the network. In order to regulate the voltages at all buses within acceptable ranges, the difference between the maximum and minimum voltages along the feeders should be less than the difference between the permissible range defined by the maximum and minimum voltages of the network. However, it is assumed that the tap changer is able to keep the secondary voltage of the main transformer within the acceptable range. This constraint is given as follows [10,22]:

$$V_{max.feeders} - V_{min.feeders} \leqslant V_{max.perm} - V_{min.perm} \tag{7}$$

$V_{max,feeders}$ and $V_{min,feeders}$ are the absolute maximum and minimum voltages considering all the feeders, respectively. $V_{max,perm}$ and $V_{min,perm}$ are the permitted maximum and minimum voltages of the system.

If Eq. (7) is satisfied, the tap condition of the transformer is calculated as follows [23]:

$$Tap = Tap_0 + \left[\frac{\left(1 + \frac{V_{max.feeders} - V_{min.feeders}}{2}\right) - V_{max.feeders}}{Tapr} \right] \tag{8}$$

where Tap_0 and $Tapr$ are the tap position of the voltage regulator before regulation and the step of the voltage regulator, respectively.

3.4. Effect of demand response on distribution network voltage

The distribution system planners generally design electrical networks in order to satisfy the previously given constraint (7) in a normal condition. However, in an emergency condition, such as outage of some DGs or of protection system, this constraint may not be satisfied by changing the transformer tap changer. The voltages at some buses may, consequently, leave the permissible range and in this condition, the use of demand curtailment option may represent a possible solution. If customers involved in a demand response program are able to alter their loads consumption as requested, the DSO can bring the voltages of critical nodes in their permissible range. More details on the implementation of demand response programs in distribution system operation as well as in energy and ancillary service scheduling have been discussed in [24,25]. The effect of load curtailment on distribution feeders' voltage profile is described in the following:

Let us consider ΔP and ΔQ as the variations of the active and reactive demand at bus 2. When considering the test systems shown in Fig. 6, the variation of the voltage at bus 2, while the voltage value at bus 1 is kept constant is calculated as follows:

$$\Delta V_2 = (R + jX)\left(\frac{\Delta P - j\Delta Q}{V_2^*}\right) \tag{9}$$

$$\Delta V_2 = \frac{(R\Delta P + X\Delta Q) + j(X\Delta P - R\Delta Q)}{V_2^*} \tag{10}$$

As the imaginary part of voltage drop is small, it can be neglected. Therefore, the voltage drop (in per unit) related to the active and reactive power flows between bus 1 and 2 is written as follows:

$$\Delta V_2 = R\Delta P + X\Delta Q \tag{11}$$

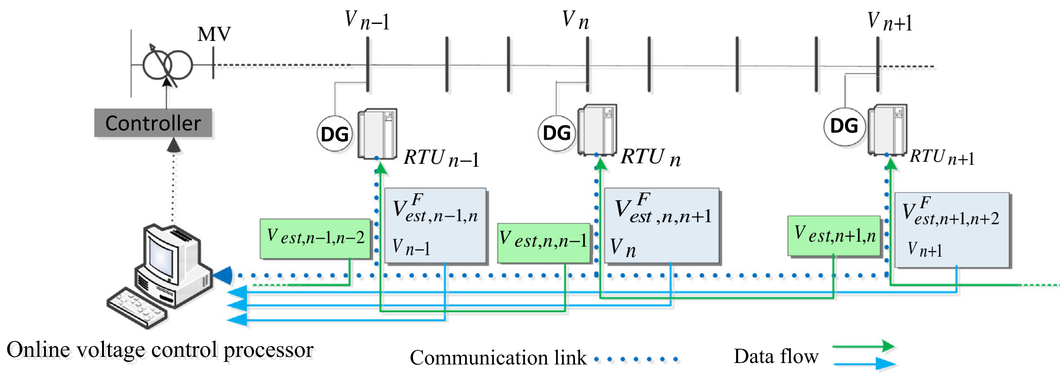

Fig. 5. The data flow of RTUs.

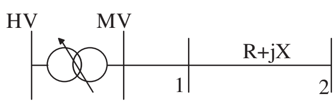

Fig. 6. A two bus test system.

