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Combined Central-Local Voltage Control of Inverter-based DG in Active Distribution Networks

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Abstract:

The increased integration of distributed generators (DGs) has exacerbated voltage violations in active distribution networks (ADNs). Utilizing the var capacity offered by DG inverters presents a potential solution for managing the voltage of ADN. By merging the merits of different hierarchies, the combined voltage control can provide better performances in addressing the variability of DGs. In this paper, a combined central-local voltage control strategy is proposed for DGs to suppress voltage fluctuations. Firstly, the control strategy for DGs is generated for global optimization, considering the coordination of discrete regulation devices and DGs in a long-time scale. Then, the local control curve for DGs is established based on the reactive power value of DGs in the central strategy. To further enhance the robustness of the local control curves, a parameter tuning model for the local control curve is built based on the distributionally robust optimization (DRO) method. The voltage violations caused by DG fluctuations can be quickly suppressed by using the local control curve. Finally, the effectiveness of the combined central-local control strategy is substantiated through validation using both the modified IEEE 33-node distribution system and the practical JMF3 80-node distribution system. The proposed method can improve voltage control performance while enhancing the adaptation to DG fluctuation.

Key words: active distribution network (ADN); combined central-local voltage control; distributed generator (DG); local control curve; distributionally robust optimization (DRO)

The short version of the paper was presented at CUE2023. This paper is a substantial extension of the short version of the conference paper.

Nomenclature

Sets		r_{ij}/x_{ij}	Resistance/reactance of branch ij
Ω_n	The set of nodes in ADN	$V_{t,i}^0$	Voltage measurement at node i in period t
Ω_b	The set of branches in ADN	ρ_l	The probability values of scenario l
Ω_d^k	The set of nodes connected with DGs in the k th local area of ADN	η_l	The adjustment value of the l th scenario probability
Ω_b^k	The set of branches in the k th local area of ADN	z	Auxiliary variable associated with the DRO model
Γ	The ambiguity set of typical scenarios	γ'_l, γ''_l	Auxiliary variable associated with the l th scenario in the DRO model
Indices		$\vartheta_{t,i}$	Auxiliary variable associated with voltage violation at node i in period t
i, j	Node indices, from 1 to N	Parameters	
ij	Branch indice	T	The total periods of time horizon
t	Time period indice	N_ω	The total number of typical scenarios
l	Typical scenario indice	N	The total number of nodes in ADN
Variables		Δt	Duration of the local control period
$V_{t,i}$	The voltage magnitude of i th node in period t	$V_{thr}^{\max}, V_{thr}^{\min}$	The maximum and minimum desired voltage of ADN
$I_{t,ij}$	The current magnitude of the branch ij in period t	$V_{thr}^{\max}, V_{thr}^{\min}$	The maximum and minimum statutory voltage of ADN
$P_{t,ij}, Q_{t,ij}$	The active and reactive power of the branch ij in period t , respectively	$I_{ij}^{\max}$	The upper current limit of branch ij
$P_{t,i}, Q_{t,i}$	The total active and reactive power consumption of i th node in period t	$\bar{Q}_i^{DG}, \underline{Q}_i^{DG}$	The upper and lower limit of reactive power provided by DG at node i
$P_{t,i}^{DG}, Q_{t,i}^{DG}$	The active and reactive power supplied by DG at node i in period t	S_i^{DG}	Capacity limit of DG at node i
$P_{t,i}^{LOAD}, Q_{t,i}^{LOAD}$	The active and reactive power consumption of load at node i in period t	$k_{ij,0}, \Delta k_{ij}$	The initial turn ratio and increment per step of OLTC on branch ij
$Q_{t,i}^{CB}$	The reactive power injection by CB at node i in period t	q_i^{CB}	The reactive power capacity of each unit of the CBs at node i
δ_i	Half length of the dead-zone in the improved local control curve of the i th DG	$K_{ij}^{\max}$	The total steps of OLTC on branch ij
$V_i^{q,\min}, V_i^{q,\max}$	Set points of the improved local control curve of the i th DG	$N_i^{CB,\max}$	The total number of CB units connect to node i
$K_{t,ij}, k_{t,ij}$	The tap steps and turns ratio of the OLTC on branch ij in period t	$\Delta^{OLTC,\max}$	The maximum number of variations in tap steps of the OLTC
$N_{t,i}^{CB}$	The number of the CB units in operation at node i in period t	$\Delta_i^{CB,\max}$	The maximum number of variations in the considered time horizon of the i th CB

$Q_{t,i}^{\text{centr}}, V_{t,i}^{\text{centr}}$	Optimal operating point in period t of the DG connected to i th node determined in the central stage	W_α, W_β	Weight coefficients associated with power loss and voltage deviation
$\Delta Q_{t,i}$	Compensative reactive power of DG connected to i th node in period t	ρ_l^0	The initial probability values of scenario l
$\Delta Q_{t,i}^{\text{q,max}}, \Delta Q_{t,i}^{\text{q,min}}$	Upper and lower limits of i th DG compensative reactive power in local stage in period t	$\eta_l^{\text{max}}, \eta_l^{\text{min}}$	The maximum and minimum value of probability fluctuations of scenario l

1. Introduction

1.1. Background

The widespread application of distributed generators (DGs) [1] imposes a considerable impact on the flexible operation [2] in active distribution networks (ADNs) [3]. In particular, the substantial penetration of DGs [4] introduces notable uncertainties in temporal distribution [5]. This results in pronounced fluctuations in feeder power [6] and gives rise to severe voltage violations [7].

A diverse array of regulation devices has been deployed to improve the voltage performance in ADNs [8], encompassing both discrete regulation devices [9] and continuous regulation devices [10]. Discrete regulation devices, such as on-load tap changers (OLTC) and capacitor banks (CB), primarily operate on longer timescales [11]. Nevertheless, owing to the sluggish response and constrained action frequency [12], the discrete regulation devices encounter challenges in effectively mitigating frequent voltage fluctuations [13]. As a result, these devices are typically regulated day-ahead based on the forecasting information [14]. In contrast, the smart inverter of DG serves as a continuous control device, providing fast reactive power for voltage control [15], which attracts more attention in the field [16].

1.2. Literature review

For DG operation, centralized control is generally used to determine the strategies of DG in-

verters [17]. However, the pursuit of global optimization through centralized control may impose significant computational and communication overheads, which pose potential challenges. By decomposing the problem into smaller sub-problems, decentralized control can markedly alleviate the optimization burdens [18]. One of the primary concerns with distributed control in its practical application is ensuring the convergence to real-time control.

Local control is extensively employed in the operation of DGs, enabling a rapid response to the fluctuations of voltage solely based on local measurements [19]. Among them, the curve-based local control method has been widely utilized in the rapid power adjustment of DGs, including $Q - P$ curve [20], $Q - V$ curve [21], and $P^{\text{curt}} - V$ curve [22]. Exhibiting robustness within intricate and uncertain operating environments, the $Q - V$ curve based local control presents notable potential in DG controls [23]. Considerable simplicity in practical engineering applications can be achieved through the utilization of the $Q - V$ curve [24], which has been incorporated into the standard of DG control in several countries [25]. In contrast to the centralized and decentralized methods, local control depends solely on the locally available data, which may lack system-wide coordination.

Merging the advantages of different control modes can handle the variability of ADN under DG access [26]. A better control performance can be achieved by adjusting the control strategy in real-time during the intra-day operation based on running conditions [27]. Xu et al. [28] proposed a multi-objective hierarchically coordinated control method, which can maximize the benefits of the inverter-based DGs with local curves. Bayrak et al. [29] proposed a two-step intelligent decision-maker method for DGs, which can enhance the reliability, durability, and stability of the grid. Wu et al. [30] proposed a continuous-time voltage control method based on hierarchical coordination, which can maximize the voltage magnitude and energy loss. Arabpour et al.

[31] proposed a combined centralized-decentralized control method considering communication failure. However, the control strategy in most of the existing works is commonly defined depending on the deterministic optimization models, which may lead to diminished control performance in practical environments characterized by frequent fluctuations in DG power.

To address the uncertainties, voltage control methods have incorporated stochastic optimization (SO) and robust optimization (RO) techniques. Baker et al. [32] pursued a robust approach for ADN with uncertainty in the forecasted noncontrollable loads and power injections. Abunima et al. [33] proposed an SO-based method aimed at minimizing operational costs and load shedding. This approach considers the probabilities associated with potential supply, load, and energy storage system (ESS) capacities. Mancilla-David et al. [34] introduced a robust optimization method, which can optimize the operation of distribution feeders, incorporating uncertainties within the optimization model.

The distributionally robust optimization (DRO) model, which merges the benefits of SO and RO, has been introduced to accommodate the uncertainties of DGs and loads [35]. The DRO-based strategy can be derived by constructing a probability confidence set. This approach seeks the optimal solution by taking into account the scenario with the most adverse conditions within the defined confidence set [36]. The strategy derived from the DRO method is characterized by its robustness while maintaining a reduced level of conservatism [37]. Thus, it is promising to utilize the DRO method to form the control strategy to address the DG uncertainty in ADNs.

1.3. Contributions

In this paper, a combined central-local voltage control strategy is proposed for DGs considering uncertainty, as shown in Fig. 1. The main contributions are summarized as follows.

- 1) A combined central-local control framework is proposed for the reactive power regulation of DGs. In the central stage, the control strategy of DGs is determined with the coordination of

discrete regulation devices for global optimization. In the local stage, the reactive power value of DGs in the central strategy is extended to the improved local control curve in each control interval. The frequent voltage fluctuations can be effectively mitigated by the improved local control curve.

