International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2018	Issue 37	Volume 10	Number 4	Pages 6-14

HIERARCHICAL DISTRIBUTED VOLTAGE MANAGEMENT IN SMART GRIDS WITH DG

A. Jodaei N.M. Tabatabaei

Electrical Engineering Department, Seraj Higher Education Institute, Tabriz, Iran
alireza.jodaei@yahoo.com, n.m.tabatabaei@gmail.com

Abstract- One of the important parts of transmission and distribution systems is the cost of modernization and capacity building. By increasing the capacity and improving the day-to-day network of power, new systems must be developed and designed to control the distribution system and solve the new problems. With the development of a distributed generation system and storage system, past systems will not be able to control these newly-developed systems, so it requires the creation and design of a new network that meets these needs, which the new system, called smart grids is known. In this paper, a distributed smart-grid method for optimal and coordinated regulation of spatial power generation and transformer power supply transformers for unbalanced power distribution networks has been presented. At the level number 1 of the proposed hierarchical control method, distributive generators try to maintain optimal network voltage profile within the permissible range. If the level number 1 control is not successful, on the level number 2, the substation transformer will be used to clean the voltage violation in the system with the first level. The subject of this dissertation is distributed distribution and voltage hierarchy in smart grids with the participation of distributed generators. The purpose of this dissertation is to reduce energy losses and to eliminate voltaic violations in the network.

Keywords: Smart Grids, Voltage Control, Distributed Generators, Distributed Control, Reactive Power Control, Power Injection.

I. INTRODUCTION

In the last two decades, based on growing consumption of electric energy and the constraints on state resources, the issue of privatization and restructuring of the electricity industry has been considered. On the one hand, the exhaustion of existing network equipment and the emergence of new technologies, on the other hand, have created a new challenge for the electricity industry [1]. In general, the smart grid delivers a solution to the challenges of the current network, including reliability challenges, environmental challenges, and energy efficiency challenges.

In power distribution systems, in addition to optimal operation, it is necessary to maintain the subscriber's voltage within the permissible range. Given the increased use of renewable resources, especially wind and solar resources, volatility in distribution systems is possible [2, 3]. Typical methods include OLTC transformers, voltage regulators and capacitor banks to control the distribution network voltage, but these devices are not suitable for dealing with rapid changes [4].

This paper proposes a distributed and harmonized intelligent network based approach for optimal distribution nodes of generators and a packet-transducer under load in an inconsistent distribution network. In this method, efficiency of energy is improved and the voltage specifications are maintained within acceptable limits in various operating conditions of the sources and loads of renewable energy. The proposed scheme is aimed at controlling the network at two levels [4, 5].

The method of level number 1 the proposed hierarchical, DG work independently to maintain the specifications of the voltage in an acceptable range at best. If the level number 1 fails, at the level number 2 OLTC will work with the level number 1 to improve the voltage violation condition in the system. The proposed solution controls the distribution network voltage profile optimally according to the distributed gradient solution.

The proposed algorithm is suitable for controlling large-scale grid lines and with a large number of distributed generators. In the following, the voltage drop is modeled on each of the 3-phase unbalanced distribution network lines. Then, by considering the control variables, the objective functions of the voltage control problem are defined in terms of state and control variables of the problem. Then, the method is distributed below the gradient to solve this problem and the partial derivatives required for calculation by each control factor will be extracted [6, 7, 8].

II. UNBALANCED 3-PHASE GRID MODELING

The reduced model of four-wire line section shows at Figure 1 which including neutral or ground wire. We assume that this model is drawn after the reduction of the krona [9].

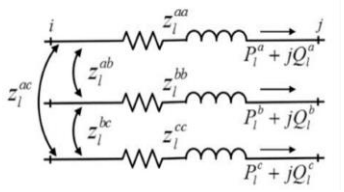

Figure 1. Reduced three-phase model [9]

The impedance matrix of this network can be presented by Equation (1) [9].

$$\left[Z_{abc}\right]=\begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \tag{1}$$

Also, the relationship between the voltage buses and the branch currents the system of Figure 1 can be shown in Equation (2) [9].

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}=\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}-\begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}\begin{bmatrix} I_{Aa} \\ I_{Bb} \\ I_{Cc} \end{bmatrix} \tag{2}$$

A. Energy Losses

The energy losses of the system can be expressed in accordance with Equation (3) [10].

$$f_{L,l}=\sum_{x=a,b,c}\frac{\left(P_l^x\right)^2+\left(Q_l^x\right)^2}{\left(V_l^x\right)^2}.\sum_{y=a,b,c} r_l^{xy}\ ,\quad l=1,...,N \tag{3}$$

where, P_l^x, Q_l^x the active power, reactive power and V_l^x the voltage of the line part *l* of the phase *x* and r_l^{xy} of the resistance between the phase *x* and *y* of the *l* line and $f_{L,l}$ of the energy losses of the *l* line [10].

In the distribution network, when all of variables are expressed as a pu, according to the active power and reactive power, as well as the resistance and reactance of the line l, between the two buses adjacent to *i* and *j*, the voltage difference between the two buses is approximately calculated as Equation (4) [10].

$$V_i^x-V_j^x=\sum_{y=a,b,c} r_l^{xy}.P_l^y+\sum_{y=a,b,c} x_l^{xy}.Q_l^y \tag{4}$$

where, V_k^x is the voltage of bus *k* in phase *x*.

The expression V_k^x, according to active power and reactive power of the bus *k*, the Equation (4) is calculated as (5) [10].

$$V_k^x=V_0-\sum_{j=1}^{N}\sum_{y=a,b,c} R_{kj}^{xy}.p_j^y+\sum_{j=1}^{N}\sum_{y=a,b,c} X_{kj}^{xy}.q_j^y \tag{5}$$

where, p_j^y and q_j^y are active power, reactive power consumption of bus *j* in phase *y*, respectively. In addition, R_{kj}^{xy} and X_{kj}^{xy} are resistance and reactance between phases *x* and *y*. The similar relations of connections for buses *k* and *j* to the bus slack are also calculated [10].

