A New Decentralized Voltage Control Method of Smart Grid via Distributed Generations

Hossein Fallahzadeh -Abarghouei, Majid Nayeripour, Eberhard Waffenschmidt, and Saeed Hasanvand

***Abstract*—This paper proposes a new decentralized voltage control approach for distribution system in order to deal with the intermittent fluctuations of the renewable energy resources. In this regard a systematic partitioning method which splits distribution networks' graph is presented. Furthermore, an adaptive Particle Swarm Optimization (PSO) algorithm is used to solve the voltage regulation problem in order to optimize the reactive power of the Distributed Generations (DGs) in the related partition. The proposed method is evaluated on the well-known PG&E 69-bus distribution system and the results are compared with another method based on Interior Point Algorithm (IPA) in both decentralized and centralized manner. These results demonstrate the ability and efficiency of the proposed method for online voltage profile control of smart grids.**

***Index Terms*-- Decentralized control, distribution grid partitioning, optimal reactive power control, zonal voltage regulation.**

I. Introduction

Increasing penetration level of DGs changes the distribution networks' nature from passive to active. This change creates some problems such as voltage fluctuations in these networks; thus, considering how to deal with the negative impacts of DGs is essential. Conventional methods, manage voltage and reactive power of distribution grids by under load tap changers, step voltage regulators and static VAR compensators [1]. However, there are some problems due to the slow time constant as well as wear and tear of some compensators to act fast and reliable. So, new methods for efficient voltage and reactive power control is needed. Existing DGs interfaced with power inverters are appropriate resources for management of voltage and reactive power. There are two main methods in order to control these resources: local and coordinated control [2, 3]. The methods based on local control have high response time, but they are not optimum due to the local data utilization. Moreover, the lack of enough knowledge about other parts of the network may lead to decision mistakes [4]. The other methods which are based on coordinated control optimize the participation proportion of reactive power controllers in voltage management problem by a bidirectional communication infrastructure between Control Center (CC) and all these devices. Most of the previous coordination methods are based on centralized architecture in which one center supervises all network's operations [5, 6]. According to the increased number of DGs and consequently the controllable variables in a smart grid, the execution time required for optimization process and the amount of information which need to be processed will greatly increase in this architecture so that a majority of them cannot be implemented as online. Therefore, it is necessary to implement coordinated methods as decentralized ones. In this regard, some researches try to decompose original centralized optimization problem to some smaller sub-problems and solve them in a parallel manner; however, the disadvantage is that a special center for coordinating the slave centers is needed [2, 7]. Furthermore, such solutions suffer from high building costs and single point failure [8].

Based on presented literature, this paper proposes a decentralized solution which eliminates the mentioned demerits of decentralized methods for coordinated voltage regulation problem in power distribution systems. The proposed method improves the computational burden and response time for online operation by dividing the distribution network into some smaller partitions. One of the major challenges in the partitioning of a network is how to determine boundaries of each partition. As well as the voltage regulation problem, network partitioning has been used in other problems, such as self-healing and network restoration [9], prevention of cascading events [10], rotor angle stability [11] and etc. These problems are analyzed by different partitioning methods such as graph-based solution [10], Spectral-based solution [12, 13], electrical distance based solution, and etc.

The first contribution of this paper is proposing a pattern matrix for the partitioning stage with respect to the voltage regulation issue and then providing a systematic spectral-based approach for partitioning this matrix which can be used for systems with different dimensions. Also there is not any dependency on the number and location of DGs in each partition; therefore, the boundaries of each partition are robust. The second contribution is an adaptive solution based on the PSO algorithm for each partition which calculates the optimum reactive power set points of DGs in an acceptable time which is essential for online computation. In comparison to other centralized approaches, the advantage of this approach is to reduce the computational burden and to eliminate the need for all network's information.

H. Fallahzadeh-Abarghouei, and M. Nayeripour are with the Department of Electrical and Electronic Engineering, Shiraz University of Technology, Shiraz, Iran (e-mail: nayeri@sutech.ac.ir; hossein.fallahzadeh@sutech.ac.ir).