2) A parameter tuning model for the improved local control curve is established based on the DRO method to further enhance the robustness of the DG control strategy. To describe the DG fluctuations, an ambiguity set is first built for DGs with historical operational data. Then, the parameters of the local control curve are tuned to adapt to more fluctuating scenarios based on the DRO method. Facilitating with the improved local control curves, a notable improvement in mitigating voltage violations can be achieved, while enhancing the performance on robustness to adapt to DG uncertainty.

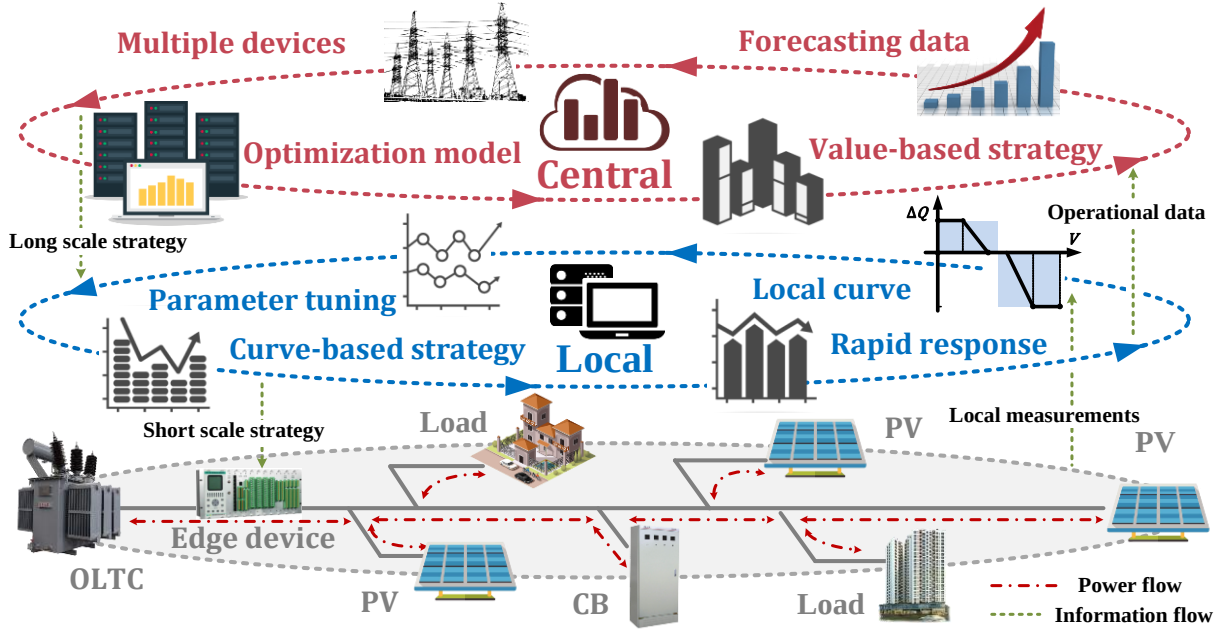


Fig. 1. Combined central-local control framework for DGs

The ensuing sections of this paper are organized as follows: Section 2 provides a detailed exposition of the combined central-local control framework for DGs. In recognition of the frequent fluctuation of DGs, Section 3 expounds upon the DRO-based parameter tuning model for refining the local control curve of DGs. Section 4 presents case studies conducted on the modified IEEE

33-node distribution system and the practical JMF3 80-node distribution system. Finally, Section 5 encapsulates the conclusions drawn from this study.

2. Combined central-local voltage control for inverter-based DG

In this section, a two-stage control framework is established to determine the central and local control strategies of DGs. The value-based strategy in the central stage achieves system-wide coordination and the curve-based strategy in the local stage responds to real-time fluctuations in DGs within the specified timeframe.

2.1. Combined central-local framework

Addressing the voltage control challenge within intricate operational contexts, a two-stage voltage control framework is proposed for inverter-based DGs, which combines the central stage and the local stage, as shown in Fig. 2.

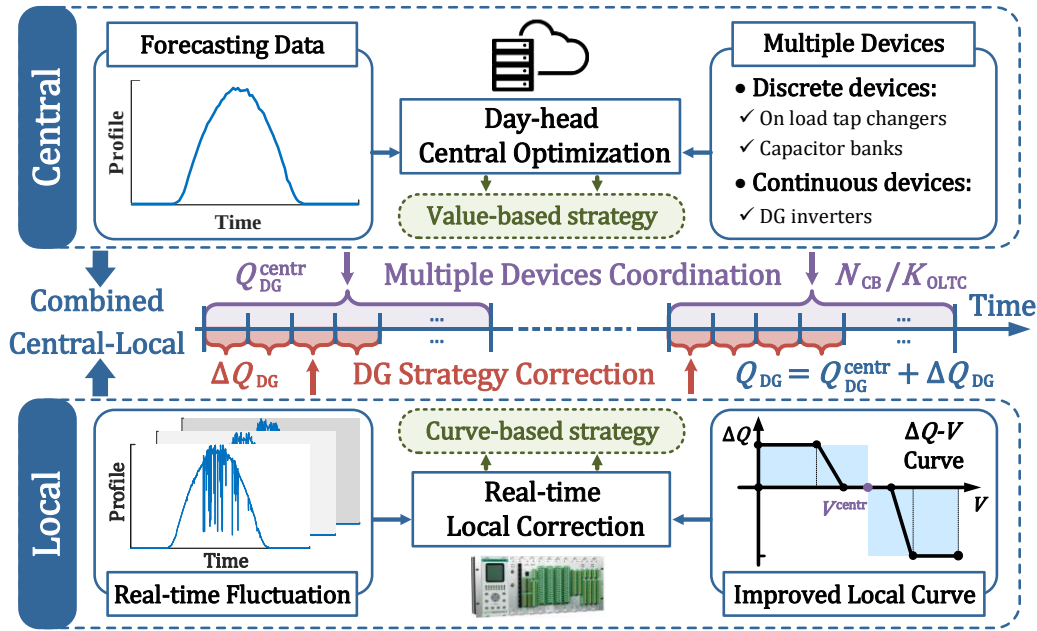


Fig. 2. The two-stage control framework for inverter-based DGs

In the central stage, an optimization model is established utilizing the day ahead forecasting data of DGs and loads. The approximate value of the reactive power output of DGs is determined day-ahead. Simultaneously, accounting for the integration of discrete control devices within

ADN, such as OLTC and CBs, the central stage facilitates the coordination of multiple control devices to achieve global optimization. It is worth noting that the central control strategy is adaptable to the long-time scheduling while not considering the uncertainty of DGs. Since only the forecasting data is available day ahead, the optimal level can be achieved by the day ahead strategy in the central stage. If, in actual operation, the fluctuations of DGs and loads are exactly the same as forecasted, the control strategy in the central stage will not require further adjustment for the intra-day operation. Considering the power of DGs is uncertain due to the fluctuating ambient conditions, the long-time-scale control strategy may be difficult to respond to such rapid fluctuations. The deviations between the forecasting data and the real-time fluctuations will be compensated for in the local stage.

In the local stage, the central DG control strategy is extended to the improved local control curve during the intra-day operation. The reactive power value of DGs and anticipated nodal voltage at the inverter-grid-connection point in the central stage determines the feasible area of the improved local control curve. By combining the central and local phases, both global coordination and a faster response to voltage fluctuations can be obtained simultaneously. To further enhance the robustness of the improved local control curves, a parameter tuning model for the improved local control curves is established with the distributional robust optimization in the local stage. The DG reactive power is promptly adjusted based on the tuned local control curves, guided by the real-time nodal voltage measurements. Enhancing voltage control performance is achievable by thoroughly exploring the potential benefits afforded by DG inverters.

Remark: In the proposed combined central-local control framework, the control interval is related to the temporal resolution of forecasting, which is selected as 15 minutes [38]. Considering the temporal resolution of forecasting in current research is diverse, encompassing scales of 1 hour [39] or even shorter [40], the proposed method can be flexibly adapted.

2.2. Day-ahead central optimization

The central control problem aims to minimize the voltage deviation and total power loss. The optimization model in the first-stage are stated as follows:

$$\min f = W_\alpha f_L + W_\beta f_V$$

$$f_L = \sum_{t=1}^T \sum_{ij \in \Omega_b} I_{t,ij}^2 r_{ij} \quad (1)$$

$$f_V = \sum_{t=1}^T \sum_{i \in \Omega_n} |V_{t,i}^2 - 1|, V_{t,i} \geq V_{\text{thr}}^{\max} || V_{t,i} \leq V_{\text{thr}}^{\min}$$

s.t.

