Optimal Coordinated Voltage Control of Distribution Networks Considering Renewable Energy Sources

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ABSTRACT

In light of the pressing concerns regarding global warming and the diminishing availability of fossil fuels, there has been a notable surge in the adoption of distributed generation (DG) systems, which harness clean and renewable energy sources. These systems are strategically placed in close proximity to end-users, thereby reducing power losses. However, without effective control mechanisms, issues such as voltage instability and increased power losses can impede the efficient functioning of the power grid. In this paper, an innovative approach termed Optimal Coordinated Voltage Control (OCVC) is designed for distribution networks integrating dispersed renewable energy sources. Employing a genetic algorithm (GA) methodology and implementing multi-core simulation using the open-source platform OpenDSS, this method aims to optimize the settings of voltage control devices remotely. Moreover, it accounts for dynamic variations in both load and generation patterns through day-ahead scheduling. To evaluate the efficacy of the proposed technique, simulations are conducted on a test distribution network featuring the integration of DG systems. Lastly, the proposed OCVC method can achieve more than a 50% reduction in OLTC and SC switching over a 24-hour schedule compared to non-coordinated techniques. Additionally, the proposed method offers the benefits of minimizing power losses and limiting changes in bus voltages.

Keywords: Coordinated voltage control (CVC), Optimization, Distributed generation (DG), Distribution network, On-Load Tap Changer (OLTC), Shunt capacitors (SCs)

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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), 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 well as the operation of voltage control devices may be affected [2].

A number of interesting research works in literature treat the issues of voltage control of the distribution networks in the presence of DG. In [3] a novel approach is introduced for the coordinated optimization of power distribution, known as Coordinated Optimal Power Dispatch with Integrated Distributed Energy Resource Scheduling (COPD-IDS). This method is designed to minimize the daily operational cost of a power system by managing the scheduling of distributed energy resources (DERs). Sometimes, conventional voltage control regulators, such as On-Load Tap Changer (OLTC), are unable to solve these problems without optimal coordination with the other control regulators. Without optimal coordination between OLTC, Shunt Capacitors (SCs), and DG, the number of switching operations will rise in a significant way, even degrading the power quality. The recommendations of [4] stipulate that DG should not contribute to the voltage control of DNs. Due to the limitation of maximum power inverter current, it can be assumed that total fault contribution from the PV source does not exceed twice the PV source rated current [5]. This concludes that the PV sources have no significant impact on the short circuit level of the distribution network.

References [6, 7] propose a technique to calculate the OLTC and SCs day-ahead operations schedules. [8] presents a feasibility study of the integration of PV sources into the isolated distribution network of Djanet in Algeria; some strategies are proposed to minimize the negative impacts. [9] Uses the gradient descent algorithm to solve the optimization problem of online coordination of the OLTC with dispatchable DGs. Reference [10] proposes a coordinated control system, Sine Cosine Adapted Improved WOA (SCiWOA), integrates Type-2 fuzzy logic control (T2FLC) for power system stabilizer (PSS). The system incorporates a modified local signal (MLS) input to enhance the performance of the Type-2 FLC. Reference [11] proposes a sensitivity investigation based on the coordination method for the voltage control in the presence of wind generators. In [12], the proposed algorithm divides the distribution network into two sub-regions for the voltage control: one region is attributed to the OLTC, and the second region is attributed to the dispatchable DG. In [13], voltage control of PV systems integrated into the distribution network has been treated as part of the coordination between electric vehicles and OLTC. In [14], a harmony search optimization algorithm was used to carry out a day-ahead planning of non-dispatchable DGs. In [15], an optimization method is proposed for OLTC, SCs, and reactive power in DG in order to minimize power losses. [16] Used dynamic programming (DP) for the voltage control to find the optimal OLTC positions and SCs switching in the next day. In [17], the GA is combined with the voltage stability-constrained optimal power flow technique to solve a Multi-Objective Function (MOF) in order to enhance the voltage stability. [18] used the Gravitational Search Algorithm (GSA) to solve the optimization problem of control devices. In [19], the objective function is developed for active power loss minimization, with the OLTC position, SCs status, and DG reactive outputs as the control variables. [20] presents a multi-objective control for multi-feeder DNs that utilize information from available voltage regulators, current, power, as well as offline databases. The objective was to find the optimal operation of Tap leading to reduced power losses and switching operations.

In this study, we propose a novel GA-based coordinated voltage control method tailored for managing voltage in distribution networks. A thorough literature review indicates that while existing research extensively addresses CVC issues, several critical aspects remain underexplored, such as time-varying load (TVL) demand and distributed generation (DG). Additionally, objectives like optimizing capacitor switching and reducing OLTC operations over a specific period were often excluded from the optimization process. The proposed multi-objective function focuses on minimizing power losses, enhancing voltage deviation and stability, maximizing DG penetration with an appropriate power factor, and reducing OLTC operations and capacitor switching. The main contributions of this paper are outlined 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 a 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 taken into consideration in the unbalanced distribution system.

- Considering more realistic MINLP, Tap operations and capacitor switching are modeled as discrete variables and incorporated into the objective function. To the best of the authors' knowledge, no literature has addressed all of these issues at the same time.

