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Selecting Candidate Buses in Distribution Grids for Distributed Voltage Control Considering End Users

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Abstract

According to the latest developments in smart grid infrastructures of today's modern networks, in this paper, end-consumers are presented as a means for participating in distribution networks voltage control. In this regard, for reactive power control of the smart grids, a new algorithm for selecting candidate buses for injecting reactive power in distributed voltage control approach is proposed. In the distributed voltage control approach, at first, ε-decomposition technique is adopted to calculate sensitivities of bus voltage to the injected reactive power. Therefore, buses with strong voltage relation are considered as a region which divides the network to some voltage related regions. Afterwards, candidate buses for reactive power injection for each one of the achieved region are identified by use of the proposed algorthim. It is noted that, candidate buses of the network are those with reasonably better response to the reactive power injection. Finally, genetic algorithm is applied to obtain optimal reactive power injection of each region. For better evaluation of the proposed selecting candidate buse algorithm, the IEEE 33-bus test system which is commonly used in literature is applied here. Simulation results clearly illustrate the effectiveness of proposed algorithm in improving voltage profile of distribution networks.

Keywords: Candidate buses for reactive power injection, distributed reactive power control, ε-decomposition, end-consumers, smart distribution grids.

Introduction

Control of reactive power and voltage to meet some goals such as maintaining voltage in permissible limit, reducing losses, and more suitably utilizing transmission grids is an essential approach in the utilization of conventional power systems and also intelligent distribution grids [1]. The problem of maintaining voltage in the required limit is important considering that the power system feeds abundant loads and is fed through many generator units. Due to the inefficient transmission of reactive power at long distances, voltage should be controlled by special devices which have been installed and expanded along the system. Selection and coordination of equipment for controlling reactive power and voltage are among main challenges for engineers and researchers of power systems [1].

Today, new issues have been created for dealing with the problems of voltage and reactive power control considering the emergence and expansion of smart grid infrastructures which make the use of capacities in distribution grids more desirable. In [2], idea of using end users has been mentioned in the issue of reactive power control. According to the issues mentioned in this reference, end users can be equipped with power factor control (PFC) which is

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currently used by many end users. The example of these users are Plug-in Hybrid Electric Vehicles (PHEVs), television, refrigerator, and computer which can be able to inject or absorb reactive power by changing the control mode of these devices. On this basis, a suitable controllable power factor corrective control model was proposed in [2].

By mentioning end consumers as one form of reactive power support, a new voltage control method was proposed in [3] and [4], which studied this concept in transmission grids. These papers introduced a control structure which can be applied for controlling reactive power of end users. Structure of the proposed intelligent control was based on incident command system (ICS) which is used for commanding, coordinating, and controlling emergency responses. The point which has not been considered in these papers was distribution grid and problem of voltage control in these grids. Further, candidate buses were selected in order to only see the effect of transmission grid and nature of end users was not found. [5] followed [3] and introduced the use of multi-agent structure as a suitable bed for the execution of incident command system. In this system, feeder relays are the centers which manage control information and activities in the desired control layers. This paper also studied the modeling of distribution grid, but did not investigate how to obtain the candidate buses and also used the central control model which required high telecommunication infrastructures.. This issue caused the presented model not to have good efficiency in smart grids.

[6] presented an algorithm for controlling optimal voltage of the secondary distribution grid and, according to the discussion in this paper, consideration of all buses in large systems caused heavy computational load and was nonoperational. For this reason, optimal distributed voltage control was presented considering distributed generation sources. This article only studied distributed generation sources as a tool for voltage control and did not investigate reactive power control sources in end users. In [7], a model based on the sensitivity of voltage and use of distributed generation sources was presented to control voltage in smart grids. Reactive power control devices in this paper were distributed generation sources and reactive power resources in end users were not discussed.

In this paper, the candidate buses for injecting reactive power in the distributed voltage control were selected using a new criterion. Considering the models presented in the papers and based on the studies by writers of this paper, such a method has not been presented to select candidate buses for the injection of reactive power in the distributed voltage control in smart distribution grids which can also concurrently model the participation of end users.

In rest of the paper, in Section 2, modeling of the problem, calculation of sensitivity matrix and power flow method, and identification of candidate buses are discussed.

In Section 3, distributed control method, objective functions of the problem, and its related constraints are explained. In Section 4, simulation and results are studied. Finally, general results of executing the proposed method on the sample test system are mentioned and analyzed in Section 5.

