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A Particle Swarm Optimization–Based Volt-VAR Control Strategy for Distribution System Incorporating Conservation Voltage Reduction

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WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Volt-VAR Control (VVC) is a crucial function in distribution networks to assure stable voltages, decrease technical losses, and increase power quality.*
- *Traditional VVC solutions focus mostly on On-Load Tap Changers (OLTCs), Automatic Voltage Regulators (AVRs), and capacitor banks, but they typically fail to respond to real-time dynamic loading.*
- *Conservation Voltage Reduction (CVR) is a well-recognized strategy for minimizing power consumption and peak load demand by operating at the lower limit of allowable voltage limits.*
- *Particle Swarm Optimization (PSO) and other optimization methods have been previously utilized to coordinate OLTCs and AVRs for loss minimization, but issues remain in handling complex test systems such as IEEE-123 bus networks and in incorporating realistic voltage-dependent load models.*

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ABSTRACT

The distribution network faces significant operational challenges in maintaining acceptable voltage levels under dynamic load conditions. Rapid load fluctuations often degrade the performance of localized voltage control schemes, leading to voltage instability and increased power losses. To address this issue, this paper proposes a centralized, optimization-based Volt-VAR control strategy that integrates Particle Swarm Optimization (PSO) with Conservation Voltage Reduction (CVR) for enhanced voltage regulation and energy efficiency in distribution systems. The proposed approach determines optimal tap positions of Automatic Voltage Regulators and On-Load Tap Changers using a system-wide optimization framework implemented in OpenDSS. A voltage-dependent load model is employed to realistically capture the impact of voltage variations on active and reactive power consumption. Simulation studies conducted on the IEEE-123 bus distribution system demonstrate that the PSO-based centralized control improves voltage regulation. It also reduces active power losses compared with conventional localized control. Additionally, peak load reduction is observed as a secondary benefit of CVR implementation. The proposed PSO-based control reduces active power losses from 4.72% to 4.59% and improves the minimum bus voltage from 0.8714 p.u. to 0.9459 p.u., ensuring voltage profiles remain within acceptable limits while enabling effective load reduction under CVR operation. The proposed framework provides a scalable and practical solution for advanced distribution management systems to improve voltage quality and energy efficiency.

Index Terms—Automatic voltage regulators, conservation voltage reduction, IEEE-123 bus system, on-load tap changers, particle swarm optimization, Volt-VAR control

I. INTRODUCTION

Modern distribution systems are becoming increasingly complex due to variable load patterns and operational demands. Maintaining stable voltage profiles is essential for power quality and reliable system operation [1]. Traditional voltage regulation methods based on the fixed settings of On-Load Tap Changers (OLTCs) and voltage regulators often fail to respond effectively to dynamic operating conditions. To address this limitation, recent approaches have focused on the online coordination of multiple voltage-regulating devices to improve adaptability, ensure voltage compliance, and enhance the overall system performance [2].

Centralized control strategies coordinate voltage regulation using system-wide information. By collecting global measurements and executing centralized optimization algorithms, these systems can efficiently manage voltage levels and optimize the operation of the control devices [3]. However, these approaches depend heavily on the communication infrastructure and are vulnerable to delays, data loss, and centralized failures [4]. In contrast, localized voltage control distributes decision-making across multiple local controllers. Each control node operates autonomously using local measurements, making the system more robust and scalable [5]. Localized strategies respond quickly to local disturbances, although they may require careful coordination to avoid conflicting control actions and to ensure system-wide performance [6].

Integrating Conservation Voltage Reduction (CVR) into control frameworks enables energy savings and peak load reduction [7]. The CVR operates the network at the lower limit of the allowable

WHAT DOES THIS STUDY ADD TO THIS TOPIC?

- *This study proposes a PSO-based centralized voltage control approach and analyzes performance compared to localized control approaches in an IEEE-123 bus system, which is more sophisticated than most preceding case studies.*
- *It combines a voltage-dependent load model (Model 4 in OpenDSS) to better represent realistic load behaviors during CVR.*
- *The proposed framework improved voltage stability, reduced losses, and significant peak demand reduction, at a 0.96 CVR factor, compared to localized controllers. It validates a scalable and practical methodology for implementing CVR and VVC in advanced distribution management systems.*

voltage range, requiring accurate load modeling and intelligent control to maintain the voltage within acceptable limits [8]. Several studies have investigated OLTC optimization approaches. A linear relationship for voltage regulation exists according to research that establishes both voltage safety and optimal reactive power compensation [9]. The study did not identify optimal methods for Automatic Voltage Regulator (AVR) and OLTC coordination.

Research has analyzed how OLTC controllers affect grid conditions during abnormal events and voltage instability processes [10]. Others have focused on voltage-based controllers to manage the voltage in power distribution grids [11], strategies for reactive power adjustments and OLTC tap position coordination [12], and cooperative OLTC scheduling for active distribution network Volt-VAR control (VVC) [13]. New dynamic dead-band control strategies offer solutions for lowering equipment failures and reducing tap switching incidents [14]. To date, research has failed to specifically examine the dynamic optimization process for AVR and OLTC tap position adjustment in the IEEE-123 Bus System framework. In [15], CVR deployment in a smart grid-enabled environment was explored, focusing on power loss minimization through reactive power support and capacitor bank control. Although the results validated the effectiveness of the CVR under different voltage reduction levels, the study did not examine how centralized and localized control schemes compared in managing these CVR functions under varying load dynamics.

Mixed-integer linear programming modeling has been utilized to determine the best tap positions for voltage regulators to enhance both the voltage quality and lower the power consumption in distribution networks [16]. The LinDist3Flow model achieves approximately 1% optimality in standard distribution networks for selecting optimal tap positions in step-voltage regulators (SVRs) [17]. These optimization methods exhibit restrictions when used for dynamic AVR and OLTC tap position control in advanced test bus systems.

Recent studies have highlighted the advanced techniques for OLTC coordination and voltage regulation in distribution networks. To improve voltage stability and lower control complexity, a coordination scheme based on local control has been suggested for OLTCs [18]. Transformer tap settings have also been optimized using Particle Swarm Optimization (PSO), which improves the voltage profiles and decreases losses [19]. Data-driven approaches are becoming increasingly effective; machine learning-based methods for tap position estimation and voltage regulator identification have been introduced, and real-time optimization frameworks for voltage regulation have been developed using operational measurements [20].

This study explores the comparative performance of localized and centralized voltage control strategies to evaluate system stability, efficiency, and performance.

OpenDSS is an open-source simulation platform developed by Electric Power Research Institute to evaluate electric power distribution systems, particularly when combined with voltage control features and distributed energy resources [21].

