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An Effective Coordination Strategy for Voltage Regulation in Distribution System Containing High Intermittent Photovoltaic Penetrations

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ABSTRACT In recent years, with increasing the penetration of renewable-based distributed generations, voltage control plays a vital role in operating distribution systems. Furthermore, the traditional voltage control devices are not fast enough to regulate the voltage due to transient events and the intermittent characteristics of renewable energy sources. On the other hand, because of the fast response of power electronic components, the photovoltaic (PV) inverter can cope with the intermittent and uncertainty of power generation due to weather changes. Therefore, this paper proposes a cooperative voltage control scheme to solve the voltage problems associated with high PV penetration. The scheme is developed based on a multi-agent system (MAS) with a distributed control architecture using time coordination between voltage regulators and reactive power control of the PV inverters. The scheme's objective is to minimize voltage deviations and reduce the stress on the traditional voltage control devices by utilizing the available reactive power of the PV inverters. Different simulations are carried out and analyzed for various operating conditions over 24 hours using the IEEE 34-bus and 123-bus test feeders. The simulation results show that the proposed control scheme can successfully reduce the total voltage deviation and decrease the number of tap operations of voltage regulators at different sun profiles.

INDEX TERMS Distributed control, multi-agent, photovoltaic, unbalanced systems, voltage deviations.

I. INTRODUCTION

The regulation of voltage in distribution systems (DS) with the high installation of distributed generations (DGs) becomes a great challenge for the system operator. Furthermore, the uncertain nature and the high penetration of renewable energy sources (RESs), in particular photovoltaics (PVs), cause various voltage problems and excessive operation of conventional devices of voltage control [1], [2].

The conventional devices of voltage regulation in the active DSs such as on-load tap-changer (OLTC), step voltage regulators (SVR), and shunt capacitors (SC) are not fast enough to act with the rapid change of voltages due to the intermittent characteristics of RESs [3], [4]. Besides, it is difficult to determine the proper control setting for those devices in the presence of high PV penetration.

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Recently, the smart inverter has the capability to deal with rapid and random fluctuations of the generated power by the PVs [5]. Hence, the PV inverter has a fast response in case of voltage violations, and it can react within a few milliseconds while other conventional devices need a few seconds to take action [4], [6].

Several studies have been conducted to solve the voltage problems caused by the high penetration of PVs in the DS. Upgrading for the control strategies of conventional devices is presented in several research studies as a solution for voltage control problems. In [7]–[9], a novel control strategy for managing the voltage regulators based on a multi-agent system (MAS) is developed by the authors; the voltages are effectively regulated by adjusting the conventional types of voltage controllers. The optimal performance is almost achieved using a simple distributed control structure.

The optimal operation of the voltage control devices is presented in several studies. In [10]–[13], the conventional voltage control devices are operated optimally to achieve the voltage regulation of the DS. Also, utilizing the reactive power of the DGs optimally to mitigate the voltage problems is discussed in [14], [15]. The optimal operation needs a centralized control structure with a high-cost investment and a robust communication system to achieve the best performance [16], [17].

On the other hand, several local control approaches have been introduced to manage the voltage regulation devices in the DSs based on local observations. The local approaches include controlling the step voltage regulators using line drop compensator [18], [19], controlling the dead band of the load tap changing (LTC) [20], reactive power control of PV inverters [21], [22], curtailment of PVs power [23], [24], and so on. The local approaches perform a real-time control that is generally reliable and robust due to their simple configuration and independent control system. However, the control performance is affected by the lack of coordination among the control devices, limiting the capability to utilize all system resources.

Coordinated control of different devices of voltage control in the DS has been presented in various researches. For voltage control, coordination between the PV inverters and battery energy storage systems (BESS) is developed using a real-time approach as described in [3]. In [10], the coordination between the OLTC and the static VAr compensator (SVC) in the DS is proposed using a two-stage approach. Based on a combination of different control concepts, coordination among different devices of voltage regulation has been presented in [25]. In [26], an optimization problem is solved to coordinate the OLTC and the reactive power of the PVs, by minimizing the number of tap changes and calculate the set point of OLTC to avoid the runaway. The coordination among the voltage control devices in the DS improves the control performance, increases the utilization capability of the system resources, and achieves a smooth operation of the control devices. On the other hand, in most cases, a robust communication system is needed to avoid the degradation of the control system and achieve an effective coordination process.

This paper fulfills the gaps in the approaches mentioned above by developing an effective coordination process using a distributed control structure based on the MAS architecture. The proposed method coordinates between the voltage regulators and the reactive power of the PV inverters to minimize the voltage deviations and decrease the number of tap operations. The developed control algorithm by the authors in [7] is upgraded to coordinate with the PV inverters capability and relieve the operation stress of the voltage regulators. Firstly, the available amount of reactive power of the PV inverters is utilized to regulate the voltage at their local nodes based on a voltage/reactive power sensitivity approach. Then, the voltage regulators use the PV nodes as observation points and act based on their regulated voltages to minimize the overall system violations. The effectiveness of the proposed method lies in the flexibility of coordination and accommodation of different control devices based on the MAS architecture. The novelty of the proposed approach lies in allowing partial updates to the existing control systems without upgrading the entire structure at a meager cost compared to other coordination techniques. Thus, the proposed system can work effectively with a high-performance in the microgrid structure for disaster recovery proposals.

The major contributions of the paper can be listed as follows:

- A cooperative voltage control scheme is proposed to solve the voltage problems associated with high PV penetrations.
- An effective MAS distributed structure is developed for time coordination between voltage regulators and reactive power control of the PV inverters.
- The proposed control scheme can minimize voltage deviations and reduce the stress on the traditional voltage control devices compared to existing works.
- Diverse simulations are performed on the IEEE 34-bus and 123-bus test feeders for various scenarios over 24 hours.

The rest of this paper is organized as follows. First, Section II discusses the voltage regulation problems and the proposed MAS structure of the control strategy. Then, the mathematical formulation of the proposed control strategy is described in Section III. After that, the control algorithm procedures are given in Section IV. Next, Section V provides the simulation case studies of the two test feeders and the analysis of the results. Finally, Section VI provides conclusions for the paper.