B. Load Flow

The *BIBC-BCBV* matrix method is one of the common methods for solving the load flow in distribution systems. For each bus, the apparent power is in the form of Equation (6) [11, 12].

$$S_i=(P_i+jQ_i)\ ,\quad i=1,2,...,N \tag{6}$$

and the injection current in the *k* repeat is equal to [11]:

$$I_i^k=I_i^r(V_i^k)+jI_i^i(V_i^k)=\left(\frac{P_i+jQ_i}{V_i^k}\right)^* \tag{7}$$

The following is how the *BIBC* and *BCBV* matrices are formed. The form of these matrices is expressed in Figure 2.

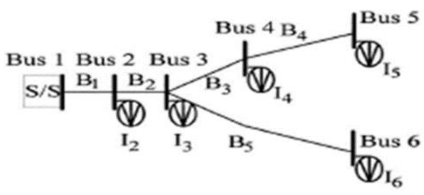

Figure 2. Sample distribution system [13]

With respect to the injected current and KCL, the current of branches B_1, B_3 and B_5 is equal to [13]:

$$B_5=I_6 \tag{8}$$

$$B_3=I_4+I_5 \tag{9}$$

$$B_1=I_2+I_3+I_4+I_5+I_6 \tag{10}$$

and for the whole system it can be written [13]:

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}=\begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \tag{11}$$

Equation (11) can be rewritten as a matrix form of Equation (12) [13]:

$$\left[B\right]=\left[BIBC\right]\left[I\right] \tag{12}$$

where, the arrays of the *BIBC* matrix have only zero and one values [13].

The relationship between the branching current and the bus voltage of the system relations is simply obtained. For example, the bus voltages 2, 3 and 4 are as follows [13]:

$$V_2=V_1-B_1Z_{12} \tag{13}$$

$$V_3=V_2-B_2Z_{23} \tag{14}$$

$$V_4=V_3-B_3Z_{34} \tag{15}$$

where, V_i is the bus voltage *i*, and Z_{ij} is the impedance line between the buses *i* and *j*.

By replacing the Equations (13) and (14) in Equation (15), the bus voltage 4 is rewritten as follows [13].

$$V_4=V_1-B_1Z_{12}-B_2Z_{23}-V_3-B_3Z_{34} \tag{16}$$

Equation (16) shows that the bus voltage can be expressed as a function of the current branches, parameters of line and reference bus voltage.

If the relationships for all the buses in Figure 2 are written, then Equation (17) will result [13]:

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (17)$$

or in the form of a matrix

$$[\Delta V] = [BCBV][B] \quad (18)$$

After the formation of *BCBV* and *BIBC* matrices that have all of the network properties and the composition of Equations (18) and (12), the difference voltage between the reference bus and the other bus is calculated as follows [14, 15].

$$[\Delta V] = [BCBV][BIBC][I] = [DLF][I] \quad (19)$$

The R_{kj}^{xy} and X_{kj}^{xy} matrices can now be defined as

$$R_{kj}^{xy} = \mathrm{real}\left(\left[DLF^{xy}\right]\right) \quad (20)$$

$$X_{kj}^{xy} = \mathrm{imag}\left(\left[DLF^{xy}\right]\right) \quad (21)$$

C. Problem Formulation

Assuming that DG are already installed, the proposed method targets the minimization of active power losses and the improvement of the desired network voltage profile by actuating reactive power distribution of DG and, if necessary, calculating the substation position of the substation transformer [10].

$$f_L = \sum_{L=1}^{N} f_{L,l} = \sum_{L=1}^{N} \sum_{x=a,b,c} \frac{\left(P_l^x\right)^2 + \left(Q_l^x\right)^2}{\left(V_l^x\right)^2} . \sum_{y=a,b,c} r_l^{xy} \ , \ l = 1,...,N \quad (22)$$

To maintain the voltage profile in the range of the target function, the voltage violation f_v is defined as follows [10].

$$f_V = \sum_{k=1}^{N} \sum_{x=a,b,c} OVF_k^x \left(V_k^x - V_k^{\max}\right)^2 + \\ + \sum_{k=1}^{N} \sum_{x=a,b,c} UVF_k^x \left(V_k^x - V_k^{\min}\right)^2 \quad (23)$$

where, OVF_k^x is over voltage from bus *k* in phase *x* and UVF_k^x is of under voltage from bus *k* in phase *x* which are defined as follow [10].

$$OVF_k^x = \begin{cases} 1 & V_k^x \rangle V_k^{\max} \\ 0 & V_k^x \le V_k^{\max} \end{cases} , \ UVF_k^x = \begin{cases} 1 & V_k^x \langle V_k^{\min} \\ 0 & V_k^x \ge V_k^{\min} \end{cases} \quad (24)$$

where, $V_k^{\max}$ maximum voltages and $V_k^{\min}$ are the minimum voltages at the bus.

In addition, the objective function of the apparent power violation of line f_s, regarding to limit linear loads less than capacity of terminal is defined as Equation (25) [10].

$$f_S = \sum_{l=1}^{N} \sum_{x=a,b,c} OSF_l^x \left(\left|S_l^x\right|^2 - \left|S_l^{\max}\right|^2 \right)^2 \quad (25)$$

where, OSF_l^x is flag of over apparent power from line *l* in phase *x* and it is defined (26) [10].

$$OSF_l^x = \begin{cases} 1 \left|S_l^x\right| > S_l^{\max} \\ 0 \left|S_l^x\right| \le S_l^{\max} \end{cases} \quad (26)$$

So that S_l^x and $S_l^{\max}$ are the apparent power and the maximum apparent power of line *l* of phase *x*, respectively . The apparent power being calculated by Equation (27) [10].

$$\left|S_l^x\right| = \sqrt{\left(P_l^x\right)^2 + \left(Q_l^x\right)^2} \quad (27)$$

The final objective function is three defined objective functions considering weighted summation and is shown in (28) [10].

$$f = w_L f_L + w_V f_V + w_S f_S \quad (28)$$

where, w_L, w_V and w_S are the weight coefficients of the objective functions that are considered constant.