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, a conclusion and future research are provided in Section 5.

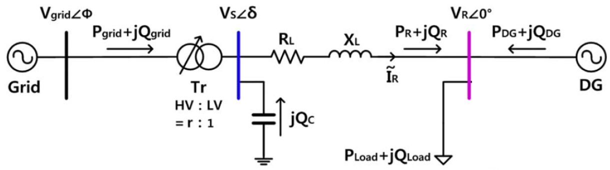

***Fig. 1**: Simplified distribution system.*

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 profile of the bus voltage between just a little bit of a percent of the rated value in order to provide or absorb the desired reactive power by the DG. Thus, the reactive power provided by each SC is near to the rated value. To make the formulas simpler, thereafter we suppose that the DN has constant power loads; the total power loss is negligible for the transformer.

Nomenclature used in the simplified distribution system:
V_{grid}, Ø: Voltage magnitude and angle of the grid.
P_{grid}, Q_{grid}: Active and reactive power from the grid.
V_S, δ : Voltage magnitude and angle at the source bus.
V_R: Voltage magnitude at the receiving bus.
Qc: Reactive power from shunt capacitor.
R_L, X_L: Resistance and reactance of the line.
P_{DG}, Q_{DG}: Active and reactive power of the DG.
P_{Load}, Q_{Load}: Active and reactive power of the load.
P_R, Q_R: Active and reactive power flowing in the line.
I_R: Current flowing in the line.

Where V_S , V_R and P_{Loss} can then be functionally expressed as [6]:

$$V_s = f_1(r, cap, Q_R) = f_2(tap, cap, Q_{DG}) \quad (1)$$

$$V_R = g_1(V_s, Q_R) = g_2(tap, cap, Q_{DG}) \quad (2)$$

$$\begin{aligned} P_{Loss} &= R_L \left| I_R \right|^2 \\ &= \left| \frac{V_S cos\delta \ + jV_S sin\delta \ + V_R}{R_L + jX_L} \right|^2 R_L \\ &= t(tap, cap, Q_{DG}), \end{aligned} \tag{3}$$

where r is the transformation ratio, cap is the capacitor value, tap is the tap changer of the transformer. $f1,\ f2,\ g1,\ g2$ and t are functions.

2.1 Coordinated Voltage Control in DNs

Nowadays, a hierarchical voltage control scheme with three levels has been developed by ESO to prohibit voltage instability and to guarantee an 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 secondary voltage control is carried out by the OLTC and SCs. Finally, the tertiary voltage control is based on an optimization strategy by using an operation schedule in order 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:

$$minF_{obj}\ (x, u) \tag{4}$$

Subject to:

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

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

With $x \in R^n$ and $u \in R^m$

Where F_{obj} represents the objective function for the problem, 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 for 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)

Electrical equipment is manufactured to operate at nominal voltage; a possible voltage deviation can reduce their performance and lifetime. Consequently, the voltage level of the system can be minimized by the sum of voltage deviations of load buses from the reference values (1 p.u.); we name this function as cumulative voltage deviation (CVD).

$$F_2 = \frac{1}{N} \sum_{i=1}^{N} \left| V_{ref} - V_i \right| \tag{8}$$

- Voltage stability index (VSI)

Voltage stability issues have taken the attention of electrical system operators (ESOs) as power systems collapses are experienced in the past for reasons of voltage instability. Voltage stability is the capability of the power system to keep the voltage level in allowed limits in all the buses, with normal operating and after being subjected to disturbances. The voltage stability index (named L-index) of each load bus is a good indicator of power system stability assessment. The value of the index varies in the interval between 0 (no load of the system) and 1 (voltage collapse) [21]. The VSI is calculated for all load buses, and the maximum value among them is considered as the global stability indicator for the power system; the objective function can be expressed as follows:

$$F_3 = max \left| 1 - \sum_{i=1}^{N_G} F_{ji} \frac{V_i}{V_j} \right| \tag{9}$$

where $F_{ji} = -\left[Y_{LL}\right]^{-1} \left[Y_{LG}\right]$ and $j = 1, 2, \ldots,\ N_L$

N_L is the number of loadbuses (PQ) and N_G is the number of generator buses (PV). Where, sub-matrices Y_{LL} and Y_{LG} are obtained from Y_{BUS} matrix after separating loadbuses (PQ) and generator buses (PV) as represented in the following matrix:

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix}$$

- Active power of the DG

In order to increase the active power delivered from the DG, the following function is added:

$$F_4 = P_{DG} \tag{10}$$

- OLTC operations

The Mixed Integer Non-Linear Problem (MINLP) in [7] proposes an objective function to reduce the number of switching regulator operations. In this paper similar terms are included with the following modifications: in order to reduce the number of OLTC operation, a penalty is imposed directly in the equation considering the last tap position $(t-1)$ rather the next tap position $(t+1)$.

$$F_5 = \left| Tap^{t-1} - Tap^t \right| \tag{11}$$

- SCs switching

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

$$F_6 = \left| Cap^{t-1} - Cap^t \right| \tag{12}$$

2.2.2 Optimization Constraints

The constraints cans be expressed as follows:

$$V_n^{min} \leq V_n^t \leq V_n^{max} \tag{13}$$

$$Tap^{min} \leq Tap^t \leq Tap^{max} \tag{14}$$

$$Cap^{min} \leq Cap^t \leq Cap^{max} \tag{15}$$

$$P_{DG}^{min} \leq P_{DGi}^t \leq P_{DG}^{max} \tag{16}$$

With $n = 1, \ldots N$; $t = 1, \ldots T$ and $i = 1, \ldots DG_{units}$.

