OPTIMAL COORDINATED VOLTAGE CONTROL OF ELECTRICAL DISTRIBUTION NETWORKS IN THE PRESENCE OF DISTRIBUTED RENEWABLE ENERGY SOURCES

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Keywords: Coordinated voltage control (CVC); Optimization; Distributed generation (DG); Distribution network; On-load tap changer (OLTC); Shunt capacitors (SCs).

Recently, distributed generation (DG), as clean and renewable energy, has increased due to the global warming problems and depletion of fossil sources. Several DGs are installed near the end-user, with the feature that this will decrease power losses. However, without optimal control, many problems, such as voltage instability and power losses, may affect the performance and the good operation of the power system. This paper proposes an optimal coordinated voltage control (OCVC) method for the distribution networks with distributed generation sources. The method is based on a genetic algorithm (GA) approach in multi-core simulation with an open-source OpenDSS to obtain the optimal setting of voltage control devices adjusted remotely. This method considers time-varying load and generation based on day-ahead scheduling. Simulations are performed in a distribution network test with DG integration to validate the performances of the proposed technique.

1. INTRODUCTION

As a controllable sub-system, a microgrid can successfully incorporate different sources of distributed generation (DG), especially renewable energy sources (RES). Control and protection are serious challenges of the microgrid, as all ancillary services for the power system stability must be present within the microgrid, and optimal control can be challenging for selected operating of the microgrid. As reported in [1], 86 % of power demand could be covered by renewable energy sources (RES), such as solar and wind. According to the percentage of PV integration and the amount of concentration, the fluctuations in irradiance can make undesirable voltage variations, as the operation of voltage control devices may be affected [2].

Several interesting research works in the literature treat the issues of voltage control of the distribution networks in the presence of DG. Reference [3] investigates the impact of RES on harmonic voltages for medium voltage (MV) and low voltage (LV) distribution networks using the DigSILENT tool. It compares the impact of different power generation technologies on harmonic voltages. Sometimes, conventional voltage control regulators such as the on-load tap changer (OLTC) can only solve these problems with optimal coordination with the other control regulators. Without optimal coordination between OLTC, shunt capacitors (SCs), and DG, switching operations will rise significantly, even degrading the power quality. The recommendations of [4] stipulate that DG should not contribute to the voltage control of DNIs. Due to the limitation of maximum power inverter current, it can be assumed that the total fault contribution from the PV source is at most twice the PV source-rated current [5].

Reference [6] proposes a technique to calculate the OLTC and SCs day-ahead operations schedules. [7] presents a feasibility study of integrating PV sources into the isolated distribution network of Djanet in Algeria. Some strategies are proposed to minimize the negative impacts. Reference [8] uses the gradient descent algorithm to solve the optimization problem of online coordination of the OLTC with dispatchable DGs. A new control method to alleviate the voltage rise problems caused by DGs integration was proposed in [9]. Reference [10] proposes a sensitivity investigation based on the coordination method for voltage control in the presence of wind generators. In [11], the proposed algorithm divides the distribution network in two sub-regions for the voltage control. In [12], voltage control of a PV system integrated into the distribution network has been treated as part of the coordination between electric vehicles and OLTC. In [13], a harmony search optimization algorithm was used to carry out day-ahead planning of non-dispatchable DGs. In [14], the photovoltaic (PV) panels are connected to the inverter via a dc-dc converter to ensure an optimal dc voltage control. The configuration can be used to obtain a wide power range. Reference [15] uses a gravitational search algorithm (GSA) to solve the optimization problem of control devices. In [16], the objective function is developed for active power loss minimization, with the OLTC position, SCs status, and DG reactive outputs as the control variables. Reference [17] presents a multi-objective control for multi-feeder DNIs that utilize information from available voltage regulators, current, and power. Reference [18] proposes an enhanced voltage-oriented control strategy (EVOC) based on super twisting sliding mode control (STSMC) for a grid-connected four-leg source voltage inverter to achieve accurate current control.