Let now consider the typical distribution feeder shown in Fig. 7, and assume that the minimum and maximum voltages occur at the end bus and at the DG bus, respectively. In this condition, the load curtailment leads to an increase of the voltage at the bus with the minimum voltage level. On the other hand, the voltage value at the bus with the maximum voltage (where DG is installed) also increases; in this case, the difference between maximum and minimum voltages may increase. Let assume, for example, that the maximum and minimum voltages are obtained at the buses 3 and 5, respectively. In this case, if a load curtailment at bus 4 is implemented, it may cause that the increase of voltage at bus 5 is larger than the increase of voltage at bus 3. So, the difference between maximum and minimum voltages values increases.

Therefore, the difference between maximum and minimum voltages depends on what loads participate in the demand response program in order to regulate the voltage. In order to analyze this issue, let assume that when the loads curtailment occurs, only the active power of load demand reduces and the reactive power demand is unchanged.

Let, now, define the vector T_P as follows:

$$T_P = [R_1, R_2, R_3, \ldots, R_n] \tag{12}$$

where n is the number of consumers that participate in the demand response program. Each element of this matrix is written as follows:

$$R_i = R_i^{max} - R_i^{min} \tag{13}$$

The calculation method of R_i^{min} and R_i^{max} is described in the following examples considering the typical distribution feeder shown in Fig. 7.

Let assume that the minimum and maximum voltages occur at the end bus and DG bus, respectively, and the load located at bus 4 is willing to participate in a demand response program; a load curtailment of ΔP leads to the increase of both maximum and minimum voltages. The voltage increase at the bus with the maximum voltage (ΔV_{max}) is defined as follows:

$$\Delta V_{max} = (r_1 + r_2 + r_3 + r_4)\Delta P \tag{14}$$

where r_i is the line resistance located between buses i and $i-1$. Let define:

$$R_4^{max} = r_1 + r_2 + r_3 + r_4 \tag{15}$$

The voltage increase at the bus with the minimum voltage (ΔV_{min}) due to the load curtailment of ΔP is calculated as follows:

$$\Delta V_{min} = (r_1 + r_2 + r_3 + r_4)\Delta P \tag{16}$$

Therefore

$$R_3^{min} = r_1 + r_2 + r_3 + r_4 \tag{17}$$

As the values of R_4^{max} and R_4^{min} are equal, R_4 is zero. It means that the load reduction at bus 4 has no effect on the difference between minimum and maximum voltages.

Now, let assume that the load at bus 7 also participates in the demand response program. A load curtailment of ΔP leads to the increase of both the maximum and minimum voltages. The voltage increase at the bus with the maximum voltage is calculated as follows:

$$\Delta V_{max} = (r_1 + r_2 + r_3 + r_4 + r_5)\Delta P \tag{18}$$

Hence,

$$R_7^{max} = r_1 + r_2 + r_3 + r_4 + r_5 \tag{19}$$

The voltage increase at the bus with the minimum voltage due to the load curtailment ΔP, is calculated as follows:

$$\Delta V_{min} = (r_1 + r_2 + r_3 + r_4 + r_5 + r_6 + r_7)\Delta P \tag{20}$$

Therefore,

$$R_7^{min} = r_1 + r_2 + r_3 + r_4 + r_5 + r_6 + r_7 \tag{21}$$

The value of R_7 is calculated as follows:

$$R_7 = R_7^{min} - R_7^{max} = r_6 + r_7 \tag{22}$$

Also the reactive power reduction in the demand response program can be considered. Eqs. (20)–(24) show the case in which the load at bus 7 curtails its reactive demand of ΔQ. The values of the voltage increases at the bus with the maximum and minimum voltages are calculated as follows:

$$\Delta V_{max} = (x_1 + x_2 + x_3 + x_4 + x_5)\Delta Q \tag{23}$$

$$X_7^{max} = x_1 + x_2 + x_3 + x_4 + x_5 \tag{24}$$

$$\Delta V_{min} = (x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7)\Delta Q \tag{25}$$

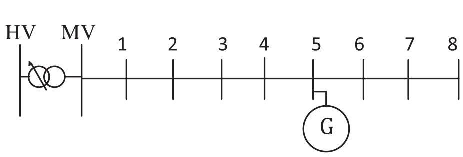

Fig. 7. A typical distribution feeder.

