Voltage Control of Unbalanced Distribution Systems with Penetration of Renewable Sources: A Gradient-Based Optimization Approach

Ramin Ebadi[1], Hande Şenyüz[2], Fathy Aboshady[3,4], Oguzhan Ceylan[5], Ioana Pisica[3], and Aydogan Ozdemir[1]

[1]Department of Electrical Engineering, Istanbul Technical University, Turkey
Email: ebadi21@itu.edu.tr, ozdemir@itu.edu.tr

[2]Management of Information Systems Department, Kadir Has University, Turkey
Email: hande.senyuz@khas.edu.tr

[3]Department of Electronic and Computer Engineering, Brunel University, London United Kingdom
Email: ioana.pisica@brunel.ac.uk, Fathy.Aboshady@ieee.org

[4]Electrical Power and Machines Engineering Department, Tanta University, Tanta, Egypt
Email: Fathy.Aboshady@ieee.org

[5]Department of Electrical and Electronics Engineering, Marmara University, Istanbul, Turkey
Email: oguzhan.ceylan@marmara.edu.tr

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***Abstract*—The penetration of distributed energy resources (DERs), including renewable energy sources (RES), into electric power systems has led to several challenges for the system operators. Despite various economic and environmental benefits offered by RES, the issue of voltage rise due to active power injection from RES is still an open problem. On the other hand, voltage decrease due to high load in distribution systems is another challenge faced by operators. In this study, we investigated the problem of over-voltage and under-voltage in the operation of unbalanced 3-phase distribution systems with penetration of RES. Moreover, We utilize derivative-based Exterior Penalty Function (EPF) optimization to solve the voltage deviation problem. The results of the tests conducted on a modified IEEE 13 Bus Test System have confirmed that the use of the tap changer voltage regulators and reactive power from PVs connected close to inverters can effectively contribute to the voltage control problem.**

***Index Terms*—Volt/Var control (VVC), Photovoltaic power, Voltage regulator, Unbalanced distribution systems, derivative-based optimization methods**

I. INTRODUCTION

The study of solutions to the problem of voltage deviation in distribution systems has attracted considerable attention from researchers in recent years. In particular, this can be of great importance in unbalanced 3-phase distribution systems. The voltage deviation includes the problems of voltage drop and voltage rise. Voltage drop occurs mainly during the high-load periods and at heavily loaded sites [1]. Considering the economic and environmental benefits of RES, the use of these energy sources in power systems is inevitable. On the other hand, the use of RES in power systems sometimes leads to over-voltage problems due to the injection of active power [2].

To deal with the above problems, researchers have developed various approaches, including centralized and decentralized voltage control methods. Although these methods have their advantages and disadvantages, they can be effective under different circumstances [3]. In particular, Volt/ Var control of smart PV inverters can be considered as an efficient method to minimize voltage deviation [4].

These control methods evaluate the voltage deviation problem in the operating phase of power systems. In general, an optimization problem in power system operation is solved with the desired objective function, such as minimizing the voltage deviation from a nominal voltage or minimizing the total power losses in the system. Considering the time efficiency and accuracy indices, different optimization approaches have been studied. In a classification, these optimization methods can be divided into four groups. First, analytical methods which are suitable for small-scale systems. Second, non-heuristic approaches that perform better than analytical methods to obtain a near-optimal answer. Third, meta-heuristic methods which are inclusive of swarm-based and evolutionary optimization techniques. Finally, hybrid methods which combine two or more optimization methods for solving the problem. It is noteworthy that for each of these groups, different advantages and also shortcomings have been demonstrated, and the selection of the most suitable method can be considered as a compromise.