This study proposes a novel coordinated voltage control GA-based method for the voltage control of distribution networks. The works cover the CVC issues in distribution networks. However, some important issues still need to be treated more widely, such as time-varying load (TVL) demand and DG generation. The proposed multi-objective (MO) function aims to minimize power losses, enhance voltage deviation, and maximize DG penetration with corresponding power factor, OLTC operations, and SCs switching. The main contributions of this paper are described as follows:

- A multi-objective CVC method is proposed to obtain all the optimal control parameters in the distribution network with multiple distributed RES. The method is based on...
genetic algorithm (GA) approach in multi-core simulation with OpenDSS.

- Based on day-ahead load predictions for one day in advance, time-varying load demand and DG generation are considered in an unbalanced distribution system.
- Considering more realistic MINLP, Tap operations and capacitor switching are modeled as discrete variables and incorporated into the objective function.

This paper is organized as follows: Section 2 explains the problem formulation and methodology. Section 3 describes the system under study and the simulated cases. Section 4 discusses and comments on the results. Finally, the conclusion and future research are provided in section 5.

2. PROBLEM FORMULATION AND METHODOLOGY

In this paper, the simple form of the distribution system used for problem formulation is represented in Fig. 1. Although the active power part of the DG can be given by ESO or pre-given by device parameters, reactive power is regulated depending on the network conditions. The OLTC of the transformer (Tr) can control the voltage of the whole DN. The SCs can be separately controlled. The OLTC and SCs keep the bus voltage profile between just a little bit percent of the rated value to provide or absorb the desired reactive power by the DG. Thus, the reactive power provided by each SC is near the rated value. To simplify the formulas, the DN has constant power loads.

![Simplified distribution system](image)

**Fig. 1** – Simplified distribution system.

**Nomenclature used in the simplified distribution system:**
- \( V_{\text{grid}}, \theta \): Voltage magnitude and angle of the grid.
- \( P_{\text{grid}}, Q_{\text{grid}} \): Active and reactive power from the grid.
- \( V_s, \theta_s \): Voltage magnitude and angle at the source bus.
- \( V_G \): Voltage magnitude at the receiving bus.
- \( Q_c \): Reactive power from shunt capacitor.
- \( R_L, X_L \): Resistance and reactance of the line.
- \( P_{\text{DG}}, Q_{\text{DG}} \): Active and reactive power of the DG.
- \( P_{\text{load}}, Q_{\text{load}} \): Active and reactive power flowing in the line.
- \( I_s \): Current flowing in the line.
- GB, LB: Generating and loading bus.
- \( V_s, V_r, \) and \( P_{\text{loss}} \) can then be functionally expressed as [6]:
  \[
  V_s = f_1(r, \text{cap}, Q_R) = f_2(tap, \text{cap}, Q_{DG}). \tag{1}
  \]
  \[
  V_r = g_1(V_s, Q_R) = g_2(tap, \text{cap}, Q_{DG}). \tag{2}
  \]
  \[
  P_{\text{loss}} = R_L|I_R|^2 = \frac{|V_s \cos \delta + jV_s \sin \delta + V_r|^2}{R_L + jX_L} \tag{3}
  \]
  where \( r \) is the transformation ratio, \( \text{cap} \) is the capacitor value, and \( \text{tap} \) is the tap changer of the transformer. \( f_1, f_2, g_1, g_2 \) and \( t \) are functions.

2.1 COORDINATED VOLTAGE CONTROL IN DN

A hierarchical voltage control scheme with three levels has been developed by ESO to prohibit voltage instability and to guarantee optimal use of the reactive power compensators. The three levels respond according to their time constant: The DG acts as the primary voltage control by keeping its terminal voltage equal to the PV inverter reference voltage. The OLTC and SCs carry out the secondary voltage control. Finally, the tertiary voltage control is based on an optimization strategy by using an operation schedule to remotely adjust the DG, OLTC, and SCs, with a specified objective function and constraints for a one-day-ahead schedule load demand and forecasted DG power output.

2.2 PROPOSED COORDINATED VOLTAGE CONTROL

The coordinated voltage control problem is expressed here as a nonlinear optimization problem with the following form:

\[
\min F_{\text{obj}}(x, u), \tag{4}
\]

subject to:

\[
G(x, u) = 0, \tag{5}
\]

\[
H(x, u) \leq 0, \tag{6}
\]

with \( x \in \mathbb{R}^n \) and \( u \in \mathbb{R}^m \).