E. Waffenschmidt is with the Cologne University of Applied Sciences, Cologne 50679, Germany (eberhard.waffenschmidt@fh-koeln.de).

S. Hasanvand is with the Young Researchers and Elite Club, Khorramabad Branch, Islamic Azad University, Khorramabad, Iran (s.hasanvand@sutech.ac.ir).

The reminder of the paper is organized as follows: section II presents the partitioning approach and its algorithm. Section III describes proposed coordinated voltage regulation algorithm for each partition. Section IV demonstrates the simulation results on the well-known PG&E 69-bus distribution system. Finally, the conclusions are drawn in section V.

II. Network Partitioning

This section will seek the boundaries of smaller partitions of the original network in a way that each partition is composed of buses which are closely connected to each other from voltage regulation perspective. The spectral method which is a powerful network partitioning method can fulfill this purpose by suitable definition of a graph for the network.

A. Graph Theory

Considering N as a set of nodes of a graph and E as a set of weighted edges, G= (N, E) represents the graph which will be partitioned. In distribution networks where a unique number is allocated for each bus, by proper definition of G, N represents the same number of network buses and the weight of edge, $e=(v_i, v_j)$, represents the cost of putting the two buses in two separate partitions.

B. Pattern Matrix Derivation

Using the input data, graph partitioning algorithms provide the possibility of clustering objects in several separate groups. Indeed, input data reflect the similarity or the difference between objects that are mainly expressed as a matrix named pattern matrix [14]. Therefore, a key step in the partitioning problem is to find pattern matrix. According to the goal of voltage regulation problem, buses voltage variations specify this similarity or difference which is in correspondence with changes in their power consumption to each other; it is called the sensitivity matrix. Therefore, in order to partition a distribution network, at first this matrix must be calculated as follows:

The vector of buses voltage variations versus active and reactive power consumption could be rewritten as (1):

$$[\Delta V]=[S^{vp}][\Delta p]+[S^{vq}][\Delta q] \tag{1}$$

Where vectors $[\Delta V]$, $[\Delta p]$ and $[\Delta q]$ depict voltage variations, active and reactive power consumption of buses respectively. Furthermore, $[S^{vp}]$ and $[S^{vq}]$ are sensitivity matrices of voltage variations versus consumed active and reactive power variations, respectively. In distribution systems, it should be noted that the bus voltage angle is not important and the magnitude of voltage drop between the two adjacent buses can be approximately calculated in per unit according to the following equation [15]:

$$V_i - V_j = R_j \cdot P_j + X_j \cdot Q_j \tag{2}$$

Where V_i and V_j are the voltage magnitude of two adjacent buses *i* and *j*, respectively. R_j, X_j, P_j, and Q_j are resistance, reactance, active and reactive power flow of the line between these buses, respectively. Given that the first bus of the network with 0 index is a slack bus, V_i can be calculated by applying eq. (2) recursively in upstream line as follows:

$$V_i = V_0 - \sum_{j\in L_i}(R_j \cdot P_j + X_j \cdot Q_j) \tag{3}$$

where L_i is the set of connecting line section between bus *i* and the slack bus. In order to express the above equation in term of active and reactive power consumption, V_i can be state as eq. (4):

$$V_i = V_0 - \sum_{j=1}^{N}(R_j^{eq} \cdot p_j + X_j^{eq} \cdot q_j) \tag{4}$$

Where p_j and q_j (Notice for lower letter in comparison with P_j and Q_j) are active and reactive power consumption of bus j respectively. R_j^{eq} and X_j^{eq} are the equivalent resistance and reactance calculated from the common path connecting between bus *i* and *j* to the slack bus. In order to calculate $[R^{eq}]$ and $[X^{eq}]$ for a radial distribution system, the direct load flow approach presented in [16] can be used. This approach is based on the development of two matrices representing the relationship between the Bus Injection to Branch Current (BIBC) and Branch Current to Bus Voltage (BCBV). In this regard, these matrices can be obtained as follows:

$$\begin{aligned}[R^{eq}] &= real([BCBV]\cdot[BIBC]) = real([DLF]) \\ [X^{eq}] &= imag([BCBV]\cdot[BIBC]) = imag([DLF])\end{aligned} \tag{5}$$

