

## Article

# Dynamic Intelligent Method for Voltage Violation Management in High-Renewable-Penetration Distribution Networks

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## Abstract

This paper proposes a dynamic intelligent method for voltage violation management in high-renewable-penetration distribution networks. The method employs a dual-agent architecture: DERMS\_Agent coordinates task scheduling, data management, and computational resource allocation, while Solution\_Agent performs three-phase unbalanced power flow calculation and MIQP-based voltage violation joint optimization. Four key technical contributions are presented. (i) An asymmetric nodal admittance matrix is developed to incorporate transformer tap-phase-shift and capacitor branches within a unified formulation. (ii) Five categories of analytical sensitivities are systematically derived, covering transformer tap, phase shift, and capacitor compensation effects for both voltage regulation and harmonic suppression. (iii) A three-parameter MIQP joint optimization model is constructed with voltage deviation minimization as the objective and three-phase unbalance and resonance avoidance as constraints. (iv) A two-stage hybrid solution strategy combining Ipopt continuous relaxation with Gurobi neighborhood enumeration is designed to achieve real-time solvability. Validation on a real 10 kV feeder with 91 transformer areas over 768 time sections (8 days) demonstrates a 95.6% voltage violation resolution rate within the first three polling cycles and an average single-section solution time of 0.83 s, satisfying the real-time requirements of 15 min operational control cycles.

**Keywords:** high renewable penetration; distribution network dynamic modeling; voltage violation management; temporal monitoring indices; digital modeling computation; optimal operation scheme; DERMS agent; solution agent; MIQP



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## 1. Introduction

### 1.1. Research Background: Voltage Violation Challenges in High-Renewable-Penetration Distribution Networks

In high-renewable-penetration distribution networks, voltage violation has become the foremost issue affecting operational safety [1,2]. Statistics indicate that the voltage deviation violation rate of a typical 10 kV feeder reaches 33%, with overvoltage accounting for 98.2% of violations—a characteristic pattern in high-penetration distributed photovoltaic regions [3]. The causes of voltage violation exhibit pronounced temporal dynamics. Reverse power flow during PV peak output periods elevates medium-voltage-side voltage, while reactive power deficiency during load peak periods causes terminal low voltage. Consequently, the same feeder may alternately experience overvoltage and undervoltage at

different times of day [4,5]. Furthermore, complex physical coupling exists among voltage regulation measures. Large-capacity reactive power compensation, while raising voltage, may trigger low-order resonance; tap up-regulation, while improving voltage, may worsen three-phase unbalance [6]. The traditional paradigm of addressing voltage issues through separate indices, separate control means, and separate time periods cannot resolve such temporally coupled challenges. It is therefore imperative to establish an online solution-decision system that manages voltage violations holistically while satisfying power quality constraints [7,8]. These violations are systematic manifestations of the growing mismatch between distributed generation variability and conventional infrastructure controllability, driving the need for automated solutions at the 15 min control cycle.

While this work focuses on AC distribution feeders, the analytical sensitivity framework—particularly the capacitor branch Y-matrix model and harmonic resonance analysis—extends methodologically to hybrid AC/DC microgrids, where interlinking converters pose additional voltage regulation and harmonic injection challenges.

### 1.2. Three-Layer Superimposed Barriers to Online Voltage Violation Management

Recent advances in AI-enabled DERMS and Volt-VAR optimization (2023–2025) have demonstrated the potential of multi-agent architectures and mixed-integer programming for distribution network control. Notable contributions include Huang et al. (2025) [9], who proposed hierarchical coordination for Volt/VAR control in electronic distribution networks; Wang et al. (2025) [10], who developed a multiscale dynamic equivalence method using deep learning with automatic parameter tuning; and Lee et al. (2025) [4], who investigated DER interconnection assessment using ADMS for stable distribution system operation. Despite these advances, existing approaches exhibit a common limitation: they either rely on offline-trained surrogate models that may not generalize to previously unseen network conditions or employ centralized optimization frameworks that do not interface with CIM-based automated model generation pipelines.

The method proposed in this paper bridges this gap by integrating physics-grounded analytical sensitivities with a two-stage MIQP solution within a dual-agent architecture that is directly driven by real-time operational indices from field measurements.

Under the premise that the companion paper has already addressed the “operation-index-driven automatic simulation model generation” problem—capable of automatically producing computable current-state assessment models at 15 min granularity from CIM archives and field measurements—online solution and management decision-making for voltage violation still faces three superimposed barriers. These barriers collectively create the engineering dilemma of “having models, data, and control means, yet being unable to rapidly generate deployable management schemes.” However, the transition from accurate state assessment to automated corrective action—from detecting a voltage violation to computing and executing the optimal set of control actions—constitutes a distinct engineering challenge. This paper bridges precisely that gap by developing the solution and decision layer that operates on top of the companion paper’s model generation pipeline.

For completeness and to reduce dependency on the companion paper, we summarize the three essential prerequisites inherited from the companion work. (1) Energy Flow Network (EFN): The EFN is constructed from SGCC CDPSC 2017 CIM archives via a three-layer parsing architecture (namespace adaptation, device object extraction, structured SQLite storage), mapping 1010 ConnectivityNodes and 869 ACLineSegments into a directed graph representation with per-phase impedance parameters for each branch. (2) Device Parameter Completion: Missing line impedance parameters—where CIM records contain only conductor type identifiers (e.g., “LGJ-240”) without R/X values—are resolved by lookup in a public device standard dataset covering distribution transformers, cables, and distribu-

tion lines; a rated tap fallback strategy handles transformers lacking tap position records. (3) Monitoring\_Agent Trigger Mechanism: Monitoring\_Agent executes three collaborative tasks at 15 min intervals—time-series measurement acquisition, national-standard-based operational index evaluation (voltage deviation rate  $\varepsilon V$ , three-phase unbalance factor  $\varepsilon U$ , transformer loading rate  $\eta$ , and system power factor  $\cos \varphi$ ), and measurement-residual-based network topology verification—and automatically pushes voltage-violation trigger events to the DERMS\_Agent task queue. These three components collectively provide the computable network model, complete device parameters, and automated violation detection upon which the voltage management solution developed in this paper depends.

The first barrier concerns the unified scheduling of temporal simulation computation tasks. Temporal three-phase unbalanced power flow calculation, harmonic penetration calculation, and operation index assessment differ in data interfaces, solver selection, and time granularity. Traditional serial script execution results in discontinuous states between sections and low computational resource utilization, making it difficult to complete the full computation chain within the 15 min cycle [11,12].

The second barrier involves the non-convex nonlinear coordinated solution of multiple control means. In engineering practice, 10 kV feeders are typically equipped with distribution transformer taps, low-voltage-side phase-segregated reactive power compensation capacitors, and Phase-Shifting Transformers (PST). However, tap changing, capacitor switching, and PST phase shifting correspond to discrete integer variables and continuous variables, respectively, and must simultaneously satisfy three-phase unbalance (GB/T 15543-2008 [13]) and resonance avoidance constraints during voltage regulation. Together, these constitute a Mixed Integer Nonlinear Programming problem with integer decision variables and non-convex constraints [9,14]. Existing studies mostly adopt single-means decoupled optimization—taps only targeting voltage deviation, capacitor switching defaulting to three-phase symmetric, and PST phase-shift control rarely incorporated into transformer-area-level joint solution. As a result, voltage management schemes lack global coordination, with per-section solution times often spanning several minutes or even hours, unable to support the real-time requirements of 15 min rolling sections [15–17].

The third barrier concerns the absence of an online closed-loop mechanism from simulation to dispatch. Traditional voltage violation management follows an offline-analysis, manual-decision, batch-deployment open-loop mode. In this mode, simulation analysis and dispatch execution are temporally decoupled, optimization schemes cannot adapt to continuous changes in grid operating conditions, and no systematic management effectiveness review or secondary correction mechanism exists after dispatch instruction issuance. Consequently, voltage violations recur and regulation strategies remain in a passive response state. Achieving the monitoring-to-simulation-to-optimization-to-dispatch-to-review online closed loop requires deep integration of solvers and dispatch execution mechanisms within a unified framework, imposing demanding requirements on both system architecture and agent coordination.