Problem modeling

For distributed voltage control in distribution grids, candidate buses for the injection of reactive power should be determined using sensitivity matrix and power flow of distribution grids. The grid is decomposed into some control areas with a suitable method and finally optimal values of reactive power injection of candidate buses are specified using genetic algorithm. Due to high R/X rate in distribution grids than transmission lines, traditional power flow methods such as Newton-Raphson which is suitable for transmission systems cannot be applied in distribution system; thus, the methods which are based on characteristics of distribution grid should be used for calculating power flow and sensitivity matrix.

Sensitivity matrix and power flow in distribution grids

Sensitivities as linearized relationships are often employed to show the impact of a small change of a variable on the rest of the system. In this paper, For calculating various sensitivity indices, it is needed to use a highly sparse Jacobian matrix associated with the power-flow equations and also the Newton–Raphson (NR) method for the load-flow solution [8], [9]. Moreover, the relatively high R/X ratio of the distribution system, as compared to the transmission system, makes the NR method unsuitable for solving the load flow of the distribution systems. Besides, the NR method sometimes fails to converge in solving the load-flow problem [10], [11]. In this regard, other sensitivity and load flow calculations suitable for distribution systems studies are needed. Here, we use load flow method described in [12], [13] and a sensitivity calculation described in [14] as good methods that support voltage constant DGs.

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Obtaining candidate buses

By knowing how to calculate the voltage sensitivity matrix to inject reactive power into different buses, candidate buses were determined. To obtain candidate buses, the buses which have more effect on the objective function than others should be specified.

The objective function studied in this paper was voltage difference from the reference value:

$$f = \sum_{i=1}^{N_b}\left[V_i - V_{spec}\right]^2 = \sum_{i=1}^{N_b}\left[\eta_i\right]^2 \qquad (1)$$

where

$$\eta_i = V_i - V_{spec} \qquad (2)$$

The said objective function satisfies the main goal of voltage control; but, it should be noted that this voltage control is provided by the injected reactive powers of the candidate buses; therefore, values of the injected reactive power should be minimized in all buses as far as possible so that the proposed design can be desirable and practicable. On this basis, the term which shows changes of reactive power in all candidate buses are added to the objective function and equation (1) is corrected as in (3).

$$g = \min\left(\sum_{i=1}^{N_b}\left[V_i - V_{spec}\right] + \alpha\sum_{j=1}^{M}\left|\Delta Q_j\right|\right) \qquad (3)$$

In this relation, $\left|\Delta Q_j\right|$ is net changes of reactive power of bus, j, M is the number of candidate buses, and α *is* penalty factor for changes of reactive power. It should be noted that control variables are the injected reactive power in the candidate buses to optimize the said objective function. Derivative of the objective function *g* relative to voltage of different buses can be selected as a criterion for determining candidate buses.

$$\nabla f = \left|2\eta\Lambda_{VQ}\right| \qquad (4)$$

However, this criterion cannot cover real conditions alone, because a bus may have high sensitivity, but have low reactive power for injection into the grid in the case of utilization. For this reason, one should consider a criterion which consider accessible reactive power in determination of candidate buses. Thus, load grouping is introduced.

Load grouping

Load grouping is the factor which has a high effect on selecting candidate buses as the injection buses of reactive power. Electric loads can be divided into some groups in terms of ability to participate in the injection of reactive power. Grouping method is based on the control structure of the electronic devices applied in end users and accessible reactive power. Structure of the applied electronic devices determines the participation of load's reactive power in terms of the control system. In this paper, only reactive power criterion was used for grouping due to the inaccessibility of the information relating to controllability of the devices used in end users.

To obtain accessible reactive power, it should be mentioned that when an electrical load is connected to the grid which can be practically regarded equal to the concept of the Participation Factor (PF). Considering the technologies in power electronic devices in the new generation of electric loads, the electrical load can be injected into reactive power grid in the off mode [15], [16]. It should be mentioned that accessibility of reactive power in the *off* mode of the electrical load is more than that in the *on* mode; i.e. an end user can give more capacity to the grid in the *off* mode, because no capacity of the electronic devices has been occupied by the active power but some capacity of them is occupied by the active power in the case the user is on and the remaining is occupied by the reactive power. Considering the mentioned facts, Equation (5) can be obtained as average reactive power Q^{avg} delivered to network:

$$Q^{avg}(i) = P_{on,i} \times Q_{on,i}^{accessable} + (1 - P_{on,i}) \times Q_{off,i}^{accessable} \qquad (5)$$

where

P_{on}: participation factor

Q_{on}: accessible reactive power in case the unit is on

Q_{off}: accessible reactive power in case the unit is off

Considering grouping of loads, selection of candidate buses is affected by another factor in addition to sensitivity factor. Considering average reactive power obtained in the previous section, Equation (6) is obtained:

$$\nabla f = \left|2\eta\Lambda_{VQ} \times Q^{avg}(i)\right| \qquad (6)$$

The buses with higher sensitivity have better control on the voltage profile; but, those with zero sensitivity have no effect on the voltage profile. By recognizing buses with the highest sensitivity on objective function, candidate buses are obtained. Flowchart of obtaining the initial conditions for calculating sensitivity matrix and selecting candidate