The variables associated in (7-16) are defined as follows:
N Buses number of the DN
T Scheduling in a day, (*T=24hours*)
V_n^t Voltage magnitude at bus n and time t
V_n^{max}, V_n^{min} Max and min voltage limits ± 0.03 p.u.
Tap^t Tap position at time t
Tap^{max}, Tap^{min} Max and min Tap position limits ± 4
Cap^t SCs position at time t
Cap^{max} , Cap^{min} Max and min SCs switching
P_{DGt}^t Active power of DG_i at time t
P_{DG}^{max} Max and min active power limits
DG_{units} Number of the DGs in the DN

$$minF_{obj} = \sum_{t=1}^{T} \omega_1 F_1^t + \omega_2 F_2^t + \omega_3 F_3^t + \omega_4 F_4^t + \omega_5 F_5^t + \omega_6 F_6^t \tag{17}$$

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:

$$\sum_{t=1}^{6} \omega_i = 1, \tag{18}$$

where ω_i are weight factors for power loss, cumulative voltage deviation (CVD), voltage stability index (L_{index}), active power of DG, Tap operations of OLTC, and number of switching of SCs, respectively.

The weight factors are variously determined according to the ESO and device characteristics. In this paper, these factors are specified as follows. w_5 is given a higher value than w_6 and because the OLTC is a more expensive piece of equipment than the SCs. Moreover, w_1 is assigned a substantially high value to ensure that power losses are regarded with the same importance as the number of switching operations of the OLTC [6]. The ESO has the choice to determine the priority of each objective function, so the weighting factors are distributed as follows: ($\omega_1 = 0.2$; $\omega_2 = 0.1$; $\omega_3 = 0.2$; $\omega_4 = 0.2$; $\omega_5 = 0.2$; $\omega_6 = 0.1$).

A flowchart of the proposed method is displayed in Fig. 2. The proposed problem is solved by minimizing the objective function equation (17), subject to the constraints (13) to (16), obtaining a set of optimal settings for all voltage control devices during a schedule of 24 hours.

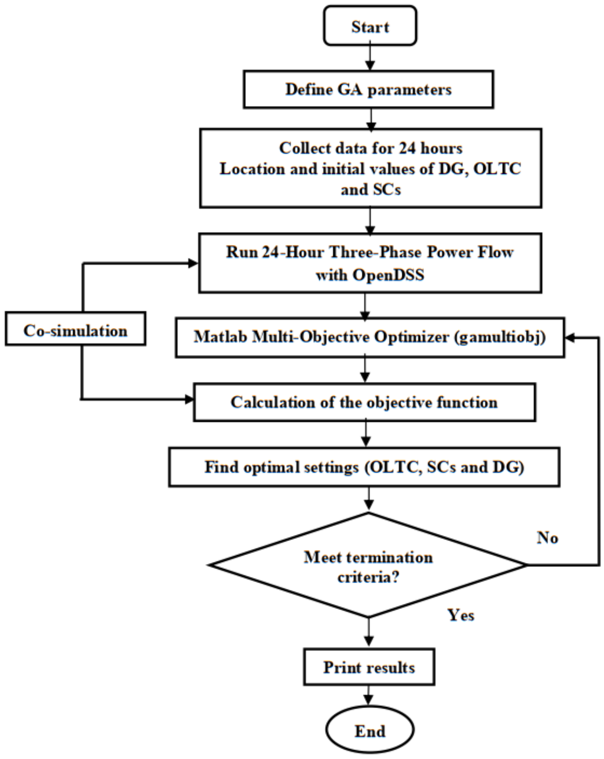

Fig. 2: *Flowchart of the proposed method.*

2.3 GA and OpenDSS implantation

The minimization problem presented is solved with the GA. The fitness equation (17) is applied to the unbalanced distribution system with no linear components, creating a mixed-integer nonlinear programming problem (MINLP) [22], due to the presence of discrete elements such as OLTC. The GA can handle such problems effectively; it is a heuristic search algorithm based on the process of natural selection and evolution of individuals. The algorithm generates a random group of individuals to be reproduced, and in each step, this group produces a new generation based on the crossover and mutation operations, evolving until the optimal solution is reached.

OpenDSS (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 the OpenDSS program that runs distribution load flow (DLF). This data exchange is achieved through a component object model (COM) interface available in OpenDSS [23]. Many researchers have worked on distribution networks using the OpenDSS program [24, 25].