The control variables include the reference values of the reactive power for DG and the secondary voltage of the tap changer in the substation; the vector of the control variable is as follow [17].

$$u = \left[q_{n1}^G, q_{n2}^G, ..., q_{nG}^G, V_0 \right]^T \quad (29)$$

In this regard, q_{ni}^G is the reactive power of generator *i* in bass *n*, and V_0 is the secondary voltage of the tap changer in the substation. The permitted range of these variables is as follows [17].

$$\begin{cases} q_i^{G\min} < q_i^G < q_i^{G\max} \\ V^{\min} \le V_0 \le V^{\max} \end{cases} \quad (30)$$

The objective function has a square problem and the form of the constraint is linear, so the problem is considered as a binding and convex optimizer.

If the number of generators is high, the system will not be optimized. To solve this problem, the distributed gradient method is used. The distributed gradient method is better and simpler than the gradient method [17].

Let $f(u): R^n \to R$ is the objection function of optimization problem. A gradient method is shown in (31) [17].

$$u(t+1) = u(t) - \alpha_t . \nabla f(u(t)) \quad (31)$$

where, $\nabla f(u(t))$ is Gradient of *f*. The distributed gradient form of (31) is [17]:

$$u_i(t+1) = u_i(t) - \alpha_t . \nabla f_i(u(t)) \quad (32)$$

where, $u_i(t)$ is the *i*th parameter of the vector $u(t)$ and $\nabla f(u(t))$ is calculated from Equation (33) [17].

$$\nabla f(u) = \left[\frac{\partial f}{\partial q_{n1}^G}, \frac{\partial f}{\partial q_{n2}^G}, ..., \frac{\partial f}{\partial q_{ni}^G}, \frac{\partial f}{\partial V_0} \right]^T \quad (33)$$

III. DISTRIBUTED DERIVATION CALCULATION

If consider $V_l^x = 1\,\text{pu}$ in Equation (22) as the proposed solution for distributed method, then

$$f_l = \sum_{L=1}^{N} \sum_{x=a,b,c} \left(P_l^x\right)^2 + \left(Q_l^x\right)^2 . \sum_{y=a,b,c} r_l^{xy} \ , \ l = 1,...,N \quad (34)$$

As it is seen in Equation (33), two derivatives will be made:

• The derivative of the objective function relative to the reactive power of generators, $\frac{\partial f}{\partial q_{n1}^G}$.

• The derivative of the target function relative to the substation voltage for the substation transformer is $\frac{\partial f}{\partial V_0}$.

A. Calculation of $\frac{\partial f}{\partial q_{n1}^G}$ for DG

The weight coefficients are constants so [10]

$$\frac{\partial f}{\partial q_i^G} = w_L \frac{\partial f_L}{\partial q_i^G} + w_V \frac{\partial f_V}{\partial q_i^G} + w_S \frac{\partial f_S}{\partial q_i^G} \quad (35)$$

To state f_L, f_S and f_V w.r.t q_i^G, p_k^x and q_k^x can be expressed as follows [10].

$$p_k^x = p_k^{x,L} - p_k^{x,G} \ , \ q_k^x = q_k^{x,L} - q_k^{x,G} \quad (36)$$

where, p_k^x and $p_k^{x,L}$ are consumption of net and consumption of load, and $p_k^{x,G}$ is active power of DG generation at bus k in phase x. The $q_k^x, q_k^{x,L}$ are also consumption of net and consumption of load, $q_k^{x,G}$ is reactive power of DG generation at bus k in phase x, respectively.

Now, according to previous relations, we can find the Equation (37) [10]:

$$\begin{aligned} P_l^x &= \sum_{k=1}^{N} bibc_{lk} . p_k^x = \sum_{k=1}^{N} bibc_{lk} .(p_k^{x,L} - p_k^{x,G}) \\ Q_l^x &= \sum_{k=1}^{N} bibc_{lk} . q_k^x = \sum_{k=1}^{N} bibc_{lk} .(q_k^{x,L} - q_k^{x,G}) \end{aligned} \quad (37)$$

Therefore, the casualty relationship can be obtained in the form of (38) [10]:

$$\begin{aligned} f_L = \sum_{l=1}^{N} \sum_{x=a,b,c} \sum_{y=a,b,c} r_l^{xy} \Bigg[\left(\sum_{k=1}^{N} bibc_{li} .(p_k^{x,L} - p_k^{x,G}) \right)^2 + \\ + \left(\sum_{k=1}^{N} bibc_{li} .(q_k^{x,L} - q_k^{x,G}) \right)^2 \Bigg] \end{aligned} \quad (38)$$

Equation (38) can be derived from q_i^G as

$$\begin{aligned} \frac{\partial f_L}{\partial q_i^G} &= -2 \sum_{l=1}^{N} \sum_{x=a,b,c} \sum_{y=a,b,c} r_l^{xy} .bibc_{li} . \sum_{k=1}^{N} bibc_{li} (q_k^{x,L} - q_k^{x,G}) = \\ &= -2 \sum_{l=1}^{N} \sum_{x=a,b,c} \sum_{y=a,b,c} r_l^{xy} .bibc_{li} . Q_l^x \end{aligned} \quad (39)$$

f_v is derived from q_i^G as:

$$\begin{aligned} \frac{\partial f_v}{\partial q_i^G} &= 2 \sum_{k=1}^{N} \sum_{x=a,b,c} OVF_k^x (V_k^x - V_k^{\max}) \frac{\partial V_k^x}{\partial q_i^G} = \\ &= 2 \sum_{k=1}^{N} \sum_{x=a,b,c} UVF_k^x (V_k^x - V_k^{\min}) \frac{\partial V_k^x}{\partial q_i^G} \end{aligned} \quad (40)$$