II. PROBLEM FORMULATION

A. PROBLEM STATEMENT

Voltage regulation is a critical issue to achieve a stable operation of the DS with the high penetrations of PVs. Usually, to control the voltage, the flow of power is traditionally regulated through the conventional devices (OLTC, SVR, SC, etc.), and the high penetration of PVs in the DS causes several problems in the operation of voltage regulators. These problems are related to disturbing the traditional strategies of voltage control devices and increasing the operation stress due to the intermittent fluctuations of the PV output power. Therefore, the voltage control of the active DS represents a big challenge for the system operator. However, with recent advances in communication and control structures, the PV inverters can be utilized to provide voltage regulation in the DSs. Thus, in this paper, a distributed voltage control strategy is developed using the voltage regulators and the reactive power of the PV inverters based on the MAS. The objectives of the proposed strategy are to minimize the voltage deviation and decrease the number of tap operations of the conventional device of voltage control in the DS.

B. PROPOSED CONTROL STRATEGY

The proposed control system is developed based on the MAS architecture as shown in Fig. 1. The proposed MAS consists of several agents. Each agent consists of several voltage controllers that act in a coordinated manner to achieve a common objective. In this paper, a simple communication platform referred to as a blackboard memory (BM) is used, and the different agents exchange their information through it.

The local agents perform a real-time control according to the data transferred through the BM. The control strategy and the target of each element can be described as follows:

[Local PV agent]

- The PV agents independently act to regulate the voltages at their local node.
- Each PV agent works as an observation point and sends its measurement to the regulator agent.

[Voltage regulator agent]

- Each voltage regulator acts independently according to the observation information and the data received from the BM.

[Management agent]

- Used for monitoring and system calculation in case of performing central approach is performed.

[BM]

- A memory used by the agents to exchange the measured and the calculated data.

Based on that, the effective operation of the DS can be realized by utilizing the reactive power of each PV to perform the voltage regulation, which will decrease the stress of the traditional voltage regulators.

III. FORMULATION OF THE CONTROL STRATEGY

Nowadays, the DS contains several devices for voltage regulation. The objective of the proposed strategy is to coordinate between the voltage regulators and the reactive power of the PV inverters to minimize the overall voltage deviations. The mathematical formulations of the control approaches for voltage regulators and reactive power of the PV inverters are described as follows.

A. VOLTAGE REGULATORS CONTROL APPROACH

1) OBJECTIVE FUNCTION

The voltage deviation function for the voltage regulators is described in (1).

$$\min \int_0^{\infty} V_{Dev.}(\boldsymbol{v})dt,\ V_{Dev.}(\boldsymbol{v}) \geq 0 \tag{1}$$

$$V_{Dev.}(\boldsymbol{v}) = \frac{1}{2}\sum_{y}\sum_{i=1}^{My} w_i^y.(v_i^y - v_R^y)^2$$
$$where,\ Y \in \begin{cases} a, b, c, & \text{for Star connected regulators} \\ ab, bc, ca, & \text{for Delta connected regulators} \end{cases} \tag{2}$$

where V_{Dev} represents the total deviations of the DS voltages from a reference value v_R^Y, and it is calculated based on the voltage measurement of the local agents (v_i^Y: measured voltage at node i). Also, $\boldsymbol{w}_i^Y$ represents the weight coefficient

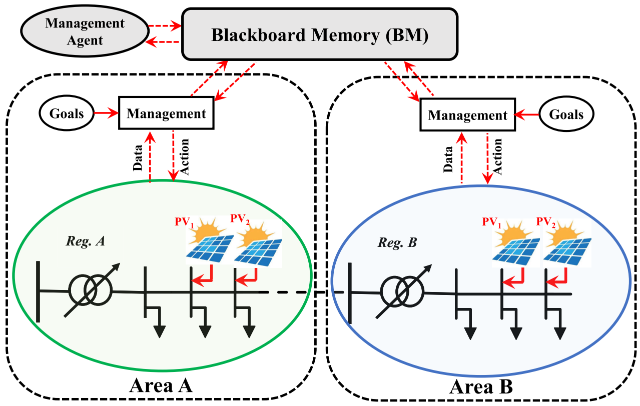


FIGURE 1. Proposed MAS voltage control structure.

of node i and indicates the importance ofeach measurement's point. The constraints of problem (1) are the power flow function (3) and the tap limits (4).

2) MATHEMATICAL FORMULATION

In this study, the coordination between voltage regulators and the reactive power of the PV inverters is used to regulate the DS voltages. Thus, the power flow calculations which govern the voltages can be described as follows:

$$\boldsymbol{v} = f(\boldsymbol{L}, \boldsymbol{n}, \boldsymbol{Q_{PV}}) \tag{3}$$

where $\boldsymbol{v} = [v_1, v_2, \ldots, v_M]$ is voltages vector, $\boldsymbol{n} = [n_1, n_2, \ldots, n_N]$ represents the tap positions of voltage regulators, $\boldsymbol{L} = [L_1, L_2, \ldots, L_p]$ represents the vector of load parameters, and $\boldsymbol{Q_{PV}} = [Q_{PV,1}, Q_{PV,2}, \ldots, Q_{PV,M}]$ is the reactive power of the PV inverters.

The coordination is performed in the proposed method by considering the PV with reactive power capability as local voltage controllers operated with their setpoints. Firstly, the PV agents regulate their node voltages according to the available amount of reactive power. Then, the voltage regulators act after the local PV agents to achieve (1). Thus, the control strategy for voltage regulator is to minimize the overall voltage deviations as illustrated in [7], and it can be briefly described as follows:

When the tap position of regulator k changes by $\Delta n_k^p(t)$ with a step size R_k, the next tap status can be expressed as in (4), and the voltage deviation function will change by $\Delta V_{Dev.}(\boldsymbol{v})$ as described in (6).