According to eq. (4), the discussed $[S^{vp}]$ and $[S^{vq}]$ in eq. (1) will be equal to $[R^{eq}]$ and $[X^{eq}]$ so:

$$\begin{aligned}[S^{vp}] &= [R^{eq}] \\ [S^{vq}] &= [X^{eq}]\end{aligned} \tag{6}$$

Considering the sensitivity matrix as a pattern matrix, the partitioning algorithm is described in the next subsection.

C. Graph Partitioning Algorithm

In the graph theory, a weighted graph in which each edge has a capacity has many applications. According to (5) and (6), the proposed pattern matrix is a real symmetric matrix. The main tool for network partitioning is to calculate the spectrum of one of the matrices related to network graph such as normalized or unnormalized laplacian matrix, adjacent matrix, or other related pattern matrices of the network graph. Spectrum based partitioning methods present general information about the structure of a graph using eigenvalues and eigenvectors of graph matrices. It should be noted that real symmetric matrices have real eigenvalues [17]. By sorting these eigenvalues for proposed pattern matrix, the signs of the elements of the eigenvector associated to the second largest eigenvalue partition the network into two separate closed parts. After partitioning the network into two parts, this process is repeated again for the largest partition which has the most number of buses. According to the network dimensions as well as the number of buses, this procedure will be continued in each step for the largest partition until the number of partitions achieves to a desired one. The optimum number of partitions can be determined with respect to the maximum acceptable time required for online calculations in each partition.

D. Case Study

Fig. 1 shows the PG&E 69-bus distribution system [18]. After applying the proposed partitioning algorithm for determining the boundaries of each control partition the results are obtained and presented in TABLE I.

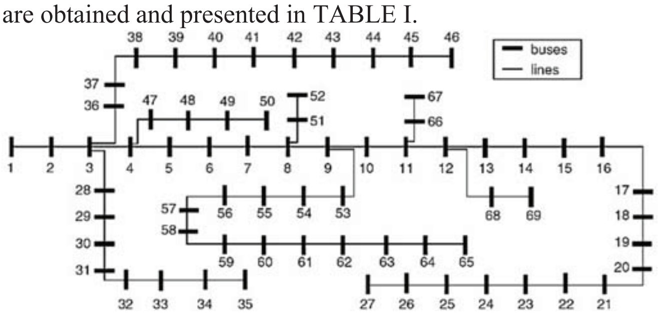

Fig. 1. PG&E 69-bus distribution test system.

TABLE I
Network partitioning results for each partition of test system

Partition	Bus index
1	1,2, 3, 4, 5, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50
2	5, 6, 7, 8, 9, 10, 11, 51, 52, 53, 54, 66, 67
3	11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 68, 69
4	54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65

III. Zonal Voltage Control

In this section the formulation of the decentralized voltage regulation method and adaptive PSO algorithm are presented by considering proposed network partitioning in the previous section.

A. Coordinated Voltage Regulating Formulation

The mathematical modeling of coordinated voltage regulation in each partition is presented as follows.

$$\min \quad f_m = \sum_{l=1}^{N_m} R_{m,l} \cdot |B_{m,l}|^2 + \sum_{i=1}^{N_m} |V_{m,i} - V_{m,0}| \qquad (7)$$