This study advances voltage regulation control and peak load management in the IEEE 123-bus distribution system through three significant contributions. First, a benchmark example without control is developed to illustrate system limitations such as unstable voltage profiles and increased losses. Second, sequential control in OpenDSS is compared with a coordinated PSO-based strategy, revealing enhanced voltage stability, reduced power losses, and optimal tap placements. Third, a PSO-based CVR framework is used to achieve load reduction and energy efficiency, with a specific case at a CVR factor of 0.96 validating its effectiveness in balancing savings and performance. Finally, to increase simulation accuracy and allow for accurate evaluation of active and reactive power variations under voltage changes, voltage-dependent load models are incorporated. These contributions provide a comprehensive and efficient control framework.

The main contributions of this work are summarized as follows:

1. Development of a PSO-based centralized VVC strategy that coordinates multiple AVRs and OLTCs in a system-wide optimization framework.
2. A comparative assessment of centralized and localized voltage control architectures under high-loading conditions on the IEEE-123 bus distribution system using OpenDSS.
3. Integration of CVR with PSO-based control to analyze its impact on voltage profiles, power losses, and peak load reduction.

4. Incorporation of a voltage-dependent load model to more accurately represent real-world load behavior under voltage variations and enhance the credibility of simulation results.

The remainder of this paper is organized as follows. An overview of VVC is given in Section II, with an emphasis on both centralized and localized approaches. The problem definition pertaining to the operation of AVRs and OLTCs is presented in Section III. The suggested methodology, which includes a PSO-based centralized voltage management strategy and a localized voltage control approach, is described in Section IV. In Section V, three case studies that compare system performance under various control situations are used to discuss the simulation studies and outcomes. The study ends with some observations regarding the efficacy of the suggested approaches and suggestions for further study.

II. VOLT-VAR CONTROL

A. Localized and Centralized Architecture

Both centralized and localized (decentralized) control strategies can be used to implement VVC in smart distribution systems; each strategy has unique benefits and drawbacks. Devices such as voltage regulators, capacitor banks, and OLTCs use set up logic to function independently in localized control based on local measurements such as voltage, time, or reactive power flow. Although this approach supports quick response times, improves reliability, and reduces communication dependencies, it may not have the capacity for global coordination and optimization.

On the other hand, centralized control, which is frequently accomplished through SCADA, DMS, or AMI-based systems, offers a comprehensive perspective of the network and makes it possible to coordinate control actions to optimize reactive power dispatch, power flow, and voltage profiles. However, it may experience latency or single-point failures and necessitate high communication bandwidth, sophisticated computational resources, and strong cybersecurity measures.

The localized VVC setup consists of devices such as capacitor banks and voltage regulators and functions independently as shown in Fig. 1. These devices act on the basis of the difference between localized measured voltage (V_m) and the set reference voltage (V_{ref}). This approach lacks device coordination but reacts faster and requires less communication. Consequently, this can lead to failure and voltage fluctuations under dynamic loading conditions.

Fig. 2 illustrates how all measured voltage V_m from the feeder side is received by the central VVC module within the advanced distribution management system (ADMS), which is the centralized VVC organization or setup. After comparing the measurement with the reference signal V_{ref}, the module sends the coordinated control signals to each device. Consequently, the voltage is stabilized and optimized. Nevertheless, it requires a strong communication infrastructure, and the control performance may be affected by any delay.

B. Conservation Voltage Reduction

According to the American National Standards Institute (ANSI) standards, the voltage at the secondary terminals of a distribution transformer must be maintained within ±5% of the nominal 120 V, resulting in an acceptable range of 114–126 V. The effectiveness of the CVR was quantitatively assessed using the CVR Factor, which is formally defined in the (1).

$$\text{CVR factor} = \frac{(\text{Percentage change in quantity})}{(\text{Percentage change in voltage})} \quad (1)$$

The CVR effect is evaluated numerically using CVR factors which refer to (2) and (3).

$$\alpha = \frac{\%\Delta P}{\%\Delta V} \quad (2)$$

$$\beta = \frac{\%\Delta Q}{\%\Delta V} \quad (3)$$

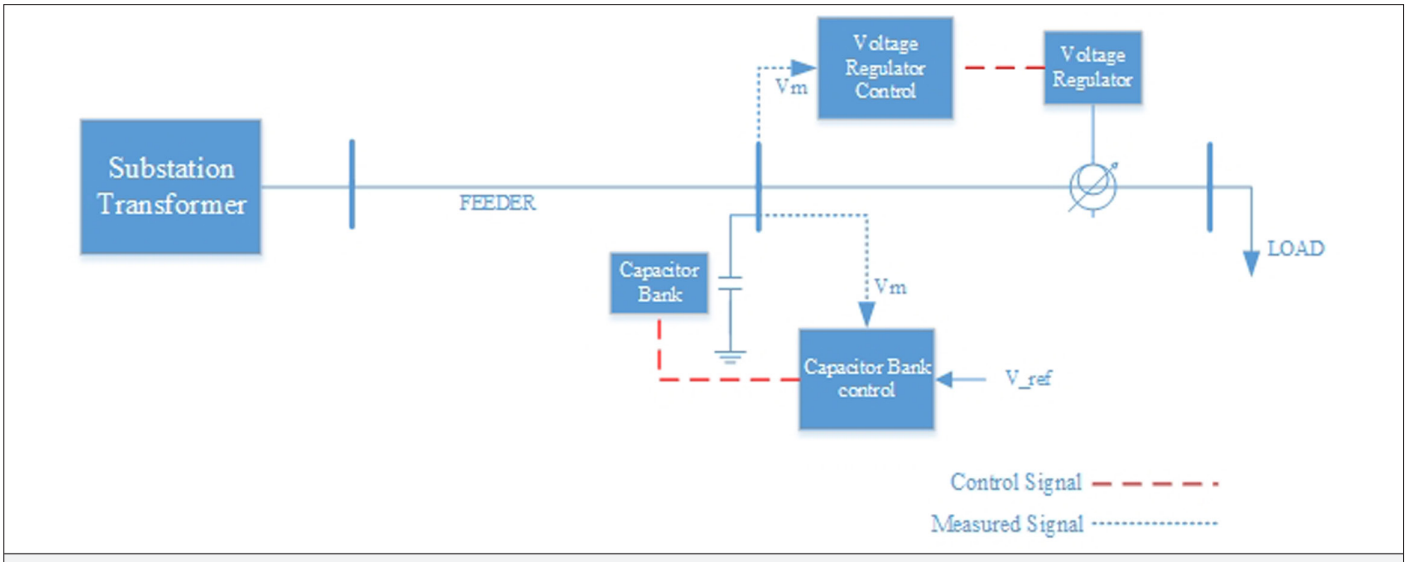

Fig. 1. Localized VVC.