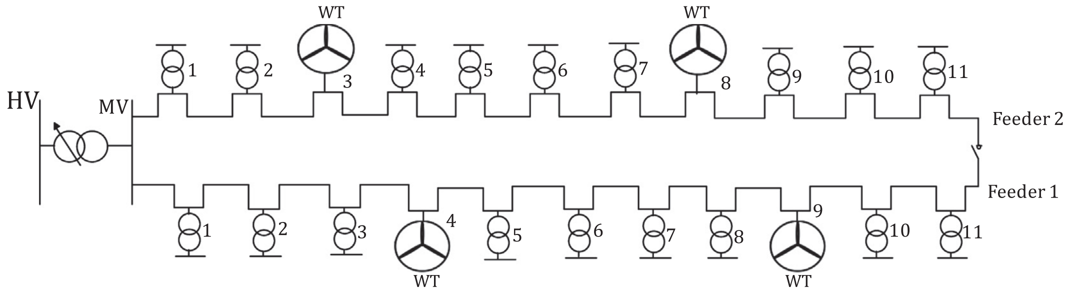

Fig. 8. Typical distribution test system.

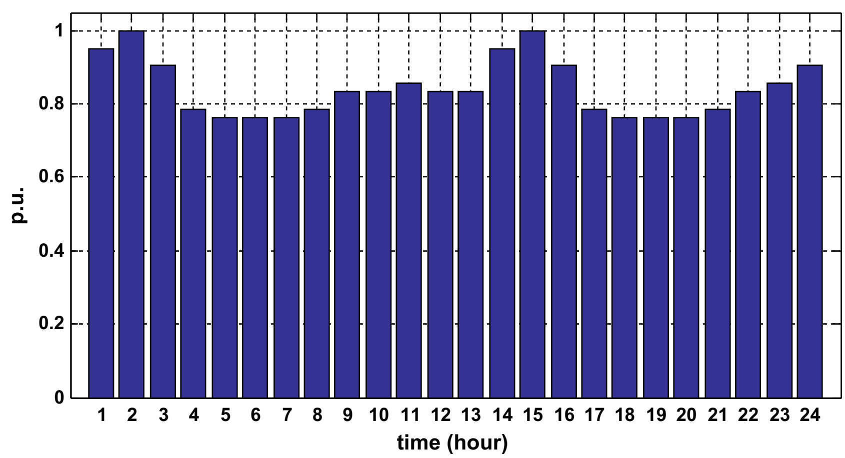

Fig. 9. Wind turbines power output.

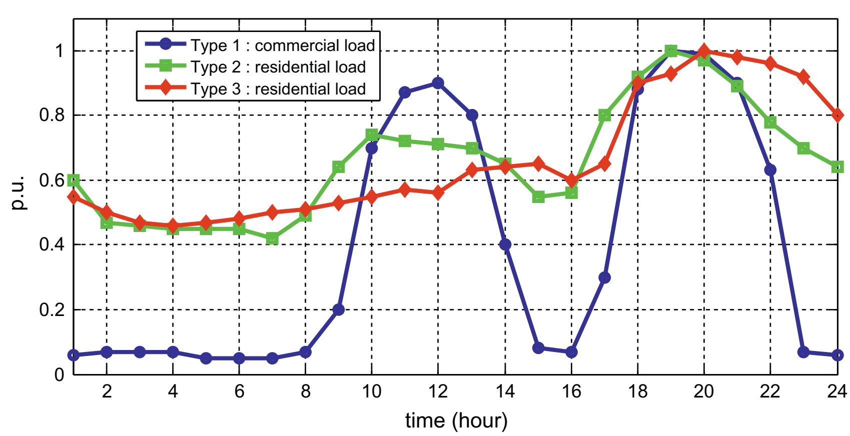

Fig. 10. Considered load profile the 24 h.

$$X_7^{min} = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 \quad (26)$$

where x_i is the line reactance located between buses i and $i-1$.

The value of X_7 is calculated as follows:

$$X_7 = X_7^{min} - X_7^{max} = x_6 + x_7 \quad (27)$$

As a consequence, with a load curtailment at bus 7, the difference $V_{max,feeders} - V_{min,feeders}$ decreases by:

$$[(R_7 \times \Delta P) + (X_7 \times \Delta Q)] \quad (28)$$

After calculating the values of R_n and X_n for bus n, where the possible load demand curtailment is available as a demand response option, these parameters are placed in the vector T_P and in the vector T_q, respectively. Using T_P and T_q, a matrix named the load curtailment sensitivity matrix can be built. This matrix is useful for carrying out a sensitivity analysis of load curtailment effects on the voltage profile of a distribution network.