Subject to:

$$\begin{aligned}
&[V]_m - [V_{m,0}] + [DLF]_m [\frac{p - jq}{V^*}]_m = 0 \\
&B_{m,l} \le B_{m,l}^{\max} \qquad l = 1,\ldots,N_m \\
&V_{m,i}^{\min} \le V_{m,i} \le V_{m,i}^{\max} \qquad i = 1,\ldots,N_m \\
&q_{m,i}^{G,\min} \le q_{m,i}^{G} \le q_{m,i}^{G,\max}
\end{aligned} \qquad (8)$$

Where $R_{m,l}$ and $B_{m,l}$ are the resistance and the current flowing through the line l in the m^{th} partition, respectively; f_m and N_m are the objective function and the number of buses or branches in this partition, respectively, $[V]_m$, $[p]_m$ and $[q]_m$ are voltage vector, total consumed three phase active and reactive powers in this partition respectively; $V_{m,0}$ is the voltage of the last bus of the adjacent upstream partition; $q_{m,i}^{G}$ is the reactive power generation of DG unit in bus i in m^{th} partition which must be optimized.

In fact, the problem of coordinated voltage regulation is an optimization problem which aims to minimize the power losses of the lines inside the partition *m* as well as voltage deviation. It also determines the reactive power set points of zonal DGs subject to zonal load flow equations, voltage, and line power flow constraints. From the information exchange point of view, the Zonal Control Center (ZCC) in each partition receives the expected power delivered to the downstream partitions, the expected power of zonal DGs, and the expected load of each bus inside the partition, then after optimization, it sends the reactive power set points of zonal DGs to them. The schematic diagram of the communication links is shown in Fig. 2.

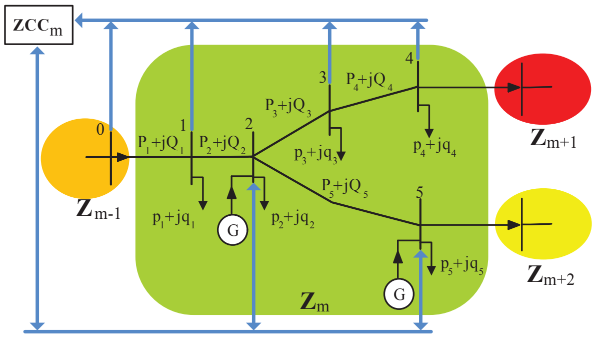

Fig. 2. Schematic diagram of the communication links for m^{th} partition.

B. Adaptive Particle Swarm Optimization Algorithm

The well-known PSO algorithm is used to solve the problem because of its high convergence speed required for the online calculations [19]. This algorithm which is inspired by the particles movement, in comparison with other intelligent algorithms, is able to converge in a shorter time with better solutions. The initial position of particles is produced according to a random population in the multi-dimensional search space and each particle in each iteration improves its position based on its own best position which has ever experienced and the best position which swarm has experienced. For each particle a velocity is defined which determines the movement direction of each particle and it is updated based on three factors in each iteration: the former velocity, the best former self position and the best former swarm position. The formulation of the mentioned process is as follows:

$$Pos_k^{iter+1} = Pos_k^{iter} + Vel_k^{iter}$$
$$Vel_k^{iter+1} = \omega^{iter} \cdot Vel_k^{iter} + c_1 \cdot rand_1(Pos_{k,best}^{iter} - Pos_k^{iter}) + c_2 \cdot rand_2(Pos_{g,best}^{iter} - Pos_k^{iter}) \quad (9)$$
$$k = 1,2,...,N_p$$

where the control variables vector Pos_k^{iter} is a potential solution in the population with size N_p which its elements are reactive power set points of N_g zonal DGs inside the partition *m*:

$$Pos = [q_{m,1}^G \quad q_{m,2}^G \quad \cdots \quad q_{m,Ng}^G]^T \quad (10)$$

where $Pos_{k,best}^{iter}$ and $Pos_{g,best}^{iter}$ are also the best position of each particle and the best swarm position so far, respectively. c_1 and c_2 are learning coefficients and ω^{iter} is an inertia coefficient with following appropriate values:

$$c_1 = c_2 = 2$$
$$\omega^{iter} = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \cdot iter/iter_{\max} \quad (11)$$
$$\omega_{\min} = 0.4 \quad , \quad \omega_{\max} = 0.9$$