### 1.3. Proposed Method Framework and Main Contributions

Addressing the above three-layer barriers, this paper proposes a Dynamic Intelligent Method for Voltage Violation Management in Distribution Networks. Building upon the companion paper's operation-index-driven automatic simulation model generation, the method constructs an online computation-optimization system composed of two collaboratively working solution-decision agents. DERMS\_Agent (Distributed Energy Resources Management System Agent) serves as the coordination hub, uniformly scheduling core computation tasks including temporal three-phase unbalanced power flow, harmonic penetration, and operation index assessment. Solution\_Agent, integrated within DERMS\_Agent

as the optimization solver module, undertakes MIQP joint optimization solving with voltage deviation minimization as the objective. Both agents follow the operational definition established in the companion paper, achieving loosely coupled coordination through the SQLite shared data layer and task queue, jointly forming a 15 min granularity voltage violation management closed loop of monitoring, simulation, optimization, dispatch, and review.

The core novelty of this work lies in uniquely integrating three capabilities into a single automated pipeline, which fundamentally distinguishes it from existing DERMS frameworks that treat monitoring and optimization as isolated functions: (i) index-driven triggering via Monitoring\_Agent that automatically identifies voltage violation events at 15 min granularity; (ii) physics-based analytical sensitivity derivation for tap, capacitor, and PST control means within a unified asymmetric nodal admittance matrix framework; and (iii) a computationally efficient two-stage MIQP solution strategy that compresses the combinatorial search space from exponential scale to near-real-time solvability. This three-in-one integration—monitoring-driven triggering, physics-grounded sensitivity modeling, and efficient MIQP optimization—constitutes the central contribution of this work.

The first contribution is the design of the DERMS\_Agent data-model-computation three-class resource collaborative scheduling mechanism, which uniformly receives voltage-violation-driven task queues pushed by Monitoring\_Agent, assembles current-state assessment models per section, sequentially activates three-phase unbalanced power flow, harmonic penetration, and index computation core tasks, and writes solution results back to the SQLite model library to form a rolling closed loop, thereby solving the unified scheduling problem of temporal simulation computation tasks.

The second contribution establishes the temporal three-phase unbalanced power flow solution procedure (Ub3PhasorLF) based on the Energy Flow Network asymmetric nodal admittance matrix, using feeder-head measured 10 kV line voltage as the voltage source boundary and aggregating each transformer area three-phase PQ measurement as nodal injections to solve the full-network three-phase voltage distribution section by section at 15 min granularity, thereby supporting online assessment and diagnosis of voltage violations.

The third contribution is the systematic derivation of five categories of analytical sensitivities, covering transformer tap on voltage, capacitor branch on voltage and harmonic resonance, and PST phase shift on harmonic current. These sensitivities quantify the coupling mechanisms of tap voltage regulation, capacitor reactive power support, resonance frequency shift, capacitor harmonic amplification, and the PST phase-shift suppression principle for harmonic currents, thereby providing a linearized physical constraint foundation for the voltage violation MIQP optimization model.

The fourth contribution constructs, with voltage deviation minimization as the objective and three-phase unbalance and resonance avoidance as constraints, the three-parameter MIQP joint optimization model of tap, phase-segregated capacitor, and PST phase. Phase-segregated asymmetric switching is explicitly modeled as an independent decision variable to enable precise management of single-phase voltage violations, and resonance avoidance constraints are linearized via the Big-M method while maintaining the overall convex MIQP structure, thereby upgrading the traditional paradigm of decoupled optimization, symmetric switching, and heuristic deployment to joint optimization, phase-segregated switching, and online solution.

The fifth contribution addresses the solution challenge posed by large-scale integer combinations through a two-stage hybrid strategy of Ipopt continuous relaxation, Gurobi neighborhood enumeration, and three-phase power flow nonlinear verification, compressing the integer enumeration scale significantly. A two-transformer-area joint optimization

single-section case study demonstrates per-section solution time of 0.83 s, maximum voltage deviation improvement of 33%, and three-phase unbalance improvement of 32%, satisfying the real-time requirements of 15 min rolling sections and providing an engineering-practical solver foundation for online voltage violation management.

To further substantiate the novelty claims, the following table provides a structured comparison of the proposed method with representative recent studies across four dimensions: methodology, optimization strategy, computational efficiency, and practical applicability (Table 1).

**Table 1.** Comparison of the proposed method with representative recent studies.

| Aspect                   | Huang et al. (2025) [9]                              | Wang et al. (2025) [10]                                      | Lee et al. (2025) [4]                      | Proposed Method                                                                                                           |
|--------------------------|------------------------------------------------------|--------------------------------------------------------------|--------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| Methodology              | Hierarchical coordination for Volt/VAR control       | Deep learning multiscale dynamic equivalence                 | ADMS-based DER interconnection assessment  | Dual-agent MIQP with physics-grounded analytical sensitivities                                                            |
| Optimization Strategy    | Decoupled Volt/VAR without joint optimization        | Automatic parameter tuning; no discrete control optimization | Interconnection feasibility screening only | Joint tap–capacitor–PST MIQP with two-stage hybrid solution (Ipopt + Gurobi)                                              |
| Computational Efficiency | Not reported                                         | Not reported                                                 | Not reported                               | 0.83 s/section for 91-transformer-area feeder; $O(N^2)$ scalability with continuous-relaxation pre-screening              |
| Practical Applicability  | Electronic distribution networks; no CIM integration | Multiscale modeling; no closed-loop dispatch                 | DER screening; no voltage optimization     | Online 15 min closed-loop (monitoring → simulation → optimization → dispatch → review) with field measurement integration |

#### 1.4. Paper Organization

This paper comprises six sections. Section 2 establishes the solution foundation for voltage violation management, deriving the asymmetric nodal admittance matrix model incorporating tap-capacitor-PST branches and five categories of voltage regulation analytical sensitivities; Section 3 briefly describes the Energy Flow Network, common equipment standard dataset, and Monitoring\_Agent voltage violation triggering mechanism used as inputs (see companion paper for details); Section 4 details the online temporal solution method for voltage violation management—DERMS\_Agent’s coordination mechanism and the “current-state assessment model → solution model” dual-model generation pipeline, presenting the MIQP mathematical programming formulation with voltage deviation minimization objective and the two-stage hybrid solution strategy, as well as differentiated dispatch instruction generation and closed-loop feedback mechanisms; Section 5 conducts temporal three-phase unbalanced power flow solution validation, current-state assessment model accuracy verification, and voltage violation joint optimization case studies using eight-day  $\times$  96-section  $\times$  91-transformer-area field measurements from a real 10 kV feeder; and Section 6 summarizes the main conclusions, research limitations, and future research directions  $\mathbf{Y}^{abc}$ .

## 2. Solution Foundation and Voltage Regulation Sensitivity Model

This section establishes the physical solution foundation for voltage violation management, deriving the  $\mathbf{Y}^{abc}$  asymmetric nodal admittance matrix incorporating tap-capacitor-PST branches and five categories of voltage regulation analytical sensitivities. The distribution network monitoring dataset, operation index system, and measurement-residual-driven topology verification method are detailed in the companion paper. The sensitivities derived in this section will serve as linearization coefficients for voltage regulation constraints in the Section 4 MIQP optimization model.

## 2.1. Measurement Data Interface and Operation Index System (Input Conventions)

The solution-decision system in this paper takes the current-state assessment model generated by the companion paper as its foundational input. The measurement variable set  $\mathcal{M}$ , 15 min sampling period, definitions of four national-standard operation indices (GB/T 12325 voltage deviation [18], GB/T 15543 three-phase unbalance [13], DL/T 836 loading rate [19], GB/T 31464 power factor [20]), and Monitoring\_Agent triggering mechanism are detailed in the companion paper and not repeated here. The solution-decision system in this paper additionally requires the dominant harmonic order set  $\mathcal{H} = \{5, 7, 11, 13\}$  and feeder-head short-circuit capacity  $S_{sc}^{(k)}$  as input parameters for harmonic penetration calculation and resonance avoidance constraints.