$$n_k(t+1) = n_k(t) + \Delta n_k(t), \quad n_{k,\min} \leq n_k \leq n_{k,\max} \tag{4}$$

$$\Delta n_k(t) = R_k \cdot Z_k(t), \quad Z_k(t) = \begin{Bmatrix} +1 & (increase) \\ 0 & (no\ change) \\ -1 & (decrease) \end{Bmatrix} \tag{5}$$

$$\begin{aligned} \Delta V_{Dev.}(\boldsymbol{v}(t)) &= V_{Dev.}(\boldsymbol{v}(t+1)) - V_{Dev.}(\boldsymbol{v}(t)) \\ &= \left[\frac{\partial V_{Dev.}}{\partial \mathrm{v}}\right] \cdot \left[\frac{d\boldsymbol{v}}{d\boldsymbol{n}}\right] .\boldsymbol{R}.\boldsymbol{Z}(t) \\ &= \boldsymbol{S}(t).\boldsymbol{Z}(t) = \sum_{k=1}^{N} S_k(t).Z_k(t) \end{aligned} \tag{6}$$

where $\boldsymbol{S}(t)$ is a sensitivity index, representing the sensitivity of the voltage deviation's function concerning the unit change of voltage regulators taps. In this paper $\boldsymbol{S}(t)$ is used as a control parameter for voltage regulators, and its value indicates the effectiveness of each regulator on the total voltage deviations. The values of the sensitivity index can be described for all system regulators can be computed as follows:

$$\boldsymbol{S}(t) = \left[\frac{\partial V_{Dev.}}{\partial \boldsymbol{v}}\right] \cdot \left[\frac{d\boldsymbol{v}}{d\boldsymbol{n}}\right] \cdot \boldsymbol{R} = \left[S_1(t), S_2(t), \ldots, S_N(t)\right] \tag{7}$$

The sensitivity index for agent k is described in (8).

$$\begin{aligned} S_k(t) &= R_k. \sum_{j=1}^{M} \frac{V_{Dev.}}{\partial v_j} . \frac{dv_j}{dn_k} \\ &= R_k. \sum_{j=1}^{M} w_j \cdot (v_j - v_R) \cdot \frac{dv_j}{dn_k} \end{aligned} \tag{8}$$

where $[d\boldsymbol{v}/d\boldsymbol{n}]$ represents the sensitivity matrix of voltage/tap, calculated based on the power flow relationship (3). The authors described the volta/tap sensitivity matrix in detail [7], [9]. In order to simplify the computation process, an approximated matrix for voltage/tap sensitivity for radial DS is used based on the network configuration.

The objective of the proposed control method for the voltage regulators is to minimize the overall voltage deviations of the DS. Thus, the optimality of this method can be achieved using the sensitivity index as described in (9).

$$\min_{k\in K} \quad V_{Dev.}(\boldsymbol{v}(t+1)) = V_{Dev.}(\boldsymbol{v}(t)) + \min_{k\in K}\{\boldsymbol{S}(t).\boldsymbol{Z}(t)\} \tag{9}$$

Based on (9), the optimal operation of the voltage regulators can be achieved if only one controller acts at a time instant, as proved in [7]. The optimal operation requires a comparison among the sensitivity indices of the agent, which will make the control approach acts as a centralized system; although the MAS can perform it, it needs a little bit complicated system to achieve high performance. Therefore, in our proposed coordinated approach, a suboptimal approach is used to avoid the complicated structure and realize the autonomous operation of the controlled agents. The suboptimal performance is almost equivalent to the optimal operation, as illustrated in [7], and it can be realized using a simple control structure. The suboptimal control method can be described as follows:

The decentralized control strategy of the regulators is performed using the sensitivity index S of each agent. The local agent acts when the index is greater than a threshold value (α) as below.

$$\begin{aligned} &if \;\; S_k(t) < -\alpha \quad then \;\; Z_k(t) = 1 \\ &if \;\; S_k(t) > \alpha \quad then \;\; Z_k(t) = -1 \\ &if \;\; |S_k(t)| < \alpha \quad then \;\; Z_k(t) = 0 \end{aligned} \tag{10}$$

The threshold value α is common and predefined for all regulators, and it represents the amount of voltage deviation that causes the regulators to act, which can be used to adjust the response time of the regulators. Based on (12), each agent can act autonomously in a simple manner, and an effective control performance near the optimal can be expected. In case of losing communication among the agents, the controller of each agent will act based on its own measurements.

B. REACTIVE POWER CONTROL OF THE PV INVERTERs

1) OBJECTIVE

The main objective of the reactive power control is to absorb the reactive power when the voltage at the PV node is above the maximum acceptable limit and inject reactive power whenever the voltage is lower than the minimum limit. The capability of reactive power compensation for voltage regulation depends on the type of the DG source. This study will use the PV as a DG source while the inverter controls the reactive power to regulate the node voltage. During the daytime, the PV sources generate active power, and the inverters are thus unused or idle in most of the daytime. Therefore, when the active power generation (P_{PV}) of the PV is less than its inverter capacity (S_{PV}), the reactive power (Q_{PV}) of the inverter can be utilized to provide voltage regulation, as shown in (11).

$$Q_{PV} = \sqrt{S_{PV}^2 - P_{PV}^2} \tag{11}$$

In this paper, a control strategy is used to manage the available reactive power of the PV sources to mitigate the voltage violations of PV-connected nodes. The control strategy is formulated based on the voltage/reactive power sensitivity, calculated using the whole system information. In addition, another method for calculating the voltage/reactive power sensitivity factors is used, based on a local measurement, to avoid complicated communication and achieve autonomous control.

2) FORMULATION OF REACTIVE POWER CONTROL APPROACH

The sensitivity of voltages with respect to the change in active/reactive power can be calculated using the power flow Jacobian as follows:

$$\begin{aligned} \begin{pmatrix} \Delta\theta \\ \\ \Delta V \end{pmatrix} &= \begin{pmatrix} \frac{\partial V}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \Delta P \\ \\ \Delta Q \end{pmatrix} \\ &= \begin{pmatrix} \frac{\partial \theta}{\partial P} & \frac{\partial \theta}{\partial Q} \\ \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \end{pmatrix} \cdot \begin{pmatrix} \Delta P \\ \\ \Delta Q \end{pmatrix} \end{aligned} \tag{12}$$

Based on (12), the change in system voltages with respect to the active and reactive power can be expressed in the following.

$$\Delta V = \frac{\partial V}{\partial P} \cdot \Delta P + \frac{\partial V}{\partial Q} \cdot \Delta Q$$

$$= \frac{\partial V}{\partial P} \cdot (\Delta P_{load} + \Delta P_{PV}) + \frac{\partial V}{\partial Q} \cdot (\Delta Q_{load} + \Delta Q_{PV}) \tag{13}$$