According to (36) and (5) we can obtain the Equation (41) [10]:

$$\frac{\partial V_k^x}{\partial q_i^G} = \sum_{y=a,b,c} X_{ki}^{xy} \ , \ x = a,b,c \quad (41)$$

and considering the Equations (40) and (41), we can obtain the Equation (42):

$$\begin{aligned} \frac{\partial f_v}{\partial q_i^G} &= 2 \sum_{k=1}^{N} \sum_{x=a,b,c} OVF_k^x (V_k^x - V_k^{\max}) . \sum_{y=a,b,c} X_{ki}^{xy} + \\ &+ 2 \sum_{k=1}^{N} \sum_{x=a,b,c} UVF_k^x (V_k^x - V_k^{\min}) . \sum_{y=a,b,c} X_{ki}^{xy} \end{aligned} \quad (42)$$

Now, f_s is derived from q_i^G:

$$\frac{\partial f_s}{\partial q_i^G} = 2 \sum_{l=1}^{N} \sum_{x=a,b,c} OSF_l^x \left(\left|S_l^x\right|^2 - \left(S_l^{\max}\right)^2 \right) \frac{\partial \left|S_l^x\right|^2}{\partial q_i^G} \quad (43)$$

Equations (36), (37) and (27) can be also obtained by Equation (44) [10].

$$\begin{aligned} \frac{\partial \left|S_l^x\right|^2}{\partial q_i^G} &= \frac{\partial \left(\left(P_l^x\right)^2 + \left(Q_l^x\right)^2 \right)}{\partial q_i^G} = \frac{\partial \left(\left(Q_l^x\right)^2 \right)}{\partial q_i^G} \\ \frac{\partial \left|S_l^x\right|^2}{\partial q_i^G} &= -2 bibc_{li} . \sum_{k=1}^{N} bibc_{lk} (q_k^{x,L} - q_k^{x,G}) \\ \frac{\partial \left|S_l^x\right|^2}{\partial q_i^G} &= -2 bibc_{li} . Q \end{aligned} \quad (44)$$

According to the Equations (43) and (44), we can obtain the Equation (45) [10]:

$$\frac{\partial f_s}{\partial q_i^G} = -4 \sum_{l=1}^{N} \sum_{x=a,b,c} OSF_l^x \left(\left|S_l^x\right|^2 - \left(S_l^{\max}\right)^2 \right) bibc_{li} . Q_l^x \quad (45)$$

B. Calculation of $\frac{\partial f}{\partial q_{n1}^G}$ for Transformer

The OLTC has a variable tap that can change the voltage of the second side. This is possible by changing the tap within the permissible range [18].

$$V_0 = V_{in} + tap.V_{tap} \quad (46)$$

where, V_{in} is primary substation bus voltage, V_{tap} tap change voltage at each stage, and *tap* is tap-changer position at system [18]. The Equation (4) can be summarized as follows (47) [18].

$$V_i - V_j = R_j P_j + X_j Q_j \quad (47)$$

According to Equation (47), for changing the voltage of a bus, the voltage at other buses also vary. Therefore, we can show the relationship between the voltages of other bus in form of Equation (48) [18].

$$V_0^{new} = V_0^{old} + \Delta V_{\max} \quad (48)$$

In this case $\Delta V_{\max}$ is defined as Equation (49) [18].

$$\Delta V_{\max} = \begin{cases} \Delta V_i & \text{abs}(\Delta V_i) \geq \text{abs}(\Delta V_j) \\ \Delta V_j & \text{abs}(\Delta V_i) \leq \text{abs}(\Delta V_j) \end{cases} \tag{49}$$

The Equation (49) shows that the highest violation should be considered for voltage variations [18].

After calculating V_0^{new}, if this value is outside of the voltage range, the minimum or maximum allowable voltage should be considered in accordance with the following equation [18].

$$V_0 = \max(\min(V_0^{new}, V_0^{\max}), V_0^{\min}) \tag{50}$$

Then we can obtain the position of the puck in Equation (51) in relative terms [18]:

$$tap_{unb} = \text{round}\left(\frac{V_0 - V_{in}}{V_{tap}}\right) \tag{51}$$

This value is in the form of a random, and the Equation (52) is used to get the correct integer [18].

$$tap = \begin{cases} tap_{\min} & tap_{unb} \leq tap_{\min} \\ tap_{unb} & tap_{\min} \leq tap_{unb} \leq tap_{\max} \\ tap_{\max} & tap_{\max} \leq tap_{unb} \end{cases} \tag{52}$$

The whole function of the objective function is derived from the second voltage [10].

$$\frac{\partial f}{\partial V_0} = w_L \frac{\partial f_L}{\partial V_0} + w_V \frac{\partial f_V}{\partial V_0} + w_S \frac{\partial f_S}{\partial V_0} \tag{53}$$

According to Equations (25) and (34), the Equation (53) is simplified as follows [10].

$$\frac{\partial f}{\partial V_0} = w_V \frac{\partial f_V}{\partial V_0} \tag{54}$$

$$\frac{\partial f_V}{\partial V_0} = 2\sum_{k=1}^{N} \sum_{x=a,b,c} OVF_k^x (V_k^x - V_k^{\max}) \frac{\partial V_k^x}{\partial V_0} + 2\sum_{k=1}^{N} \sum_{x=a,b,c} UVF_k^x (V_k^x - V_k^{\min}) \frac{\partial V_k^x}{\partial V_0} \tag{55}$$

According to (5), $\frac{\partial V_k^x}{\partial V_0}$ can be obtained as follows.

$$\frac{\partial V_k^x}{\partial V_0} = 1 \ , \ x = a,b,c \tag{56}$$

The placement of Equation (56) is obtained in Equation (55) to the final Equation (57) [10].

$$\frac{\partial f_V}{\partial V_0} = 2\sum_{k=1}^{N} \sum_{x=a,b,c} OVF_k^x (V_k^x - V_k^{\max}) + 2\sum_{k=1}^{N} \sum_{x=a,b,c} UVF_k^x (V_k^x - V_k^{\min}) \tag{57}$$

After updating all of the control variables using the Equation (32), if any of these variables is outside the permissible range, then the variable must be limited to its upper and lower bound on the basis of (30). It is determined by the relative position of the tap by Equation (50), and the exact position of the tap and the required information can be obtained according to previous statements.