## 2.2. Asymmetric Nodal Admittance Matrix $Y^{abc}$ and Voltage Regulation Sensitivities

### 2.2.1. Theoretical Foundation

The basic construction rules of the nodal admittance matrix  $Y \in \mathbb{C}^{n \times n}$ —series admittance  $y_{ij} = 1/z_{ij}$ , diagonal elements  $Y_{ii} = \sum_j y_{ij}$ , off-diagonal elements  $Y_{ij} = -y_{ij}$  [21,22]—and the three-phase asymmetric extension  $Y^{abc} \in \mathbb{C}^{3n \times 3n}$  are detailed in the companion paper. Building upon the  $Y^{abc}$  framework, this paper further introduces refined models of transformer tap-phase-shift branches and phase-segregated capacitor branches; the following two subsections constitute this paper's exclusive contributions.

### 2.2.2. Transformer Branch Y-Matrix Model Incorporating Tap and Phase Shift

Distribution transformers and power transformers are core components for distribution network voltage regulation. To accurately characterize the voltage regulation (tap adjustment) effect of transformers within the Y-matrix, a complex turns-ratio branch model is introduced, naturally incorporating the linear asymmetric Y-matrix into the Energy Flow Network.

#### Complex Turns-Ratio Definition

Let an ideal transformation ratio link exist between the transformer primary side (node  $i$ ) and secondary side (node  $j$ ); the complex turns-ratio is defined as

$$\bar{a} = a \cdot e^{j\alpha} \quad (1)$$

where  $a$  is the turns-ratio magnitude,  $a = (N_1/N_2) \cdot (1 + \tau/100)$ ,  $\tau$  is the tap adjustment percentage (in this paper, distribution transformer  $\tau \in [-5\%, +5\%]$ , 5 positions, 2.5% per step); and  $\alpha$  is the primary-secondary phase shift angle (determined by winding connection group: Dyn11 corresponds to  $+30^\circ$ , Yd1 to  $-30^\circ$ ; Phase-Shifting Transformers (PST) can produce adjustable  $\alpha$  via phase-shifting windings).

Let the transformer leakage reactance admittance referring to the secondary side be  $y_t = 1/(r_t + jx_t)$ ; then the transformer branch contribution to the Y-matrix is an asymmetric  $2 \times 2$  block:

$$Y_T = \begin{bmatrix} \frac{y_t}{|\bar{a}|^2} & -\frac{y_t}{\bar{a}} \\ -\frac{y_t}{a} & y_t \end{bmatrix} = \begin{bmatrix} \frac{y_t}{a^2} & -\frac{y_t}{a} e^{j\alpha} \\ -\frac{y_t}{a} e^{-j\alpha} & y_t \end{bmatrix} \quad (2)$$

#### Key Properties

When the complex turns-ratio corresponds to no phase shift, the admittance sub-block remains symmetric and degenerates to the standard line admittance form, with the tap regulating effective series admittance solely via the turns-ratio magnitude. When a phase shift is present, the asymmetry of the admittance sub-block renders the overall Y-matrix an asymmetric complex matrix, which constitutes the mathematical root cause of phase-

shift regulation affecting harmonic propagation. This unified model is simultaneously applicable to On-Load Tap Changers (OLTC), conventional two-winding transformers, and Phase-Shifting Transformers (PST), serving as the universal foundation for voltage violation management modeling.

#### Tap Sensitivity for Voltage Regulation

Taking the partial derivative of secondary-side voltage with respect to tap  $a$  in the nodal current equation  $\mathbf{I}_T = \mathbf{Y}_T [U_i, U_j]^T$ , under the engineering assumption of constant secondary-side injection:

$$S_{U,a}^{(j)} = \left. \frac{\partial U_j}{\partial a} \right|_{I_j=\text{const}} \approx -\frac{U_j}{a} \quad (3)$$

That is, for every 1% tap adjustment, the secondary-side voltage changes inversely by approximately 1%. Taking the 91 transformer areas in this paper as an example, if a distribution transformer operates in an over-voltage state ( $\delta U = 10\%$ ), adjusting the tap from position 0 to position  $-1$  ( $\tau = -2.5\%$ ) is expected to reduce secondary-side voltage by approximately 2.5%, bringing  $\delta U$  to approximately 7%, precisely falling within the compliance interval. This linear sensitivity relationship directly guides the error attribution reasoning of the tap sensitivity analysis in the companion paper.

#### Phase-Shift Sensitivity for Harmonic Suppression

For the  $h$ -th harmonic current ( $h = 5, 7, 11, 13, \dots$ ), the transformer secondary-side harmonic current phase undergoes an additional  $h\alpha$  rotation relative to the primary side:

$$\dot{I}_j^{(h)} = \dot{I}_i^{(h)} \cdot e^{jh\alpha} \quad (4)$$

Harmonic current sensitivity to phase shift:

$$S_{I_h,\alpha} = \left| \frac{\partial \dot{I}_j^{(h)}}{\partial \alpha} \right| = h \cdot \left| \dot{I}_j^{(h)} \right| \quad (5)$$

**Harmonic Cancellation Principle:** When the phase-shift difference between two parallel transformers is  $\Delta\alpha = 180^\circ/h$ , the  $h$ -th harmonic currents completely cancel at the common bus:

For instance, a 30-degree phase-shift difference (Dy-Yy combination) cancels the 5th and 7th harmonics, corresponding to the classic 12-pulse rectifier suppression scheme, while a 15-degree difference (24-pulse scheme) further cancels the 11th and 13th harmonics, significantly reducing Total Harmonic Distortion (THD).

#### Theoretical Guidance for Voltage Violation Management Pathways

The above dual-parameter sensitivities provide two independent and complementary mathematical pathways for voltage violation management (Table 2).

**Table 2.** Correspondence between transformer dual parameters and voltage violation management pathways.

| Adjustment Parameter | Physical Effect           | Management Objective                                     | Typical Management Scheme                                  |
|----------------------|---------------------------|----------------------------------------------------------|------------------------------------------------------------|
| Tap $a$              | Adjusts voltage magnitude | Voltage deviation rate $\delta U$                        | OLTC automatic voltage regulation/Offline tap optimization |
| Phase shift $\alpha$ | Adjusts harmonic phase    | Resonance avoidance (indirect voltage quality assurance) | PST phase-shift configuration                              |

In DERMS\_Agent's solution model, when Monitoring\_Agent identifies an overvoltage problem (trigger condition  $\delta U > 7\%$ ), the  $S_{U,n}$  sensitivity is preferentially invoked to search for the optimal tap position; PST phase-shift regulation serves as an auxiliary means for resonance avoidance, ensuring that parallel resonance amplification does not occur during capacitor switching voltage regulation. This theoretical framework provides a unified mathematical foundation for the voltage violation management MIQP optimization model in Section 4.

### 2.2.3. Distribution Transformer Area Low-Voltage-Side Reactive Power Compensation Capacitor Branch Y-Matrix Model

Distribution transformer area low-voltage sides (0.4 kV bus) are commonly equipped with Shunt Capacitor Banks (SCB) for local reactive power compensation, power factor improvement, and bus voltage support. Compensation capacitors, as pure susceptance branches connected to node  $k$ , appear in the Y-matrix as node-to-ground shunt admittance, forming an indispensable modeling element for transformer-area-level voltage control and harmonic analysis.