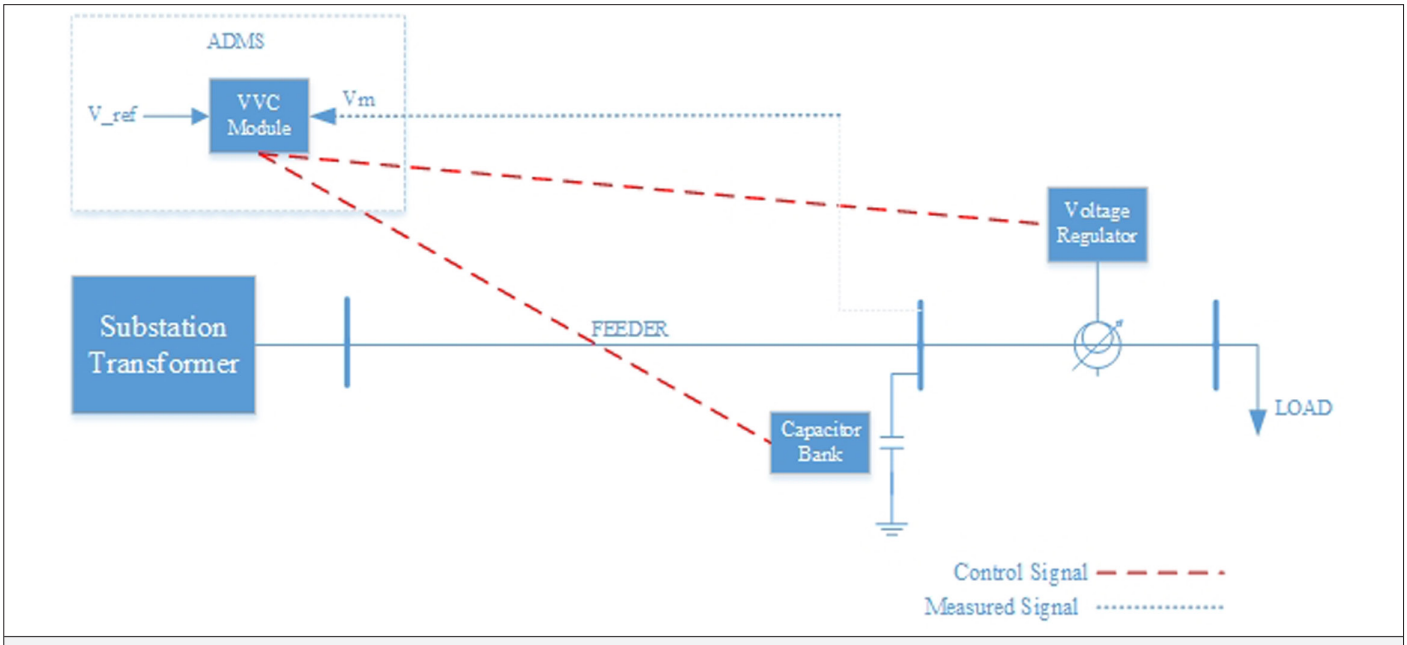

Fig. 2. Centralized VVC.

The calculation defines $\%\Delta P$ and $\%\Delta Q$ as the percentage changes in the active and reactive powers owing to a percentage voltage change $\%\Delta V$.

C. Voltage-Dependent Load Model

The voltage-dependent Load Model has been applied in OpenDSS, which specializes in CVR studies. The load model regulates the active power (P) linearly along with the reactive power (Q), which follows a quadratic pattern during voltage variations [21].

The selection of the load model type serves as a fundamental factor for achieving a realistic simulation of voltage-dependent characteristics in distribution power systems. The voltage-dependent load model represented by Model 4 is the most suitable for CVR studies because it shows how the active and reactive power values change based on the voltages within the power system. The model is especially efficient for determining how voltage control plans affect the maximum usage decreases and power system stability.

Although the ZIP load model is more accurate, it requires six parameters to be specified for each load. It is difficult to estimate these parameters as it requires high-frequency measurements from PMUs. There is usually a lack of such information at the level of the distribution system.

Therefore voltage-dependent load models are utilized for this study. These models require only two parameters which usually vary in the range of 0.6 to 2.5.

The CVR analysis accuracy was improved through the implementation of CVR factors specifically CVRwatts and CVRvars which measure the power consumption response to voltage fluctuations. This particular study determined that a one percent voltage decrease results in CVRwatts = 0.6, which simultaneously reduces active power usage by 0.6%, thus enhancing energy efficiency. A two-and-a-half percent reduction in reactive power can be expected for every one percent decrease in voltage based on a CVRvars value of 2.5. This ability allows for improved reactive power management and decreases unwanted power losses.

The voltage-dependent load model is an essential tool for conserving energy during the CVR procedures. General equations form the basis for the computation of the CVR analysis in (4) and (5).

$$P = P_0\left(\frac{V}{V_0}\right)^{\alpha} \tag{4}$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{\beta} \tag{5}$$

where:

- Power components P and Q operate as the active and reactive power at voltage V.
- Power components P_0 and Q_0 operate the active and reactive powers, respectively, at the nominal voltage V_0.
- α (CVR factor for real power) represents the extent to which the active power changes with the voltage.
- β (CVR factor for reactive power) represents the extent to which reactive power changes with voltage.

CVR Factor Definition:

Typical Values of α and β for CVR [22]:

- Residential Loads: $\alpha \approx 0.6-0.9$, $\beta \approx 2.0$
- Commercial Loads: $\alpha \approx 0.4-0.7$, $\beta \approx 1.5-2.0$
- Industrial Loads: $\alpha \approx 0.1-0.5$, $\beta \approx 1.0-1.5$

Implication in CVR:

The peak load reduction during reduced voltage escalates according to the α value. The voltage impact on reactive power Q exceeds the effect of active power P. CVR works best when loads are not of

constant power but have a mix of resistive (constant impedance) and inductive (constant current) components.

The model enables studies on how voltage controls implemented by AVRs and OLTCs affect the energy consumption throughout the IEEE-123 bus network. The model serves CVR studies by simulating power savings from minor voltage reductions; therefore, it becomes a crucial tool for optimizing distribution system voltage control strategies.

III. PROBLEM DEFINITION

In the standard Volt-VAR optimization problem, the objective is to minimize the voltage deviations around a reference value of voltage magnitude, usually 1.0 pu.

In the objective function V_{ref} is replaced by the V_{CVR} to realize the impact of implementing CVR.