A. Literature review

Voltage control of unbalanced distribution systems is a well-known problem that has been addressed by several researchers. Although there have been various recent studies in this area, improving the solution method in terms of convergence and time efficiency in special cases is an open problem. Voltage deviation as a result of the integration of PV units in distribution networks has been studied in [5]. In this study, the authors applied a heuristic optimization method, namely Grey Wolf Optimization (GWO) , to solve the operation problem of the 33 and 69 Bus Test systems integrated with tap changers and capacitors. In [6], the authors have presented an online volt/var control (VVC) system for unbalanced distribution systems with distributed energy sources. To improve the convergence speed, the projected Newton method was used. Voltage control problem of PV installed unbalanced IEEE 123-bus test system is further studied in [7] using the voltage regulators and the magnetizing reactance of the voltage regulators. In the mentioned work, the authors used Augmented Lagrangian Multipliers as a non-heuristic method to solve the optimization problem. The simulation results show that a large number of tap operations are required to keep the voltages within an allowable deviation, and that this large number of tap operations is sometimes insufficient to force the voltage into the allowable voltage range. Voltage regulation problem by means of reactive power control and on-load tap changer of distributed energy resources in 123-bus radial distribution system is investigated in [8]. The proposed control framework is maintained in two stages of a centralized controller, for minimizing delivery losses and voltage profile improvement, and local controller for voltage stability. Specifically, the local proportional-integral (PI) controller considered in this study, can detect the optimal voltage at renewable-integrated buses with a proper accuracy and can reduce the tap changer operations during the fluctuations of renewable sources. In [9], the allocation and planning problem of DG units and storage systems in distribution networks was considered by proposing a multi-objective framework aimed at improving the voltage profile, minimizing annual investment, operation, and maintenance costs, and maximizing energy transfer between off-peak and peak hours. In [10], coordinated performance of the demand response and Volt/Var optimization in unbalanced distribution systems with PV inverters, voltage regulators, on-load tap changers and capacitor banks is studied as a novel and comprehensive framework. The multi-objective particle swarm optimization (MOPSO) approach is utilized to solve the problem and the results illustrate that the proposed framework contributes to the voltage regulation and has better performance in comparison to the conservation voltage reduction method. In particular, the presented scheme results in significant peak load reduction as well as energy losses. In [11], the data-driven optimization is compared to the linearized power flow-based optimization approach for voltage control problem of the distribution systems with penetration of DERs as well as tap changer voltage regulators and capacitors. Results validated that the proposed framework can perform better in terms of voltage regulation in comparison to the traditional methods. To alleviate the computational burden of centralized voltage control method of large-scale distribution systems by the reactive power of distributed energy resources, authors in [12] have presented an innovative distributed control scheme by network partitioning method. In the mentioned study the effect of integrating energy storage systems besides the renewable sources in the distribution networks have been considered.

Deep reinforcement learning techniques are used for voltage control of unbalanced distribution networks in [13]–[15]. In [13] the relationship between the power injections and the voltage deviations in each node is obtained by supervised training as a surrogate model. Then, the deep reinforcement learning technique is used to define the optimal control method. The advantage of the proposed strategy is the ability to make decisions in real time to handle sudden voltage deviations as a result of changes in PV generation. Specifically, in [14] a physical-model-free voltage control method is presented to decrease the need for exact parameters of the distribution systems. Moreover, the control method in this study is suitable for either fast time scale, by means of PV inverters, or slow time scale, by means of on-load tap changers and capacitor banks.

B. Contribution

We study the distribution system voltage control problem in an unbalanced IEEE 13-bus test system in this paper as a medium voltage (MV) grid. The penetration of PV power is considered with a smart PV inverter which can inject or absorb reactive power to control over-voltage or under-voltage problems. In addition, a voltage regulator has been considered in this system as another option to control voltage deviation. A derivative-based optimization method, namely the Exterior Penalty Function (EPF), is used to solve the optimization problem [16], [17]. The main contributions of this paper can be summarized as follows:

- Voltage control problem in an unbalanced modified IEEE 13 Bus test system has been investigated by considering active and reactive power from PV as well as tap changer voltage regulator.
- EPF optimization approach has been utilized as a derivative-based method for solving the operation problem of the system.

The remainder of this paper is organized as follows:
The methodology of the proposed framework is presented in Section II. Section III represents the case studies, results and discussions. Finally, the paper is concluded in Section IV.