As the dimension of each partition and the number of control variables associated with DG units are variant quantities, therefore an adaptive method is developed to adjust the population size and the maximum number of iterations for the optimization algorithm in each partition. This adaptive method is expressed as follows after several trial and error:

$$N_p = N_m + N_g + 50$$
$$iter_{\max} = N_m + N_g \quad (12)$$

IV. Simulation Results

In order to validate the performance of the proposed partitioning and voltage regulation methods, a case study is implemented on the aforementioned test system using a personal laptop having Core i5 processor, 2.40 GHz, and 4 GB of RAM in MATLAB software. The modified results of reference [20] are mentioned in the TABLE II are considered as location and capacity of 23 DG units installed in the test system.

TABLE II
Location and capacity of DG units

Location	6, 14, 15, 18, 19, 20,21, 22, 24, 26, 27, 29, 34, 40, 49, 50, 51, 53, 54, 55, 57, 58, 64
Capacity (kW)	75, 75, 75, 225, 75, 75, 150, 75, 75, 75, 75, 75, 150, 75, 75, 75, 525, 75, 225, 75, 375, 150, 75

In this paper the worst scenarios in voltage regulation of the studied test case are simulated and the results are presented. Obviously, when the proposed algorithm succeeds to manage the voltage problem of the worst cases, it can manage all other system conditions. The voltage profile is evaluated by two decentralized and centralized approaches based on the proposed PSO algorithm. The cases are also evaluated by these approaches based on the classic IPA which uses partial derivatives to solve the optimization problem. It is assumed that the slack bus voltage is 1.0 *pu* and the acceptable range for voltage profile is ±1.05 *pu*.

A. Case 1: full load – minimum generation

In this case, all the system loads are at their maximum power values and DG active power generations are assumed to be 5% of the rated power. It can be estimated that at the end of the lines, voltage drop can occur. Fig. 3 represents the results of the proposed PSO-based solution for this test case. When DG units only generate active power without reactive power control (RPC) the voltage profile exceeds the voltage lower limit. Using the proposed decentralized approaches for reactive power control of DGs, the system voltages return to the admissible range as can be seen in Fig. 3. Moreover, the results of the proposed decentralized approach and the results of the same solution in centralized manner in spite of the fact that control processes are independent in different partitions are the same.

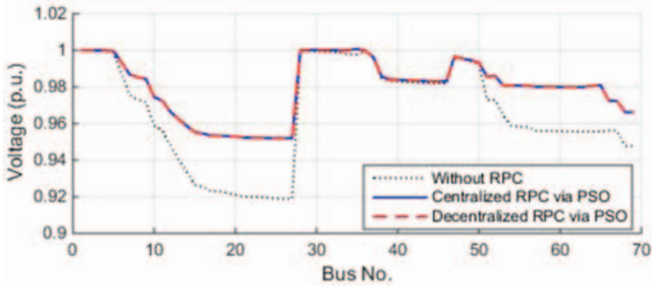

Fig. 3. Voltage profile control via proposed PSO solution in case 1.

Fig. 4 represents the results of decentralized PSO solution in comparison with centralized and decentralized IPA. As can be seen, not only the decentralized IPA cannot eliminate voltage violation in buses 17 to 27 but also the voltage improvement is significantly less than the same PSO-based solution in other buses. However, the proposed decentralized PSO solution present remarkable results in comparison with centralized IPA.