The system should operate at a voltage level that matches its reference CVR value. The mathematical representation of this problem becomes the following:

1) Voltage Deviation Objective: The objective function of the voltage deviation is shown in (6).

$$\min f = \sum_{i=1}^{N} \left(V_{CVR} - V_i\right)^2 \tag{6}$$

Where:

The actual voltage at bus i is designated as V_i. The total number of buses is denoted by N.

2) Constraints:

a) The voltage control optimization is subject to the steady-state power-flow constraints of the distribution network. The active and reactive power balance at each bus i is given by the standard nonlinear power-flow equations:

$$P_i = V_i \sum_{j=1}^{N} V_j \left(G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}\right) \tag{7}$$

$$Q_i = V_i \sum_{j=1}^{N} V_j \left(G_{ij} sin\theta_{ij} + B_{ij} cos\theta_{ij}\right) \tag{8}$$

Where and are the active and reactive power injections at bus i, V_i and V_j are the voltage magnitudes at buses i and j, G_{ij} and B_{ij} are the conductance and susceptance of the network admittance matrix, and θ_{ij} is the voltage angle difference between buses i and j. These equations are solved at each iteration using the OpenDSS power-flow engine, which provides the voltage profile used in the PSO-based optimization.

b) Voltage Limits: To maintain electrical network voltage stability at every bus within predefined boundaries during operation shown in the equation (9).

$$V_{min} \le V_i \le V_{max}, \forall i \in buses \tag{9}$$

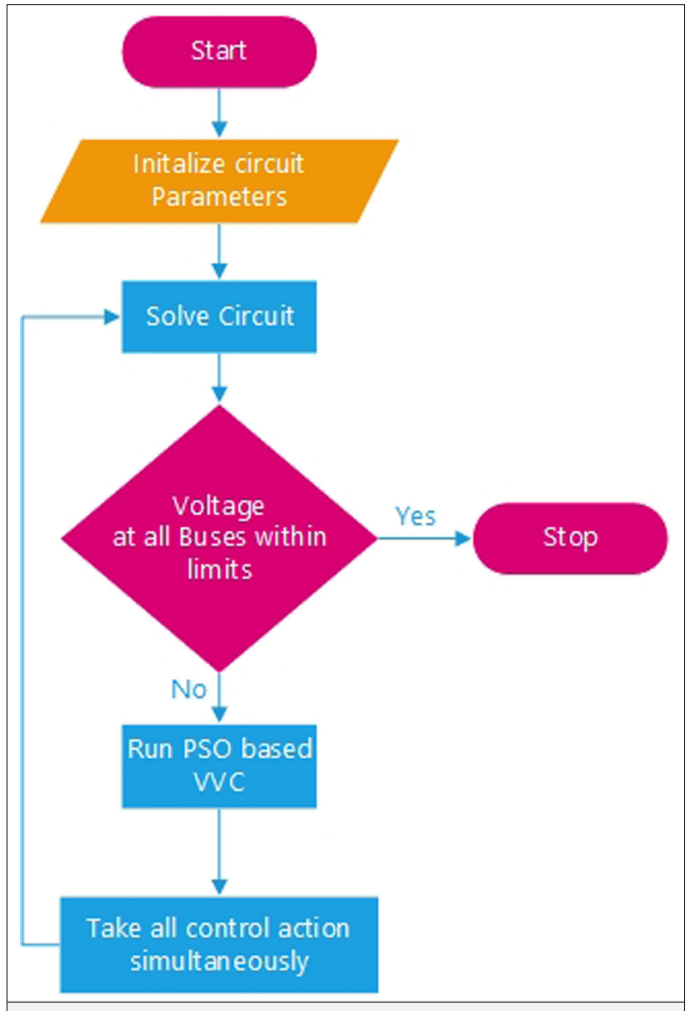

Fig. 3. Flowchart of localized voltage control strategy.

Where V_{min} and V_{max} are the minimum and maximum allowable voltages (e.g., 0.95 p.u. and 1.05 p.u.).

c) Tap Position Limits: The tap settings on both AVRs and OLTCs experience physical limitations shown in the equation (10).

$$T_{min} \le T_k \le T_{max}, \forall k \in taps \tag{10}$$

Where T_{min} and T_{max} represent the lower and upper limits for each tap.

IV. METHODOLOGY

In this study, two control strategies for VVC, centralized and localized, were compared. This section presents the methodology adopted to implement the strategies used in the testing system.

A localized voltage control approach is shown in Fig. 3. A control sequence, usually iterating through all control devices (i = 1 to N), is defined following the circuit initialization. The circuit is solved for every device or control point, and a sample of the voltage at the relevant bus is obtained. A control action is implemented at that precise location if the voltage is outside allowable bounds. Subsequently, the system advances to the following control device. This procedure

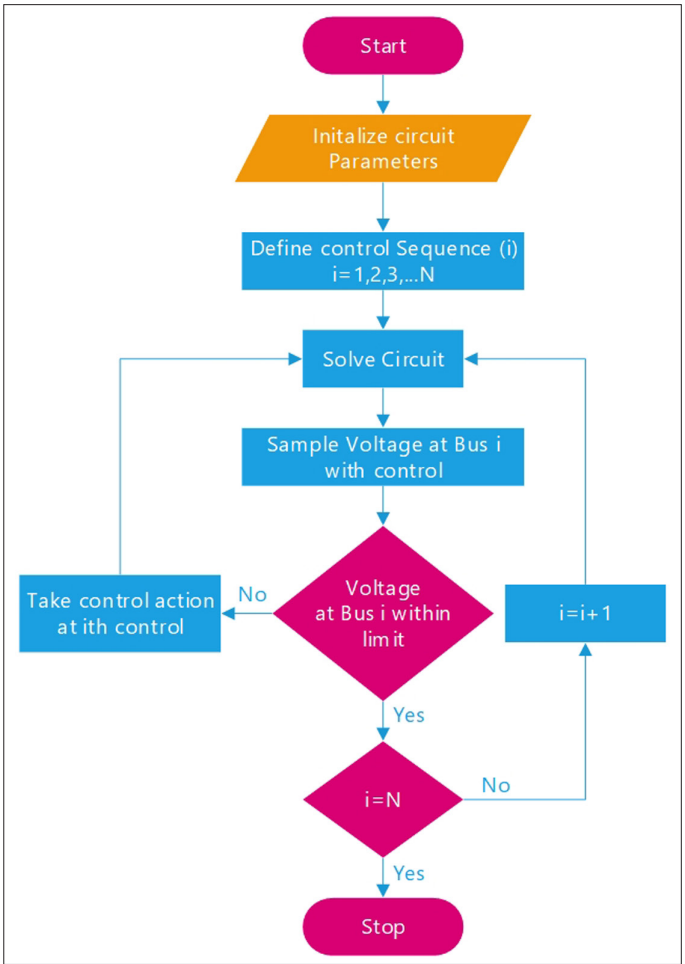

Fig. 4. Flowchart of PSO-based centralized voltage control strategy.

continued until the device was assessed. This approach enables modular control without requiring full system optimization at each iteration by supporting localized and prioritized controls.