As noted above, the proposed control solution adjusts the control settings for these partial derivatives. It should be noted that in order to optimize the objective function of the active power losses based on the relationships of this partial derivative, it is required to measure reactive power across all lines for updating local control variables. But for the target function of the voltage violation, the voltage of all the bases must be calculated for partial derivatives. This possibility can be provided through the multi-agent systems described in the next section.

IV. MAS-BASED INFRASTRUCTURE

The communication and multidisciplinary context required for proposed distributed method is shown in Figure 3. In this figure, three types of agents are visible as the measurement agent (MA), supervisor agent (SA) and control agent (CA). The measurement agent is responsible for measuring the voltage range of the bus, as well as the reactive power transmitted through the lineup and sending this information to the supervisor agent. Supervisor agents are responsible for collecting data from all the measurement agent in the entire network and delivering this information to controlling agents.

Finally, the task of control agent in the transformers, is calculating the next position of the tap for DG, which calculates the next working point of reactive power. Each controller based on the distributed method can update its point of view when receiving the required information from the supervisor agent without having to communicate with other control agent. This process is repeated until the optimal response is reached or the start of a new period of optimization by changing the operating state [10].

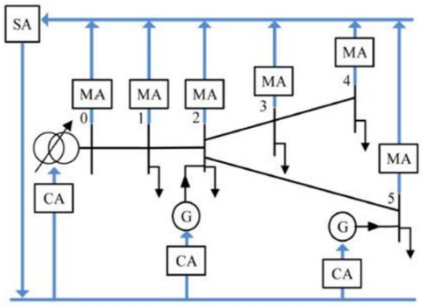

Figure 3. MAS-based infrastructure [10]

To build the network needed for MAS, a simpler method can be developed than the method shown in Figure 3. For buses that have one of the DG or OLTC equipment installed. We can combine MA and CA together and make a combination CA.

Two hierarchical levels are proposed to reduce the depreciation of the mechanical section of the OLTC. At the level number 1, DGs CA try to delete voltage vibration and ameliorates energy efficiency. After considering a logical delay, the control variables of the DG converged to their optimal work points, If the level number 1 is not successful in overcoming the voltage vibration, then at the level number 2, OLTCs CA cooperate with other CA's to receive the goal. When the OLTCs CA has achieved this goal, its CA keeps the tap location constant till until the next voltage vibration occurs, which DG cannot to remove voltage vibration.

V. SIMULATIONS

In this section, the simulation of the mentioned method is discussed. This method is implemented on the systems of 34 buses, 123 buses and 229 buses which are shown in Figures 4, 6 and 7. Simulations are done in the MATLAB environment.

A. Case 1: 34-Bus Network

The 34-bus test network shown in Figure 4 has 4 DGs which the information is provided in Table 1 [19].

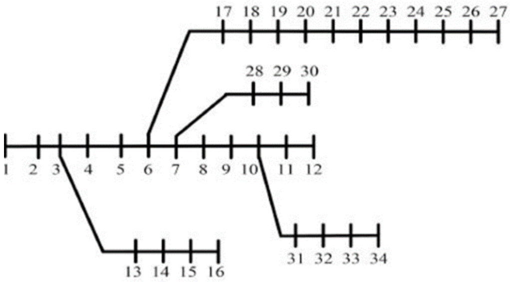

Figure 4. 34-bus system [19]

Table 1. DGs information of system [19]

Number of DG	Number of installed bus	Capacity (kW)
1	16	400
2	27	1600
3	30	1200
4	34	800

The control variables for this system include adjusting the operating voltages of four installed DGs and positioning the tap of the OLTC in the base bus. The permitted range of voltage variations of $\pm 5\%$ is considered around the rated voltage of the network. The tap changer range is $\pm 16 + 0.00625$ pu and the delay time of the OLTC for each step is 1 sec.

In order to perform simulations of the distributed solution, it is assumed that 10 repetitions of the first level function are performed. If the control factors of the generators do not succeed in eliminating the voltage violation, then the second level function which controls the OLTC is activated. The length of time for each stage is considered one second. The input voltage of the transformer is assumed to be 1 pu and the transformer tap are in the middle position.

The case conditions are considered as follows:

$w_L = 0.1,\ w_V = 3,\ w_S = 3,\ \alpha = 0.1$

Figures 5a, 5b, 5c and 5d show energy loss, minimum voltage variations, maximum voltage and OLTC tap sequence, respectively.

In this case, the energy loss starts at 480 kW and converges at 273 kW. In comparison with the uncontrolled method, which starts at 450 kW and reaches a minimum of 390 kW, the distributed method is significant and better than uncontrolled method and reduces about 117 kW of losses. It can be noted that total centralized energy loss starts from 450 kW and converges to 250 kW in comparison with the distributed method including OLTC control.

The centralized method yields a better result than the distribution method, and the loss of this method is less. But due to drawbacks of the centralized method and length of the centralized control process as well as disadvantages mentioned in the previous sections, it can be concluded that the distributed method is more convenient and more practical than centralized method.

The variations in the pulses have changed in the whole of the three steps, which first step involves a stepping up and then two other steps involve to decrease. This method has better advantages than other methods as well as implementation and operation of this method is easier which energy losses in this method have been improved with respect to other methods. But one of disadvantages is related to changing three steps.