$$\sum_{ji \in \Omega_b} (P_{t,ji} - r_{ij} I_{t,ji}^2) + P_{t,i} = \sum_{ik \in \Omega_b} P_{t,ik}$$

$$\sum_{ji \in \Omega_b} (Q_{t,ji} - x_{ij} I_{t,ji}^2) + Q_{t,i} = \sum_{ik \in \Omega_b} Q_{t,ik}$$

$$V_{t,i}^2 - V_{t,j}^2 + [(r_{ij})^2 + (x_{ij})^2] I_{t,ij}^2 = 2(r_{ij} P_{t,ij} + x_{ij} Q_{t,ij}) \quad (2.1)$$

$$I_{t,ij}^2 V_{t,i}^2 = P_{t,ij}^2 + Q_{t,ij}^2$$

$$P_{t,i} = P_{t,i}^{\text{DG}} - P_{t,i}^{\text{LOAD}}, Q_{t,i} = Q_{t,i}^{\text{DG}} + Q_{t,i}^{\text{CB}} - Q_{t,i}^{\text{LOAD}}$$

$$(V^{\min})^2 \leq V_{t,i}^2 \leq (V^{\max})^2, I_{t,ij}^2 \leq (I_{ij}^{\max})^2$$

$$\underline{Q}_i^{\text{DG}} \leq Q_{t,i}^{\text{DG}} \leq \bar{Q}_i^{\text{DG}}$$

$$0 \leq \sqrt{(P_{t,i}^{\text{DG}})^2 + (Q_{t,i}^{\text{DG}})^2} \leq S_i^{\text{DG}} \quad (2.2)$$

$$V_{t,i} = k_{t,ij} V_{t,j}$$

$$k_{t,ij} = k_{ij,0} + K_{t,ij} \Delta k_{ij}$$

$$\sum_{t=1}^T |K_{t,ij} - K_{t-1,ij}| \leq \Delta^{\text{OLTC,max}}$$

$$-K_{ij}^{\max} \leq K_{t,ij} \leq K_{ij}^{\max}, K_{t,ij} \in \mathbb{Z}$$

$$Q_{t,i}^{\text{CB}} = N_{t,i}^{\text{CB}} \cdot q_i^{\text{CB}}$$

$$\sum_{t=1}^T |N_{t,i}^{\text{CB}} - N_{t-1,i}^{\text{CB}}| \leq \Delta_i^{\text{CB,max}} \quad (2.4)$$

$$0 \leq N_{t,i}^{\text{CB}} \leq N_i^{\text{CB,max}}, N_{t,i}^{\text{CB}} \in \mathbb{Z}$$

Constraint (2.1) denotes the nonlinear DistFlow model. Constraint (2.2) describes the capacity limits of DGs. This paper concentrates on the reactive power adjustment of inverter-based DGs,

wherein the dispatch of OLTCs and CBs can be integrated into the central optimization problem. The operation constraints of OLTC and CB are described as (2.3) and (2.4), respectively.

2.3. Real-time local correction

Compared with the central control, the curve-based local control exhibits greater potential for the rapid power adjustment of DGs. The local stage aims to determine an improved local control curve to minimize the impact of real-time DG fluctuations on ADN. The objective function of the optimization model in the local stage can be described as (3).

$$\min f^k = \sum_{t=1}^{\Delta t} \sum_{i \in \Omega_d^k} |V_{t,i} - V_{t,i}^{\text{centr}}| \quad (3)$$

The minimum difference in the effect of control strategy between central and local stages can be achieved with (3) during the intra-day operation.

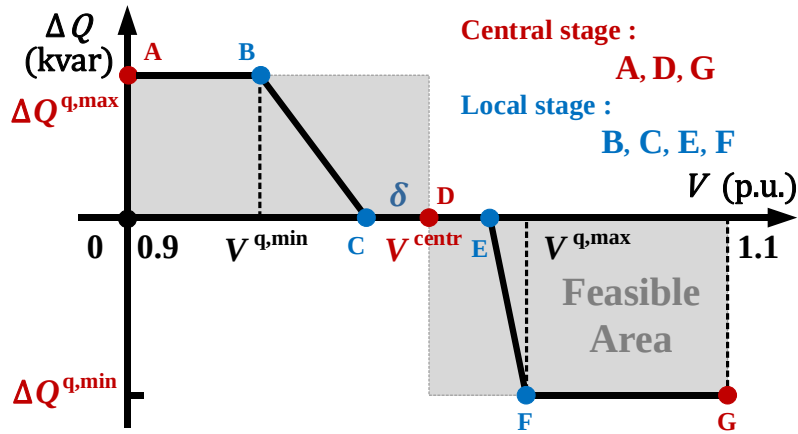


Fig. 3. The improved local control curve of DG

The improved local control curve constructed in this paper can be described as (4), as shown in Fig. 3.

$$\Delta Q_{t,i} = \psi(V_{t,i}^0)$$

$$\psi(V_{t,i}^0) = \begin{cases} \Delta Q_i^{\text{q,max}} & V \in [0.9, V_i^{\text{q,min}}) \\ \frac{\Delta Q_i^{\text{q,max}}}{(V_{t,i}^{\text{centr}} - \delta_i) - V_i^{\text{q,min}}} (V_{t,i}^{\text{centr}} - \delta_i) - \frac{\Delta Q_i^{\text{q,max}}}{(V_{t,i}^{\text{centr}} - \delta_i) - V_i^{\text{q,min}}} V_{t,i}^0 & V \in [V_i^{\text{q,min}}, V_{t,i}^{\text{centr}} - \delta_i) \\ 0 & V \in [V_{t,i}^{\text{centr}} - \delta_i, V_{t,i}^{\text{centr}} + \delta_i) \\ \frac{\Delta Q_i^{\text{q,min}}}{(V_{t,i}^{\text{centr}} + \delta_i) - V_i^{\text{q,max}}} (V_{t,i}^{\text{centr}} + \delta_i) - \frac{\Delta Q_i^{\text{q,min}}}{(V_{t,i}^{\text{centr}} + \delta_i) - V_i^{\text{q,max}}} V_{t,i}^0 & V \in [V_{t,i}^{\text{centr}} + \delta_i, V_i^{\text{q,max}}) \\ \Delta Q_i^{\text{q,min}} & V \in [V_i^{\text{q,max}}, 1.1] \end{cases} \quad (4)$$

The improved local control curve is comprised of seven points, designated as A, B, C, D, E, F, and G. $V_{t,i}^{\text{centr}}$ is the optimal operating point of DG, which is determined by the central strategy. $V_i^{\text{q,min}}$, $V_i^{\text{q,max}}$ and δ_i are the flexible parameters that need to be adjusted in the local stage, which can make the curve applicable to uncertain operation states. $V_i^{\text{q,min}}$ and $V_i^{\text{q,max}}$ should satisfy the following constraints.

$$\begin{aligned} 0.9 &\leq V_i^{\text{q,min}} \leq V_{t,i}^{\text{centr}} - \delta_i \\ V_{t,i}^{\text{centr}} + \delta_i &\leq V_i^{\text{q,max}} \leq 1.1 \\ \delta_i &\geq 0 \end{aligned} \quad (5)$$

$\Delta Q_{t,i}^{\text{q,max}}$ and $\Delta Q_{t,i}^{\text{q,min}}$ are the upper and lower reactive power limits of DG at node i in the local stage, which can be calculated by Eq. (6).

$$\begin{aligned} \Delta Q_{t,i}^{\text{q,max}} &= \sqrt{(S_i^{\text{DG}})^2 - (P_{t,i}^{\text{DG}})^2} - Q_{t,i}^{\text{centr}} \\ \Delta Q_{t,i}^{\text{q,min}} &= -\sqrt{(S_i^{\text{DG}})^2 - (P_{t,i}^{\text{DG}})^2} - Q_{t,i}^{\text{centr}} \end{aligned} \quad (6)$$

where $Q_{t,i}^{\text{centr}}$ is the optimal reactive power supply of DG at node i in period t , which is determined in the central stage.

It is worth noting that the central stage and the local stage are tightly coupled in the proposed control framework. The optimality is guaranteed by the global optimization in the central stage, meanwhile, the local control curve is established to respond quickly to uncertain fluctuations. Since $V_{t,i}^{\text{centr}}$ and $Q_{t,i}^{\text{centr}}$ are obtained based on the global optimization in the central stage, the improved local control curve can effectively blend the strategy with multiple regulation devices integration. Meanwhile, the local strategy of DGs can be further optimized by flexibly adjusting $V_i^{\text{q,min}}$, $V_i^{\text{q,max}}$ and δ_i , which will be described in detail in Section 3.

3. Local curve tuning considering uncertainties

Local curve-based strategies enable efficient corrections to the long-time-scale strategies in

the central stage. To enhance adaptability to the fluctuation of DG power, this section constructs a DRO-based parameter tuning model to optimize the shape of the improved local control curve.

3.1. Uncertainty modeling of DG power

The forecasting data for the active power of DGs is typically acquired through probabilistic methods [41]. However, owing to environmental variations, the actual operational active power of DGs tends to fluctuate in proximity to the predicted values. Notably, the active power of photovoltaic (PV) systems can experience fluctuations exceeding 50 percent within seconds, particularly during transient cloud movements [42]. The practical operating state of PV is shown in Fig. 4. By statistically analyzing the historical operation data of PVs, the fluctuation range can be obtained, which is shown in Fig. 5.