II. METHODOLOGY

Generally, the operation problem of the power systems can be formulated as an optimization scheme in which the power flow is performed for the intended system. At first, the proper power flow method for the studied system is explained. Afterwards, the operation problem of the distribution system is formulated as an optimization framework.

A. Power Flow

In terms of convergence criterion, the Backward-forward sweep (BFS) method is considered as one of the most efficient approaches to solve the power flow problem of radial distribution systems in comparison to the Newton-Raphson (NR) method. The detailed formulation and algorithm of the BFS method are proposed below [18]. Consider the series impedance of a line section as:

$$Z_l = \begin{pmatrix} Z_{aa,l} & Z_{ab,l} & Z_{ac,l} \\ Z_{ab,l} & Z_{bb,l} & Z_{bc,l} \\ Z_{ac,l} & Z_{bc,l} & Z_{cc,l} \end{pmatrix} \tag{1}$$

by considering the root node as slack node and initializing the voltage of other nodes equal to the root node, the iterative algorithm can be lunched in three steps. At first step, the nodal currents are calculated. Backward sweep is implemented in step 2 to calculate line currents. Finally, at third step, Forward sweep is done to calculate node voltages. When all of these three steps are done, a nodal voltage is calculated for each bus and one iteration is completed. After each iteration the calculated root node voltage is compared to the predefined root voltage and if the error is smaller than a convergence threshold the procedure is finished. On the other side, if the error is greater than the threshold, next iteration will start from step 1 by considering the calculated node voltages from the previous iteration. The detail description of the iterative method is as follows:

1) Nodal current calculations:
Considering the type of load connected to each node, the nodal current for each bus is calculated in this step. In Eq. 2 the coefficeints C_1, C_2 and C_3 can be calculated based on the bus load and initialized node voltages. Eq. 3 represents the shunt elements' admittance matrix at node i. Finally, the nodal currents are calculated by Eq. 4.

$$\begin{pmatrix} C_1 \\ C_2 \\ C_3 \end{pmatrix} = \begin{pmatrix} (S_{ia}/V_{ia}^{(k-1)})^* \\ (S_{ib}/V_{ib}^{(k-1)})^* \\ (S_{ic}/V_{ic}^{(k-1)})^* \end{pmatrix} \tag{2}$$

$$Y_l = \begin{pmatrix} Y_{ia} & 0 & 0 \\ 0 & Y_{ib} & 0 \\ 0 & 0 & Y_{ic} \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} I_{ia}^{(K)} \\ I_{ib}^{(K)} \\ I_{ic}^{(K)} \end{pmatrix} = \begin{pmatrix} C_1 \\ C_2 \\ C_3 \end{pmatrix} - Y_l * \begin{pmatrix} V_{ia}^{(K-1)} \\ V_{ib}^{(K-1)} \\ V_{ic}^{(K-1)} \end{pmatrix} \tag{4}$$

Where, S_{ia}, S_{ib} and S_{ic} are the scheduled load at node i and phases a, b and c, respectively. V_{ia}, V_{ib} and V_{ic} are representative of initialized voltages at node i in three phases. k is the indicator of iterations. Y_{ia}, Y_{ib} and Y_{ic} stand for the admittance of all shunt elements at node i. Finally, I_{ia}, I_{ib} and I_{ic} are the current at node i in different phases corresponding to the constant load and shunt elements.

2) Backward sweep to calculate line currents:
Based on the Kirchhoff's current law (KCL), Starting from the end nodes (the last node in each branch) to the root node, the current on line l can be calculated as:

$$\begin{pmatrix} J_{la}^{(K)} \\ J_{lb}^{(K)} \\ J_{lc}^{(K)} \end{pmatrix} = - \begin{pmatrix} I_{ja}^{(K)} \\ I_{ja}^{(K)} \\ I_{ja}^{(K)} \end{pmatrix} - \begin{pmatrix} J_{ma}^{(K)} \\ J_{mb}^{(K)} \\ J_{mc}^{(K)} \end{pmatrix} \tag{5}$$

Where J_{la}, J_{lb} and J_{lc} stand for the currents flowing on line l in phases a, b and c, respectively. The set of lines which are connected to bus j are indicated by m.