OpenDSS can include generation and new loads to

***Table 1**: GA Parameters.*

Parameter	Specification
Population	40
Selection Method	Normalized
Crossover Function	Scattered
Number of Generations	1000
Population Type	Integer
Reproduction	Crossover 0.8
Mutation	Gaussian
Termination Criteria	Best Fitness Value

perform calculations over variable time step sizes. In this work, the program is driven from Matlab (Fig. 3), which is used to calculate the input data and the control of the procedure. The distribution network IEEE 13-node test feeder is used for the simulation, data from [26]. In this paper, the parameters of GA used for solving the problem are displayed in Table 1.

The program was implemented in the Matlab environment to obtain the minimum of the multiple functions utilizing GA. The minimum of the sum of the multi-objectives is calculated with Decision Maker (DM); for each series of solutions, the set of solutions that have the minimum is chosen.

2.4 PV generator modelling

ESO forecasts the availability of PV power output on an hourly sequence. The hourly forecast data are required to predict the performance of PV energy. The solar irradiance to energy conversion function of the PV system can be expressed as follows [22], [27]:

$$P_S(G) = \begin{cases} 0 & G = 0 \\ P_{sr}(\frac{G^2}{R_c G_{std}}) & R_c > G > 0 \\ P_{sr}(\frac{G}{G_{std}}) & G \geq R_c \end{cases} \tag{19}$$

Where G is the solar irradiance in (W/m^2), G_{std} is the solar irradiance in standard environment set as 1000 W/m^2. R_c presents a certain irradiance point set as 150 W/m^2. P_{sr} is the rated output power of the PV system in (W). Here, it is assumed that the temperature of PV cell is neglected and the PV output power is mainly subordinated on the irradiance [27]. PV solar irradiance is unpredictable and intermittent due the weather variations. A Beta Distribution Function (BDF) is used to describe the random phenomenon of the irradiance data for each unimodal, as follows:

$$f(G_S) = \begin{cases} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} G_S^{(\alpha-1)}(1-G_S)^{(\beta-1)} & 0 \leq G_S \leq 1 \text{ and } \alpha, \beta \geq 0 \\ 0 & \text{Otherwise} \end{cases} \tag{20}$$

Where G_S is solar irradiation in kW/m^2, $f(G_S)$ is Beta distribution function of G_S. α and β are the parameters of the BDF, Γ is Gamma function. In order to calculate the parameters of the BDF, the mean μ and standard deviation σ of the random variable G_S are used as follows:

$$\alpha = \frac{\mu\beta}{1-\mu} \text{ and } \beta = (1-\mu)(\frac{\mu(1+\mu)}{\sigma^2} - 1) \tag{21}$$

The PV generator model presented in Equation (20) calculates the electrical power derived from PV irradiance (G_S) samples. In this paper, it is assumed that the irradiance G is known according to a 24-hour schedule. The objective is to achieve an optimal voltage profile and reactive power dispatch using an OCVC system based on remote control, in accordance with a specified objective function, for a one-day-ahead load demand and PV output power schedule. In this study, it is assumed that the PV inverter, OLTC, and SCs can be adjusted remotely.

3. CASE STUDY

In this work, a new method has been performed on the IEEE13-bus unbalanced distribution test feeder as displayed in Fig. 4.

This test feeder benchmark is a well-known system, featuring both spot and distributed loads, two shunt capacitors, and a voltage regulator. The shunt capacitor (SC1) at node 675 provides 600 kVAr of reactive power, while the shunt capacitor (SC2) at node 611 provides 100 kVAr of reactive power. Comprehensive data for this test feeder can be found in [27].

The proposed OCVC is performed in the Matlab environment and OpenDSS program. The OpenDSS is an electric power Distribution System Simulator (DSS) to perform DG integration and power system improvements. It has the capability to simulate a very large DN with low CPU time. Moreover, it is an open-source distributed by EPRI.

Fig. 5 shows the COM interface tools 3D graphic performing the voltage profile variation of all 13 nodes during a schedule of 24 hours.

In this case study, a voltage variation of ± 0.03 p.u. is permitted for all simulations, as the test feeder is relatively small. However, for larger distribution networks with multiple DGs, the allowable voltage variation is set to ± 0.05 p.u. in accordance with the standard [4]. The reference voltage of the OLTC is maintained at 1 p.u, and the power factor of the DG can vary between 0.8 and 1, both leading and lagging.

Fig. 6 shows the base forecasted profiles of both load demand and PV power output levels for one-hour time intervals for the system under the study.

To account for time-varying load and generation, it is assumed that both load demand and PV power output profiles are provided for a specific day of the year, as illustrated in Fig. 6. These profiles are considered effective only for that particular day and may vary depending on seasonal changes and weather conditions, such as humidity, temperature, and more.