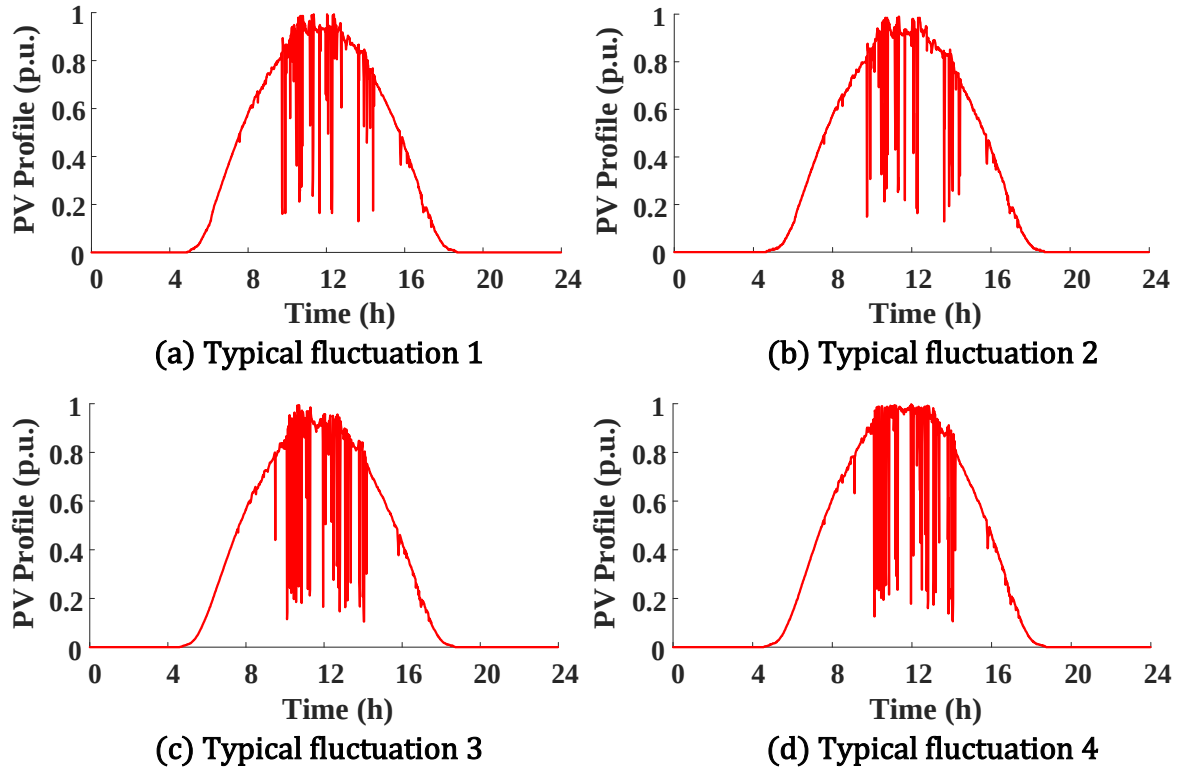


Fig. 4. The actual fluctuations of DGs

Utilizing the historical operation curves of DGs, the typical scenario set considering the uncertainty fluctuations is generated by clustering based on the K-means clustering method. The typical scenario set contains N_ω scenarios. The initial probability distribution of each scenario is ρ_i^0 ,

which satisfies the following constraints.

$$\begin{aligned} \sum_{l=1}^{N_\omega} \rho_l^0 &= 1 \\ 0 \leq \rho_l^0 &\leq 1, l = 1, 2, \dots, N_\omega \end{aligned} \quad (7)$$

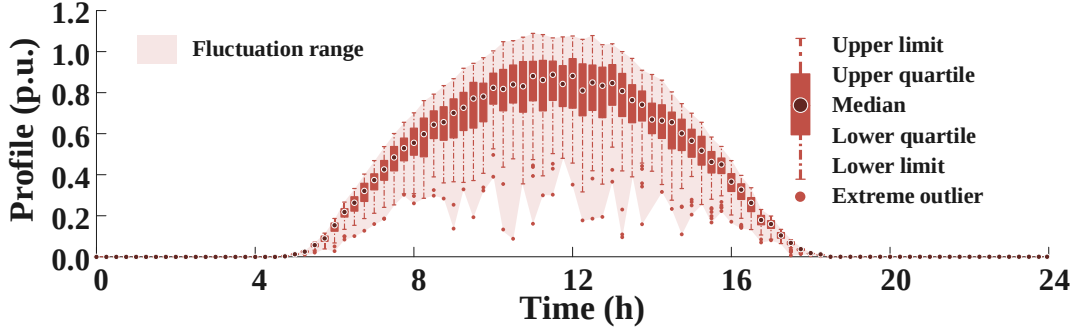


Fig. 5. The uncertainty fluctuation of PV active power

Consider that the probability values ρ_l^0 are imprecise, a box ambiguity set is further built to describe the DG fluctuations.

$$\begin{aligned} \Gamma &= \{\rho: \rho_l = \rho_l^0 + \eta_l, l = 1, 2, \dots, N_\omega\} \\ \sum_{l=1}^{N_\omega} \eta_l &= 0, \eta_l^{\min} \leq \eta_l \leq \eta_l^{\max} \end{aligned} \quad (8)$$

The bounds of the ambiguity set are denoted by $\eta_l^{\min}$ and $\eta_l^{\max}$, which can be determined with the historical distributions.

Note that this paper is mainly oriented toward the intense DG fluctuations caused by fast cloud movements in cloudy weather. Thus, the ambiguity set is built based on the historical data under cloudy weather to support the construction of the local control curve. For overcast or sunny weather conditions, the proposed method in this paper can also be flexibly adapted with a corresponding dataset using historical fluctuation data under overcast or sunny weather.

Distributionally robust optimization seeks to minimize the maximum observed objective function value within the defined ambiguity set of imprecise probabilities. Thus, the objective function of the DRO model can be described as (9).

$$\min_{\rho \in \Gamma} \max \left\{ \sum_{l=1}^{N_\omega} \rho_l f_l^k \right\} \quad (9)$$

To achieve an efficient solution, the problem in (9) can be further transformed into (10), with constraints added as (11).

$$\min \sum_{l=1}^{N_\omega} (\rho_l^0 f_l^k + \eta_l^{\max} \gamma_l' + \eta_l^{\min} \gamma_l'') \quad (10)$$

$$\begin{aligned} z + \gamma_l' + \gamma_l'' &= f_l^k, l = 1, 2, \dots, N_\omega \\ \gamma_l' &\geq 0, \gamma_l'' \leq 0, l = 1, 2, \dots, N_\omega \end{aligned} \quad (11)$$

where, z , γ_l' , and γ_l'' are auxiliary variables associated with the DRO model.

3.2. DRO-based parameter tuning model for DGs

The effectiveness of local voltage control strategies relies on the optimization of curve parameters associated with DGs. After the central strategy is settled, the improved local control curve of DGs is determined only by the values of $V_i^{q,\min}$, $V_i^{q,\max}$ and δ_i . Thus, a DRO-based parameter tuning model is built in each local area in each control period, while improving the voltage control performance of ADN.

The objective function in (3) can minimize the difference in the effect of central and local control strategies. To achieve accuracy and efficiency in solving, (3) can be linearized as (12).

$$\min f_l^k = \sum_{t=1}^{\Delta t} \sum_{i \in \Omega_d^k} \vartheta_{t,i} \quad (12)$$

While adding the relevant constraints as (13).

$$\begin{aligned} \vartheta_{t,i} &\geq V_{t,i} - V_{t,i}^{\text{centr}} \\ \vartheta_{t,i} &\leq -V_{t,i} + V_{t,i}^{\text{centr}} \\ \vartheta_{t,i} &\geq 0 \end{aligned} \quad (13)$$

The operational constraints specific to the local area can be delineated as expressed in (14).

$$\begin{aligned} \sum_{ji \in \Omega_b^k} P_{t,ji} + P_{t,i} &= \sum_{ik \in \Omega_b^k} P_{t,ik} \\ \sum_{ji \in \Omega_b^k} Q_{t,ji} + Q_{t,i} &= \sum_{ik \in \Omega_b^k} Q_{t,ik} \end{aligned} \quad (14)$$

$$\begin{aligned}
V_{t,i} &= V_{t,j} + 2(r_{ij}P_{t,ij} + x_{ij}Q_{t,ij}) \\
P_{t,i} &= P_{t,i}^{\text{DG}} - P_{t,i}^{\text{LOAD}}, Q_{t,i} = Q_{t,i}^{\text{DG}} + Q_{t,i}^{\text{CB}} - Q_{t,i}^{\text{LOAD}} \\
V^{\min} &\leq V_{t,i} \leq V^{\max}
\end{aligned}$$

It is essential to note that the linear power flow model is used in the local stage due to the limited computational resources of the local area.

The reactive power of DGs is the result of combining the strategies determined in central and local stages. The operational constraints for DGs are modified as follows:

$$\begin{aligned}
\underline{Q}_i^{\text{DG}} &\leq Q_{t,i}^{\text{centr}} + \Delta Q_{t,i} \leq \bar{Q}_i^{\text{DG}} \\
\Delta Q_{t,i} &= \psi(V_{t,i}^0) \\
0 &\leq \sqrt{(P_{t,i}^{\text{DG}})^2 + (Q_{t,i}^{\text{centr}} + \Delta Q_{t,i})^2} \leq S_i^{\text{DG}}
\end{aligned} \tag{15}$$

Thus, the DRO-based parameter tuning model for DGs can be summarized as (16).

$$\begin{aligned}
&\min \sum_{l=1}^{N_\omega} (\rho_l^0 f_l^k + \eta_l^{\max} \gamma_l' + \eta_l^{\min} \gamma_l'') \\
&\text{s. t. (4) - (6), (7) - (8), (11), (12) - (13), (14), (15)}
\end{aligned} \tag{16}$$

In summary, leveraging the corrections introduced in the local stage, the voltage control strategy for DGs is anticipated to exhibit enhanced performance in terms of voltage improvement and power loss reduction. Greater adaptation to the DG uncertainty volatility can be achieved in practice by exploring the potential benefits of DGs.

4. Case Studies and Analysis

The effectiveness of the proposed combined central-local control strategy for inverter-based DG is demonstrated in this section. The experiments are conducted on both the modified IEEE 33-node distribution system and the JMF3 80-node practical distribution system. The numerical simulations are executed on a computer equipped with an Intel(R) Core(TM) i7-8700H CPU processor, which operates at 3.20 GHz.

4.1. Modified IEEE 33-node distribution system

A substation and 32 branches are comprised of the modified IEEE 33-node distribution system. The rated voltage level of the test system is 12.66 kV. Fig. 6 illustrates the structure of the test system.