#### Fundamental-Frequency Capacitor Branch Model

Let the rated capacity of the reactive power compensation device at transformer area  $k$  be  $Q_c^{(k)}$  (unit: kvar), rated voltage  $U_n = 0.4$  kV; then the capacitance value and capacitive susceptance at fundamental frequency ( $\omega_1 = 2\pi \cdot 50$  rad/s) are

$$C_k = \frac{Q_c^{(k)}}{\omega_1 U_n^2}, \quad b_c^{(k)} = \omega_1 C_k = \frac{Q_c^{(k)}}{U_n^2} \quad (6)$$

The capacitor branch contributes only to the diagonal elements of the Y-matrix (off-diagonal elements are zero); its Y-matrix update rule is

$$Y_{kk} \leftarrow Y_{kk} + j b_c^{(k)} \cdot s_k \quad (7)$$

where  $s_k \in \{0, 1\}$  is the switching state (for group switching,  $s_k$  can be extended to  $\{0, 1/N, 2/N, \dots, 1\}$ , with  $N$  being the number of capacitor bank groups). For three-phase symmetric compensation devices (Y-type or  $\Delta$ -type connection), the corresponding diagonal elements of the three-phase admittance matrix  $Y^{abc}$  all increase by  $j b_c^{(k)}$ ; asymmetric compensation (phase-segregated switching) updates only the affected phases.

#### Capacitor Sensitivity for Voltage Regulation

Let the Thévenin equivalent reactance at node  $k$  be  $X_k^{Th}$  (derived inversely from short-circuit capacity  $S_{sc}^{(k)}$ ,  $X_k^{Th} \approx U_n^2 / S_{sc}^{(k)}$ ); the steady-state voltage rise at the node after switching in capacity  $Q_c^{(k)}$  is approximately

$$\Delta U_k \approx \frac{X_k^{Th} \cdot Q_c^{(k)}}{U_n} = \frac{Q_c^{(k)}}{S_{sc}^{(k)}} \cdot U_n \quad (8)$$

Capacitor sensitivity for voltage:

$$S_{U, Q_c}^{(k)} = \frac{\partial U_k}{\partial Q_c^{(k)}} \approx \frac{X_k^{Th}}{U_n} = \frac{U_n}{S_{sc}^{(k)}} \quad (9)$$

That is, the smaller the short-circuit capacity (the weaker the grid), the more significant the voltage rise from the same compensation capacity. Taking the typical transformer area in this paper's case study with  $S_{sc} \approx 5$  MVA,  $U_n = 0.4$  kV, each 30 kvar of capacitor switching

raises bus voltage by approximately  $0.4 \times 30/5000 = 2.4$  V (equivalent to 0.6%), providing a quantitative basis for low-voltage ( $\delta U < -7\%$ ) transformer area management.

#### Capacitor Sensitivity for Harmonic Resonance

The capacitor branch and system equivalent inductance  $L_s^{(k)} = X_k^{Th}/\omega_1$  form a parallel resonance circuit; the harmonic order corresponding to the resonance frequency is

$$h_{\text{res}}^{(k)} = \frac{1}{\omega_1 \sqrt{L_s^{(k)} C_k}} = \sqrt{\frac{S_{sc}^{(k)}}{Q_c^{(k)}}} \quad (10)$$

Resonance order sensitivity to compensation capacity:

$$S_{h,Q_c}^{(k)} = \frac{\partial h_{\text{res}}^{(k)}}{\partial Q_c^{(k)}} = -\frac{h_{\text{res}}^{(k)}}{2Q_c^{(k)}} \quad (11)$$

The negative sign indicates that increasing compensation capacity shifts the resonance frequency toward lower harmonic orders. Once  $h_{\text{res}}^{(k)}$  approaches the system's dominant harmonic orders (typically 5th, 7th, 11th, 13th), parallel resonance amplification will be triggered, causing capacitor overcurrent burnout and even abrupt bus harmonic voltage rise. The engineering criterion requires  $h_{\text{res}}^{(k)}$  to avoid the forbidden zones of dominant harmonic orders  $\pm 0.5$  (e.g.,  $h_{\text{res}} \in (4.5, 5.5)$  or  $(6.5, 7.5)$  is considered a hazardous configuration).

#### Capacitor Sensitivity for Harmonic Penetration

At the  $h$ -th harmonic frequency, the capacitor branch admittance is linearly amplified by a factor of  $h$  relative to the fundamental frequency:

$$b_c^{(k,h)} = h\omega_1 C_k = h \cdot b_c^{(k)} \quad (12)$$

Therefore, the harmonic current flowing through the capacitor is as follows:

$$\dot{I}_c^{(k,h)} = jhb_c^{(k)} \cdot \dot{U}_k^{(h)} \quad (13)$$

Harmonic current magnitude sensitivity to compensation capacity:

$$S_{I_h,Q_c}^{(k)} = \left| \frac{\partial \dot{I}_c^{(k,h)}}{\partial Q_c^{(k)}} \right| = \frac{h \cdot \left| \dot{U}_k^{(h)} \right|}{U_n^2} \quad (14)$$

This relationship reveals the capacitor's amplification (attraction) effect on higher-order harmonics: the larger the compensation capacity and the higher the harmonic order, the greater the harmonic current absorbed by the capacitor, forming a "harmonic penetration" path. Without series reactors (tuning reactance ratio  $k_L = 6\%$  or  $12\%$ ), the actual capacitor operating current may far exceed the rated value, accelerating insulation aging.

#### Three-Phase $\mathbf{Y}^{abc}$ Extension and Asymmetric Switching Modeling

The above single-phase equivalent model only provides scalar diagonal element update rules. In the three-phase admittance matrix  $\mathbf{Y}^{abc} \in \mathbb{C}^{3n \times 3n}$ , the  $3 \times 3$  self-admittance sub-block  $\mathbf{Y}_{kk}^{abc}$  corresponding to transformer area  $k$  must be finely modeled according to the capacitor bank's connection type and phase-segregated switching state.

Y-grounded ( $Y_g$ ) Connection:

Let the three-phase independent switching state vector be  $\mathbf{s}_k = [s_k^a, s_k^b, s_k^c]^T, s_k^\phi \in \{0, 1/N, 2/N, \dots, 1\}$  ( $N$  is the number of groups per phase). Under phase voltage  $U_n/\sqrt{3}$ , the per-phase-to-ground susceptance is  $b_c^{(k)} = Q_c^{(k)}/U_n^2$ . The sub-block contribution is a diagonal matrix:

$$\Delta \mathbf{Y}_{kk}^{abc, Y_g} = j b_c^{(k)} \cdot \text{diag}(s_k^a, s_k^b, s_k^c) = j b_c^{(k)} \begin{bmatrix} s_k^a & 0 & 0 \\ 0 & s_k^b & 0 \\ 0 & 0 & s_k^c \end{bmatrix} \quad (15)$$

Asymmetric switching (e.g., only phase  $a$  switched in  $\mathbf{s}_k = [1, 0, 0]^T$ ) produces no phase-to-phase coupling, but because per-phase-to-ground admittances are unequal, it introduces additional three-phase unbalance components that must be accounted for in the  $\varepsilon$  index constraint during switching decisions.

$\Delta$ -Type Connection:

A  $\Delta$ -type capacitor bank consists of three phase-to-phase branches. Let the branch switching states be  $s_k^{ab}, s_k^{bc}, s_k^{ca}$ , with each phase-to-phase branch susceptance  $b_\Delta^{(k)} = Q_c^{(k)}/(3U_n^2)$ . Through the  $\Delta$ -to- $Y$  nodal admittance transformation rule, the sub-block contribution is a symmetric  $3 \times 3$  full matrix:

$$\Delta \mathbf{Y}_{kk}^{abc, \Delta} = j b_\Delta^{(k)} \begin{bmatrix} s_k^{ab} + s_k^{ca} & -s_k^{ab} & -s_k^{ca} \\ -s_k^{ab} & s_k^{ab} + s_k^{bc} & -s_k^{bc} \\ -s_k^{ca} & -s_k^{bc} & s_k^{bc} + s_k^{ca} \end{bmatrix} \quad (16)$$

Under three-phase symmetric switching ( $s_k^{ab} = s_k^{bc} = s_k^{ca} = s_k$ ), the above reduces to

$$\Delta \mathbf{Y}_{kk}^{abc, \Delta} = j b_\Delta^{(k)} s_k \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (17)$$

Compared with  $Y_g$  connection, the off-diagonal terms of the  $\Delta$  connection reflect phase-to-phase capacitive coupling, which is key to analyzing three-phase unbalanced harmonic propagation. The three-phase branch topology, switching configuration, and  $\mathbf{Y}^{abc}$  sub-block mapping relationship for  $\Delta$ -type connection are shown in Figure 1.