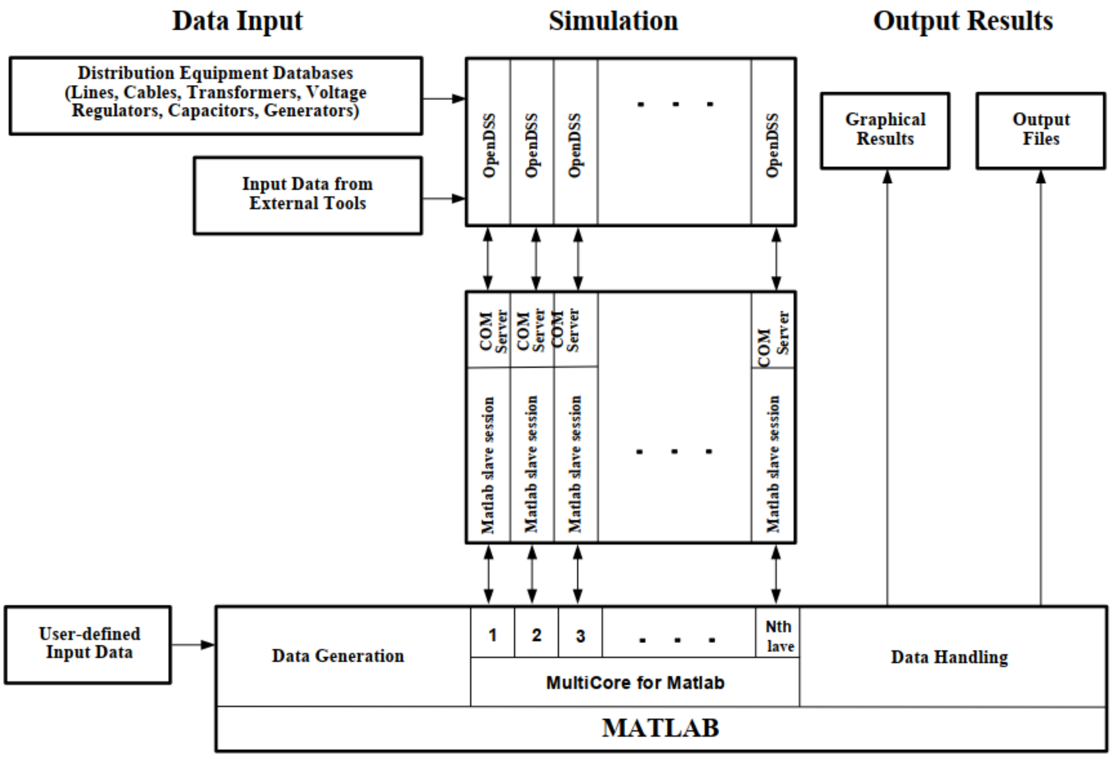

***Fig. 3**: Scheme of MATLAB – OpenDSS interaction.*

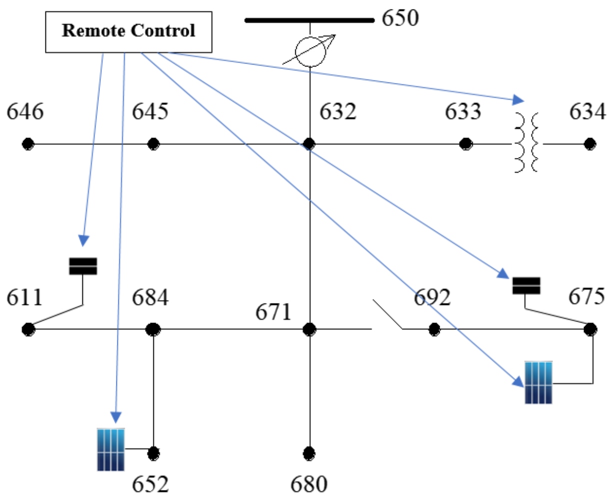

***Fig. 4**: Single line diagram of modified IEEE 13 bus.*

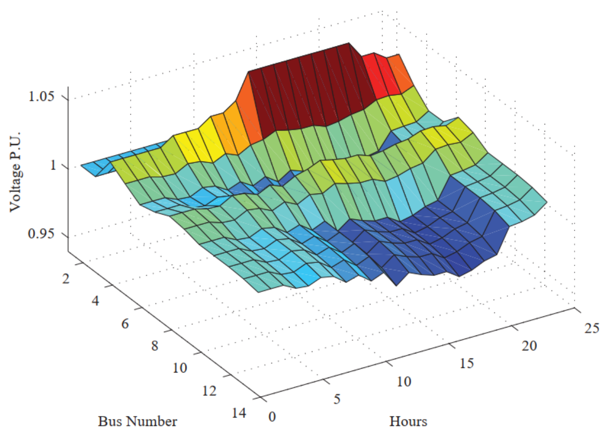

***Fig. 5**: Voltage profile of all IEEE 13-bus in 24 hours.*

The test feeder includes two PV inverters connected to buses 652 and 675, as illustrated in Fig. 4. Each PV inverter is equipped with Volt/VAr control capabilities. [28] proposes a control strategy for PV sources integrated into distribution networks, utilizing two control loops: an external loop that adjusts the DC voltage and an internal loop that regulates 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. 7. 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 there is excess capacity available in the inverter. This functionality includes the adoption of reactive power functions to provide adequate local voltage regulation for a voltage variation caused by the intermittent nature of the DG. From the control setting curve shown in Fig. 7, the inverter does not supply any reactive power during the dead band (d) range. If the voltage is below v_2, the inverter operates in a capacitive mode, thus supplying reactive power. On the other hand, if the voltage is above v_3, the inverter operates in an inductive mode, thus absorbing the reactive power. Moreover, when the voltage is between v_1 and v_2 as well