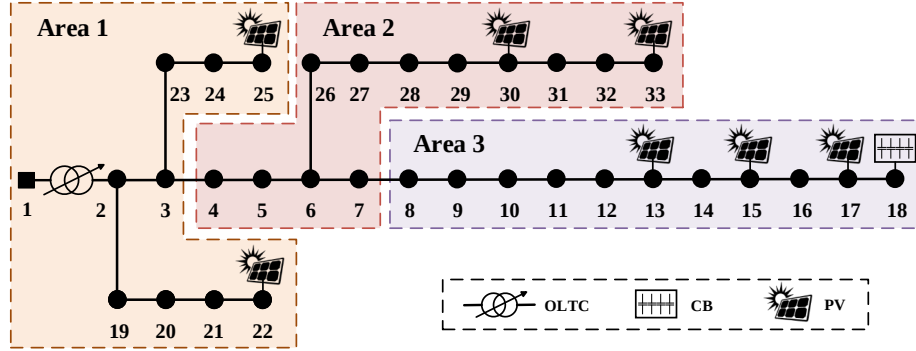


Fig. 6. Structure of the modified IEEE 33-node distribution system

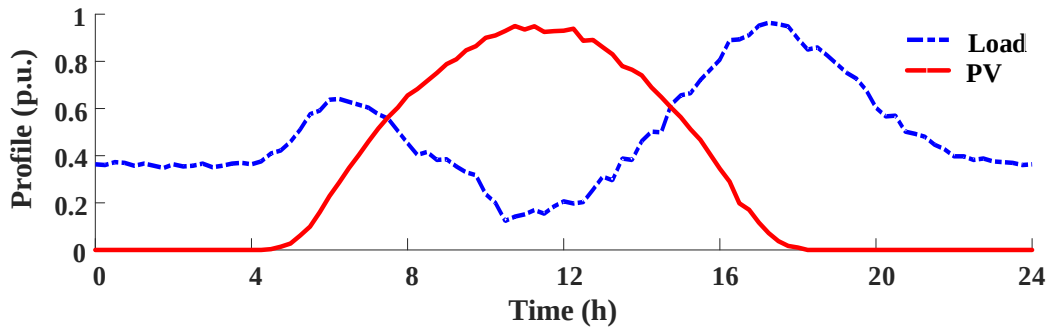


Fig. 7. The forecasting data of DG and load

It is assumed that the test system is divided into three local areas with computing capabilities. To account for the high DG penetration, 7 PV units are integrated into the test system. The capacity of each PV is 400.0 kVA. The penetration rate of DG reaches 75%. An OLTC is positioned between nodes 1 and 2, which is equipped with ten tap steps of 1% regulation per tap. Additionally, 5 CBs each with a capacity of 60 kvar are linked to node 33. Considering the action frequency limited of discrete regulation devices, $\Delta^{\text{OLTC},\text{max}}$ and $\Delta^{\text{CB},\text{max}}$ are configured as 4 times per day, with a minimum action interval of 1 hour. The control period is set as 15 minutes, which means the improved local control curves of each local area are adjusted every 15 minutes. The reactive power of DGs is adjusted in every 1 minute, guided by the improved local control curve and nodal

voltage measurements. The statutory voltage range limits for the ADN are established at 1.10 p.u. for the upper limit and 0.90 p.u. for the lower limit. Within the test distribution system, the desired voltage range is configured to span from 0.95 p.u. to 1.05 p.u.

The day-ahead forecasting fluctuation of DG and load are depicted in Fig. 7. Considering the power fluctuations in practical operation, the actual operating curves of load and DG in the intra-day operation are illustrated in Fig. 8 and Fig. 4, respectively.

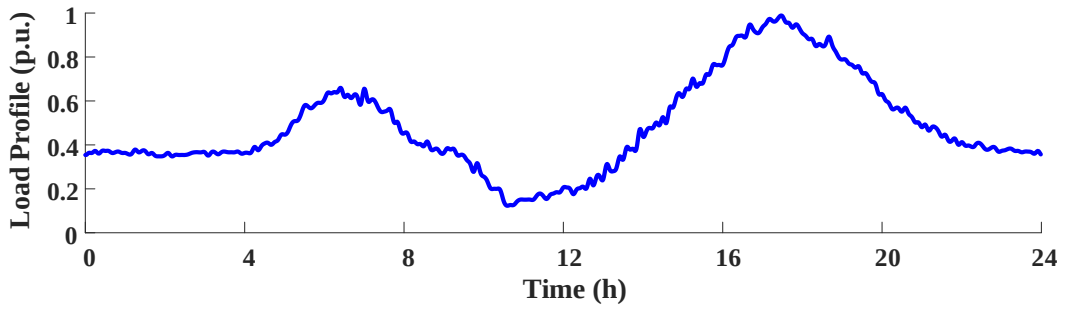


Fig. 8. The actual fluctuations of load

It is assumed that the DGs at neighboring geographical distances are assumed to have the same fluctuation in this paper, which can realize simultaneous active power changes according to the weather. Meanwhile, the communication is assumed as ideal, so that the control strategy of DGs can be executed synchronously, which enables a simultaneous adjustment of the reactive power of DGs in ADN.

1) Effectiveness analysis of combined central-local strategy

With the forecasting data of loads and DGs, the control strategy of DGs on long-time-scale is determined in the central stage. Then, the improved local control curve is built and tuned locally to realize rapid response to DG fluctuations. Simultaneously, utilizing the combined central-local control framework allows for the coordination of multiple controllable devices, such as OLTC, CBs, and DGs, across various time scales. To validate the efficacy of the proposed combined central-local voltage control strategy, four scenarios are implemented.

Scenario I: No control strategy is applied to the regulation devices, as the initial operational

state of the ADN is obtained.

Scenario II: The control strategy of DGs and discrete regulation devices is determined based on the day-ahead forecasting data in the central stage.

Scenario III: The combined central-local strategy is employed to regulate the reactive power of DGs, in which the DG strategy is further modified based on the improved local curve during the intra-day operation.

Scenario IV: Real-time centralized control is implemented to achieve an optimal control effect for the ADN.

The network loss and voltage deviation of ADN are selected to describe the optimization effect of different scenarios, which is converted into economic costs to be compared. The specific calculation formula is shown as follows.

$$\begin{aligned} \text{TTL} &= C_L + C_V \\ C_L &= c_L \sum_{t=1}^T \sum_{ij \in \Omega_b} I_{t,ij}^2 r_{ij} \\ C_V &= c_V \sum_{t=1}^T \sum_{i \in \Omega_n} |V_{t,i}^2 - 1| \end{aligned} \quad (17)$$

where, c_L and c_V are the cost coefficients associated with power losses and voltage deviation respectively.

Table 1 shows the optimization results for the four scenarios.

Table 1 Optimization results of the four scenarios

Scenario	Minimum voltage (p.u.)	Maximum voltage (p.u.)	Cost of voltage deviations (CNY)	Cost of power loss (CNY)	Operational costs (CNY)
I	0.9219	1.060	969.6	622.7	1592
II	0.9525	1.020	149.0	769.3	918.3
III	0.9834	1.020	133.6	746.3	880.0
IV	0.9838	1.020	113.9	699.0	812.8

In Scenario I, the significant uncertainties associated with the extensive integration of DGs lead to severe voltage deviation and frequent fluctuation of ADN. The voltage profiles of ADN in Scenario I are illustrated in Fig. 9.

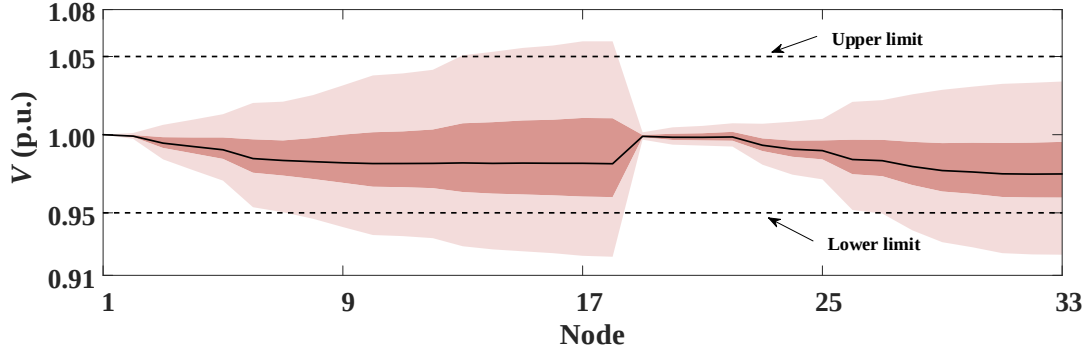


Fig. 9. The voltage profiles in Scenario I

Remark: The density of the voltage distribution is described with the grayscale in figures. The light color indicates the range between the quartile value and the extreme value of the nodal voltage, while the dark color indicates the range between the quartile value and the mean value of the nodal voltage.

Utilizing the day-head forecasting data, a long-time-scale control strategy of multiple regulation devices can be obtained in the central stage. The control strategies of the discrete regulation devices in Scenario II are shown in Fig. 10.

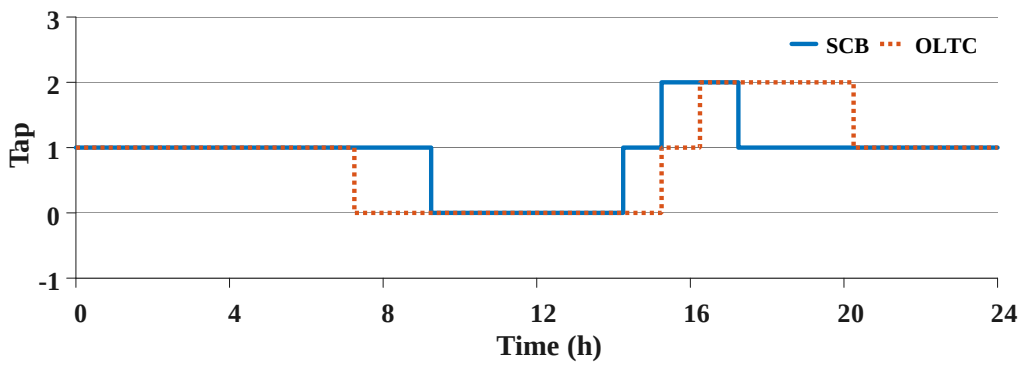


Fig. 10. The control strategies of discrete regulation devices

Compared with the initial operation state in Scenario I, the voltage deviation of ADN is significantly alleviated. However, due to the uncertainty of DGs, there are still some nodes in the system

that suffer frequent voltage fluctuations. The voltage profiles in Scenario II are shown in Fig. 11.