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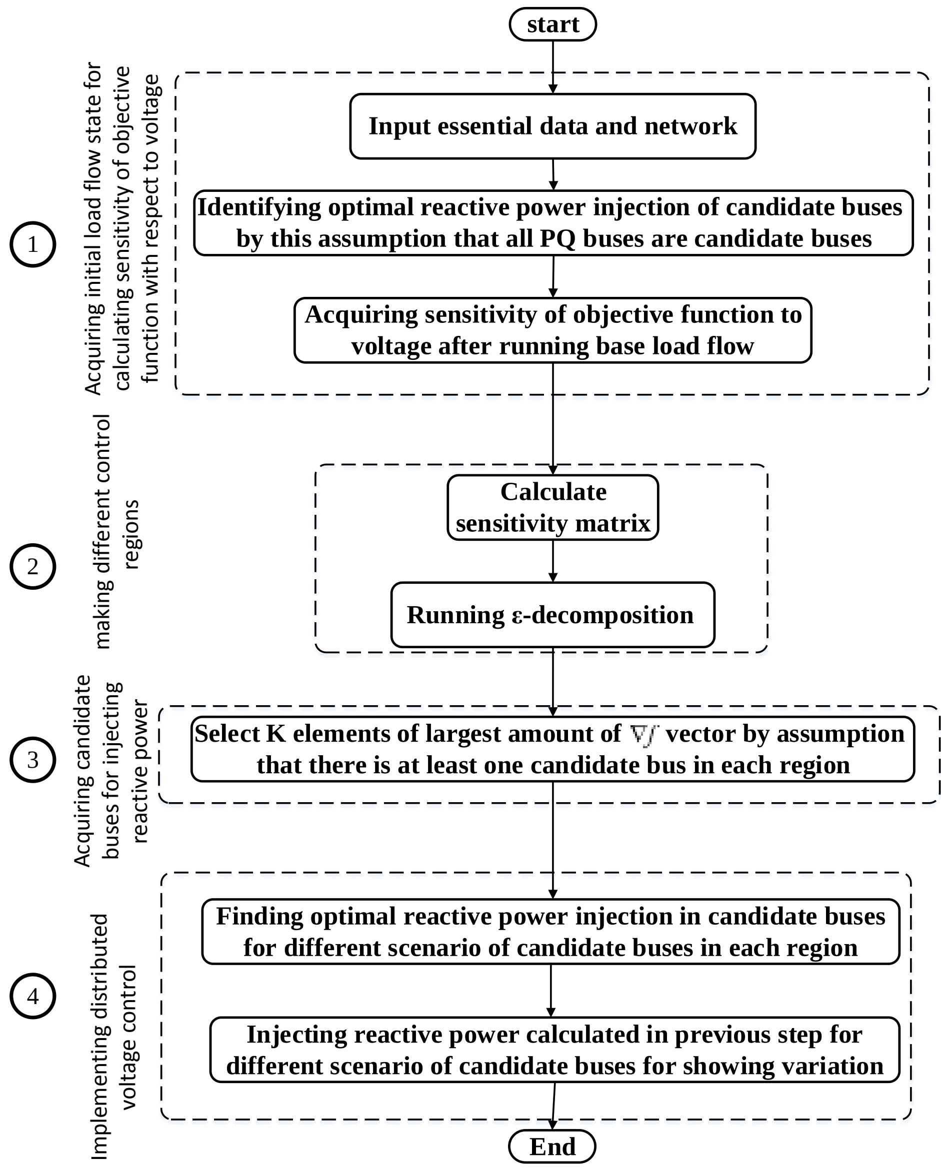

Figure 1. Proposed algorithm for selecting candidate buses and implementing distributed voltage control.

buses for reactive power injection are presented in section 1 and 2 of Figure 1. According to the algorithm in section 1 of Figure 1, by the assumption that all load buses are candidate buse, optimal injection of buses is obtained for the improvement of the objective functions using genetic algorithm. Then, sensitivity matrix and equation (6) are obtained by using optimal value of reactive power injection in each bus. After calculating ∇f , according to section 3 of Figure 1, the number of k element is selected from its highest values as candidate buses.