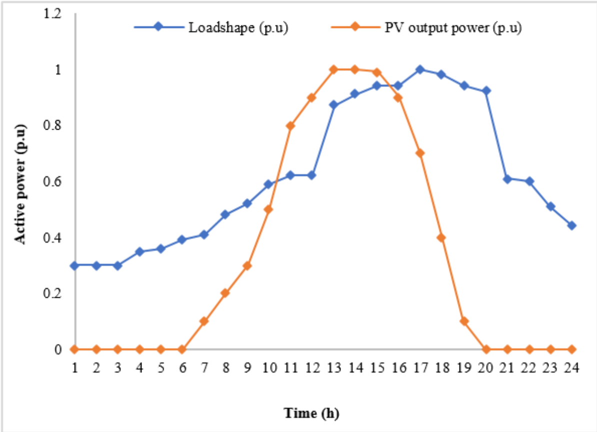

***Fig. 6**: Active power of load demand and PV of the system during 24 hours.*

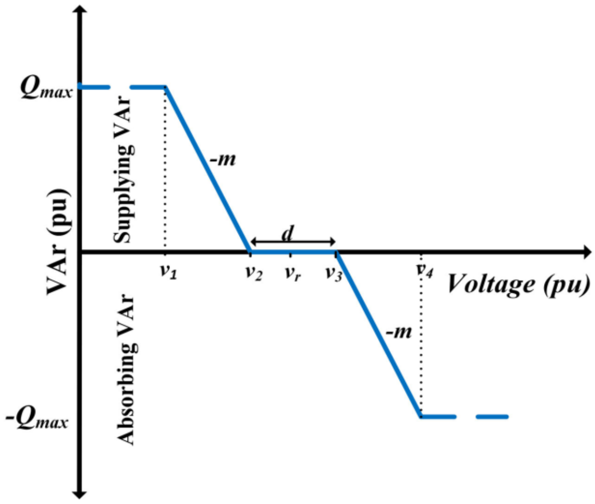

***Fig. 7**: Volt VAr control curve of the PV inverter.*

as v_3 and v_4, the inverter supplies and absorbs reactive power as a function of the slope (m), respectively.

In this paper, the optimal control setting curve points (v_1, v_2, v_3 and v_4) for the PV inverter are determined based on the dead band (d), slope (m), and the reference voltage (v_r), expressed as follows:

$$\begin{aligned} v_1 &= \frac{2 \times m \times v_r - d \times m - 2 \times Q_{max}}{2 \times m} \\ v_2 &= \frac{2 \times v_r - d}{2} \\ v_3 &= \frac{2 \times v_r + d}{2} \\ v_4 &= \frac{2 \times m \times v_r + d \times m + 2 \times Q_{max}}{2 \times m} \end{aligned} \tag{22}$$

Where Q_{max} is the maximum available reactive power from the PV inverter.

The Volt/VAr function mode of the PV inverter can produce reactive power using either watt priority or VAr priority modes. During the watt priority mode, the active power is prioritized over reactive power production. Therefore, the PV inverter does not produce reactive power when the PV inverter absorbs or supplies active power at its full capacity.

The proposed OCVC method is applied to the IEEE 13-bus distribution test system, utilizing the load and PV output power profiles shown in Fig. 6. Bus voltages are determined through a series of load flow calculations, which are conducted using three-phase load flow analysis with OpenDSS. These calculations are performed for each hour, accounting for the variation in PV power output conditions. Each case study presented in this work involves comparing the proposed OCVC method with three scenarios: (1) without distributed generation (DG) installed, where the OLTC and SCs are controlled locally; (2) with two DGs (each PV unit rated at 500 kW) connected to buses 652 and 675, which experience weak voltage profiles; and (3) a total RES penetration level of 30% of the peak load [22].

Local control strategies are employed in different cases: Case 2 involves local control of OLTC and SCs; Case 3 includes Volt/VAr control with local management of OLTC, SCs, and DG inverters; and Case 4 tests the proposed OCVC method with OLTC, SCs, and DG inverters. A summary of these cases is provided in Table 2. The results of the case study will be discussed in the following section.

***Table 2**: Case studies.*

	DG	DG Inverter	SCs	OLTC	Coordinated control
Case 1	N	N	Y	Y	N
Case 2	Y	N	Y	Y	N
Case 3	Y	Y	Y	Y	N
Case 4	Y	Y	Y	Y	Y

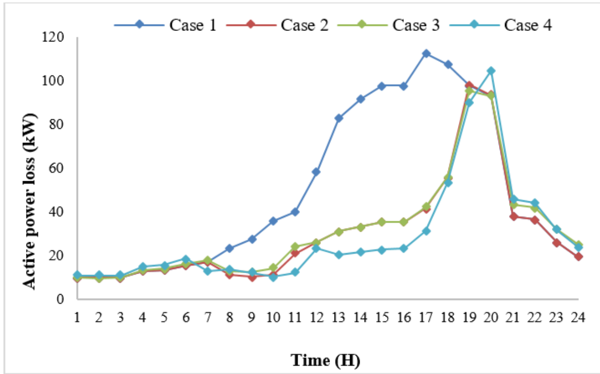

***Fig. 8**: Active power loss for the four different cases in a schedule interval of 24 hours.*

4. RESULTS AND DISCUSSIONS

The proposed OCVC method is applied to the distribution test feeder described in Section 3. The objective of this optimal control approach is to minimize power

***Table 3**: Daily total active and reactive losses.*

	Active energy loss (kWh)	Reactive energy loss (kVArh)
Case 1	1171.7	3395.1
Case 2	709.2	1883.3
Case 3	742.6	1979.6
Case 4	677.6	1806.9

losses, limit voltage fluctuations, prevent voltage violations, and optimize the switching operations of OLTCs and SCs while comparing the results with the previously discussed cases.