The centralized control strategy shown in Fig. 4 uses PSO to regulate the voltage across all buses in the distribution system. After initializing the circuit parameters, the system is solved under the current operating conditions, and the voltage levels at all buses are evaluated against acceptable limits. If violations are detected, the PSO algorithm is applied to determine optimal VVC settings. Once the algorithm converges, the resulting control actions are implemented simultaneously across all control devices. This method is effective for systems requiring coordinated global optimization.

OpenDSS software was used to implement both the control strategies. It provides functionalities for modeling various distribution system elements such as transformers, lines, cables, loads, OLTC, and AVR.

From a practical standpoint, the centralized PSO-based control requires higher computational effort due to its iterative optimization process. In contrast, the localized control operates with simpler rule-based actions and therefore involves lower computational overhead. This highlights a trade-off between computational speed and control performance: localized control is more suitable for low-latency applications, whereas centralized PSO-based control is preferable when improved voltage regulation and coordinated system-wide operation are prioritized in ADMS environments.

All simulations were performed on an Intel i7-7700 CPU with 16 GB RAM.

V. SIMULATIONS AND RESULTS

This study evaluates VVC and CVR performance using PSO. An IEEE 123-bus test system was used to conduct the aforementioned studies [23]. This system provides a suitable platform to evaluate VVC and CVR strategies using both localized and control strategies.

The system operates at 4.16 kV voltage level. The one-line diagram of the network, shown in Fig. 5, has 85 loads (some single-phase and other poly-phase). The system is equipped with one main substation transformer (12kV/4.16kV) and four wye (Y)-connected SVRs: On-Regulator-1 (150, 149) on all three phases, On-Regulator-2 on single-phase A (9–14), On-Regulator-3 on phases A–C (25, 26), and On-Regulator-4 on all three phases (160, 67).

At the edge of the distribution network (61, 610), a delta-delta transformer with a 150 kVA rating and a line-to-line voltage ratio of 4.16 kV/0.48 kV.

The system is primarily radial but can be converted into a meshed configuration using tie switches. Overall, 11 switches were present in the system. There were four capacitor banks on buses 83, 88, 90, and 92. The base frequency of the system is set to 60 Hz.

IEEE 123-bus test networks were modified in this study to represent real-world operating conditions more accurately. To simulate peak loading conditions, such as those that arise during periods of high residential or commercial usage, a load multiplier of 1.5 is used. This ensured that the voltage regulation methods were evaluated under demanding and realistic loading conditions.

In addition, constant power load models were replaced with a voltage-dependent load model, as described in Section II (C). In order to accurately represent loads with voltage sensitivity, the CVR factors are set at $\alpha = 0.6$ for real power (CVRwatts) and $\beta = 2.5$ for reactive power (CVRvars). When evaluating the effectiveness of the peak load reduction during CVR implementation, these values were considered optimal.

To evaluate the proposed technique, the following cases were applied to the modified IEEE 123 bus test network.

Case A: Snapshot simulation without exercising control.

Case B: Snapshot simulation with respect to localized control of regulators and capacitor banks as described in Section III.

Case C: A snapshot simulation with centralized control of regulators and capacitors using PSO is described in Section IV.

The three strategies were compared based on voltage profiles and power losses.

The voltage profile plot illustrates the impact of different control strategies on voltage regulation across the IEEE-123 bus system. Initially, significant voltage deviations were observed in Case A, with some buses experiencing voltage conditions, indicating a voltage

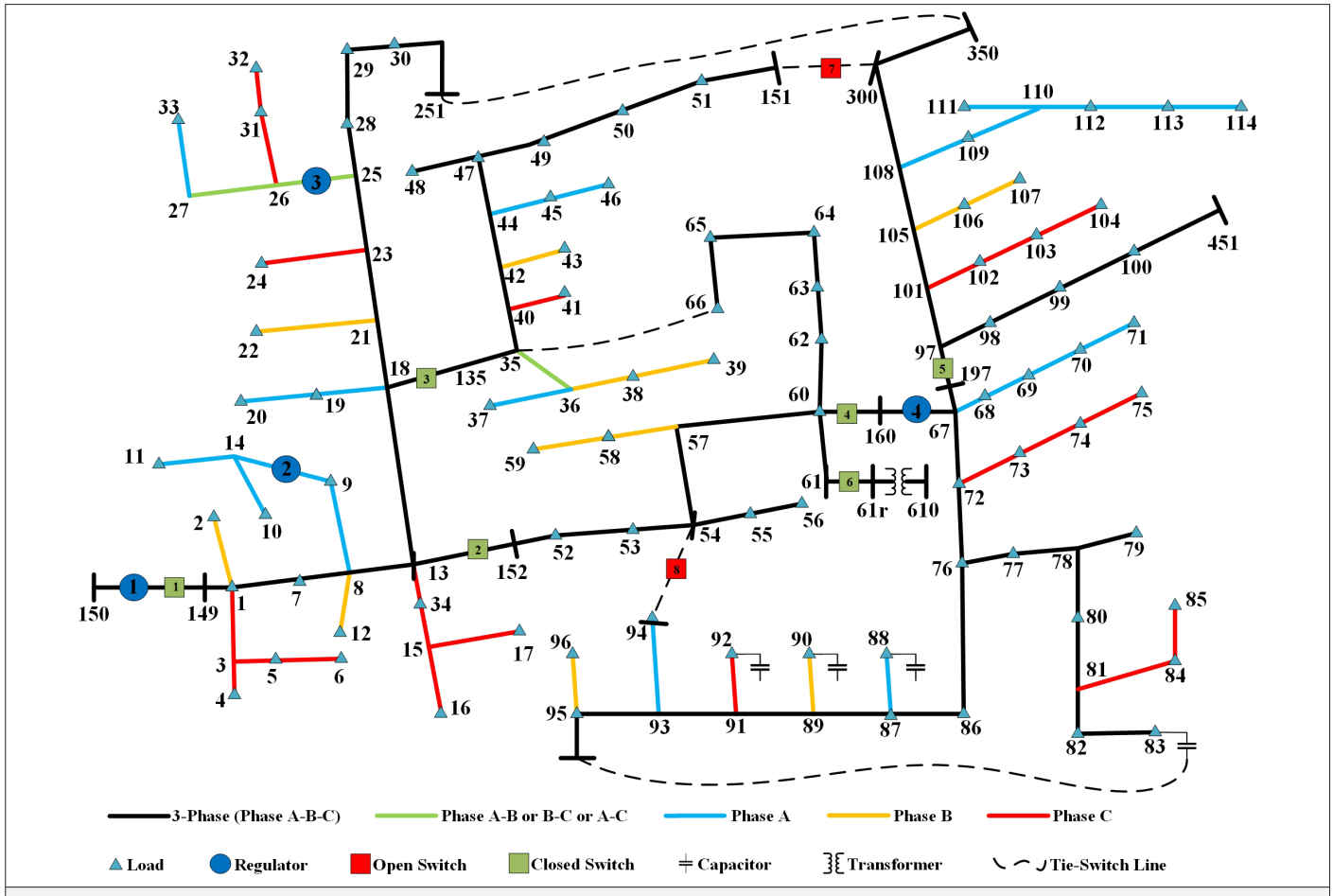

Fig. 5. Modified IEEE-123 bus system distribution test networks.