3.5. Tap changer and demand response coordination

As a result of the previous considerations, for all consumers participating in a demand response program, the value of R and X should be calculated in order to define vectors T_P and T_q. In an emergency condition $V_{max,feeders} - V_{min,feeders} \geqslant V_{max,perm} - V_{min,perm}$

Table 1
The load characteristics in each feeder.

Feeder 1				Feeder 2			
Bus number	Maximum active power (kW)	Type of customer	Power factor	Bus number	Maximum active power (kW)	Type of customer	Power factor
1	286	1	0.8	1	330	2	0.85
2	440	3	0.9	2	440	1	0.8
3	605	2	0.85	4	770	1	0.8
5	660	2	0.85	5	880	3	0.9
6	825	1	0.8	6	605	2	0.85
7	495	3	0.9	7	385	2	0.85
8	495	1	0.8	9	385	3	0.9
10	770	1	0.8	10	660	2	0.85
11	825	3	0.9	11	550	1	0.8

Table 2
The load reduction offer at each bus.

Candidate buses-Feeder	Maximum time (h)	Load reduction offer	
		Active power (kW)	Reactive power (kVar)
5-1	4	120	74.4
6-1	2	95	71.2
7-1	2	110	53.3
8-1	3	80	60
10-1	3	130	95.5
11-1	3	140	67.8
2-2	1	100	75
4-2	2	80	60
9-2	4	120	58.2
11-2	3	110	82.5

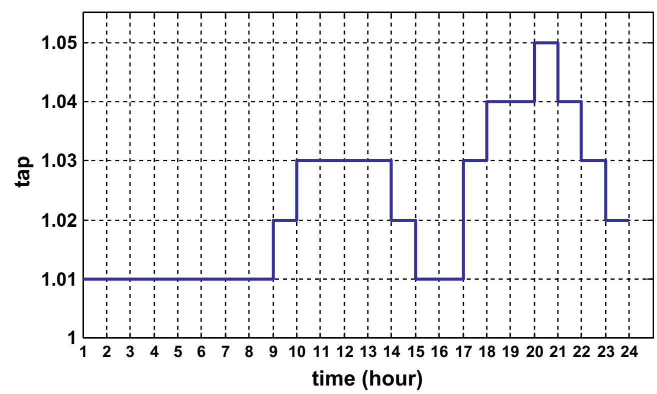

Fig. 12. Taps condition after voltage regulation.

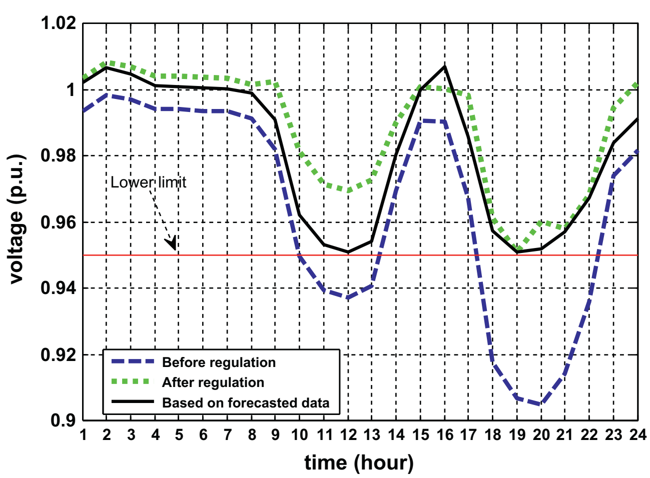

Fig. 11. Voltage profile of bus 11 of feeder 1 before and after regulation.

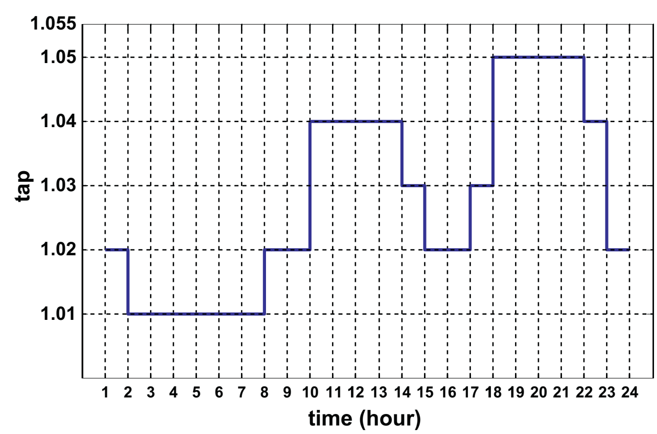

Fig. 13. Tap condition of transformer after regulation in scenario 2.