During controlling the voltage using the reactive power of PV inverters, the powers at the load nodes and the active power of the PVs will not change significantly. Thus, in (13), when the PV reactive power is changed by ΔQ_{PV}, the change in the voltage will be as follows:

$$\Delta \boldsymbol{V} = \frac{\partial \boldsymbol{V}}{\partial \boldsymbol{Q}} \cdot \Delta \boldsymbol{Q_{PV}} \tag{14}$$

$$\begin{pmatrix} \Delta V_1 \\ \vdots \\ \Delta V_N \end{pmatrix} = \underbrace{\begin{pmatrix} \frac{\partial V_1}{\partial Q_1} & \cdots & \frac{\partial V_1}{\partial Q_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial V_N}{\partial Q_1} & \cdots & \frac{\partial V_N}{\partial Q_N} \end{pmatrix}}_{\substack{Volt/Var \\ sensitivity\ matrix}} \cdot \begin{pmatrix} \Delta Q_{PV,1} \\ \vdots \\ \Delta Q_{PV,N} \end{pmatrix} \tag{15}$$

The amount of reactive power required to regulate the voltages of PV node i can be calculated based on the sensitivity factor in (15) as follows:

$$\begin{aligned} \Delta Q_{PV,i} &= \left[\frac{\partial v_i}{\partial Q_i}\right]^{-1} .\Delta v_i = \Delta v_i / S_{(Volt/Var),i} \\ &if\ v_i > v_{Max},\ \Delta Q_{PV,i} = -(v_i - v_{Max})/S_{(Volt/Var),i} \\ &if\ v_i < v_{Min},\ \Delta Q_{PV,i} = (v_{Min} - v_i)/S_{(Volt/Var),i} \\ &where, \quad -\left|Q_{PV,i}\right| \le \Delta Q_{PV,i} \le \left|Q_{PV,i}\right| \end{aligned} \tag{16}$$

where $S_{(Volt/Var)}$ is the voltage/ reactive power sensitivity factor of node i and the upper and the lower limits of voltages are v_{max}, and v_{min}, respectively. The voltage/reactive power sensitivity matrix is calculated based on the power flow Jacobian, which depends on the system configuration and needs the overall data of the system. Moreover, in case of lack or shortage in the system data, the PV agent can calculate its own voltage/ reactive power sensitivity factor ($S_{(Volt/Var),i}$) based on local measurements. The PV agent will inject a certain amount of reactive ($\Delta Q_{PV,i}$) power, and the node voltage will be measured before ($v_{0,i}$) and after ($v_{1,i}$) the reactive power injection. The sensitivity will be calculated by dividing the difference between the measured values by the injected reactive power as expressed in (17).

$$S_{(Volt/Var),i} = (v_{0,i} - v_{1,i})/\Delta Q_{PV,i} \tag{17}$$

In this paper, the reactive power control of the PV is performed by utilizing the available capacity of the inverter without affecting the active power generation.

IV. CONTROL ALGORITHM

The proposed strategy is formulated using a decentralized control approach, in which the coordination between the reactive power of the PV inverters and the voltage regulators is performed. As shown in Fig. 2, agent k consists of a voltage regulator and several PV sources. Two stages of control are implemented based on time coordination, as described below.

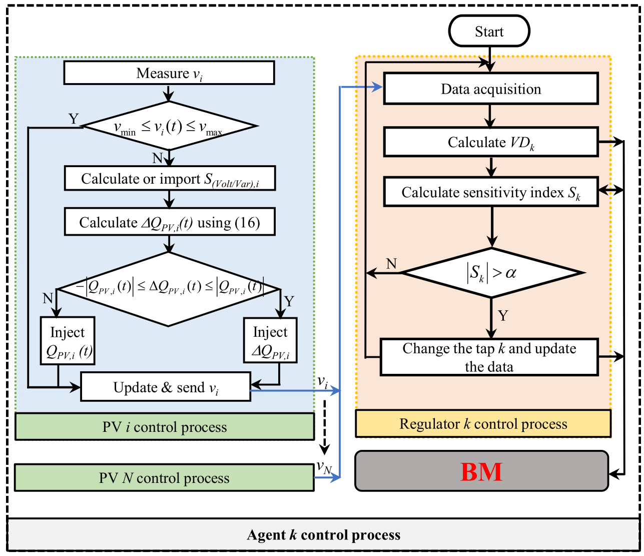


FIGURE 2. **Proposed control process for agent *k*.**

A. STAGE 1: LOCAL PV CONTROL PROCESS

Because of the fast response of the power electronic devices, the PV inverter performs the voltage regulation as the first stage of control by utilizing the reactive power capability, as shown in Fig. 2. Firstly, the voltage is measured at PV node i. Then if the node voltage violates the desired limits, the inverter of the PV will implement the control strategy of reactive power to mitigate the voltage deviation. In this case, the proposed control strategy can be described as follows:

- **a)** Calculate or import the sensitivity factor $S_{(Volt/Var),i}$.
- **b)** Calculate the required amount of reactive power $\Delta Q_{PV,i}$ for voltage regulation based on (16).
- **c)** Update the voltage v_i after the injection/absorption of $\Delta Q_{PV,i}$.
- **d)** Send the voltage v_i to the regulator k controller.

The PV nodes are used as observation points for the control system of the voltage regulators. Thus, each PV agent will implement the abovementioned control process, and then the voltages will be updated and sent to the voltage regulator agent to minimize the overall violations. The control agent of each voltage regulator will perform the proposed control strategy described in the next section.