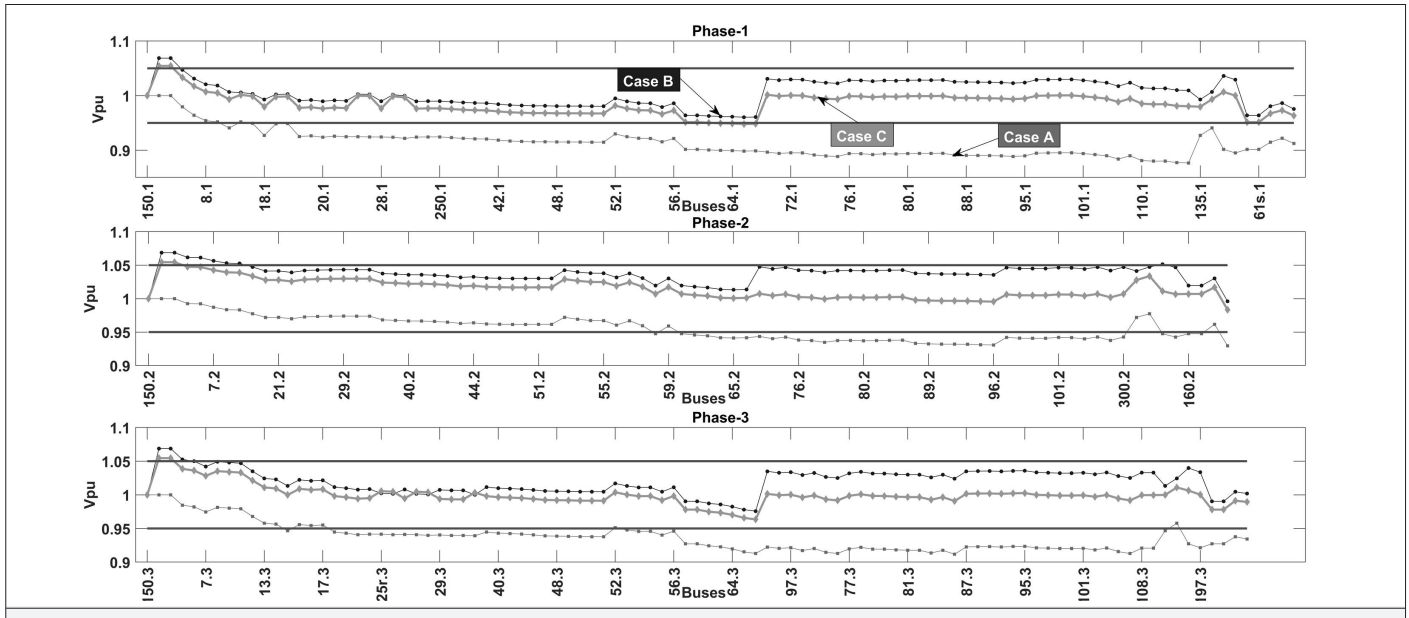

Fig. 6. Voltage Profile of IEEE-123 Bus: Comparison of Case A, Case B, and Case C.

limit violation in the system. For Case B, the voltage profile improved, reducing fluctuations and maintaining voltage levels closer to the acceptable range.

Case C achieved the best performance by maintaining stable voltage levels across the grid. The advanced optimization techniques represented by PSO demonstrate higher effectiveness for improving

voltage stability, power system reliability, and voltage violation mitigation in comparison to traditional control methods.

Fig. 6 presents the per-unit voltage profiles across all three phases of the IEEE-123 bus distribution system under three different scenarios: Case A, Case B, and Case C. The x-axis denotes the bus numbers corresponding to each phase, while the y-axis shows the voltage magnitude in per unit (p.u.), ranging from 0.85 to 1.1 p.u. Horizontal red lines indicate the standard acceptable voltage limits (0.95–1.05 p.u.). Case A exhibits several voltage violations, particularly noticeable with values falling below the lower voltage limit of 0.95 p.u., indicating poor voltage regulation and potential under voltage conditions. In contrast, Case B shows improved voltage regulation compared with Case A, but some voltage values remain marginally outside the optimal range. Case C demonstrates the best performance among the three methods. The voltage magnitudes remained consistently within the acceptable limits across all buses and phases. This demonstrates the effectiveness of the PSO-based control in maintaining voltage stability and enhancing the overall system performance.

Overall, the results highlight significant improvements achieved through optimization-based control compared with conventional methods, making PSO a promising approach for advanced VVC in distribution networks.

The improved voltage performance of the PSO-based centralized control can be attributed to its ability to coordinate multiple voltage regulating devices simultaneously across the entire network. In the localized approach, each regulator or capacitor operates based solely on local measurements, which can lead to conflicting control actions and voltage violations at remote buses. In contrast, the centralized PSO framework evaluates the impact of each control action on the whole system and optimally adjusts OLTC tap positions and capacitor switching in a coordinated manner. This global coordination mitigates voltage propagation effects along the feeder, reduces local overcompensation or undercompensation, and results in a smoother and more uniform voltage profile across all buses.

The details of the maximum and minimum voltage levels achieved in each case study are presented in Table I. In Case A, the maximum voltage is 1 p.u. at bus 1.1 and the minimum voltage is 0.8714 p.u. at bus 90.1. In Case B, the maximum voltage was 1.0625 p.u. at bus 2.1 and the minimum voltage was 0.8711 p.u. at bus 52.1. In Case C, the maximum voltage was 1.0597 p.u. at bus 2.1 and the minimum voltage was 0.9459 p.u. at bus 52.1.