3) Forward sweep to calculate node voltages:
Considering the Kirchhoff's voltage law (KVL), the following equation is used to update the node voltages, starting from the root node to the end nodes.

$$\begin{pmatrix} V_{ja}^{(K)} \\ V_{jb}^{(K)} \\ V_{jc}^{(K)} \end{pmatrix} = \begin{pmatrix} V_{ia}^{(K)} \\ V_{ib}^{(K)} \\ V_{ic}^{(K)} \end{pmatrix} - Z_l \begin{pmatrix} J_{la}^{(K)} \\ J_{lb}^{(K)} \\ J_{lc}^{(K)} \end{pmatrix} \tag{6}$$

B. Optimization approach by EPF

Since the computation time of operational problems are very important, especially when it is close to real-time simulation, the EPF method can be considered as an option for this purpose. In general, the overall scheme of an optimization problem can be considered as follows:

$$\begin{aligned} &\text{maximize} && f(x) \\ &\text{subject to} && g(x) = 0, \\ &&& h(x) \leq 0 \end{aligned} \tag{7}$$

where $f(x)$ is the objective function. $g(x)$ and $h(x)$ are the equality and inequality constraint(s), respectively. The general procedure in EPF is changing the constrained problem into a sequential unconstrained framework. To satisfy the constraints in this method, a penalty multiplier is considered as represented in Eq. 8.

$$max \quad P = f(x) + \lambda g(x) + \mu h(x) \tag{8}$$

Here λ and μ are the penalty multipliers for equality and inequality constraints, respectively. It is notable that the EPF is highly sensitive to the initial values in the simulation process. Therefore, choosing a proper initial point is inevitable and various starting points may result in different answers.

To sum up, the optimization framework that is studied in this paper can be formulated as follows:

- Objective function
  The aim of this paper is to force the voltages near to the nominal value. Furthermore the objective function can be considered as Eq. 9:

$$\text{minimize} \quad \sum_{i=1}^{I}(1-V_{i,t})^2 \tag{9}$$

  In which V_i is the node voltage at bus i. I is the total number of buses. t is the index of time in hours and T is the total number of hours in the scheduling horizon.

- Constraints
  Voltage magnitudes of all buses should be between 0.95 p.u. and 1.05 p.u. which is defined by Eq. 11. Moreover, tap position values cannot exceed a predefined limit. This is described by Eq. 12. Finally, the reactive power of the PV inverter should satisfy the upper and lower limits as Eq. 13. It might be of a great interest to note that the reactive power of the inverter is a function of its active and apparent power that is given in Eq. 14.

$$\begin{aligned} & & & (10)\\ \text{subject to} \quad & V^{min} \le V_{i,t} \le V^{max}, & & (11)\\ & TP^{min} \le TP_t \le TP^{max}, & & (12)\\ & Q_t^{min} \le Q_t \le Q_t^{max} \quad , & & (13)\\ & P^2 + Q^2 \le S^2 & & (14) \end{aligned}$$

here V^{min} and $V^{max}$are the lower and upper limit of the bus voltages, respectively. TP_t is the tap position values at each hour and TP^{min} and TP^{max} are the limit values of the tap positions. Q_t is the reactive power transfer in each hour and Q_t^{min} and Q_t^{max} are the upper and lower boundaries of the PV unit's reactive power in each hour t. Finally, P is the active and S is the apparent power of the inverter, respectively.

III. TESTS AND RESULTS

The studied system is unbalanced IEEE 13-bus distribution network and the single line diagram of the unbalanced modified IEEE 13 Bus Test System is depicted in Fig. 1. As shown in the figure a PV unit with 600KW capacity is installed at end node 675. Since the IEEE 13 bus standard system is operating at 4.16 KV it can be considered as a medium voltage (MV) grid. Moreover, the R/X ratio in this system is considered to be 3.11. In addition, a voltage regulator is used between nodes 650 and 632. The maximum and minimum tap position value is assumed to be 16 and -16, respectively. The coefficients of PV power generation and hourly load are presented in Fig. 2.