ε-decomposition

To decompose a grid into control areas, a method should be used for decomposition of the network. In this paper, ε-decomposition method was used as an efficient method for decomposition of the grid into control areas [6, 17].

$$\Lambda_{VQ} = \Lambda'_{VQ} + \varepsilon R \tag{7}$$

In this equation, Λ'_{VQ} is a sensitivity matrix with larger elements than ε value which means strong dependencies in the network. The term εR is the remaining matrix which means weak dependencies in

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the network. All elements of the matrix R are smaller than or equal to 1. Now, structure of the areas created by ε-decomposition can be obtained through Λ'_{VQ} matrix. After decomposing the gird to the separate areas, there may be buses which are not located in any area. Coverage limit of these areas is changeable by making ε amount small and large.

Since ε-decomposition divides the system into smaller independent areas; the required telecommunication system in the grid is also divided into some subsystems. Division of the telecommunication system into some subsystems considerably reduces the required telecommunication system and converts the distributed control method as an applicable method.

Distributed voltage control

After determining the candidate buses, modeling of the distributed voltage control problem was studied. Due to inefficiency of the central control in smart grids and that it is not economically justifiable to cover all buses, the distributed control is regarded as an option which has lower communication infrastructure than the central control. For distributed control of voltage in a grid, the grid should be divided into some areas [6]. For this reason in this paper, the grid was first divided into some areas with the ε-decomposition of sensitivity matrix. Optimal values of the injected reactive power were calculated with candidate buses.

The objective function and constraints of optimization problem are as given in equation (8)-(10):

$$Objective = \min\left(\sum_{i=1}^{N_b}\left[V_i - V_{spec}\right] + \alpha\sum_{j=1}^{M}\left[\Delta Q_j\right]\right) \quad (8)$$

$$V_l < V_i < V_{up},\ i = 1,\dots,N_{sub-network} \quad (9)$$

$$\Delta Q_j < Q_j^{accessable},\ j = 1,\dots,M \quad (10)$$

In these equations, V_{up} and V_l are high and low permissible voltages, respectively, and $Q_j^{accessable}$ is the maximum injected reactive power. To calculate accessible reactive power value, a separate analysis should be done in a smart grid and within a definite time; also, relations between active, reactive power, and capacity of the available converters should be obtained. Considering that these evaluations are beyond the framework of this paper, accessible reactive power is assumed equal to average reactive power.

Simulation and presentation of results on

In this Section, the mentioned method is executed on the IEEE 33-bus test system to simulate the distributed control and evaluate the proposed method for the selection of the candidate buses. The data relating to this grid were extracted from [18] and [19]. In decomposition of the areas, ε value was assumed equal to 0.00005 and the distributed voltage control was studied with two scenarios for selection of candidate buses:

- First scenario: Selecting the candidate buses considering average reactive power
- Second scenario: Selecting the candidate buses without considering average reactive power

To study the effect of increasing the number of candidate buses, three candidate buses 5, 12, and 20 were considered.

In this section of the paper, because performance of the study is considered on a typical test grid and due to lack of real information such as participation factors and accessible reactive power in the case the end users are off and on, accessible average reactive power is assumed and is available in the Appendix Section. It is evident that the related real information can be used wihout any limitation for the use of the model presented in the real systems.

The created areas are shown in Figure 2 with ε-decomposition. As shown in Figure 2, two areas are obtained based on ε-decomposition. With flowchart described in Figure 1, injecting reactive power of the candidate buses is obtained in both scenarios and the results are given in Table 2. To execute distributed control and calculate optimal values of reactive power injection of candidate buses, genetic algorithms [20] is used. Parameters of the genetic algorithm are given in Table 1.

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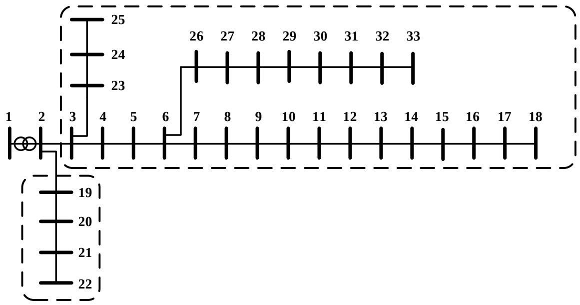

Figure 2. State of the grid in decomposition with ε - value of 0.00005

Table 1. genetic algorithm parameters

Generation	Population	Crossover	Mutation	Reproduction	Shift
200	100	0.1	0.7	0.1	0.1