\( F_{\text{obj}} \) represents the problem’s objective function, \( x \) is the state variable vector, \( u \) is the control variable vector, \( G \) is equality constraints representing the power flow equations, and \( H \) is the inequality constraints.

2.2.1 OBJECTIVE FUNCTIONS

**Power loss**

Considering the minimization of power losses as an important aspect of ESO. The objective function of active power losses is expressed as follows:

\[
F_1 = \sum_{n=1}^{N} P_L(n), \tag{7}
\]

where \( P_L \) is the power loss in each distribution bus, and \( N \) is the bus number.

**Cumulative voltage deviation (CVD)**

Quality constraint involves that all bus voltage must be as near as possible to the reference value (1 p.u.). We name this function as cumulative voltage deviation (CVD).

\[
F_2 = \frac{1}{N} \sum_{i=1}^{N} |V_{\text{ref}} - V_i|. \tag{8}
\]

**Active power of the DG**

To increase the active power delivered from the DG, the following function is added:

\[
F_3 = P_{DG}. \tag{9}
\]

**OLTC operations**

The mixed integer non-linear problem (MINLP) in [6] proposes an objective function to reduce the number of switching regulator operations. In this paper, similar terms are included with the following modifications: to reduce the number of OLTC operations, a penalty is imposed directly in the equation considering the last tap position \( t \) rather than the next tap position \( t+1 \).

\[
F_4 = |Tap_{t-1} - Tap_t| \tag{10}
\]
SCs switching

The total switching of SCs is obtained using the following term:

\[ F_s = |Cap_t^{t-1} - Cap_t^t| \quad (11) \]

2.2.2 OPTIMIZATION CONSTRAINTS

The power balance equations can be expressed as follows:

\[ P_{di} - P_{gi} = V_i \sum_{n=1}^{N} V_n \left( G_{di} \cos(\theta_i - \theta_j) + B_{di} \sin(\theta_i - \theta_j) \right), \]

\[ Q_{di} + Q_{gi} = V_i \sum_{n=1}^{N} V_n \left( G_{di} \cos(\theta_i - \theta_j) - B_{di} \sin(\theta_i - \theta_j) \right) \quad (13) \]

where \( N \) is the number of buses, \( P_d, Q_d \) are active and reactive load demand, respectively. \( P_g, Q_g \) are active and reactive power of generators connected to bus \( i \), respectively. \( G_{ij} \) is the conductance, and \( B_{ij} \) is the susceptance connecting the buses \( i \) and \( j \), respectively.

The constraints can be expressed as follows:

\[ \begin{align*}
V_{n_{\text{min}}} & \leq V_n^t \leq V_{n_{\text{max}}} \quad \text{and} \quad S_{n_{\text{min}}} & \leq S_n \leq S_{n_{\text{max}}} , \\
T_{\text{ap}_{\text{min}}} & \leq T_{ap}^t \leq T_{\text{ap}_{\text{max}}} , \\
Cap_{\text{min}} & \leq Cap^t \leq Cap_{\text{max}} , \\
p_{\text{DG}_{\text{max}}} & \leq p_{\text{DG}}^t \leq p_{\text{DG}_{\text{max}}} ,
\end{align*} \]

with \( n=1,...,N; t=1,...T \) and \( i=1,...,\text{DG}_{\text{units}} \).

The variables associated in (7-17) are defined as follows:

\[ \begin{align*}
N & \text{ Buses number of the DN} \\
T & \text{One-hour scheduling interval in a day (T=24 hours)} \\
V_n^t & \text{Voltage magnitude at bus \( n \) and time \( t \)} \\
V_{n_{\text{max}}}, V_{n_{\text{min}}} & \text{Max and min acceptable voltage limits} \\
T_{\text{ap}}^t & \text{Tap position at time \( t \)} \\
T_{\text{ap}_{\text{max}}}, T_{\text{ap}_{\text{min}}} & \text{Max and min Tap position limits} \\
Cap^t & \text{SCs position at the time \( t \)} \\
Cap_{\text{max}}, Cap_{\text{min}} & \text{Max and min SCs switching operations} \\
p_{\text{DG}_{\text{max}}} & \text{Active power of \( DG \) at time \( t \)} \\
p_{\text{DG}}^t & \text{Max and min active power limits} \\
\text{DG}_{\text{units}} & \text{Number of the incorporated \( DG \) in the DN} \\
S_{n_{\text{max}}}, S_{n_{\text{min}}} & \text{Max and min loading line}
\end{align*} \]

\[ \begin{align*}
\text{min } F_{\text{obj}} = \sum_{i=1}^{\text{DG}} \left( \alpha_1 F_1^i + \beta_1 F_2^i + \alpha_2 F_3^i + \beta_2 F_4^i + \alpha_3 F_5^i \right) 
\end{align*} \] (18)