Multi-Objective Effects of Asymmetric Switching:

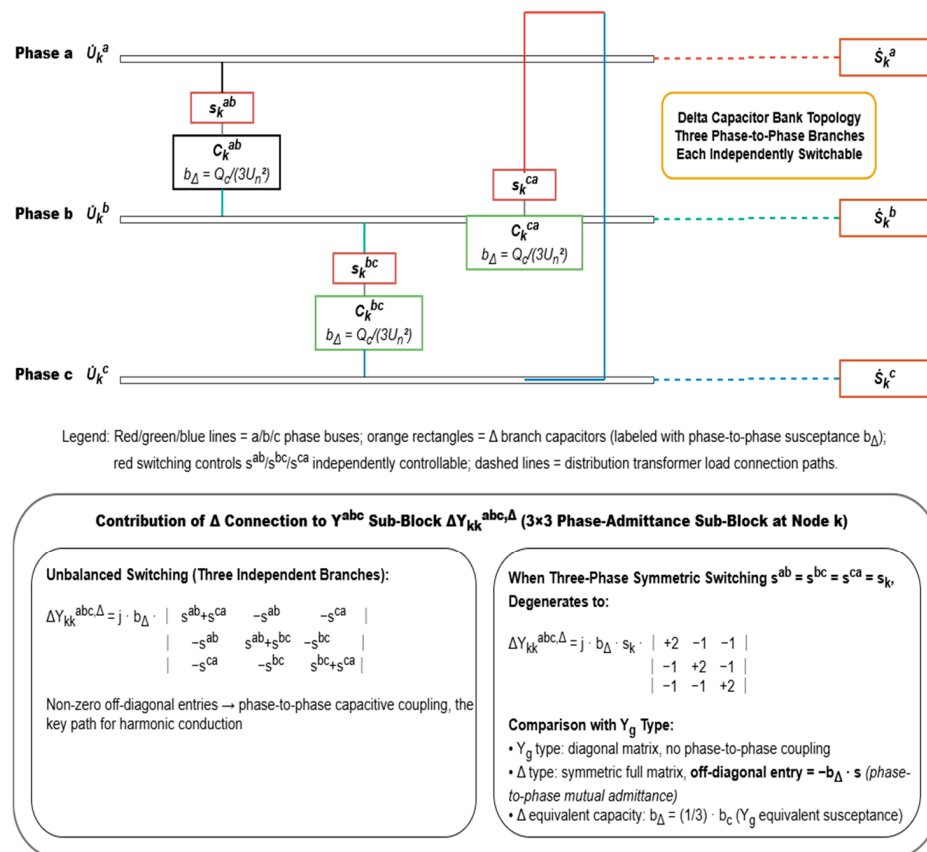
Asymmetric switching simultaneously affects four indices; their coupling relationships are summarized in Table 3.

**Table 3.** Comprehensive effects of three-phase asymmetric switching on power quality indices.

| Switching Mode                                    | $\delta U_\phi$<br>(Phase-Segregated) | $\varepsilon$ (Unbalance) | $\cos\phi$                             | $\mathbf{h}_{\text{res}}$        |
|---------------------------------------------------|---------------------------------------|---------------------------|----------------------------------------|----------------------------------|
| Three-phase symmetric<br>( $s^a = s^b = s^c$ )    | Three-phase<br>synchronous rise       | Unchanged                 | Three-phase synchronous<br>improvement | Three-phase<br>synchronous shift |
| Single-phase switching<br>( $s^a = 1$ , others 0) | Only phase a rises                    | Significantly increased   | Only phase a improved                  | Only phase a                     |
| Two-phase switching<br>( $s^a = s^b = 1$ )        | Phases a, b rise                      | Moderately increased      | Two-phase improvement                  | Two-phase                        |

Under conditions where Monitoring\_Agent identifies single-phase undervoltage while the other two phases are compliant, asymmetric switching can serve as a precise management means invoked by DERMS\_Agent; however, it must be solved under the  $\varepsilon < 2\%$  constraint to avoid introducing new unbalance problems.

### Delta-Connected Reactive Power Compensation Capacitor Bank — Three-Phase Coupling Circuit and $Y_{abc}$ Sub-Block Mapping



**Figure 1.**  $\Delta$ -connected capacitor bank phase-to-phase coupling circuit and  $Y_{abc}$  sub-block mapping.

### Correspondence with Voltage Violation Management Pathways

The three capacitor sensitivities collectively constitute the voltage regulation constraint system (Table 4):  $S_{U, Q_c}$  is the positive means for voltage rise, while  $S_{h, Q_c}$  and  $S_{I_{h, Q_c}}$  are safety constraints during voltage regulation (resonance avoidance and overcurrent protection).

**Table 4.** Capacitor compensation sensitivity correspondence with voltage violation management.

| Sensitivity      | Voltage Regulation Effect                     | Safety Risk                                       | Engineering Constraint                    |
|------------------|-----------------------------------------------|---------------------------------------------------|-------------------------------------------|
| $S_{U, Q_c}$     | Voltage rise, improves undervoltage           | Excessive switching causes overvoltage            | $\  \Delta U_k \  < 7\%$                  |
| $S_{h, Q_c}$     | No direct voltage regulation effect           | Resonance frequency approaches dominant harmonics | $h_{res} \notin [h^* \pm 0.5]$            |
| $S_{I_{h, Q_c}}$ | Local reactive power balance supports voltage | Harmonic current amplification and overheating    | Configure $k_L = 6\%/12\%$ tuning reactor |

In DERMS\_Agent's solution model, capacitor switching optimization uses  $S_{U, Q_c}$  as the positive voltage regulation means (filling voltage deficits), with  $S_{h, Q_c}$  and  $S_{I_{h, Q_c}}$  as constraint conditions (avoiding resonance and overcurrent), forming a voltage violation joint management model complementary to transformer taps (Section 2.2.2): tap voltage regulation responds to steady-state voltage deviation, capacitor switching provides local reactive power support and phase-segregated precise voltage regulation, and PST phase shift ensures resonance safety during capacitor switching; all three are uniformly scheduled within the same sensitivity framework.

### 2.2.4. Nodal Current Equation

Based on the above  $\mathbf{Y}^{abc}$  matrix, the nodal injection current vector and nodal voltage vector satisfy  $\mathbf{I} = \mathbf{Y}\mathbf{U}$ , which is the unified constraint equation for subsequent temporal three-phase unbalanced power flow and harmonic penetration calculations (Section 4). The measurement-residual-driven Y-matrix self-verification mechanism is detailed in the companion paper.

## 3. Simulation Model and Triggering Mechanism (Prerequisites)

The solution-decision system in this paper uses the Energy Flow Network (EFN) constructed by the companion paper as the unified computational carrier. The EFN maps all physical components of the SGCC CDPSM 2017 CIM archive [23] according to “node–branch” mapping and, after three-layer parsing, is constructed as a directed graph containing 1010 nodes and 869 branches. Missing parameters for distribution transformers, cables, and distribution lines are automatically supplemented from the common equipment standard dataset by model field matching. The measurement-residual-driven topology/parameter self-verification mechanism ensures that  $\mathbf{Y}^{abc}$  is consistent with the actual network topology. The CIM parsing process, standard dataset construction, EFN definition, and measurement residual verification method are detailed in the companion paper.