B. STAGE 2: VOLTAGE REGULATOR CONTROL PROCESS (SUBOBTIMAL APPROACH)

The control agent of the voltage regulator collects the observation nodes' voltages of its control area, which includes the updated voltages of the PV nodes, as shown in Fig. 2. Then, the voltage control approach will be performed, which can be described as follows for the regulator k area:

- **a)** *Calculate the center voltage* ($V_{c,k}$): based on the observations' node voltages, each area's minimum and maximum values are used to obtain the center voltage (18).

$$V_{C,k} = \frac{\min(v_1 : v_{o,k}) + \max(v_1 : v_{o,k})}{2} \tag{18}$$

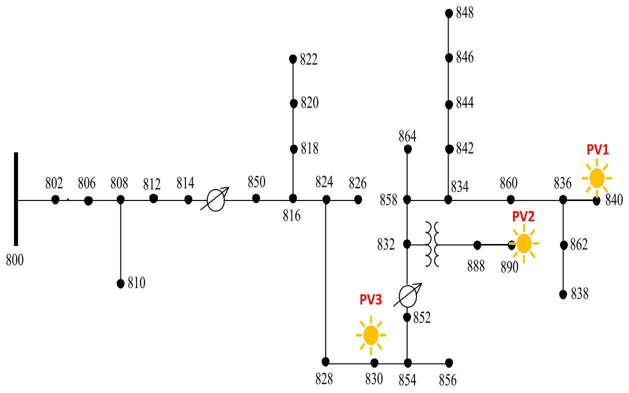


FIGURE 3. IEEE 34-bus feeder.

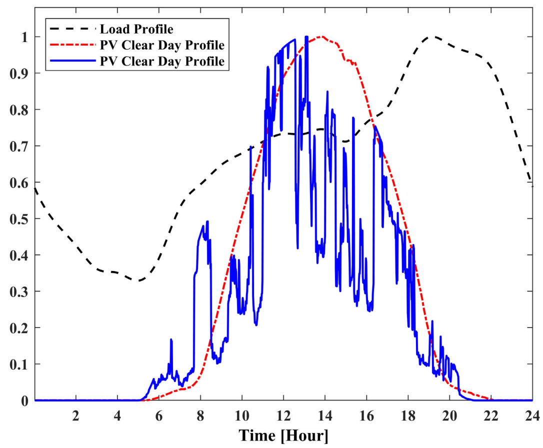


FIGURE 4. Normalized Load and PV generation profiles.

where o represents the number of observation points for the control area of the regulator agent k.

b) *Calculate the voltage deviation* ($V_{D,k}$) : $V_{D,k}$ represents the difference between the center voltage ($V_{C,k}$) calculated in (18) and the reference center voltage ($V_{C,R}$), which is calculated based on the standard voltage limits as described in (19).

$$V_{D,k} = (V_{C,k} - V_{C,R} - db)$$
$$V_{C,R} = \frac{v_{Upper} + v_{Lower}}{2} \tag{19}$$

where v_{Upper} and v_{Lower} represent the standard voltage limits, and db represents a dead band adjusted by the system operator.

c) *Send the value of the voltage deviation $V_{D,k}$ to the BM.*

d) *Calculate the sensitivity parameter S_k* : by importing the values of the voltages/tap sensitivity matrix dv/dn_k and the voltage deviation $V_{D,k}$ from the BM, the sensitivity parameter for agent k can be calculated using (8).

e) *Send the value of the sensitivity parameter S_k to the BM.*

f) *Change the tap position based on the suboptimal control approach described in (11).*

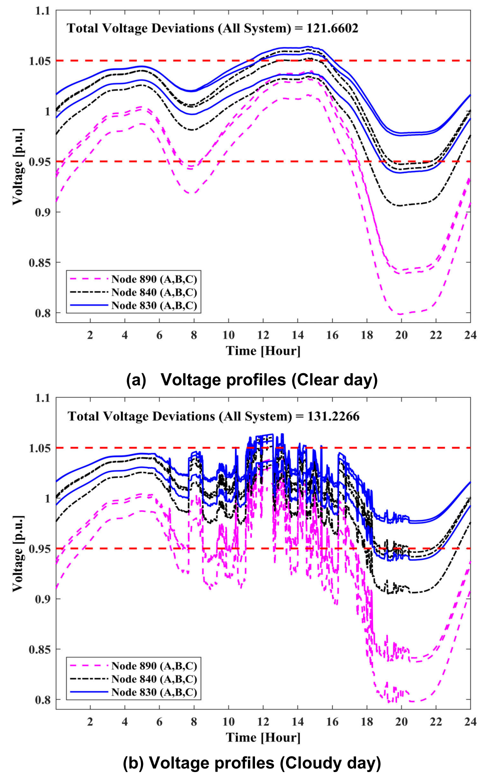


FIGURE 5. Voltage profiles of case 1: Without control.

C. THE COORDINATION PROCESS

The coordination process between the voltage regulators and the reactive power of the PV to minimize the overall voltage deviation of the system can be achieved using a proper time setting for the PV inverter and the regulator controllers. Firstly, the inverter controller will utilize the available amount of reactive power to minimize the voltage violations of the local nodes. Then, based on a reasonable time delay for voltage regulators, the controller will act to overcome the remaining voltage deviations, which will decrease the number of tap operations.

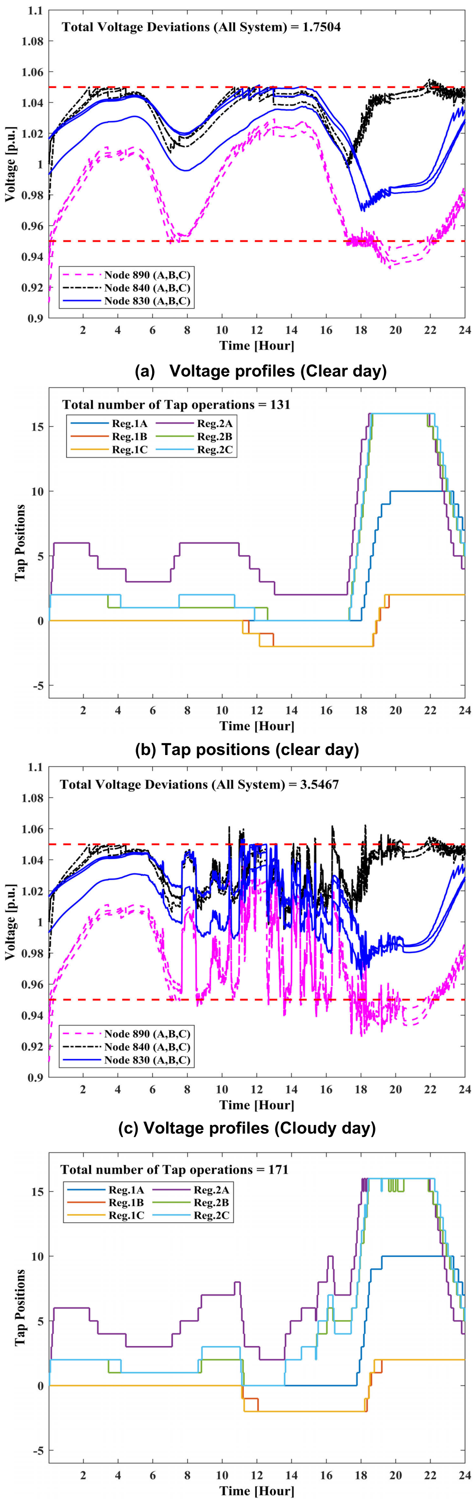
V. RESULTS AND DISCUSSIONS

The performance of the proposed control strategy is evaluated using two standard distribution test feeders, the IEEE 34-bus feeder and the IEEE 123-bus feeder, as follows:

A. IEEE 34-BUS FEEDER

The IEEE 34-bus feeder is characterized by unbalanced loading, shunt capacitors, and two voltage regulators, as shown in Fig. 3. The test feeder with three PV sources is implemented using MATLAB software. The active and reactive power of the loads and the PV outputs are shown in Fig. 4. Different case studies are simulated as follows:

[Case 1] Without control.
[Case 2] With tap control.
[Case 3] Proposed control method.



(a) Voltage profiles (Clear day)

(b) Tap positions (clear day)

(c) Voltage profiles (Cloudy day)

(d) Tap positions (cloudy day)

FIGURE 6. Results of Case 2: With tap control.

1) CASE 1: WITHOUT CONTROL

Case 1 simulates the test system without applying any technique of voltage control. The three-phase voltage profiles of the PV nodes for clear and cloudy days are shown in Fig. 5. The total voltage deviations of the system are listed in Table 1. As is seen from the figures, several voltage violations occur in the test system. In the voltage profiles of case 1, a voltage rise problem occurred in the daytime during the peak period of PV generations at some phases of nodes 830 and 840. Also, a voltage drop problem occurred during most of the nighttime for node 890 and at hours 19:23 for nodes 840 and 830. In addition, on a cloudy day PV generation, fluctuations appear in the voltage profiles due to the variations of PV output. The overall system voltage deviations for the clear and cloudy days are listed in Table 1, as it noticed the system has high voltage deviations in both PV profiles.

TABLE 1. Total voltage deviation and no. of tap changes for the 34-bus test feeder.

Cases Studies	Clear day		Cloudy day	
	Total VD	Tap changes	Total VD	Tap changes
Case1: Without control	121.66	-	131.23	-
Case2: With Reg. Tap Control	1.75	131	3.55	171
Case3: With Reg. Tap and PV Reactive Power Control	0.16	33	0.36	37

2) CASE 2: WITH TAP CONTROL

In this case study, the proposed suboptimal control approach for voltage regulators has been adopted to demonstrate the performance of the proposed technique in minimizing the voltage deviations of the test feeder. The proposed algorithm uses the MAS architecture according to the exchanged information between the regulators' agents and the BM. For this case study, the same threshold value is used for all system regulators. The results of this case for clear and cloudy PV generations profiles are shown in Fig. 6 and Table 1. As it is noticed from the results and compared with case 1, the suboptimal proposed algorithm for regulators minimizes the overall voltage deviations for clear and cloudy profiles without any tap problems. This demonstrates that the proposed control is efficient for managing the regulators even in the case of voltage fluctuations due to the intermittent fluctuation of the PV output power. Thus, the suboptimal control method for voltage regulators can be realized using a simple and autonomous control architecture based on the MAS.

3) PROBLEMS OF TAP CONTROL

The proposed tap control method successfully manages the tap changes of regulators to minimize the voltage deviations. Nevertheless, as noticed from the voltage profiles in Fig. 6, the voltage regulators cannot solve the voltage drop problem totally, and the regulators needed to have frequent operations to solve the voltage problems. Moreover, as shown in Fig. 6, regulator no.2 reached the maximum tap limit between hours 18 and 22. Thus the voltages profiles of node 830 still violate the lower limit of voltage in this period.

Also, the total number of tap changes is a little bit high, which increases the stress on the voltage regulators and reduces the lifetime of those devices. Based on that, the number of tap operations should be reduced, and the stress on the voltage regulators needs to be relieved. Therefore, a coordination strategy between the regulators and the reactive power