The weight factors are chosen depending on the ESO and equipment’s characteristics. The weight factors of MOF play an important role. They assign priority to an objective related to the operating conditions. The weights can be expressed as follows:

\[ \sum_{i=1}^{\text{DG}} \alpha_i = 1, \quad (19) \]

where \( w_i \) are weight factors for power loss, cumulative voltage deviation (CVD), the active power of DG, Tap operations of OLTC, and several switching of SCs, respectively, the factors are explained as \( w_1 \) is attributed a high value to ensure that the power losses are important and, therefore, directly impact the cost. \( w_5 \) has been assigned a higher value than \( w_3 \) because the OLTC is more expensive than the SCs [6]. In this paper, the ESO has the choice to determine the priority of each objective function, so the weighting factors are distributed as follows: \( w_1 = 0.3; w_2 = 0.2; w_3 = 0.1; w_4 = 0.3; w_5 = 0.1 \). A flowchart of the proposed method is displayed in Fig. 2. The proposed problem is solved by minimizing the objective function equation (18), subject to the constraints (12) to (17), obtaining a set of optimal settings for all voltage control devices, during a schedule of 24 hours.

2.3 GA AND OpenDNS IMPLANTATION

In this paper, the MOF treated is formulated as a MINLP problem [19,20] and solved with GA. GA is an efficient optimization technique, independent of the complexity of problems where no preliminary information is available. OpenDNS (open distribution system simulator) is a power distribution system simulator released by EPRI (Electrical Power Research Institute). The algorithm was coded in MATLAB. It is based on two-way data exchange between MATLAB code and OpenDNS program that runs distribution load flow (DLF). This data exchange is achieved through a component object model (COM) interface available in OpenDNS [21].

2.4 PV GENERATOR MODELING

ESO forecasts the availability of PV power output on an hourly sequence. The hourly forecast data are required to test the performance of PV energy. The solar irradiance to energy conversion function of the PV system can be expressed as follows:

\[ P_\text{PV}(G) = \begin{cases} 
0, & G = 0, \\
P_{\text{opt}} (\frac{G}{G_{\text{ref}}}), & R_c > G > 0, \\
P_{\text{opt}} (\frac{G}{G_{\text{ref}}}), & G \geq R_c. 
\end{cases} \] (20)

where \( G \) is the solar irradiance in (W/m²), and \( G_{\text{ref}} \) is the solar irradiance in the standard environment set as 1000 W/m². \( R_c \) presents a certain irradiance point set as 150 W/m². \( P_{\text{opt}} \) is the rated output power of the PV system. Here, it is assumed that the temperature of the PV cell is neglected, and the PV output power is mainly subordinated to the irradiance. PV solar irradiance is unpredictable and intermittent due to weather variations. A Beta Distribution Function (BDF) is used to describe the random phenomenon of the irradiance data for each unimodal, as follows:

\[ f(G) = \begin{cases} 
\Gamma(\alpha+\beta) \left( \frac{G}{G_{\text{ref}}} \right)^{\alpha-1} \left( 1 - \frac{G}{G_{\text{ref}}} \right)^{\beta-1}, & 0 \leq G \leq 1 \text{ and } \alpha, \beta \geq 0, \\
0, & \text{otherwise.} 
\end{cases} \] (21)

where \( G_{\text{ref}} \) kW/m² is solar irradiation, \( f(G) \) is the Beta distribution function of \( G \). \( \alpha \) and \( \beta \) are the parameters of the BDF, \( \Gamma \) is the Gamma function. To calculate the parameters
of the BDF, the mean $\mu$ and standard deviation $\sigma$ of the random variable $G_i$ are used as follows:

$$\alpha = \frac{\mu^6}{1^\mu} \text{ and } \beta = (1 - \mu) \left(\frac{e^{(1+\mu)} - 1}{\sigma^2}\right).$$  \hspace{1cm} (22)

The PV generator model shown in (21) gives electrical power obtained from PV irradiance ($G_i$) samples. For the rest of the paper, assuming that the irradiance $G$ is known within 24 hours. The OCVC based on the remote control is desired to obtain an optimum voltage profile and reactive power dispatch, according to a specified objective function, for one day ahead of load demand and PV output power scheduling. This paper assumes that the PV inverter, OLTC, and SCs are adjusted remotely.