In Scenario III, the improved local control curves are constructed and fine-tuned in the local stage to better address DG fluctuations. By expanding the control strategy obtained in the central stage into a curve, a basis for correcting the reactive power of DGs is provided for the intra-day operation. Noting that, because of the same fluctuations in DGs, the improved local control curves for DGs in the same area have the same feasible range. That is, the $\Delta Q_i^{q,\max}$ and $\Delta Q_i^{q,\min}$ values are the same for DGs in the same local area. However, the curve shape is different due to the location of DGs, which means that $V_i^{q,\min}$, $V_i^{q,\max}$ and δ_i take different values. Taking the DG installed at nodes 30 and 33 as an example, the tuned improved local control curve at 18:00 is shown in Fig. 12.

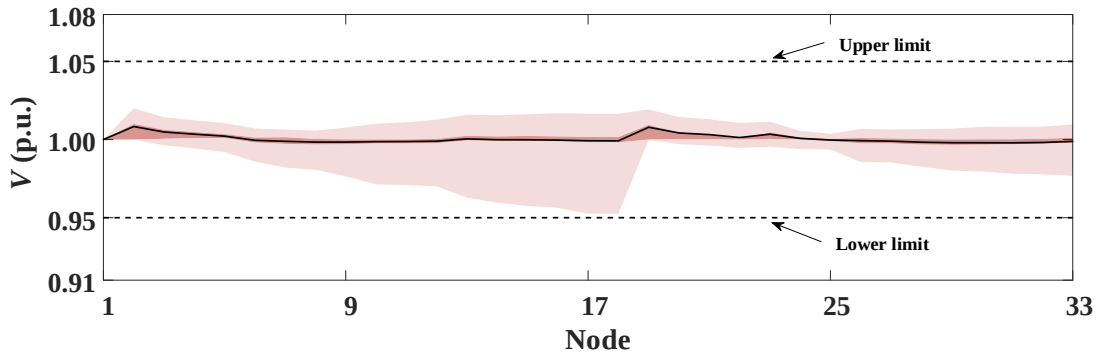


Fig. 11. The voltage profiles in Scenario II

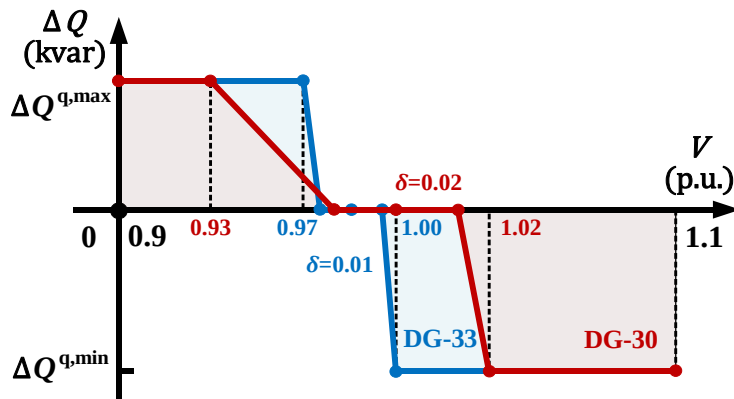


Fig. 12. The tuned local control curve of DG on nodes 30 and 33 at 18:00

In the actual operation, by utilizing the nodal voltage measurements at the inverter-grid-connection point of DGs, the reactive power adjustment $\Delta Q_{t,i}$ can be calculated correspondingly

with tuned curves. Illustrated with the example of the DG installed at node 33, Fig. 13 shows the reactive power adjustment of the DG.

The uncertainty fluctuations of DG are effectively responded to with the improved local control curves in Scenario III. Enhanced control performance is attained with improved voltage and reduced power losses. The voltage profiles in Scenario III are depicted in Fig. 14.

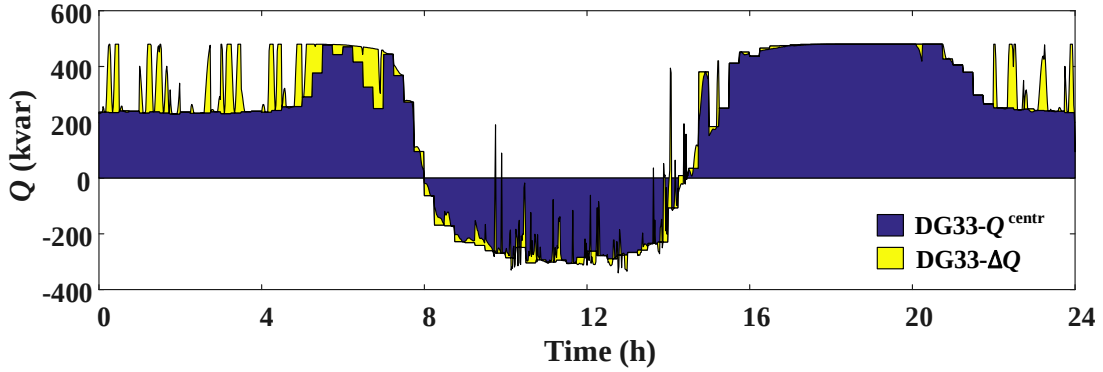


Fig. 13. The reactive power of DG on node 33

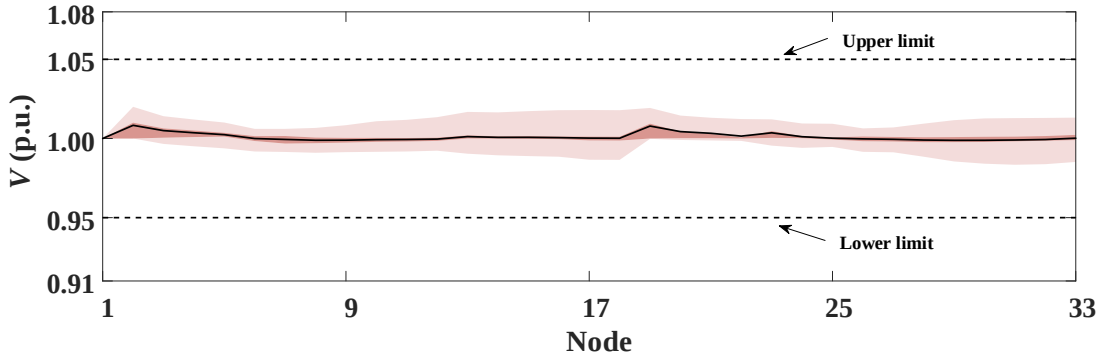


Fig. 14. The voltage profiles in Scenario III

It is worth noting that the proposed DRO-based parameter tuning method can flexibly adapt to the clustering results of historical operational data. The different representative scenarios do not have much influence on the tuning result of the local control curve. However, the number of typical scenarios will affect the solution duration of the local control strategy. Taking the comparison between three representative scenarios and ten representative scenarios as an example, the operational costs and the computing time are shown in Table 2.

Theoretically, optimal control performance can be achieved through real-time centralized control in Scenario IV. This is commonly used as a baseline for the optimization algorithms. By ignoring the computational delay and communication effects, Scenario IV has the smallest voltage deviation and network power loss. The voltage profiles in Scenario IV are shown in Fig. 15.

Table 2 Analysis of the impact of the representative scenarios

Scenario	Minimum voltage (p.u.)	Maximum voltage (p.u.)	Cost of voltage deviations (CNY)	Cost of power loss (CNY)	Operational costs (CNY)	Computing time (s)
III						
With 3 scenarios	0.9834	1.020	133.6	746.3	880.0	105.1
III						
With 10 scenarios	0.9834	1.020	135.1	742.8	878.0	659.9

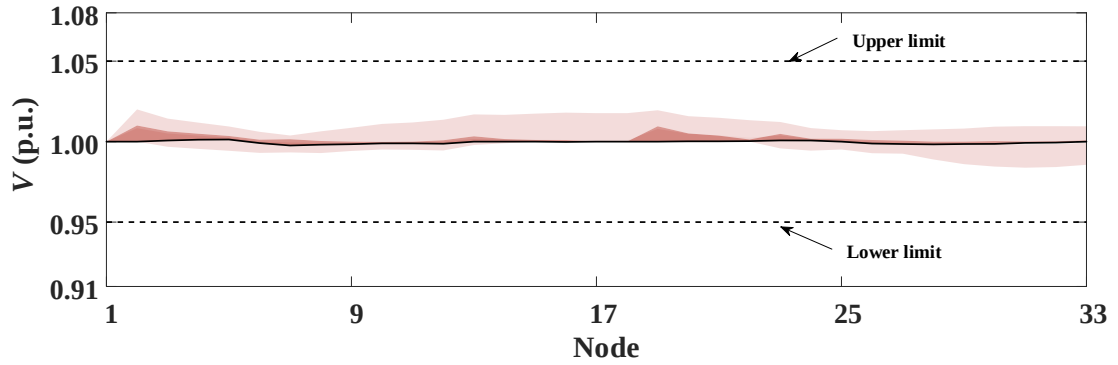


Fig. 15. The voltage profiles in Scenario IV

2) The advancement of improved local control curve

To illustrate the advancement of the proposed improved local control curves, Scenario V is further presented for comparison. The local control curve in Scenario V is shown in Fig. 16.