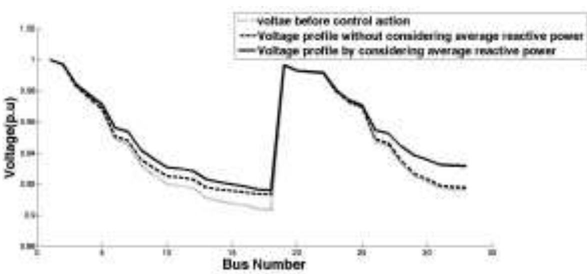

Figure 3. Voltage value before and after distributed voltage control with 5 candidate buses in two scenarios

As shown in Figure 3, the voltage profile considerably improved by executing the distributed control and this improvement was made in the buses which had low voltage. For this reason, reactive power injection was almost done in the candidate buses which improved the voltage of these buses. As shown above, adding average reactive power index in the candidate bus selection criterion caused better voltage control. Figure 4 shows improvement of voltage with 12 candidate buses. Also, addition of average reactive power index caused the voltage profile in scenario 1 in some buses to be less than the voltage profile in scenario 2; however, generally, improvement of voltage in scenario 1 was better. Figure 5 shows improvement of voltage profile with 20 candidate buses; improvement of voltage in scenario 1 was better than that in scenario 2; but, this difference was very slight and the voltage profile almost overlapped each other in both scenarios in most buses.

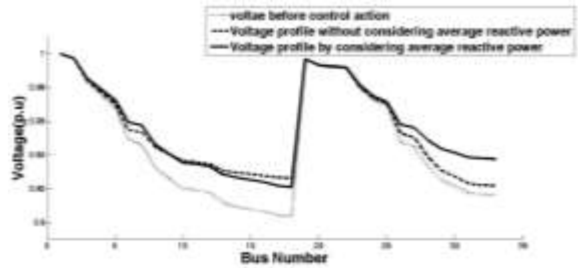

Figure 4. Voltage value before and after distributed voltage control with 12 candidate buses in two mentioned scenarios

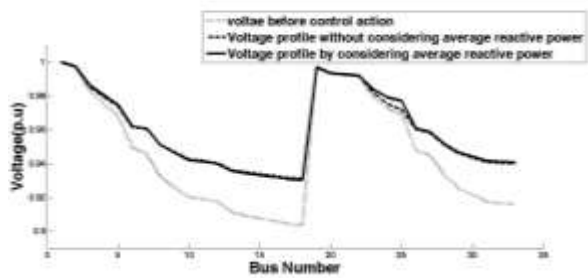

Figure 5. Voltage value before and after distributed voltage control with 20 candidate buses in two mentioned scenarios

Table 2. Candidate buses

Candidate buses by considering average reactive power										
5 bus	**30**	**14**	**32**	**8**	**22**	-	-	-	-	-
12 bus	**7**	**8**	**13**	**14**	**16**	**17**	**18**	**22**	**29**	**30**
	31	**32**	-	-	-	-	-	-	-	-
20 bus	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
	17	**18**	**22**	**24**	**25**	**29**	**30**	**31**	**32**	**33**
Candidate buses without considering average reactive power										
5 bus	**18**	**17**	**16**	**15**	**22**	-	-	-	-	-
12 bus	**18**	**17**	**16**	**15**	**14**	**13**	**12**	**11**	**10**	**9**
	8	**22**	-	-	-	-	-	-	-	-

20 bus	18	17	16	15	14	13	12	11	10	9
	8	33	32	31	30	29	28	7	27	22

Conclusion

In this paper, a new method was proposed for selecting candidate buses in distributed voltage control problem with end users. Suitable locations were first specified for the injection of reactive power with power flow of the distribution grids and the proposed flowchart and then the grid was divided into some control areas with ε-decomposition. By executing the distributed control, optimal values of injected reactive power in candidate buses were obtained in each area. To execute the distributed control and calculate optimal values of reactive power injection of candidate buses, the distributed control was executed using genetic algorithm. The proposed method for selecting the candidate buses considerably improve the voltage profile and results showed that, when the number of the candidate buses increased, voltage improvement amount was reduced in the case of addition of average reactive power and the voltage profile overlapped each other by selecting 20 buses as candidate buses in two scenarios.

Appendix

Average reactive power in IEEE 33-bus test system

Bus Number	Average available reactive power (KVAr)	Bus Number	Average available reactive (KVAr) power
2	74.5	18	52.76
3	52.85	19	55.33
4	90.16	20	55.92
5	37.25	21	60.88
6	23.95	22	55.97
7	130.35	23	56.25
8	125.53	24	370.13
9	38.29	25	261.19
10	33.85	26	36.33
11	33.15	27	35.55
12	40.24	28	35.05
13	39.86	29	75.54
14	91.04	30	340.57
15	31.84	31	95.08
16	37.07	32	136.54
17	23.19	33	43.35

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