3. CASE STUDY

In this work, a new method has been performed on the IEEE13 bus distribution test feeder, as displayed in Fig. 3.

This test feeder benchmark is a very well-known test system. It has spot and distributed loads, two shunt capacitors, and a voltage regulator. The shunt capacitor (SC1) at node 675 has 600 kVAR reactive power, and the shunt capacitor (SC2) at node 611 has 100 kVAR reactive power. The proposed OCVC is performed in a MATLAB environment and OpenDSS program. In this case study, if $\pm0.03$ p.u. voltage variation is permitted for all simulation cases since the test feeder is very small. However, in the case of large distribution networks with several DGs, the interval of the allowed voltage variations is $\pm0.05$ p.u. by the standard [4]. The reference voltage of the OLTC is maintained at (1 p.u.), and the power factor of the DG can change between 0.8 and 1 (leading and lagging).

Figure 4 shows the base forecasted load demand profiles and PV power output levels for one-hour time intervals for the system under the study. To consider time-varying load and generation, it is assumed that both load demand and PV power output profiles are given for one day whatever in the year, as shown in Fig. 4. Both load demand and PV power output are effective only for a particular day and can be different depending on the season and weather conditions such as humidity, temperature, etc.

The test feeder has two PV inverters connected to the bus 652 and 675, shown in Fig. 3. Each PV inverter has a Volt/VAr control capability. [22] proposes a control for PV sources integrated into distribution networks, which uses two control loops: an external control loop, which adjusts the DC voltage, and an internal control loop, which regulates the active and reactive currents. In Volt/VAr control, the reactive power is provided or absorbed according to the limit voltage of the inverter, as shown in Fig. 5. The amount of reactive power output is a percentage of available VArS given the present active power and the apparent power rating of the inverter. The priority is given to the active power, and reactive power is provided if excess capacity is available in the inverter.

![Fig. 3 – Single line diagram of modified IEEE 13 node test feeder.](image1.png)

![Fig. 4 – Active power of load and PV of the system during 24 hours.](image2.png)

![Fig. 5 – Volt/VAr control of the PV inverter used in the simulation.](image3.png)

The proposed OCVC method is applied to the IEEE 13-bus distribution test with the load and PV output power profiles shown in Fig. 6. The bus voltages are determined by performing a series of load flow calculations using the three-phase load flow performed with OpenDSS. The power flow is performed for each hour as PV power output conditions are assumed to change for each hour. Each of the case studies presented in this work has been carried out as follows:

<table>
<thead>
<tr>
<th>Different four cases treated with the IEEE 13-bus test feeder</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DG</strong></td>
</tr>
<tr>
<td>Case 1</td>
</tr>
<tr>
<td>Case 2</td>
</tr>
<tr>
<td>Case 3</td>
</tr>
<tr>
<td>Case 4</td>
</tr>
</tbody>
</table>

**Y/N** denotes that the subject is/is not considered.

The proposed OCVC method presented in the previous section will be compared with three different cases, i.e., without DG installed in the system, the OLTC and SCs are controlled locally (case 1). For the following cases, two DGs (PV-500kW each) are connected to the bus 652 and 675, which have weak voltage profiles. The total penetration level of RES is 30% of the total peak load [19]. OLTC and SCs are controlled locally (case 2), V/VAr control where OLTC, SCs, and DGs inverter are controlled locally (case 3), the proposed OCVC method has been tested considering OLTC, SCs and DGs inverter (case 4). All the cases are summarized in Table 1. The results of the case study are discussed in the following section.

4. RESULTS AND DISCUSSIONS

The proposed OCVC method is carried out for the
distribution test feeder described in section 3. The goal of the optimal control is to minimize the power losses, limit the changes in bus voltages and avoid exceeding voltage limits, optimize OLTC and SCs switching while comparing with the cases already illustrated.