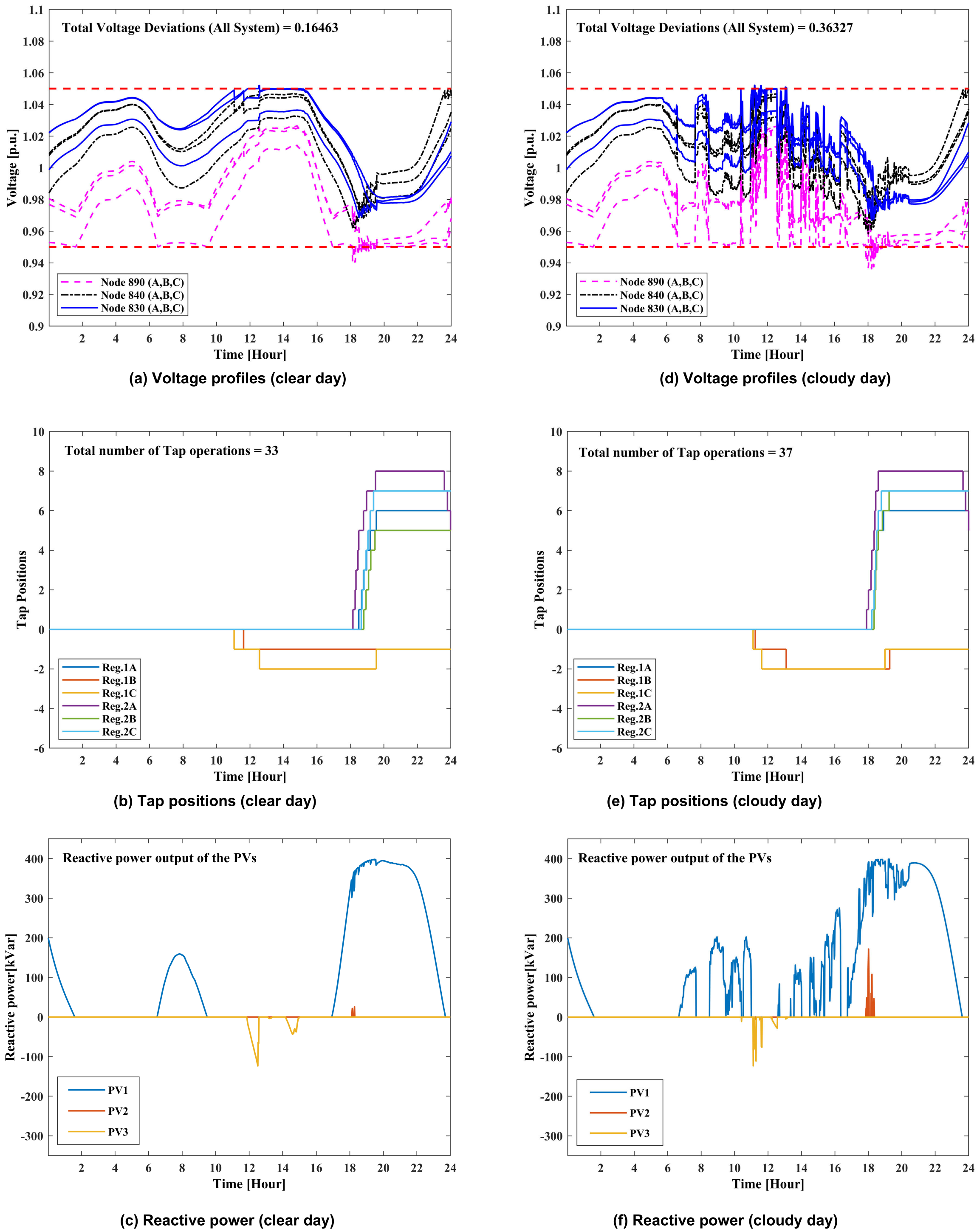


FIGURE 7. Results of Case 3: With tap and PV inverters reactive power control.

of the PVs inverters is discussed in the next section to reduce this stress.

4) CASE 3: PROPOSED CONTROL METHOD

As mentioned in the previous section, the frequent tap changes of the voltage regulators should be avoided to increase the device's lifetime. Therefore, utilizing the reactive power capability of the PV sources can be beneficial to decrease the tap changes. In this section, the performance of the coordinated process, which is described in section IV, is checked. The voltage profiles, the tap operation, and the reactive power of the PVs for the clear and cloudy day are

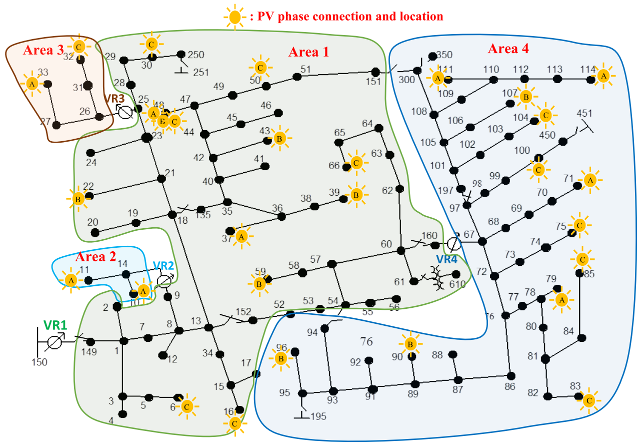


FIGURE 8. IEEE 123-bus test feeder.

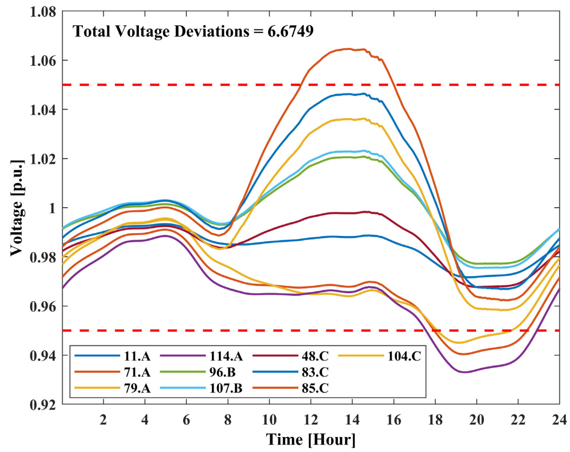


FIGURE 9. Voltage profiles of IEEE 123-bus: Without control (Case 1).

shown in Fig. 7. The results show that the voltage deviations are minimized, and the number of tap operations is reduced by more than 70% compared with case 2 for clear and cloudy PV profiles. Furthermore, Fig. 7 shows that the utilization of the PV reactive power decreases the stress of regulator no.2 during hours 18 and 22 comparing with case 2. Also, the available amount of the reactive power of the PV inverter is used without any curtailment of active power.

TABLE 2. Total voltage deviation and no. of tap changes for the 123-bus test feeder.

Cases Studies	Clear day PV generation profile		
	Total VD (PV nodes)	Total VD (All system)	Tap changes
Case1: Without control	6.6749	7.3208	-
Case2: With Reg. Tap Control (Suboptimal Approcah)	0.0039	0.5839	8
Case3: Proposed Control Method	0.0025	0.0030	3
Case4: Conventional Method	0.0029	0.0029	18

B. IEEE 123-BUS FEEDER

The IEEE 123-bus feeder is characterized by unbalanced loading, and it has four voltage regulators with different configurations, as shown in Fig. 8. Thus, the feeder is divided into four areas operating as four control agents. The studied cases for clear day PV generation profile are listed in Table 2 and described as follows:

Case 1: represents the IEEE 123-bus feeder with several PV sources without any voltage control technique. The voltage profiles of some PV nodes are shown in Fig. 9, and the total voltage deviations are listed in Table 2. The voltage rise problem occurs at some system nodes during the peak generation of the PV powers. In addition, a voltage drop problem occurs between hours 17 and 23 for some system nodes.

Case 2: in this case, the suboptimal strategy for voltage regulator control is performed to minimize the voltage deviations using the PV nodes as observation points. It is observed from the results that the total voltage deviations are decreased compared with case 1 (see Table 2), and the voltage profiles are controlled within the desired limits, as shown in Fig. 10.