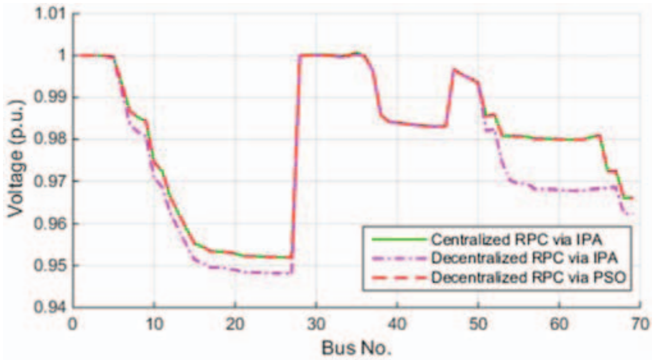

Fig. 4. The comparison of voltage profile control via PSO and IPA solutions.

TABLE III presents the optimum reactive power set points of DGs based on the presented order in TABLE II.

TABLE III
Optimum reactive power set points of DGs with different centralized and decentralized solution in case 1

Dec. PSO	71.9375, 71.9375, 71.9375, 215.8124, 71.9375, 71.9375, 143.8749, 71.9375, 71.9375, 71.9375, 71.9375, 36.1891, 143.8749, 71.9375, 71.9375, 71.9375, 503.5623, 71.9375, 215.8124, 71.9375, 359.6874, 143.8749, 71.9375

Cen. PSO	71.9375, 71.9375, 71.9375, 215.8124, 71.9375, 71.9375, 143.8749, 71.9375, 71.9375, 71.9375, 71.9375, 71.9375, 143.8749, 71.9375, 71.9375, 71.9375, 503.5623, 71.9375, 215.8124, 71.9375, 359.6874, 143.8749, 71.9375
Dec. IPA	71.9300, 71.9375, 71.9375, 215.8124, 71.9375, 71.9375, 143.8749, 71.9375, 71.9375, 71.9375, 11.7006, 53.2519, 124.7582, 70.3253, 62.9424, 71.9308, 503.5557, 71.9323, -165.3475, -34.2743, 229.1607, 66.3721, 32.0002
Cen. IPA	71.9375, 71.9375, 71.9375, 215.8124, 71.9375, 71.9375, 143.8749, 71.9375, 71.9375, 71.9375, 71.9375, 71.9375, 143.8749, 71.9375, 71.9375, 71.9375, 503.5623, 71.9375, 215.8124, 71.9375, 359.6874, 143.8749, 71.9375

B. Case 2: minimum load – maximum generation

In the second case, the loads and DGs are considered to be 25% and 100% of their respective rated values. Fig. 5 shows the voltage profile of the system before and after the reactive power control of DGs. As can be seen, without reactive power control of DGs the biggest voltage violation is found at bus 27. Based on the proposed solution new voltage profiles within acceptable range are obtained which are similar in both centralized and decentralized manner. The reactive power set points of DGs are presented in TABLE IV.

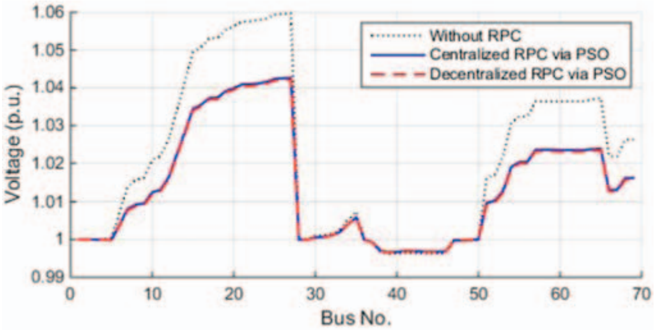

Fig. 5. Voltage profile control via proposed PSO solution in case 2.