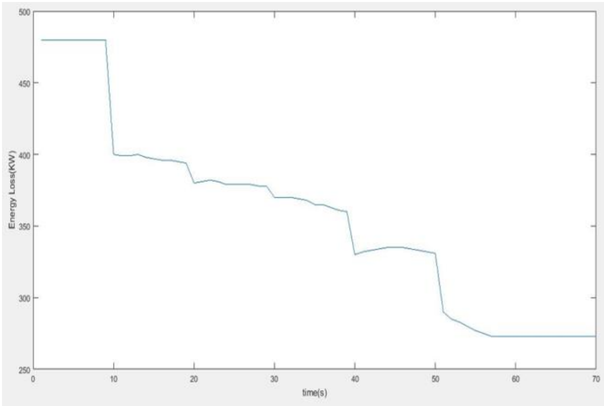

Figure 5a. Energy loss

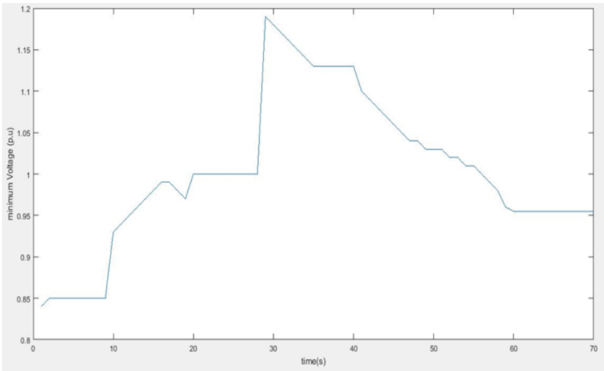

Figure 5b. Minimum voltage

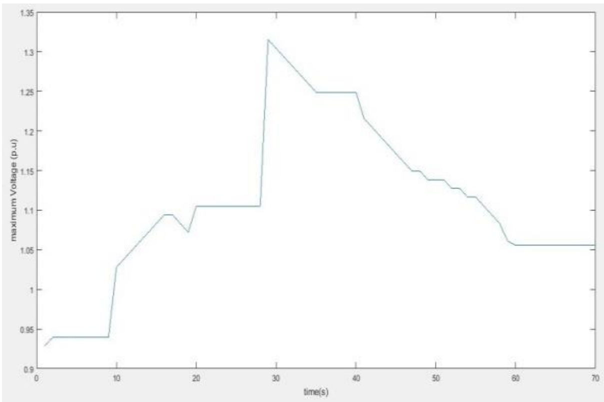

Figure 5c. Maximum voltage

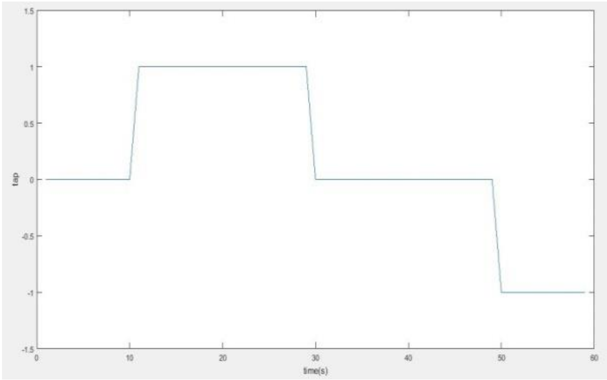

Figure 5d. OLTC tap sequence

B. Case 2: 123-Bus Network

The 123-bus test network shown in Figure 6 has 27 DG which the information is provided in [20]. The control variables, tap settings and simulations process are also considered as the case 1.

The case conditions are also considered as follows:

$w_L = 0.1,\ w_V = 3,\ w_S = 3,\ \alpha = 0.1$

In this case, the energy loss starts at 310 kW and converges at 242 kW. In comparison with the uncontrolled method, which starts at 210 kW and reaches a minimum of 340 kW, the distributed method is significant and better than uncontrolled method and reduces about 68 kW of loss. It can be noted that total centralized energy loss starts from 210 kW and converges to 300 kW in comparison with the distributed method including OLTC control.

It can be easily concluded that the distributed method is very effective and has more advantages than control with the transformer. One of the biggest disadvantages of controlling the OLTC is a large number of changes in the tap, which is costly due to depreciation.

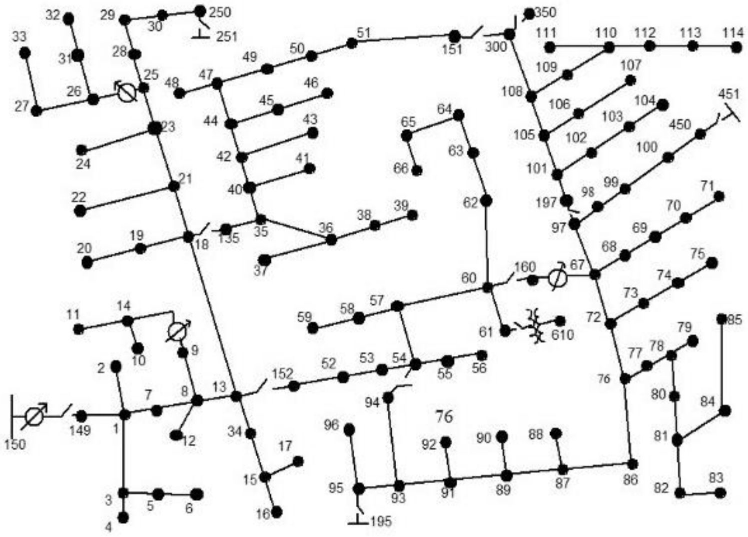

Figure 6. 123-bus system [20]