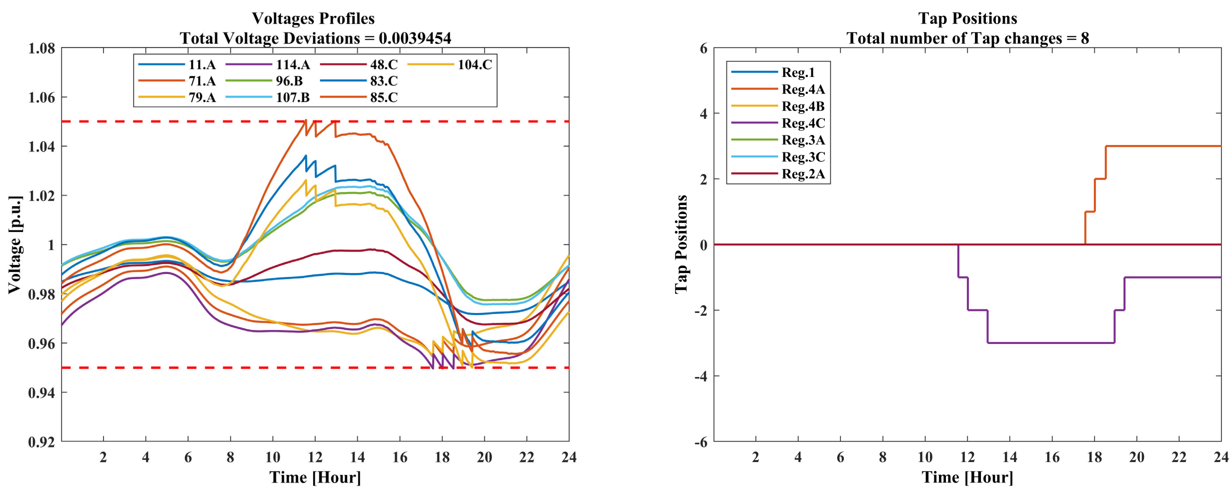


FIGURE 10. IEEE 123-bud test feeder: with tap control (Case 2).

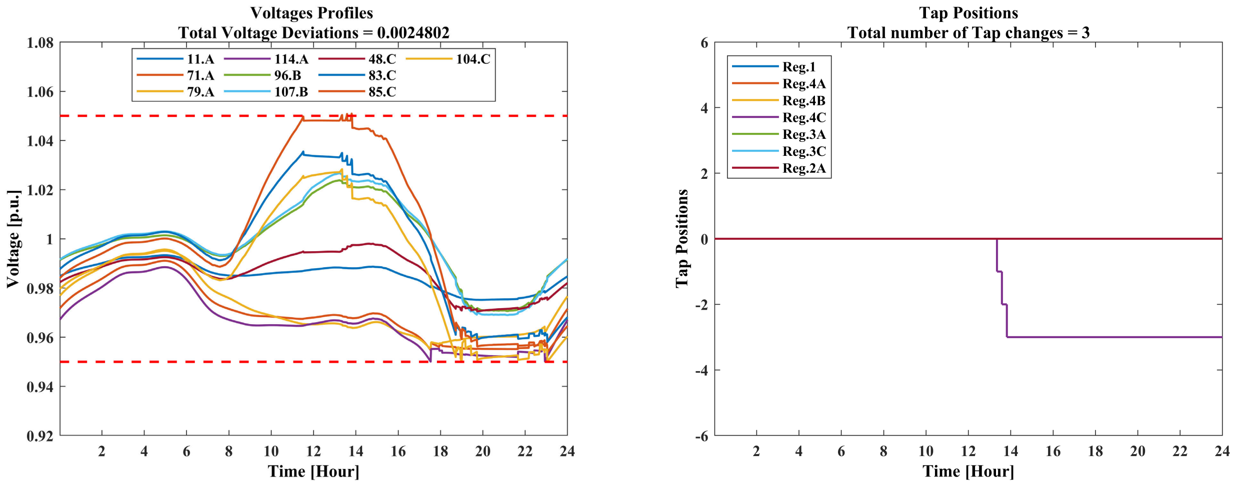


FIGURE 11. IEEE 123-node test feeder: Proposed control (Case 3).

Case 3: in this case, the reactive power capabilities of the PV sources are used to decrease the stress on the voltage regulators. As shown in Table 2 and Fig. 11, the voltage profiles are controlled within the standard limit, the voltage deviations are minimized, and the number of tap changes decreased from 8 to 3 compared with cases 1 and 2.

Case 4: the voltage regulators are controlled using a conventional line drop compensating method, and also the PV sources utilize their reactive power capabilities to controlling the local nodes' voltages. As listed in Table 2, the voltage violations are decreased, and the number of tap operations is reduced.

Compared with the conventional control method, the proposed method has a high performance, and the number of tap operations is decreased significantly, increasing the lifetime of the regulators.

VI. CONCLUSION

This paper proposes a coordination strategy for voltage control based on the MAS for the DS operation considering the voltage regulators and the reactive power capability of the PV inverters. The objective of the proposed method is to minimize the voltage deviations while reducing the stress of the traditional voltage regulators by utilizing the available amount of reactive power of the PVs. The effectiveness of the control schemes has been demonstrated using the IEEE 34-node and IEEE 123-node distribution test feeders characterized by several voltage regulators and PV sources. The simulated results confirm that the coordinated strategy between the voltage regulators and the reactive power of the PVs inverters has an effective performance in mitigating the voltage deviations and decreasing the number of tap operations. Furthermore, the proposed method represents a simple decentralized scheme that can be realized in the DS with low investments.

The future work will introduce various distributed energy resources, such as wind turbines, electric vehicles, BESS, etc., to the proposed control method. In addition, it will be applied to promising microgrid systems.

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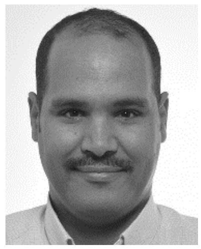

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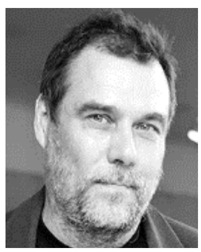

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