Fig. 6 shows a daily active power loss comparison between the four different cases (No DG, DG without control, DG inverter + OLTC + SCs controlled locally, and the proposed OCVC method for the fourth case) to the IEEE 13-bus test feeder. The simulation uses the daily profiles of load and PV patterns shown in Fig. 4. With the proposed OCVC method, active power losses present the best results. The optimal coordination between the voltage control devices leads to dynamic change in the PV output power according to the load variation to reduce the total power loss.

In case 1, the power losses (1171.7 kWh) present the highest value compared with the other cases, as shown in Fig. 6. The active power losses are higher in case 3 due to the non-coordination between the control devices. Thus, there is a higher reactive power flux in the DN. In case 4 (Proposed OCVC), the active power loss is more minor than in the other cases due to the network’s optimal reactive power dispatch. In this case, OCVC manages the reactive power to reduce losses. The desired results of MOF are to minimize losses as much as possible, as illustrated in Fig. 6.

All network buses’ voltage profiles are maintained in the allowed range [0.97 – 1.03] p.u. given by eq. (14), and it is greatly improved, with the optimal voltage control settings in a schedule of 24 hours.

The voltage deviations for the four different cases at bus 680 in a scheduled interval of 24 hours are shown in Fig. 8. The voltage deviations are significantly reduced with the proposed OCVC method compared with the other cases. The total voltage deviation is 1.072, with no coordination between control devices (local control), and 1.0595 in the OCVC method, as indicated by Fig. 8.

Figure 9 shows the results for the optimal OLTC operations during 24 hours for different cases. The PV connection without local control leads to 9 tap operations. With local control (case 3), the number of tap movements is 6. However, in the OCVC (case 4) method, the number of tap operations is reduced to only 3 during a day with a 50% reduction.

Fig. 9 – Optimal daily OLTC positions for different cases.

When comparing Fig. 9 and Fig. 10 to Fig. 4, a strong correlation between PV output power, load demand, and OLTC and SCs operations is observed.

High PV output power with low load resulted in lower OLTC and SCs operations, while low PV output power and high load resulted in higher operations of the OLTC and SCs.

The proposed OCVC allows the DG to mitigate the impact of load demand variations on the distribution networks and to participate in the voltage regulation as a voltage regulator instead of OLTC and SCs by reducing the operations of the VAr control devices if the discontinuous features of switching devices may provoke transient and steady-state voltage variations in the networks.

Table 2 compares CVD values and power loss ($P_{loss}$) from previous published works and the values obtained from the
proposed methodology. According to this table, the proposed methodology can achieve better, more logical results than other methods.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Technique</th>
<th>MO</th>
<th>TLV</th>
<th>DG</th>
<th>CVD</th>
<th>P\textsubscript{load}(kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[6]</td>
<td>DP</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>0.49 - 1.03 /</td>
<td></td>
</tr>
<tr>
<td>[23]</td>
<td>/</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>0.45 - 1 /</td>
<td></td>
</tr>
<tr>
<td>[24]</td>
<td>GA</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>50 - 110 /</td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>GA</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>0.016 - 10.14 /</td>
<td>0.088 - 104.62</td>
</tr>
</tbody>
</table>

Y/N denotes that the subject is/is not considered.

5. CONCLUSIONS

This paper proposes a voltage control technique in unbalanced distribution networks under time-varying load and DG generation. From an optimization problem, the proposed method OCVC has the object to find all optimal settings for the control devices using GA and OpenDSS in a co-simulation environment. Both non-coordinated and coordinated voltage control are treated with and without DG concerned in the voltage control. The proposed OCVC aims to reduce the power loss, decrease the number of VAR devices switching as possible, and contribute to increasing the amount of RES integration. The proposed method achieves an optimal voltage profile and reactive power dispatch by considering time-varying load and generation based on day-ahead scheduling. The results indicate that the involvement of DG in voltage control will result in reduced switching of devices (OLTC, SCs). Some important issues can be addressed in future research, such as incorporating hybrid DG sources and storage devices, and dynamic weight factors can be included in the multi-objective problem formulation.

Received on 19 December 2022

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