and the demand response program is called with the following procedure:

(1) The amount of the required voltage change is calculated as follows:

$$\Delta V_{required} = (V_{max,perm} - V_{min,perm}) - (V_{max,feeders} - V_{min,feeders}) \tag{29}$$

(2) A load reduction signal is sent to the bus having the largest value in T_P and T_q.
(3) The value of $\Delta V_{required}$ is updated as follows:

$$\Delta V_{required} = \Delta V_{required} - [(T_{P,i} \times \Delta P_i) + (T_{q,i} \times \Delta Q_i)] \tag{30}$$

(4) The procedures goes to stage 2 until the value of $\Delta V_{required}$ becomes lower or equal to zero.
(5) Finally, the tap of the transformer is set based on Eq. (8) and the updated voltage value.

4. Case study

The proposed method was applied to a 22 bus 20-kV radial distribution test system shown in Fig. 8. The impedance of each line is considered $0.79 + 0.73i$ ohm. The voltage of network is 20 kV. The number of taps of HV/MV transformer tap changer is 10 and each tap ratio is 0.01 p.u. The default tap position that has been determined before real time operation is supposed to be set at 1 p.u.

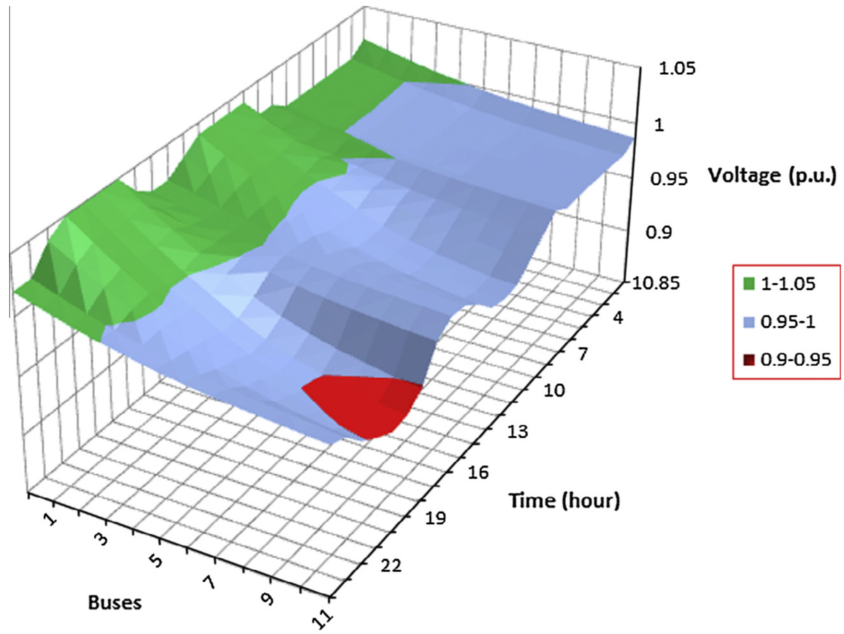

Fig. 14. Voltage profile of feeder 1 after voltage regulation in scenario 2 (without DR).

Table 3
Selected buses for load reduction.

Hours with violation in voltage range	Selected buses for load reduction (feeder 1)
18	11
19	7, 8, 10, 11
20	6, 7, 8, 10, 11
21	8,10

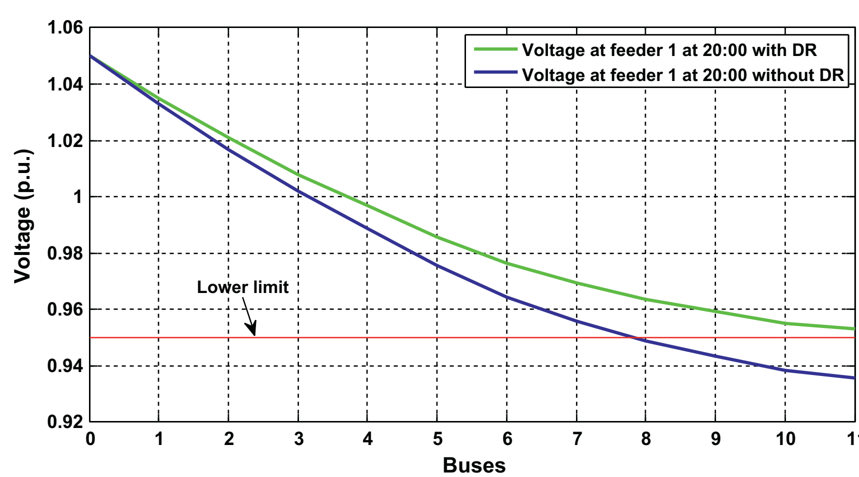

Fig. 15. Voltage profile of feeder 1 at 20:00.