TABLE IV

Optimum reactive power set points of DGs with different centralized and decentralized solution in case 2

Dec. PSO	-39.7995, -39.7995, -39.7995, -119.3985, -39.7995, -39.7995, -79.5990, -39.7995, -39.7995, -39.7995, -39.7995, -39.7995, -79.5990, 39.7995, 39.7995, -39.7995, -278.5965, -39.7995, -119.3985, -39.7995, -198.9975, -79.5990, -39.7995
Cen. PSO	-39.7995, -39.7995, -39.7995, -119.3985, -39.7995, -39.7995, -79.5990, -39.7995, -39.7995, -39.7995, 39.7995, 39.7995, -79.5990, 39.7995, 39.7995, -39.7995, -278.5965, -39.7995, -119.3985, -39.7995, -198.9975, -79.5990, -39.7995
Dec. IPA	-39.6418, -39.6643, -39.6684, -119.2785, -39.6820, -39.6852, -79.4847, -39.6863, -39.6906, -39.6915, 0, 0, 0, 0, 0, -39.6589, -278.4578, -39.6873, -56.8492, -7.9066, -173.9031, -57.1473, -33.2910
Cent. IPA	-39.7977, -39.7989, -39.7989, -119.3979, -39.7989, -39.7990, -79.5985, -39.7990, -39.7990, -39.7990, -39.5246, -39.7815, -79.5927, 39.7968, 39.6248, -39.7979, -278.5949, -39.7986, -119.3976, -39.7986, -198.9966, -79.5981, -39.7987

C. Discussion

The proposed decentralized PSO based solution, in addition to presenting more optimum results, provides acceptable results compared to both centralized methods. The indices in TABLE V show the energy losses and voltage violation for four controlled solutions in case 1 has reduced. But in case 2, because of the confliction of objective functions the energy loss has been increased in order to improve the voltage deviation.

TABLE V

The comparison of PSO and IPA based methods

	w/o RPC	Dec. PSO	Cen. PSO	Dec. IPA	Cen. IPA
Loss (kW) in case 1	136.8	123.1	123.11	107.6	123.1
Voltage Deviation in case 1	2.38	1.41	1.41	1.661	1.41
Loss (kW) in case 2	85.6	141.16	136.85	132.45	141.16
Voltage Deviation in case 2	1.56	1.03	1.06	1.1	1.03

The major advantage of the proposed decentralized approach in comparison with centralized methods is to provide the capability of online implementation. In this regard, as can be seen in TABLE VI the maximum execution time which is obtained for partition 1 is less than 1.5 s. The notable speed of the proposed solution comes from the fact that the proposed decentralized method developed for the distribution systems does not need the time-consuming procedure of the centralized methods. Indeed, separating the optimization algorithm in four partitions does not need all system data in the optimization problem. In fact, by the use of the zonal data in each partition, only the effects of the controllable variables in same partition are considered for voltage control in this partition.

Some other details about adaptive feature of the proposed method have been described in TABLE VI. As can be seen, by changing partition dimensions and the number of variables, the population size and the maximum iteration required for algorithm convergence will be different in various partitions and result in different execution time at each center.

TABLE VI

The parameters and time details of the proposed adaptive method for each partition.

Partition	1	2	3	4
Bus No.	28	13	19	12
DG No.	5	4	9	5
Population Size	83	67	78	67
Maximum Iteration	33	17	28	17
Execution Time (s) in Case 1	1.44	0.58	1.01	0.49
Execution Time (s) in Case 2	1.45	0.59	1.01	0.50

The simulation results show by splitting one global centralized problem to some smaller decentralized ones, the computational burden decreases and the possibility of online optimization is achieved. As the simulations in this paper are performed on a personal laptop, the execution times will surely have further decrease via stronger processors in control centers.

V. Conclusion

This paper, initially presents an approximate solution for calculation of distribution system voltage sensitivity matrix versus consumed active and reactive power variations. Then, the network graph has been partitioned according to this pattern matrix using the spectral partitioning method. After that, the adaptive particle swarm optimization algorithm is used in each partition to determine optimum reactive power set points of DGs.

In order to validate the performance of the proposed method, the well-known 69-bus distribution test system is divided to four control partitions, and then by considering 23

DGs the proposed decentralized method as well as the centralized one are simulated under two different operating conditions. In comparison with the classical IPA, the results prove the ability of the proposed decentralized PSO based method for successful voltage regulation in an admissible time required for online computations.

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