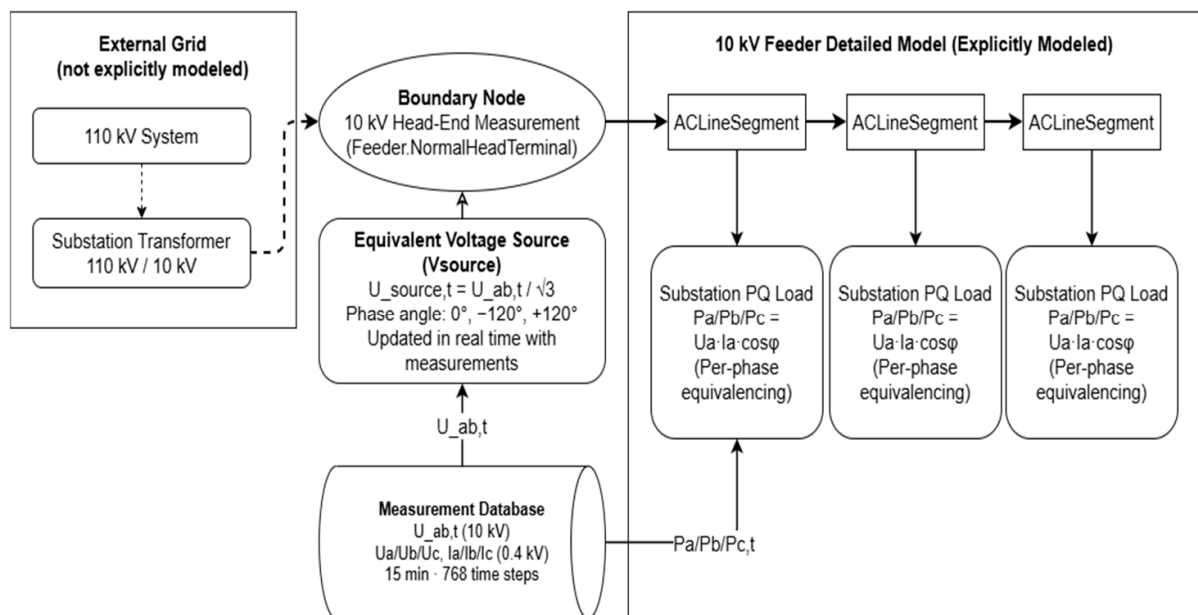
Monitoring\_Agent uses a 15 min measurement sampling period as the polling interval, computing operation indices such as voltage deviation rate  $\delta U$  for each transformer area. When any transformer area detects voltage violation ( $\delta U > 7\%$  or  $\delta U < -7\%$ ), Monitoring\_Agent immediately pushes that transformer area into the driving task queue, activating DERMS\_Agent to start the voltage violation management solution-decision pipeline. Monitoring\_Agent’s three-layer architecture and index definitions are detailed in the companion paper.

## 4. Online Temporal Solution Method for Voltage Violation Management

### 4.1. DERMS\_Agent Positioning and Voltage Violation Management Activation

DERMS\_Agent (Distribution Energy Resources Management System Agent) is the execution agent for distribution network voltage violation management. After receiving the voltage-violation-driven task queue pushed by Monitoring\_Agent, it collaboratively invokes three classes of resources: data resources to extract boundary parameters including feeder-head 10 kV line voltage and all transformer area three-phase PQ measurement values for the corresponding section from the measurement database; model resources to read the EFN topology and Y parameters that have passed the self-verification closed loop from SQLite, the construction process of which is detailed in the companion paper; and computational resources to invoke the three-phase unbalanced power flow solver (Ub3PhasorLF) for executing power flow calculations.

DERMS\_Agent follows the dual-stage principle of “assess first, then optimize,” sequentially generating the current-state assessment model (diagnosing voltage violation severity and distribution) and the solution model (solving the optimal management strategy), forming a voltage violation management closed loop of “monitoring detection → simulation diagnosis → optimization decision → dispatch execution → review assessment” (Figure 2). The current-state assessment model is completed by DERMS\_Agent directly scheduling the Ub3PhasorLF three-phase power flow solver; the solution model is handled by the Solution\_Agent sub-module integrated within DERMS\_Agent, responsible for mathematical modeling and MIQP solving (see Section 4.3), with solution results written back to SQLite by DERMS\_Agent and dispatched to the equipment execution queue.



**Figure 2.** DERMS\_Agent dual-model generation pipeline. Solid line represents explicitly modeled electrical topologies and data transmission links within the 10 kV feeder system. Dashed line illustrates the electrical coupling of the external 110 kV grid, which is simplified as an equivalent boundary voltage source without detailed component modeling.

#### 4.2. Current-State Assessment Model (Temporal Three-Phase Unbalanced Power Flow)

The current-state assessment model is driven by field measurement data at trigger time section  $t$ , reproducing the current operating state of the distribution network and providing a precise physical basis for problem diagnosis.

Boundary Equivalent Method [10]: The feeder-head measured 10 kV line voltage  $U_{ab,t}$  serves as the voltage source boundary:

$$U_{source,t} = \frac{U_{ab,t}}{\sqrt{3}} \quad (18)$$

The initial phase angles of phases A, B, C are set to  $0^\circ$ ,  $-120^\circ$ , and  $+120^\circ$ , respectively, according to symmetrical components. During the validation period, the 10 kV line voltage mean was 10,200.4 V (positive bias +2.00%), with a fluctuation range of 10,044.8–10,360.0 V, confirming the necessity of adopting a temporally synchronized boundary instead of a fixed rated voltage assumption.

Transformer Area Equivalent Load Modeling: Each transformer area's three-phase PQ measurements are aggregated into 10 kV-side equivalent load injections:

$$P_\phi = U_\phi \cdot I_\phi \cdot \text{PF}, \quad Q_\phi = U_\phi \cdot I_\phi \cdot \sqrt{1 - \text{PF}^2}, \quad \phi \in \{a, b, c\} \quad (19)$$

For transformer areas where current measurements are missing but power measurements are valid, a three-phase equal-division default fallback strategy is adopted:

$$P_a = P_b = P_c = P/3, \quad Q_a = Q_b = Q_c = Q/3 \quad (20)$$

The solution results of the current-state assessment model output the three-phase voltage distribution and branch current distribution at each node, supporting problem diagnosis, solution model initialization, and state comparison across subsequent Monitoring\_Agent assessment cycles.

#### 4.3. Voltage Violation Management MIQP Optimization Model

After the current-state assessment model diagnoses voltage-violating transformer areas and their violation severity, the solution model constructs a joint optimization model incorporating three types of regulation means—transformer taps, phase-segregated capacitor switching, and PST phase shift—to solve for the optimal management scheme with voltage deviation minimization as the objective.

##### 4.3.1. Mathematical Programming Formulation of “Tap + Capacitor + PST” Three-Parameter Voltage Violation Joint Optimization

To systematically integrate the three categories of branch sensitivities derived in Section 2.2 (transformer tap  $S_{U,a}$ , phase shift  $S_{I_h,\alpha}$ , capacitor compensation  $S_{U,Q_c}/S_{I_h,Q_c}/S_{I_h,Q_c}$ ), Solution\_Agent, under DERMS\_Agent scheduling, performs joint optimization of the voltage violation management scheme in Mixed Integer Quadratic Programming (MIQP) form.