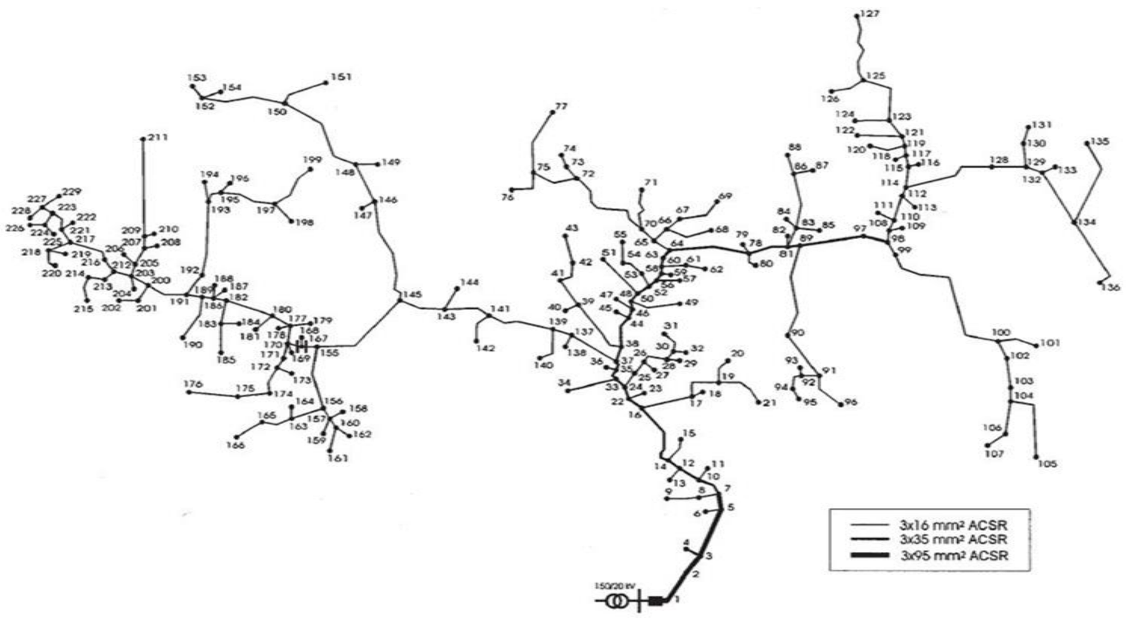

Figure 7. 229-bus system

C. Case 3: 229-Bus Network

The 229-bus test network shown in Figure 7 has 46 DGs which the information is provided in [21]. The control variables, tap settings and simulations process are also considered as the case 1.

C.1. Scenario 1

The scenario conditions are considered as follows:

$w_L = 0.1,\ w_V = 3,\ w_S = 3,\ \alpha = 0.1$

In this scenario, the energy loss starts at 600 kW and converges at 362 kW. The energy loss in uncontrolled state is 550 kW, which shows an acceptable non-controlling method. But the strong variation of the voltage and the longtime of converging can be considered as the disadvantages of this scenario. The minimum voltage in this scenario starts at 0.86 pu and converges to 0.958 pu, and the maximum voltage starts at 0.95 pu and converges to 1.05 pu.

For a good conclusion, we can change the weight coefficients of the case and again calculate the variables that are implemented in the second scenario.

C.2. Scenario 2

The scenario conditions are considered as follows:

$w_L = 0.5,\ w_V = 0.3,\ w_S = 0.3,\ \alpha = 0.1$

In this scenario, due to the change in the coefficients, especially reduction of W_S and W_V, it is expected that the convergence results will be achieved in short time with less fluctuations, which will result in a more favorable outcome.

In this scenario, energy loss starts at 600 kW and converges at 353 kW. From above mentioned, the energy loss in uncontrolled state is 550 kW, which shows an acceptable non-controlling method. The second scenario has less fluctuation and short time amounts as n advantageous rather than the first scenario. Also, the minimum voltage in this scenario starts at 0.86 pu and converges to 0.956 pu and the maximum voltage starts from 0.95 pu and converges to 1.056. pu The minimum and maximum voltages were not significantly different from the first scenario, and only the control period is reduced, which can be considered as a great advantage.

From the results of the two scenarios, it can be concluded that by changing the constant coefficients, the convergence time can be reduced, and the amount of fluctuations in energy loss and also maximum and minimum voltages can be improved. And considering the low voltage oscillation, it can be concluded that the variations of the transformer pulse will be decreased, which it will reduce the system's depreciation.

VI. CONCLUSION

In comparison of the distributed control method and other related methods, the total number of tap changing rate is great. The reason is related to increasing the frequency of tap switching in this method. i.e. each time the algorithm is executed, then all of the repetitions occur, and the generators are updated. In the distributed strategy, the control points are updated at the end of each repetition, and then, all of the control variables on the network are updated at the next repetition performing and this process will bring complete convergence.

In this method, given the free capacity of the generators connected to the network, when the distributed solution starts at $t = 1$ sec. Also, due to the existence of severe voltage disturbances in the grid before the start of the control process, the control factors bring the maximum reactive power to the circuit to eliminate the voltage violation. By applying this decision to the generators and updating their reactive power points, at the very beginning of the work, the voltage violation is partially overcome and the network losses, as indicated in the graphs, drop sharply.

Furthermore, due to the relative reduction of losses, control factors are sought to reduce the reactive power injected by distributive generators into a safe and stable state. But as the reactive power injected decreases, the system voltage drops again, causing a collapse in the balance, and control factors must be introduced, this process is repeated frequently. It is observed with these interpretations that the distributed method is not as consistent as other methods, so that it can only control the system using reactive power and requires the use changing tap of OLTC. The advantages of this approach include less computational load and scalability for larger networks compared to centralized methods and higher reliability than other methods, which cannot be overlooked. Enhanced reliability is such that even if a single agent fails, the system is able to continue its work, although it is less efficient, but in a decentralized manner, with the destruction of the regional control center, only the control of that area is lost, and in a centralized way Failure of one part will stop the entire system's performance.