Three cases are studied as follows and the results are presented:

- Case 1- Base case: No voltage control method is implemented.
- Case 2: Only voltage regulator is considered and changing tap positions are the only option for controlling the voltage.
- Case 3: Both PV unit and the voltage regulator are considered and the reactive power and tap positions are the options for voltage control.

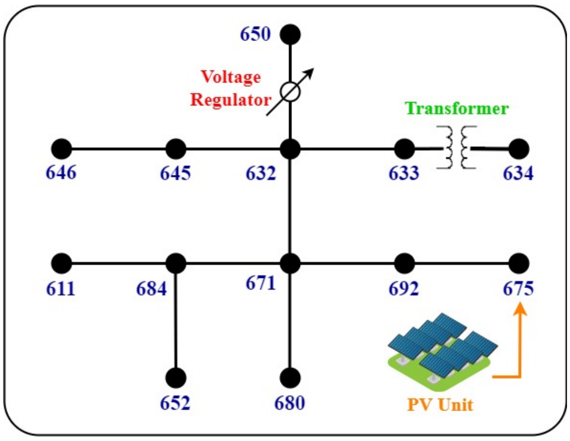

Fig. 1. Single line diagram of modified IEEE 13 Bus Test System

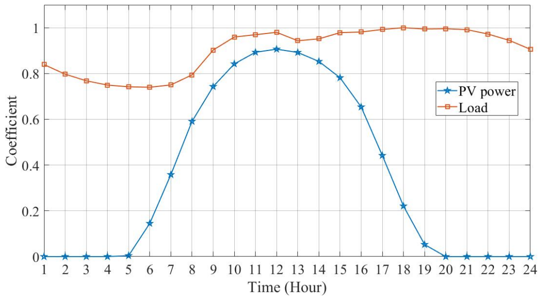

Fig. 2. Hourly coefficients of the PV power and load profile

1) Case 1: Base case study does not consider any control method for voltage magnitudes, thus the impact of PV unit's active power as well as reactive power of the PV and tap positions have been ignored. The sum of the objective function for this condition using 24 hours of simulations is calculated as 3.0627. Fig 3 shows the phase voltage magnitudes for 24 hours. We show the voltage profile of one bus over 24 hours, i.e. bus 634, to provide a better comparison. As can be understood from this figure, even though the voltage profile of phase 'b' does not involve a dramatic under-voltage or over-voltage issue, it is not near the nominal voltage (1 p.u.). However, the voltage magnitudes of phases 'a' and 'c' have under-voltage problem due to high loading and the overall voltage profile of them is below the allowed limit at 0.95. Specifically, the maximum and minimum voltage of the mentioned bus is bounded between 0.9246 and 0.9815 which is illustrated in Fig. 3 by green dashed lines.

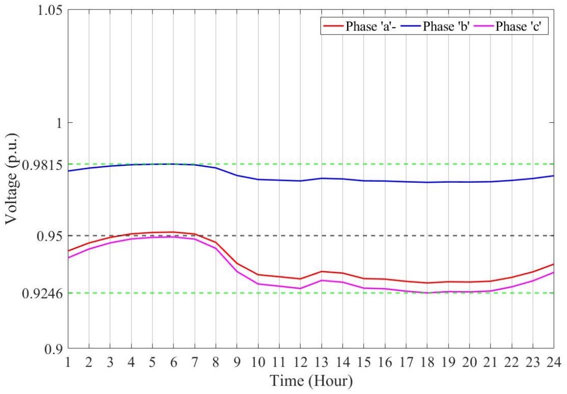

Fig. 3. 3-phase voltage profile of bus 634 in 24 hours before implementing control method- Base Case