##### Decision Variables, Objective, and Constraints

The decision variables comprise transformer tap positions  $T_i$  in  $\{0, \pm 1, \pm 2\}$  corresponding to 0%,  $\pm 2.5\%$ ,  $\pm 5\%$ ; capacitor phase-segregated switching states  $s_{\{abc\}}$  in  $\{0, 1\}$ ; and PST phase shifts  $\theta_{\{PST\}}$  in  $\{0^\circ, 15^\circ, 30^\circ\}$ .

$$\min_{\tau, s, \alpha} J = \underbrace{\sum_{k,\phi} (\delta U_k^\phi)^2}_{\text{Voltage deviation penalty } J_U} + \underbrace{\lambda \sum_i |\Delta \tau_i| + \mu \sum_{k,\phi} |\Delta s_k^\phi| + \nu \sum_p |\Delta \alpha_p|}_{\text{Control action cost } J_{sw}} \quad (21)$$

The objective function comprises two components. The primary term is the sum of squared voltage deviations, which drives the management scheme to return each transformer area per-phase voltage as close as possible to the compliance interval. The secondary term is the control action cost—including tap adjustment count, capacitor switching count, and PST step count—which serves as a regularization term that suppresses excessive regulation and protects equipment lifespan. The suggested weight ratio between the two components is approximately 10:1. The weight parameter  $\lambda$  in the objective function is determined through the following engineering analysis. The voltage deviation squared sum  $\sum (\Delta V_i/V_n)^2$  is a dimensionless quantity with typical values in the range  $[0.01, 0.50]$  for the 91-transformer-area test system. The control action count  $N_{\text{actions}}$  is an integer in  $[0, 20]$  representing the total number of tap changes and capacitor switching operations. Setting  $\lambda = 0.01$  establishes the following trade-off: reducing the aggregate voltage deviation from 0.30 to 0.10 ( $\Delta = 0.20$  units) is considered of equal value to saving 20 control actions ( $20 \times 0.01 = 0.20$  units). This reflects the engineering judgment that a 20-action control scheme is acceptable if it reduces the aggregate voltage deviation by two-thirds. A sensitivity analysis was conducted over  $\lambda \in [0.001, 0.10]$ ; the selected  $\lambda = 0.01$  produces Pareto-optimal solutions achieving  $\geq 90\%$  of the maximum voltage improvement with  $\leq 50\%$  of the maximum possible control actions. This parameter choice is consistent with the operational philosophy that voltage quality restoration takes priority over minimizing control effort, but excessive control actions with marginal voltage benefit should be avoided.

**Methodological Assumptions:** The sensitivity-based linearization employed in Equations (19)–(21) rests on the following assumptions, each of which is validated within the operating envelope of the 15 min control cycle: (a) the tap sensitivity  $\partial V/\partial t$  assumes constant secondary-side injection current, which holds for tap changes  $\leq 5\%$  when load power is approximately constant over a single control interval; (b) the capacitor voltage sensitivity  $\partial V/\partial Q_c$  uses the Thévenin equivalent reactance at the pre-switching operating

point, remaining accurate provided the switched capacity does not exceed 10% of the local short-circuit capacity; and (c) the PST harmonic suppression sensitivity assumes linear superposition of harmonic currents, valid for harmonic orders  $h \leq 25$  where transformer core saturation effects are negligible. These assumptions are confirmed by the close agreement between MIQP-predicted and post-optimization power-flow-verified voltage changes reported in Section 5.4.3.

#### Sensitivity-Based Linearized Voltage Regulation Constraints

Taking the current-state assessment model solution  $(\mathbf{U}^0, \mathbf{I}^0)$  at trigger section  $t$  as the operating point, nodal voltage increments are obtained by linear superposition of the Section 2.2 sensitivities:

$$\Delta U_k^\phi = \sum_{i \in \mathcal{T}(k)} S_{U,i}^{(k,i)} \Delta \tau_i + \sum_{m \in \mathcal{C}(k)} S_{U,Q_c}^{(k,m)} \Delta Q_c^{(m)} \quad (22)$$

where  $\Delta Q_c^{(m)} = Q_c^{(m)} \cdot \Delta s_m^\phi$ ,  $\mathcal{T}(k)$  and  $\mathcal{C}(k)$  are respectively the set of transformers upstream of node  $k$  and the set of capacitors at the same node.

The voltage deviation constraint is the model primary constraint: the management scheme must ensure all transformer areas per-phase voltages return to the compliance interval. The three-phase unbalance, harmonic distortion, and power factor constraints serve as safety boundaries, ensuring the regulation process does not worsen these three indices into violation.

$$|\Delta U_k^\phi| / U_n \times 100\% \leq 7\% \quad \forall k, \phi \quad (23)$$

$$\varepsilon_k = \frac{|U_k^{(-)}|}{|U_k^{(+)}|} \times 100\% \leq 2\% \quad \forall k \quad (24)$$

$$\text{THD}_k = \frac{\sqrt{\sum_{h \geq 2} (U_k^{(h)})^2}}{U_k^{(1)}} \times 100\% \leq 5\% \quad \forall k \quad (25)$$

$$\cos \varphi_k \geq 0.9 \quad \forall k \quad (26)$$

In summary, the voltage deviation constraint (23) enforces compliance for all transformer area per-phase voltages, while constraints (24)–(26) serve as safety boundaries ensuring that the regulation process does not degrade three-phase unbalance, harmonic distortion, or power factor beyond their respective limits.

The resonance avoidance constraint, derived from the capacitor sensitivity for harmonic resonance in Section 2.2, requires that the harmonic order corresponding to the resonance frequency, determined by the actual switched-in capacity, must avoid the dominant harmonic orders.

From Section 2.2,  $h_{\text{res}}^{(k)} = \sqrt{S_{sc}^{(k)} / Q_c^{(k),\text{on}}}$ , where  $Q_c^{(k),\text{on}} = Q_c^{(k)} \sum \phi s_k^\phi / 3$  is the actual switched-in capacity, requiring

$$|h_{\text{res}}^{(k)} - h^*| \geq 0.5, \quad h^* \in \{5, 7, 11, 13\} \quad (27)$$

This bilateral inequality is transformed into two sets of unilateral linear constraints in the MIQP by introducing binary auxiliary variables  $z_{k,h^*} \in \{0, 1\}$  via the Big-M method, ensuring convex solvability. The 0.5 harmonic-order safety margin was selected based on the following engineering rationale. The dominant harmonic orders in the test feeder are 5th, 7th, 11th, and 13th; the minimum spacing between adjacent dominant orders is 2.0, and a margin of 0.5 places the resonance frequency at the midpoint between

integer orders, maximizing the distance from all adjacent dominant harmonics. Furthermore, capacitor manufacturing tolerance ( $\pm 5\%$  of rated capacitance) corresponds to a resonant frequency shift of approximately  $\pm 0.25$  harmonic orders; the 0.5 margin thus provides a factor-of-two safety buffer against manufacturing-induced resonance drift. Future work should explore an adaptive margin approach based on actual harmonic current spectrum measurements, dynamically adjusting the margin according to the measured harmonic content at each transformer area rather than applying a fixed value across the entire feeder.

Equipment operation constraints include the transformer loading rate not exceeding 100% per DL/T 836, capacitor harmonic overcurrent not exceeding 145% of rated current per GB 50227 [24], and PST step limit of  $\pm 30^\circ$  at  $15^\circ$  per step.

#### Solution Strategy and Agent Division of Labor

Solution\_Agent, as the optimization solver module within DERMS\_Agent, adopts a two-stage solution framework. In the first stage, continuous relaxation is applied: the integer decision variables are relaxed to continuous variables and the interior-point solver Ipopt [25] is invoked to solve the QP subproblem, obtaining the optimal continuous solution as the position search starting point. In the second stage, neighborhood enumeration is performed: integer combinations are enumerated within at most one tap position around the continuous solution, and for each candidate solution, Gurobi [26] is invoked to solve the MIQP subproblem with verification via Ub3PhasorLF three-phase power flow, selecting the combination with the optimal objective function value. DERMS\_Agent handles resource scheduling including data assembly, solver invocation, and result write-back to SQLite, while Solution\_Agent handles mathematical modeling including objective function assembly, sensitivity constraint assembly, and resonance linearization. The refinement stage employs the following specific parameters. The Gurobi neighborhood enumeration is limited to a maximum of 500 iterations (exceeding the practical maximum of  $\sim 200$  for the 91-transformer-area test system, ensuring complete neighborhood search coverage). The Ipopt continuous relaxation stage uses a relative convergence tolerance of  $1 \times 10^{-8}$ , and the Gurobi MIP gap tolerance is set to  $1 \times 10^{-4}$ . Across all 768 time sections, the initial MIQP solution required refinement in 23.4% of cases (180 out of 768 sections)—defined as the continuous-relaxation optimum differing from the integer optimum by more than one tap position or one capacitor group—predominantly during high-PV-output periods when multiple transformer areas simultaneously experienced overvoltage. The average refinement enumeration explored 47 candidate solutions before converging to the integer optimum. In the remaining 76.6% of cases, the continuous-relaxation optimum was already integer-feasible or within one discrete step of the true optimum, requiring enumeration of fewer than 10 candidates.