TABLE I. COMPARISON OF VOLTAGE PROFILES AND POWER LOSSES UNDER DIFFERENT CONTROL STRATEGIES

		Case A	Case B	Case C
Voltages and Location	V_max(pu)	1	1.0625	1.0597
	Location	1.1	2.1	2.1
	V_min(pu)	0.8714	0.9591	0.9459
	Location	90.1	52.1	52.1
Losses	%PLosses	4.7273	4.6371	4.5944
	%Qlosses	15.4	14.803	15.059

TABLE II. TAP POSITION FOR THE REGULATORS AT DIFFERENT CONTROLS

	Case A	Case B	Case C
Reg_1a	0	12	10
Reg_2a	0	−2	−1
Reg_3a	0	1	3
Reg_3c	0	−1	0
Reg_4a	0	13	9
Reg_4b	0	6	1
Reg_4c	0	9	5

It can be observed that there are significant voltage violations in Case A, especially for the lower limits. For Cases B and C, the voltage limit violations are minimal, and the voltage profile can maintain a stable voltage profile considering the high load conditions imposed in the system.

The results shown in Table I also indicate variations in both active (P) and reactive (Q) power losses under different control strategies. The application of control mechanisms contributed to a reduction in active power losses. The highest losses are observed in the absence of control (4.72%), whereas the introduction of control strategies led to marginal improvement. Among these strategies, PSO demonstrates the most effective reduction in active power losses, achieving a final loss percentage of 4.59%. Similarly, reactive power losses improve with the implementation of the control mechanisms. Case A proved to be the most effective in minimizing the Q losses, reducing them to 14.80%, surpassing both Case A and C.

The main controls utilized by the VVC system are setting the tap position of the voltage regulator and switching the capacitors. The available capacitor banks were not utilized in case A, but were fully utilized in cases B and C.

The regulator tap settings for the three cases are listed in Table II. In case A, the tap positions for the regulators (Reg_1a, Reg_2a, Reg_3a, Reg_3c, Reg_4a, Reg_4b, and Reg_4c) without control are fixed at positions. In case B, when a control strategy is applied, these positions are adjusted to 12, −2, 1, −1, 13, 6, and 9, demonstrating that tap adjustments are used to compensate for voltage variations. In case C, the PSO algorithm optimizes these taps further to positions 10, −1, 3, 0, 9, 1, and 5, showing that it fine-tunes these positions to improve system performance.

Furthermore, the performance of the proposed technique is evaluated by applying CVR. CVR can only be applied by exercising regulator control in the transformer. Hence, case A (without control) strategy is omitted from this study, and only two cases are considered.

The CVR reference voltage is reduced gradually in steps of 0.01 starting from 1.0 p.u. and decreasing to 0.96 p.u..

The comparative results for cases (B and C) are shown in Tables III and IV, respectively.

Distribution network optimization techniques gain effectiveness analysis through studies of power loss and voltage stability under various control approaches. Efficient voltage regulation

TABLE III. IMPACT OF CVR VOLTAGES ON POWER LOSSES, VOLTAGE LEVELS, AND PEAK LOAD REDUCTIONS

		Active Power (kW)	Reactive Power (kVAR)	%Plosses	%Qlosses	Plosses (kW)	Qlossses (kVAR)	Vmax (pu)	Vmin (pu)	Change in PeakLoad (kW)
CVR voltage (pu)	1.00	5498.6	2548.47	4.05	17.6	223	448.58	1.0625	0.96387	–
	0.99	5455.9	2544.87	4.13	17.82	225.4	453.56	1.05	0.95057	−42.7
	0.98	5429.8	2544.43	4.15	17.89	226.26	455.3	1.0437	0.9439	−68.81
	0.97	5385.1	2535.81	4.24	18.12	228.32	459.54	1.0312	0.9309	−113.52
	0.96	5355.3	2532.67	4.274	18.18	228.88	460.67	1.025	0.92437	−143.29

TABLE IV. IMPACT OF CVR VOLTAGES ON POWER LOSSES, VOLTAGE LEVELS, AND PEAK LOAD REDUCTIONS USING PSO

		Active Power (kW)	Reactive Power (kVAR)	%Plosses	%Qlosses	Plosses (kW)	Qlossses (kVAR)	Vmax (pu)	Vmin (pu)	Change in PeakLoad (kW)
CVR voltage (pu)	1.00	5452.2	3041.4	4.37	15.81	238.04	480.93	1.0552	0.9485	–
	0.99	5407.7	2987.1	4.4	16.09	237.97	480.88	1.0447	0.9378	−44.5
	0.98	5372.6	2944.6	4.42	16.31	237.71	480.19	1.0371	0.9308	−79.6
	0.97	5312.2	2902	4.48	16.6	238.24	481.76	1.0238	0.9166	−140
	0.96	5263.9	2860.4	4.52	16.82	237.92	481.24	1.0143	0.907	−188.3

plays a vital role in minimizing power loss and ensuring power quality, particularly in systems with dynamic load conditions. By comparing the impact of various control mechanisms, this study highlights the advantages and limitations of both traditional and PSO-based approaches for optimizing the power distribution performance.

Although PSO effectively reduces active power losses, it does not outperform traditional control methods in managing reactive power losses, achieving a slightly higher loss percentage of 15.06%. These findings highlight the importance of selecting an appropriate voltage control strategy for optimizing power system efficiency.

The PSO optimization technique improves the minimum voltage level to 0.9459 p.u. but achieves this result less effectively compared to conventional control systems. These results highlight the effectiveness of voltage control strategies in maintaining system stability and ensuring reliable power delivery.

Fig. 7 shows that the hourly tap positions of regulators and Table IV presents a comprehensive study of the active power, reactive power, percentage power losses (%P losses and %Q losses), absolute power losses (P losses and Q losses), voltage fluctuations (Vmax and Vmin), and peak demand reductions associated with various CVR voltages. A reduction in the CVR voltage results in a decrease in both active and reactive power, concurrently causing a marginal increase in power losses. The reduction in power usage decreases peak demand, illustrating the effectiveness of voltage reduction measures in demand-side energy management. The voltage range (Vmax and Vmin) exhibited a declining pattern, ensuring that the voltage levels were maintained within permissible limits while attaining peak load reduction. The graph explores these changes, enabling the visualization of the correlation among the CVR voltages, power losses, and peak demand reductions shown in Fig. 8. These results demonstrate the advantages of CVR in reducing the total power demand and increasing system efficiency.

Further, the effectiveness of the proposed strategy is evaluated by running simulations in daily mode for 24 hours at a 1.0 CVR. The following cases are considered:

Case D: Daily simulation with localized control.

Case E: Daily simulation with centralized control using PSO.