An offline load flow, in which DG units are modeled as PQ buses and considered as negative loads, is used for generating real time data as in [26,27].

The proposed real-time voltage control model uses the real time data, the type of renewable generations has no effect on its performances. All types of renewable and conventional distribution generation units installed in the distribution system, as well as their combination, can be considered in the proposed model. However, for simplicity of analysis in this section, it is assumed that the test system contains four wind turbines installed at bus 4 of feeder 1 and bus 3 of feeder 2 with a capacity of 168 kW, at bus 8 of feeder 2 with a capacity of 630 kW, and at bus 9 of feeder 1 with a capacity of 1575 kW. The wind power variation for this area is shown in Fig. 9.

The load types of this test system are categorized as: one commercial and two residential load types with the profiles shown in Fig. 10.

The load consumption for each feeder, as well as the type of loads and their power factors are given in Table 1.

The list of loads that are willing to participate in the DR program by reducing the offer in related to their active and reactive power consumption is given in Table 2.

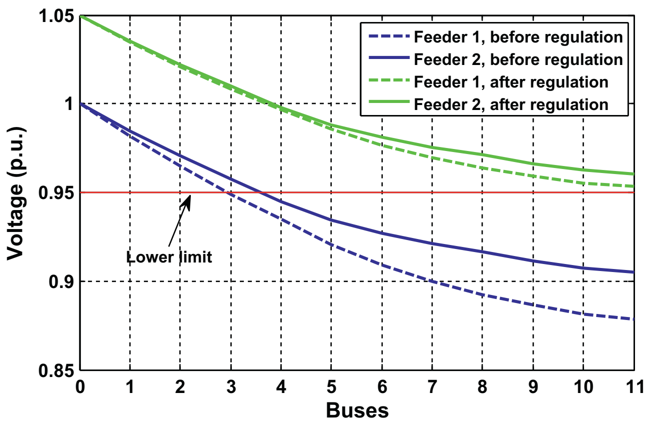

Fig. 16. Voltage profile at 20:00.

In this section, the proposed voltage control approach is applied considering two different scenarios. In order to show the effectiveness of proposed emergency voltage control model, two unpredictable events, such as wind power intermittency and DGs outage are considered to occur in real time.

4.1. Scenario 1: unpredictable wind and load fluctuations

In this scenario, it is supposed that wind generation and load consumption unexpectedly change from their forecasted values, mainly due to the intermittent nature of renewable generation and load demand. The voltage profile before and after the voltage regulation in this condition is shown in Fig. 11 for bus 11 of feeder 1, with the worst voltage profile among all other buses. As shown in Fig. 11, on the basis of forecasted values of wind power and load demand, the voltage profile of bus 11 of feeder 1 is within its permissible range.

Due to unpredictable variations of wind power and load demand and, without any corrective action for voltage regulation, the voltage should drop below the permissible value during peak hours. After the voltage regulation, carried out by using the tap changer, the voltage brings to its permissible range during all the day. So, in this scenario, the voltage regulation is carried out only by setting the tap changer and, therefore, it is not required to use the load reduction. In the proposed voltage control model, it is, in fact, assumed that the first corrective action for voltage regulation is carried out by the tap changer. If it is able to bring the voltage back to its permissible range, the emergency demand response program is not used.

The tap changer condition in this scenario after applying voltage regulation is shown in Fig. 12. The tap levels increase during peak hours in order to compensate the voltage drop.