Fig. 8 presents a comparison of daily active power losses across four different scenarios: no DG, DG without control, DG inverter with OLTC and SCs controlled locally, and the proposed OCVC method. These scenarios are applied to the IEEE 13-bus test feeder, using the daily load and PV profiles illustrated in Fig. 6. The results demonstrate that the proposed OCVC method yields the lowest active power losses. This improvement is attributed to the optimal coordination between voltage control devices, which dynamically adjusts the PV output power in response to load variations, effectively minimizing total power losses.

In Case 1 (without DG), the power losses (1171.7 kWh) are the highest compared to the other cases, as shown in Fig. 8 and Table 3. The active power losses are particularly significant in Case 3 due to the lack of coordination among control devices, leading to higher reactive power flux in the distribution network. In Case 4 (Proposed OCVC), the active power loss is the lowest among all cases, attributed to the optimal dispatch of reactive power in the network. In this scenario, OCVC effectively manages reactive power to minimize losses. The goal of the MOF is to reduce losses as much as possible, as illustrated in Fig. 8 and Table 3.

Table 3 presents the daily comparison of total active and reactive energy losses across four different scenarios over a 24-hour period. It is evident that the proposed OCVC method significantly reduces total energy losses.

This was observed both prior to the implementation of coordinated control and following the application of the proposed method in all cases. This clearly demonstrates the substantial impact of the proposed OCVC method on voltage variation.

The voltage profile at all network buses is consistently maintained within the allowable range of [0.97 - 1.03] p.u., as defined by Eq. (13), and is significantly improved with the optimal voltage control settings over a 24-hour schedule. Figure 10 illustrates the voltage deviations for four different cases at bus 680 over this 24-hour period. The proposed Optimal Coordinated Voltage Control (OCVC) method greatly reduces voltage deviations compared to other methods. Specifically, the total voltage deviation is 1.072 p.u. without coordination between control devices (local control) and 1.0595 p.u. with the OCVC method, as shown in Fig. 10.

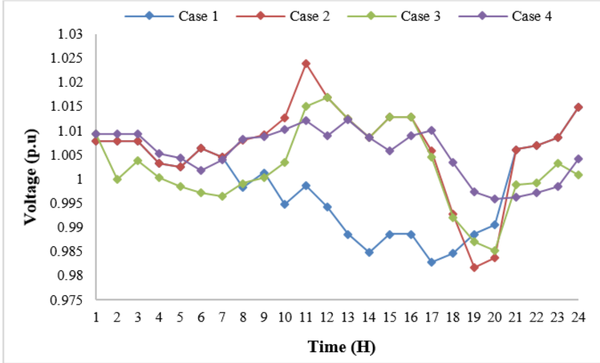

***Fig. 9**: Voltage profile variations at bus 680 phase A, for the four different cases.*

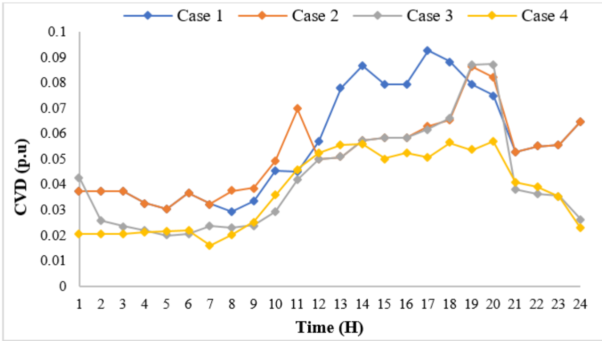

***Fig. 10**: CVD at bus 680 for the four different cases in a schedule of 24 hours.*

Fig. 11 illustrates the voltage stability index L_{indx} across various scenarios. It is evident that incorporating the PV inverter has enhanced the stability of the test system.

Fig. 12 illustrates the results of optimal OLTC operations over a 24-hour period for various scenarios. In the case without local control of the PV connection, there are 9 tap operations. With local control (Case 3), the number of tap movements is reduced to 6. However, with the OCVC method (Case 4), the number of tap operations decreases to just 3, representing a 50% reduction over the course of the day.