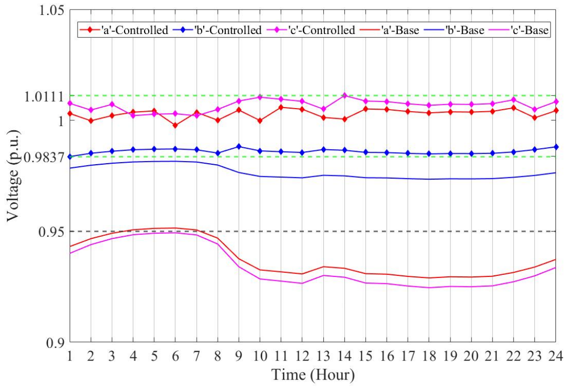

Fig. 4. 3-phase voltage profile of bus 634 in 24 hours before and after implementing control method- Case 2

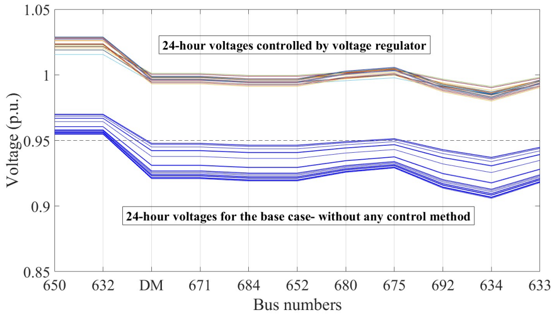

Fig. 5. Node voltages of phase ’a’ in 24 hours before and after implementing control method- Case 2

2) Case 2: In this case only the voltage regulator is taken into account for voltage deviation minimization and the final voltage profile is as shown in Fig. 4. The final voltage is satisfying the constraints and is close to the nominal voltage (1 p.u.) that is modified sufficiently in comparison to the base case. In particular, as illustrated by green dashed lines, the maximum and minimum voltage deviation is limited between 0.9837 and 1.0111 after implementing the control method. In comparison to the base case, it is obvious that applying the control method with voltage regulator has shifted the overall voltage profile to an interval near 1 p.u. and inside the allowed boundaries. In addition, Fig. 5, Fig. 6 and Fig. 7 are representative of the all nodal voltages in the studied system for phases a, b and c, respectively. In this case the objective function value is 0.1523 which is lower in comparison to Case 1. Moreover, Fig 8 illustrates the calculated optimal tap positions for each simulated hour. Since there is not much voltage problem in phase ’b’, the tap positions related to this phase is relatively close to zero and also not varying that much during the simulation horizon. On the other side, since there is an under-voltage problem in phases ’a’ and ’c’, the tap positions related to these phases are fluctuating more to bring the voltage magnitude in a desired interval. For instance, after hour 6 AM, an under-voltage trend is started in the voltage profile of all 3 phases in the base case. As a result, the tap position values are started to increase , specially in phases ’a’ and ’c’ to overcome this problem until hour 11 AM.

3) Case 3: In this case both reactive power and tap positions are the options for voltage deviation minimization. Since in this case there are two control options, it is expected that the results will be better in comparison to the previous two cases. In other words, the voltage profile will be smoother and the objective function value will be smaller which is validated by results where the objective function value is 0.1301 that is lower than the two previous cases. Fig. 9 illustrates the 24-hour voltage profile of bus 634 for 3 phases. Moreover, the voltage profile of other buses are also between the desired boundaries and near to the nominal value (1 p.u.). As shown in Fig. 9 the voltage profile in 24 hours is closer to 1 p.u. and the maximum and minimum voltage deviation after implementing the control method is forced between 0.979 p.u. and 1.0097 p.u. that is shown by dashed green lines on the figure. To provide a general overview of the all node voltages, voltage profile of the phases a, b and c are depicted in Fig. 10, Fig. 11 and Fig. 12, respectively. Moreover, the reactive power profile of the smart PV inverter and tap position values are depicted in Fig. 13 and Fig. 14, respectively. As can be seen in Fig 13 the reactive power flow is zero between hours 1-4 and 20-24 since there is no sun irradiation during that hours. On the other side, between hours 5-19 the inverter injects reactive power in case of under-voltage (positive values on the figure) and absorbs reactive power during over-voltage (negative values on the figure) to control the voltage fluctuations. For instance the inverter injects reactive power at hour 14 in phase ’b’ of bus ’634’ and absorbs reactive power at the same time from phase ’c’ of the mentioned bus. In addition, Fig 14 illustrates the tap position values of voltage regulator in 24 hours and for three phases. By comparing these two figures it can be concluded that in the given topology of the system and defined load and PV scales, the system tends to control the voltage mostly by tap position values rather than the reactive power of PV unit.