Scenario V: The local control curves outlined in [43] are employed for implementing DG control, while the coordinated control strategy is determined by the central method.

Compared to the local control curve in [43], the improved local control curve proposed in this paper adds two additional adjustable points, which can gain more flexibility in adjustment. This makes the improved local control curve more effective in controlling voltage fluctuations. The

optimization results for Scenarios III and V are presented in Table 3. Voltage profiles of the test system in Scenario V are shown in Fig. 17.

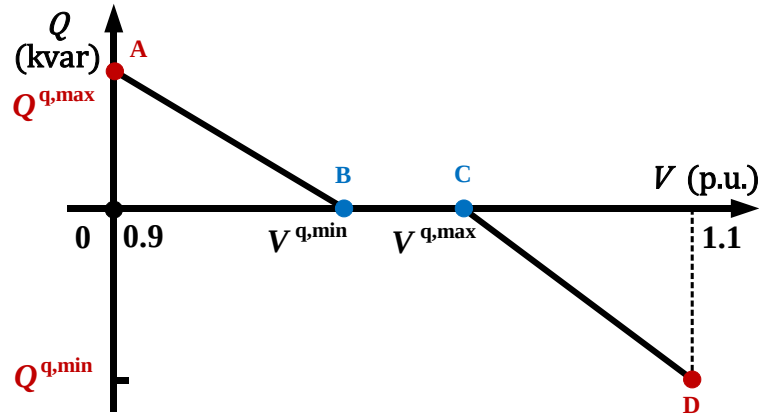


Fig. 16. The local control curve in Scenario V

Table 3 Optimization results of the two scenarios

Scenario	Minimum voltage (p.u.)	Maximum voltage (p.u.)	Cost of voltage deviations (CNY)	Cost of power loss (CNY)	Operational costs (CNY)
III	0.9834	1.020	133.6	746.3	880.0
V	0.9740	1.031	298.5	597.9	896.4

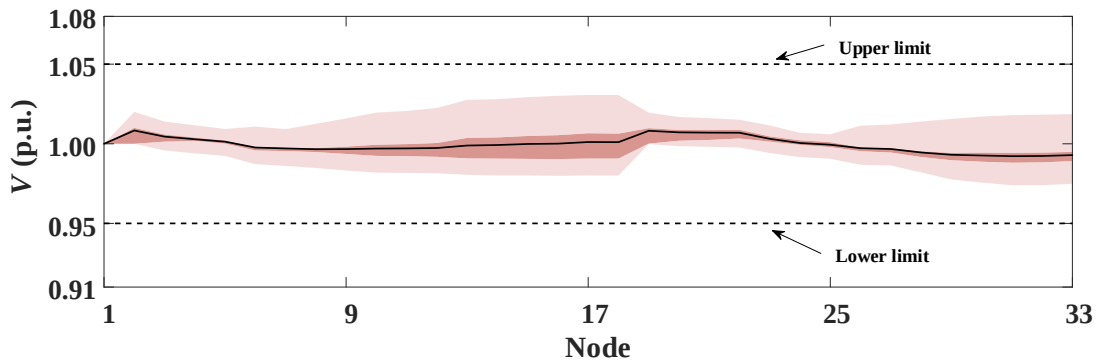


Fig. 17. The voltage profiles in Scenario V

3) The superiority of DRO-based local curve tuning method

To validate the effectiveness of the DRO method, the uncertainty realizations with 100 scenarios are sampled using the Monte Carlo method to simulate the actual power fluctuations in DG power. The comparison results Scenario II, III and VI are shown in Table 4.

Compared to the central long-time-scale strategy in Scenario II, the curve-based local control

strategy has superior performance in responding to DG fluctuations. This includes lower voltage deviations and more stable voltage extremes. That is, the curve-based strategy in Scenario III is more robust in responding to DG uncertainty.

To illustrate the superiority of the proposed DRO-based tuning method, Scenario VI is further presented for comparison.

Table 4 Robust test results of Scenario II, III, and VI

	Scenario II		Scenario III		Scenario VI	
	Mean	Extremum	Mean	Extremum	Mean	Extremum
Minimum voltage (p.u.)	0.9562	0.9389	0.9755	0.9645	0.9467	0.9366
Maximum voltage (p.u.)	1.023	1.026	1.038	1.042	1.046	1.052
Cost of voltage deviations (CNY)	165.0	170.8	144.2	149.0	182.3	188.2
Cost of power loss (CNY)	781.7	788.6	753.5	768.8	746.5	764.5
Operational costs (CNY)	946.7	955.4	897.7	914.3	928.8	947.8

Scenario VI: The improved local control curves of DGs are tuned based on the day-ahead forecasting data in a deterministic manner, while the coordinated strategy of multiple devices is determined in the central stage.

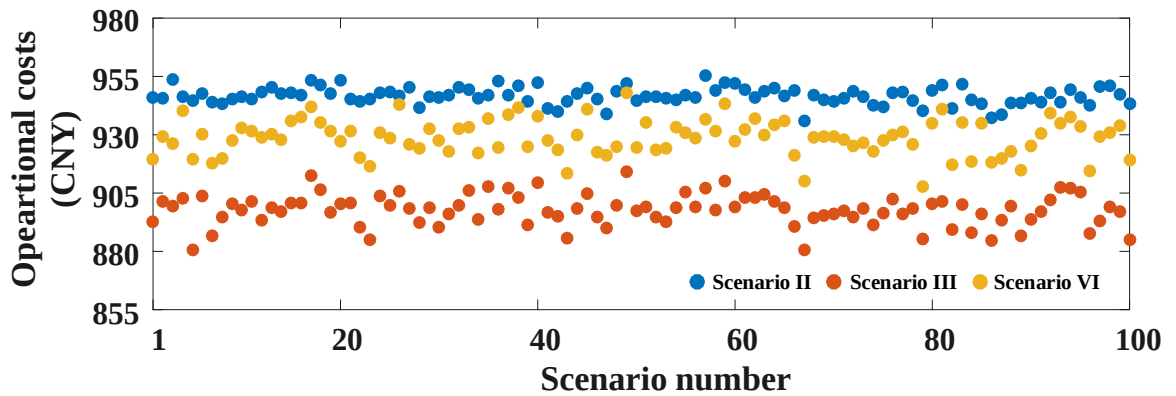


Fig. 18. Robust test results of Scenario II, III, and VI

Considering the robustness of the improved local control curve, Scenario VI effectively reduces

the voltage fluctuation of the system, which can realize a lower operating cost compared to Scenario II. However, since more types of scenarios are taken into account, the proposed DRO-based tuning method is more adaptable to DG fluctuations. Therefore, Scenario III has a better control performance in the robust testing, compared with Scenario VI. The adaptability to DG fluctuations of Scenario II, III, and VI are illustrated in Fig. 18.

4.2. JMF3 80-node practical distribution system

To further illustrate the scalability of the proposed combined central-local strategy, a test case is further constructed based on an actual large-scale distribution system.

The practical distribution system, JMF3 system, consists of an 80-node configuration encompassing a substation and 79 branches. The rated voltage level for the test system is 110 kV. Fig. 19 shows the structure of the practical distribution system.

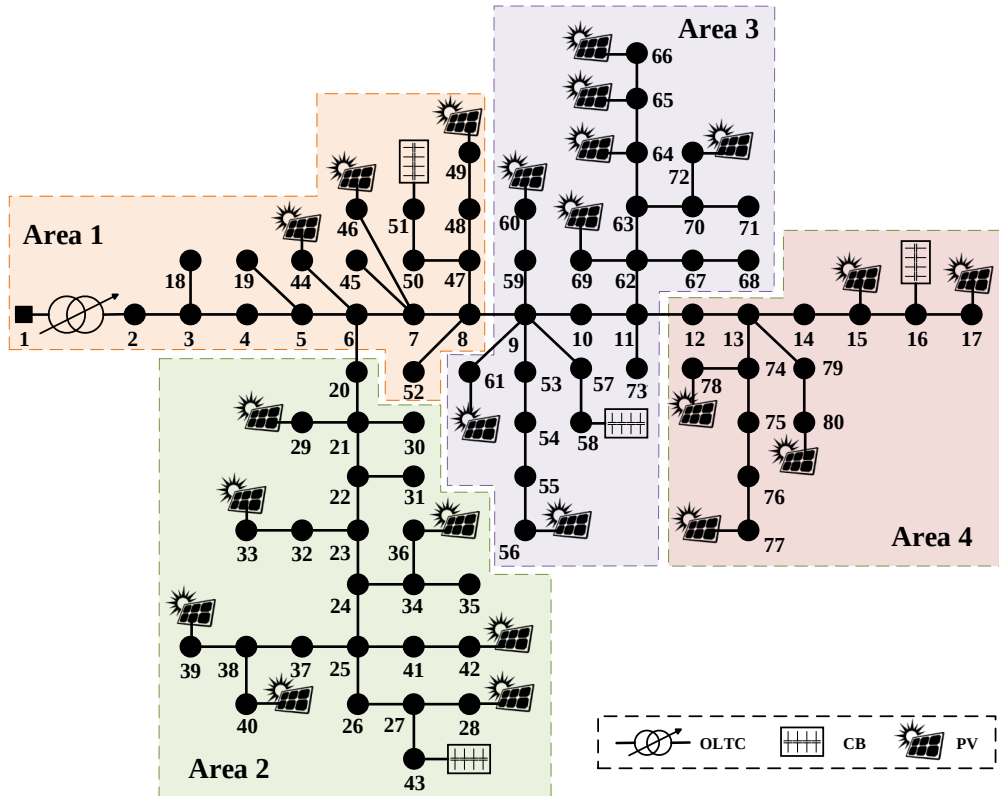


Fig. 19. Structure of the JMF3 80-node practical distribution system

23 PV units are integrated into the networks to simulate high penetration of DG, with their

active power reaching nearly 85% of the peak demand. Table 5 presents the basic parameters of DGs integrated into the system. There is an OLTC situated between nodes 1 and 2. Additionally, the CBs are installed on nodes 16, 43, 51, and 58. The parameters of CBs and OLTC are configured to match those of the IEEE 33-node distribution system.