REFERENCES

[1] M.E. Baran, I.M. El-Markabi, "A Multiagent-Based Dispatching Scheme for Distributed Generators for Voltage Support on Distribution Feeders", IEEE Trans. Power Syst., Vol. 22, No. 1, pp. 52-59, 2007.

[2] M. Brenna, E. De Berardinis, L. Delli Carpini, et al., "Automatic Distributed Voltage Control Algorithm in Smart Grids Applications", IEEE Trans. Smart Grid, Vol. 4, No. 2, pp. 877-885, 2013.

[3] M. Kenzunovic, "The Next Generation EMS Design", CIGRE Lisbon Symposium, Lisbon, Portugal, 2013.

[4] H. Song, M. Kenzunovic, "A New Analysis Method for Early Detection and Prevention of Cascading Events", Electric Power Systems Research, Vol. 77, No. 8, pp. 1132-1142, 2007.

[5] C.M. Hird, H. Leite, N. Jenkins, et al., "Network Voltage Controller for Distributed Generation", IEE Proc. Gener. Transm. Distrib., Vol. 151, No. 2, pp. 150-156, 2004.

[6] A. Bose, "Smart Transmission Grid Application and Their Supporting Infrastructure", IEEE Transaction on Smart Grid, Vol. 1, No. 1, pp. 11-19, June 2010.

[7] M. Kenzunovic, J. McCalley, T. Overbye, "Smart Grids and Beyond: Achieving the Full Potential of

Electricity Systems", Proceedings of the IEEE, Vol. 100, pp. 1329-1341, 2012.

[8] J. Giri, M. Parashar, J. Trehern, V. Madani, "The Situation Room", IEEE Power and Energy Magazine, Vol. 10, No. 5, pp. 58-69, 2012.

[9] T. Jen-Hao, "A Direct Approach for Distribution System Load Flow Solutions", IEEE Trans. Power Deliv., Vol. 18, No. 3, pp. 882-887, 2003.

[10] H. Fallahzadeh Abarghouei, M. Nayeripour, S. Hasanvand, E. Waffenschmidt, "Online Hierarchical and Distributed Method for Voltage Control in Distribution Smart Grids", IET Generation, Transmission & Distribution, 2017.

[11] IEEE Working Group on Distribution Automation, "IEEE Tutorial Course on Distribution Automation", IEEE Power Engineering Society, 1988.

[12] "IEEE Tutorial Course on Power Distribution Planning", Series: IEEE Tutorial Course, 1992.

[13] W.M. Lin, M.S. Chen, "An Overall Distribution Automation Structure", Elect. Power Syst. Res., Vol. 10, pp. 7-19, 1986.

[14] B. Stott, O. Alsac, "Fast Decoupled Load Flow," IEEE Trans. Power Apparat. Syst., Vol. 93, pp. 859-869, May/June 1974.

[15] J.H. Teng, W.M. Lin, "Current-Based Power Flow Solutions for Distribution Systems", IEEE Int. Conf. Power Syst. Technol., Beijing, China, pp. 414-418, 1994.

[16] T.S. Chen, M.S. Chen, T. Inoue, E.A. Chebli, "Three-Phase Cogenerator and Transformer Models for Distribution System Analysis", IEEE Trans. Power Delivery, Vol. 6, pp. 1671-1681.2, Oct. 1991.

[17] A. Nedic Ozdaglar, "Distributed Subgradient Methods for Multi-Agent Optimization", IEEE Trans. Autom. Control, Vol. 54, No. 1, pp. 48-61.

[18] M.E. Elkhatib, R.E. Shatshat, M.M.A. Salama, "Decentralized Reactive Power Control for Advanced Distribution Automation Systems", IEEE Trans. Smart Grid, Vol. 3, No. 3, pp. 1482-1490, 2012.

[19] M. Chis, M. Salama, S. Jayaram, "Capacitor Placement in Distribution Systems Using Heuristic Search Strategies", IEE Proc. Gener. Transm. Distrib., Vol. 144, No. 3, pp. 225-230, 1997.

[20] Distribution Test Feeder Working Group, "Distribution Test Feeders", 2010, http://ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html.

[21] S. Safigianni, G.J. Salis, "Optimum Voltage Regulator Placement in a Radial Power Distribution Network", IEEE Trans. Power Syst., Vol. 15, No. 2, pp. 879-886, 2000.

BIOGRAPHIES

Alireza Jodaei was born in Tabriz, Iran, in 1993. He received the B.Sc. degree in Electrical Engineering from University of Bonab, Bonab, Iran and the M.Sc. degree in Power Engineering from Seraj Higher Education Institute, Tabriz, Iran in 2018. Currently, he is studying the Ph.D. in Power Engineering at University of Semnan, Semnan, Iran. His areas of research interests include distributed voltage and reactive power management and smart grids.

Naser Mahdavi Tabatabaei was born in Tehran, Iran, 1967. He received the B.Sc. and the M.Sc. degrees from University of Tabriz (Tabriz, Iran) and the Ph.D. degree from Iran University of Science and Technology (Tehran, Iran), all in Power Electrical Engineering, in 1989, 1992, and 1997, respectively. Currently, he is a Professor in International Organization of IOTPE (www.iotpe.com). He is also an academic member of Power Electrical Engineering at Seraj Higher Education Institute (Tabriz, Iran) and teaches power system analysis, power system operation, and reactive power control. He is the General Chair and Secretary of International Conference of ICTPE, Editor-in-Chief of International Journal of IJTPE and Chairman of International Enterprise of IETPE, all supported by IOTPE. He has authored and co-authored of 8 books and book chapters in Electrical Engineering area in international publishers and more than 160 papers in international journals and conference proceedings. His research interests are in the area of power system analysis and control, power quality, energy management systems, microgrids and smart grids. He is a member of the Iranian Association of Electrical and Electronic Engineers (IAEEE).