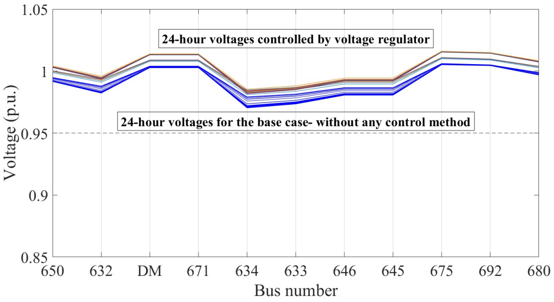

Fig. 6. Node voltages of phase ’b’ in 24 hours before and after implementing control method- Case 2

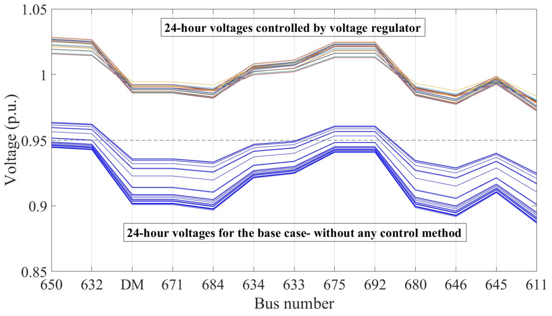

Fig. 7. Node voltages of phase ’c’ in 24 hours before and after implementing control method- Case 2

IV. Conclusion

In this paper the voltage control problem of unbalanced distribution networks on IEEE 13-bus test system is studied. Among various methods of voltage control the voltage regulator and smart PV inverter is utilized to optimize the voltage deviation issue in the system. to obtain a better convergence as well as numerical stability the EPF method is used as a gradient-based optimization approach to solve the problem. Three case studies are investigated to analyze the effect of mentioned control methods on the 13-bus system. Based on the results it can be concluded that implementing the proposed method can contribute effectively to the voltage control problem of the distribution system. In particular, the objective of the paper was to force the voltages inside the desired boundaries and near to the nominal voltage. Results validated that by using a voltage regulator the value of objective function is decreased by 95.75% in comparison to the case that there is not any voltage control strategy. Moreover, by using the voltage regulator and smart PV inverter simultaneously, there is 14.57% more decrement in the value of the objective function in comparison to the case with only voltage regulator.

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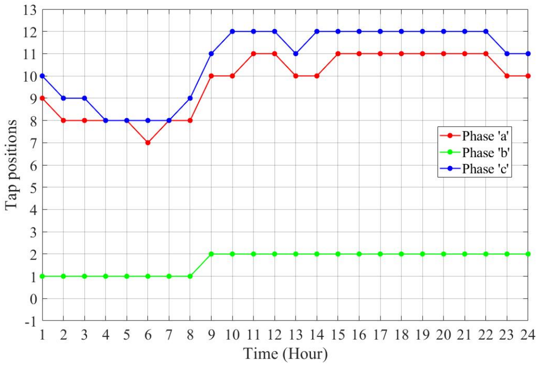

Fig. 8. Tap position changes of the voltage regulator in 24 hours- Case 2

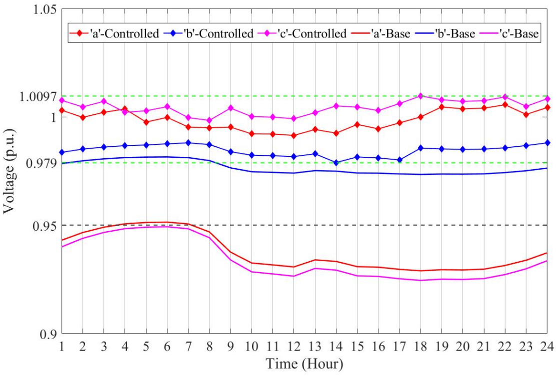

Fig. 9. 3-phase voltage profile of bus 634 in 24 hours before and after implementing control method- Case 3