Table 6 shows the optimization results for the four test scenarios. With a similar conclusion in Section 4.1, the proposed combined central-local strategy can effectively respond to the uncertainty of DGs.

Table 5 Basic installation parameters of DGs

Area	Node	Capacity (kVA)
1	44, 46, 49	200
2	28, 29, 33, 36, 39, 40, 42	300
3	64, 65, 66, 72, 56, 60, 61, 69	500
4	15, 17, 77, 78, 80	400

The proficient coordination of multiple regulatory devices yields effective mitigation of voltage fluctuations within ADN, concomitantly enhancing economic performance. The voltage profiles and the control strategies of the discrete regulation devices under Scenario I, II, III, and IV are represented in Fig. 20 to Fig. 24. These visualizations serve to illustrate the scalability of the proposed combined central-local control strategy on large-scale ADNs.

Table 6 Optimization results of the four scenarios

Scenario	Minimum voltage (p.u.)	Maximum voltage (p.u.)	Cost of voltage deviations (CNY)	Cost of power loss (CNY)	Operational costs (CNY)
I	0.9271	1.034	2546	1940	4486
II	0.9840	1.020	799.5	1679	2479
III	0.9834	1.022	342.6	1666	2008
IV	0.9823	1.023	286.9	1576	1863

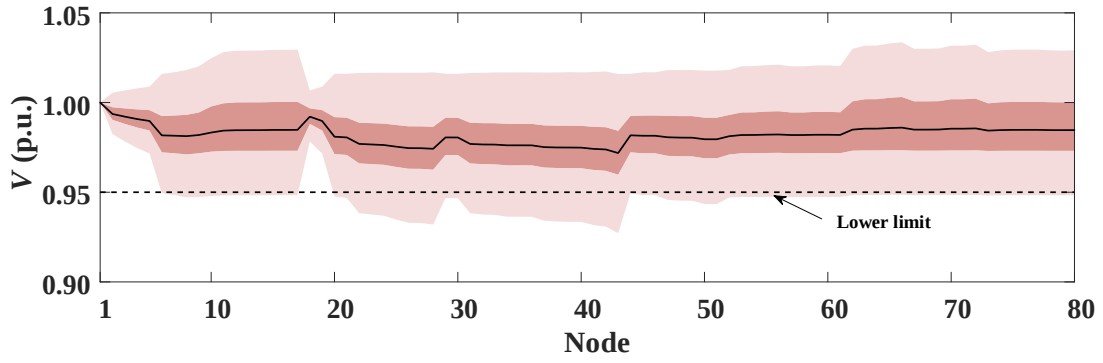


Fig. 20. The voltage profiles in Scenario I

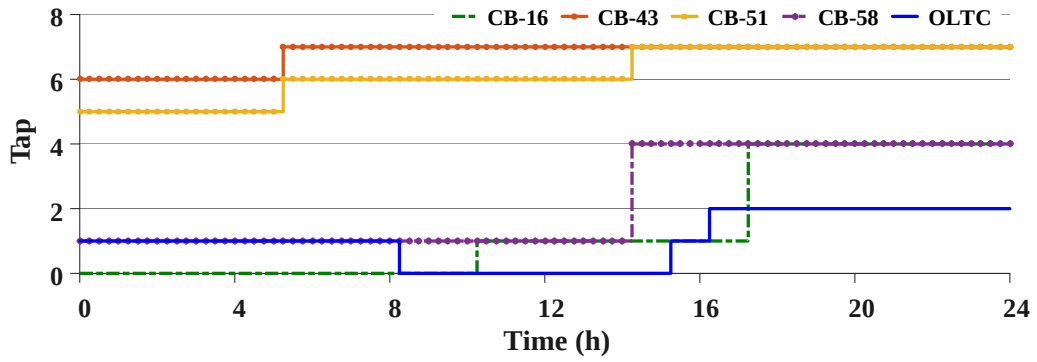


Fig. 21. The control strategies of discrete regulation devices in Scenario II

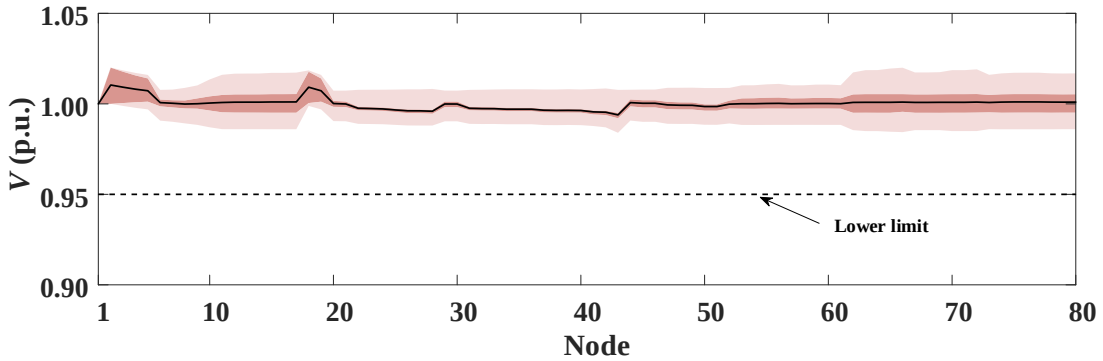


Fig. 22. The voltage profiles in Scenario II

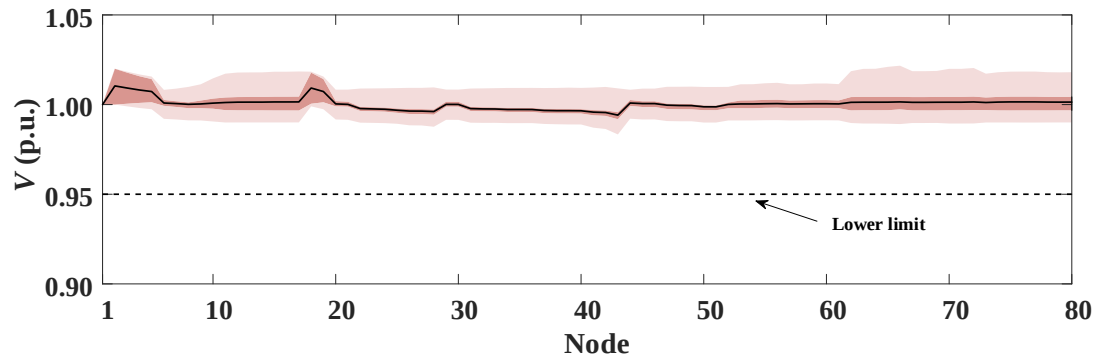


Fig. 23. The voltage profiles in Scenario III

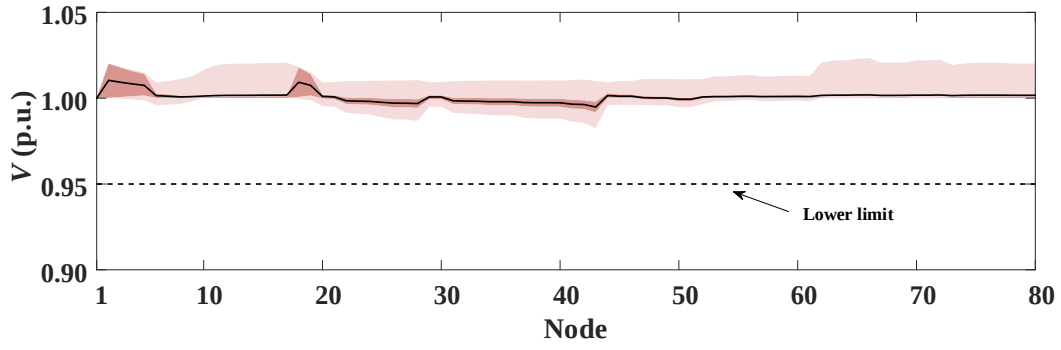


Fig. 24. The voltage profiles in Scenario IV

5. Conclusions

To eliminate voltage violations effectively, a combined central-local voltage control strategy for DGs is proposed in this paper. The test results show that the proposed control strategy is effective. The coordination of discrete regulation devices is realized with the control strategy of DGs determined in the central stage day ahead. The frequent voltage fluctuations are mitigated by the improved local control curves in the local stage. The global optimization and rapid fluctuation response are simultaneously achieved based on the proposed strategy. Meanwhile, in the test of robustness, the proposed DRO-based parameter tuning model enables the greater robustness of the DG control strategy. More fluctuation scenarios can be adapted according to the robust control strategy. In the test of an actual large-scale system, enhanced control performance is attained by utilizing local measurements through the compensation of the central strategy, while illustrating the scalability of the proposed method. A notable improvement in mitigating voltage violations is achieved owing to the considerations for DG uncertain fluctuations.

Numerous prospective research avenues warrant exploration in the future. Considering the strong uncertainty in the practical environment, how to respond to the DG fluctuations in the central stage remains to be further researched. With the deep integration of communication and distribution networks, the impact of communication links on ADN operations can be further taken into account in future research. At the same time, how to realize the flexible segmentation and adjustment of the local control curves will also be a major difficult issue to be addressed.

Acknowledgements

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