It can be seen from the data given in Table V, there is a clear reduction in energy consumption and peak load in the case of proposed centralized control using PSO (case E). However, this comes with increased losses and slightly degraded voltage profiles as compared to case D. Overall, the advantages of the proposed control strategy outweigh those of traditional localized control mechanisms. These tables collectively indicate the impact of CVR on voltage regulation, power consumption, and peak demand reduction. The results indicate that controlling voltage levels through CVR strategies can significantly decrease power consumption while maintaining system stability, making this an acceptable approach for improving the efficiency of electrical distribution networks. The graphical representation of these results allows for a greater understanding of the trends and patterns coming from the investigation, making it an essential tool for decision-makers in power distribution planning.

VI. CONCLUSION

This study presented a comprehensive analysis of voltage regulation and peak load management in the IEEE 123-bus distribution system by comparing decentralized (localized) control with a centralized PSO-based VVC strategy. A benchmark case without control was first used to demonstrate voltage instability and increased system losses. The comparison showed that decentralized control, although

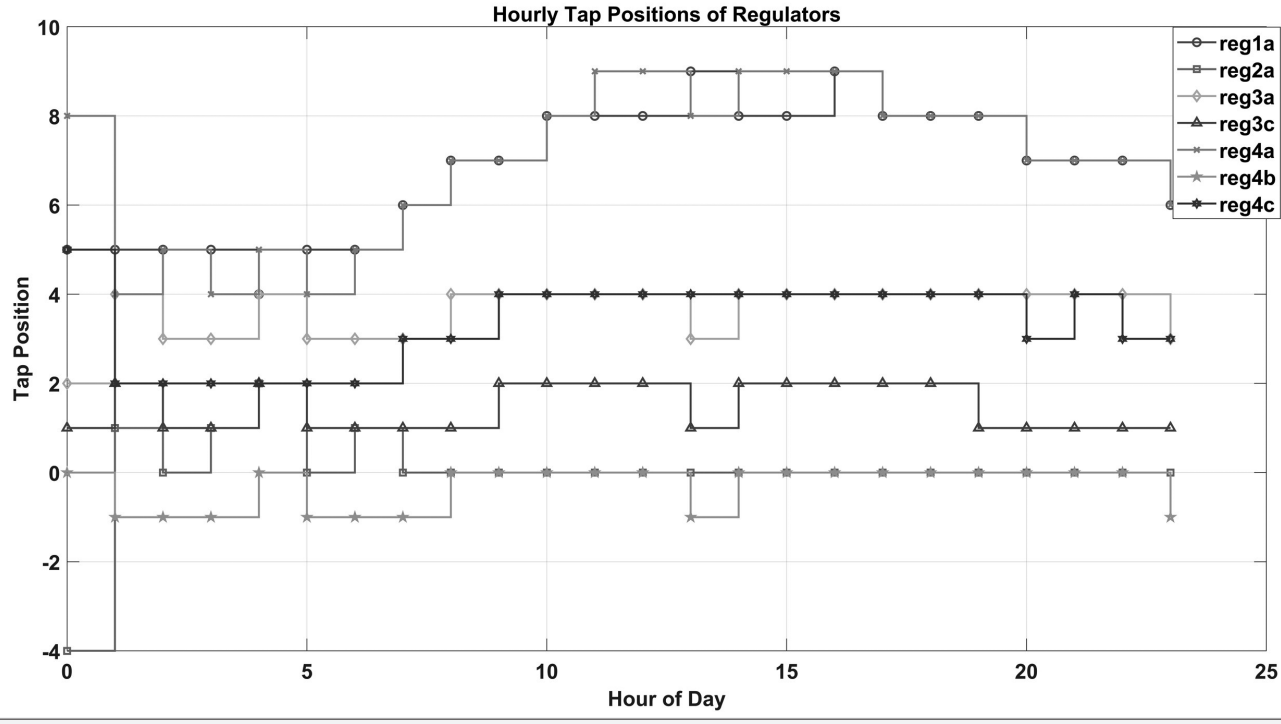

Fig. 7. Hourly Tap Positions of Regulators.

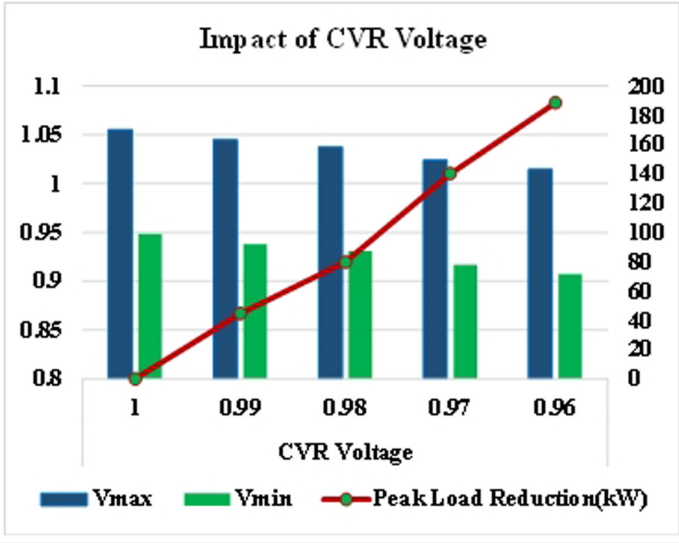

Fig. 8. Effect of CVR on Voltage Profiles and Change in Peak Load.

TABLE V. COMPARATIVE RESULTS FOR 24-HOUR SIMULATION

	Energy (kWh)	Max Power (kW)	Energy Losses (kWh)	V_max (pu)	V_min (pu)
Case-D	108934	5519	3788	1.050 (149)	0.9889 (46)
Case-E	107255	5453	3980	1.037 (149)	0.9735 (46)

simple and computationally efficient, operates based on local measurements and may lead to less coordinated voltage regulation. In contrast, the centralized PSO-based approach enables coordinated optimization of multiple AVRs and OLTCs, resulting in improved voltage stability, reduced power losses, and optimized tap operations across the network.

The integration of CVR within the centralized framework further demonstrated effective load reduction and enhanced energy efficiency, while the use of a voltage-dependent load model improved the accuracy of system behavior under voltage variations. Overall, the results confirm that centralized optimization provides superior system-wide performance compared with decentralized control, making it a promising solution for ADMS.

Future work will also investigate the impact of communication latency, data loss, and cyber-security constraints in practical ADMS environments, while extending the proposed framework to distribution networks with high penetration of renewable energy sources and comparing PSO with other classical and metaheuristic optimization techniques.

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APPENDIX

PSO Parameter	Value
Number of decision variables	7
Population size	*nPop* = 50
Maximum iterations	*MaxIt* = 100
Inertia weights	*w* = 1
Inertia damping ratio	*wdamp* = 0.9
Cognitive coefficient	*c1* = 2.0
Social coefficient	*c2* = 2.0
Position bounds	-16 to +16

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