Fig. 13 illustrates the status of the two shunt capac-

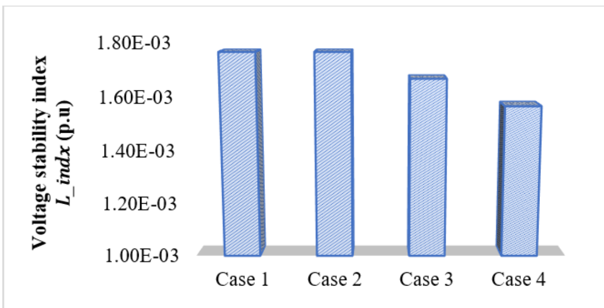

***Fig. 11**: Voltage stability index Lindx for different cases.*

***Table 4**: Comparison of CVD values and power loss obtained from different methodologies.*

Ref.	Algorithm	MO	TVL	DG	CVD	Ploss (kW)
[6]	DP	N	Y	N	0.490 - 1.030	-
[16]	-	Y	Y	N	0.450 - 1.000	-
[29]	GA	Y	Y	N	-	50.00 - 110.00
Proposed	GA	Y	Y	Y	0.016 - 0.088	10.14 - 104.62

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

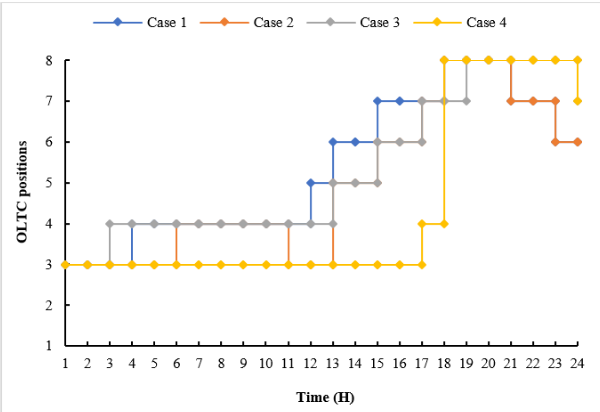

***Fig. 12**: Optimal daily OLTC positions for different cases.*

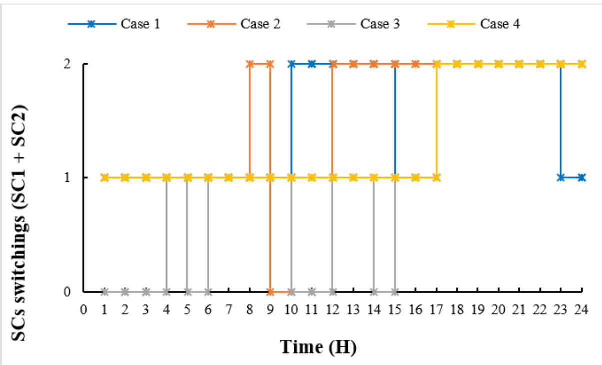

***Fig. 13**: Optimal daily SCs switching's for different cases.*

itors across various cases, where a status of 0 indicates that the capacitor is switched off, and 1 indicates that it is switched on. The figure clearly demonstrates that the proposed OCVC method significantly reduces the number of shunt capacitor switchings to just 2.

Comparing Figures 12 and 13 with Figure 6 reveals a strong correlation between PV output power, load demand, and the operation of OLTC and SCs. Specifically, high PV output power coupled with low load demand is associated with reduced operations of both OLTC and SCs. Conversely, low PV output power combined with high load demand leads to increased operations of OLTC and SCs.

The proposed OCVC enables DGs to mitigate the impact of load demand variations on distribution networks and participate in voltage regulation as an alternative to OLTC and SCs. By reducing the reliance on VAr control devices, the OCVC method addresses the transient and steady-state voltage variations typically caused by switching devices, thereby enhancing voltage stability. Furthermore, incorporating power loss and DG output power into the MOF allows for precise control of DG voltage, ensuring that the distribution network operates within its acceptable voltage range. With the DG voltage regulated consistently, the network voltage remains high and within the acceptable range, a benefit not always achievable with OLTC and SCs alone. Consequently, this approach reduces both total power loss and the frequency of VAr device switching. Maintaining a stable voltage profile is crucial for network stability, ensuring that the voltage at each bus remains as close as possible to the allowable range at all times.

Table 4 compares the CVD values and power loss (P_{loss}) from previously published works with those obtained using the proposed methodology. The results indicate that the proposed approach delivers more accurate and rational outcomes compared to the methods reported in [6, 16, 29].

5. CONCLUSIONS

This paper presents a voltage control technique for unbalanced distribution networks, considering time-varying load demand and distributed generation (DG). The proposed method, OCVC, addresses an optimization problem to identify optimal settings for control devices using Genetic Algorithms (GA) and OpenDSS in a co-simulation environment. A comparative analysis of various distribution network scenarios with DGs was conducted, examining both coordinated and non-coordinated voltage control, with and without DG involvement. The OCVC method aims to reduce power loss, enhance voltage stability, minimize the number of VAr device switchings, and support increased integration of renewable energy sources (RES). By accounting for time-varying load and generation through day-ahead scheduling, the proposed method achieves an optimal voltage profile and reactive power dispatch. The results demonstrate that involving DG in voltage control reduces the switching frequency of devices such as OLTCs and SCs. Future research could explore incorporating hybrid DG sources and storage devices, as well as including dynamic weight factors in the multi-objective problem formulation.

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