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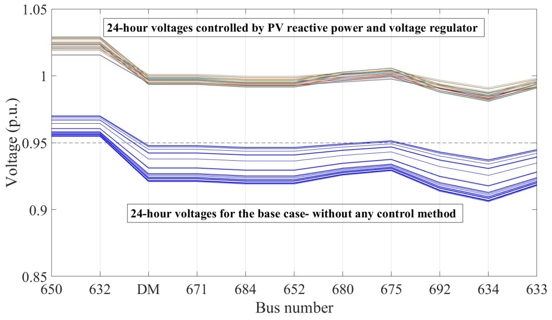

Fig. 10. Node voltages of phase 'a' in 24 hours before and after implementing control method- Case 3

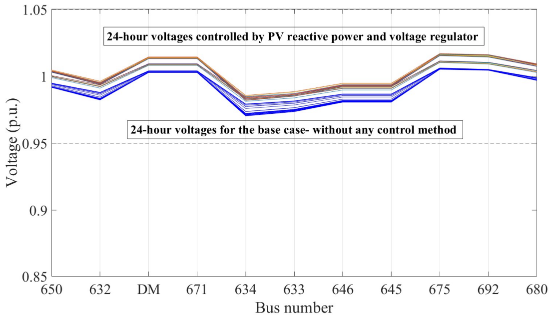

Fig. 11. Node voltages of phase 'b' in 24 hours before and after implementing control method- Case 3

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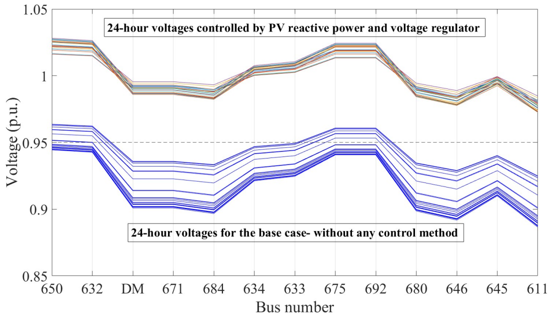

Fig. 12. Node voltages of phase 'c' in 24 hours before and after implementing control method- Case 3

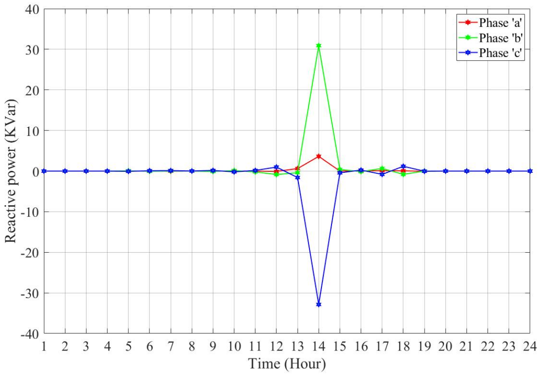

Fig. 13. Reactive power flow of smart inverter in 24 hours- Case 3

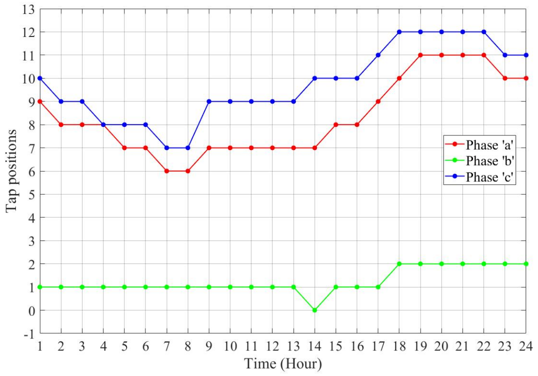

Fig. 14. Tap position values of voltage regulator in 24 hours- Case 3