4.2. Scenario 2: wind turbine outage

Let, now, consider that a contingency, deeply affecting the voltage profile, occurs in a distribution system. This is an emergency state in the distribution system operation. In this scenario, it is supposed that the wind turbine located at bus 9 of feeder 1 suddenly fails. As a result, the voltage on feeder 1 will experience a severe voltage drop. At first, the tap changer program sets the taps conditions which are shown in Fig. 13. The voltage profile at all nodes is illustrated in Fig. 14. In spite of the fact that the tap changer reacts to this contingency in order to bring back the voltage levels within the permissible range, during the hours from 18 to 21 the voltage drop at some buses is below 0.95 p.u. During these hours the tap of the transformer is located at its higher level, nonetheless the system experiences unacceptable voltage levels at some buses.

Therefore, the proposed emergency voltage control model is used in this scenario. Based on the proposed method, the selected buses for load reduction are shown in Table 3.

Although the load reduction at bus 11 of feeder 1 has the higher effect on voltage profile, at hour 21:00 this bus is not selected for load reduction as the maximum offered load reduction duration is 3 h at bus 11 of feeder 1, and this reduction has been already scheduled at its maximum duration.

The voltage profile on feeder 1 before and after voltage regulation considering the only tap changer action is shown in Fig. 15. As shown in this figure, the tap changing could not control the voltage drop so that voltages are inside their permissible range without using DR. In other words, the voltage regulation carried out by using only the tap-changer as voltage regulator device is not able to compensate the voltage drop at all buses.

The voltage profile of feeder 1 at hour 20:00 before and after applying the voltage regulation using both the tap changer and the load reduction is shown in Fig. 16. As expected, when the wind turbine failure occurs, the minimum voltages on feeders 1 and 2 drop below 0.95 p.u. and this is not acceptable. So, the proposed control acts in order to regulate the voltage in this emergency condition. Firstly, the tap changer reacts to this state and brings the

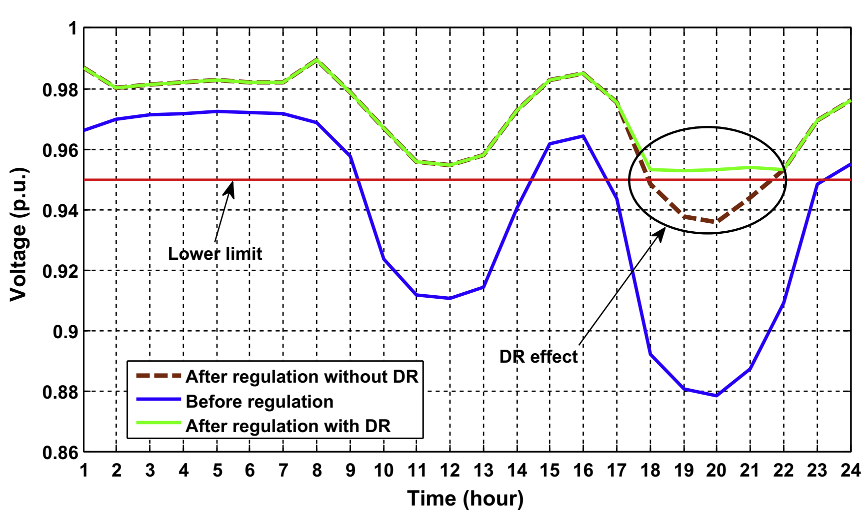

Fig. 17. Voltage profile on bus 11 of feeder 1.

voltage back to the permissible range at most buses. Although the tap level is located at its maximum level during peak hours, there is still a problem with regards to the voltage drop at some buses. After that, according to the proposed control method, some buses are selected in order to curtail their load demands. For example, at hour 20:00, the load demands at buses 6, 7, 8, 10, and 11 on feeder 1 are selected in order to reduce their load consumption.

In Fig. 17, the voltage profile at bus 11 of feeder 1 before and after the voltage regulation in the emergency condition is shown. Without the DR program, the voltage leaves the permissible range during hours 18–21. After the load curtailment at some selected buses, the voltage brings back to its permissible range.

5. Conclusion

This paper analytically proves that the load curtailments according to a demand response program in a distribution network can change the distribution feeders' voltage profile. The proposed real time voltage control algorithm uses demand side participation in order to maintain distribution nodes' voltage within permissible range in emergency conditions. Load curtailment sensitivity matrices have been also developed in order to effects of each load variation on the feeders' voltage. The results showed that applying load reductions on the basis of the proposed method allows reducing voltage drops across the distribution feeders, and causing a boost in the voltage at the far end of the feeders. Also, the robust integration of demand response into conventional voltage control methods allows maintaining smooth voltage profile of the distribution system.

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