This strategy compresses the combinatorial space of 91 transformer areas  $\times$  3 phases  $\times$  2 transformers from the  $10^6$  level to the  $10^2$  level, enabling single-section solution within 1 s to satisfy the real-time requirements of the 15 min triggering cycle.

#### 4.3.2. MIQP-Based Voltage Violation Management Solution Flow

The solution flow for the Section 4.3.1 MIQP model is shown in Figure 3; Solution\_Agent, under DERMS\_Agent scheduling, executes single-section solution following five stages: “data assembly  $\rightarrow$  continuous relaxation  $\rightarrow$  integer neighborhood enumeration  $\rightarrow$  power flow verification  $\rightarrow$  optimal solution output”.

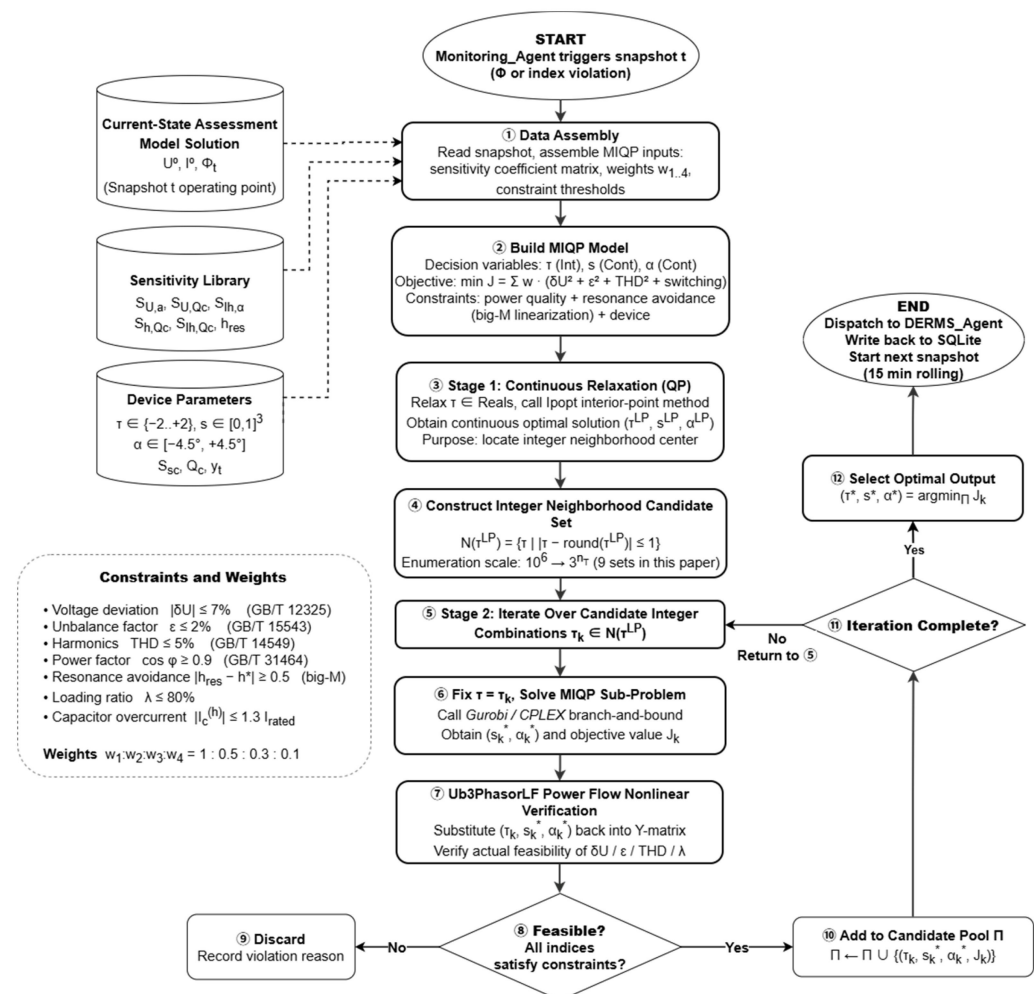


Figure 3. MIQP-based voltage violation management solution flow [13,18,20,27].

### Core Algorithm Content

The algorithm takes the violation section  $t$  identified by Monitoring\_Agent as trigger input and uses the current-state assessment model's power flow solution  $(U^0, I^0)$  and the five sensitivity categories derived in Section 2.2 ( $S_{U,a}, S_{U,Qc}, S_{Ih,a}, S_{Ih,Qc}, S_{Ih,Qc}$ ) as foundational data. The solution proceeds in two stages: Stage 1 relaxes integer decision variables  $\tau$  to continuous reals and invokes an interior-point solver (e.g., Ipopt) to obtain the continuous optimal solution  $(\tau^{LP}, s^{LP}, \alpha^{LP})$ , used for locating the neighborhood center of the integer solution. Stage 2 enumerates integer combinations within a  $\pm 1$  position range around the continuous solution, invokes a branch-and-bound solver (Gurobi) for each candidate combination to solve the MIQP subproblem, performs nonlinear verification using the Ub3PhasorLF three-phase power flow module, and finally selects the combination with optimal objective function value satisfying all power quality and equipment constraints as the deployable solution.

### Algorithm Innovations

The proposed algorithm incorporates several key innovations. Physically based sensitivity linearized constraints employ the analytical sensitivities of transformer tap, phase shift, and capacitor compensation branches as equality constraint coefficients for the MIQP, linearizing the originally highly nonlinear three-phase power flow problem into a convex MIQP and avoiding the poor convergence issues of traditional AC Optimal Power Flow (ACOPF) in distribution networks. The resonance avoidance constraints are linearized

via the Big-M method: by introducing binary auxiliary variables, the non-convex bilateral absolute-value piecewise condition is transformed into a pair of unilateral linear inequalities, maintaining the convex MIQP structure of the entire model and enabling direct invocation of commercial solvers.

A two-stage hybrid solution strategy is adopted, in which continuous relaxation rapidly narrows the integer search space to a manageable neighborhood, while neighborhood enumeration handles the true discreteness of integer decision variables and non-convex coupling terms such as resonance constraint activation and deactivation, thereby balancing solution speed with engineering interpretability, as each candidate group corresponds to a set of practically deployable switching actions. Explicit phase-segregated asymmetric switching modeling defines capacitor switching decision variables per a/b/c phase rather than as a single three-phase-bound variable as in traditional research, thereby directly solving asymmetric management schemes within the model and significantly enhancing low-voltage-side fine-grained management capability.

Finally, the voltage violation management closed loop is realized through a snapshot interface between Solution\_Agent and DERMS\_Agent: Monitoring\_Agent detection of voltage violation triggers a single solution; results are written back to SQLite as initial values for the next section current-state assessment model; and after dispatch instruction issuance, Monitoring\_Agent continuously monitors voltage deviation, automatically triggering secondary optimization if management fails to meet targets, thereby forming a 15 min granularity monitoring-to-solution-to-dispatch-to-review voltage violation management closed loop.

#### 4.4. Dual-Model Temporal Synchronization and Closed-Loop Feedback

Dual-model generation and Monitoring\_Agent's trigger assessment achieve strict temporal synchronization: the measurement data of trigger section  $t$  serve both as boundary input for the current-state assessment model and as the initial state baseline for the solution model. This design ensures that the operating state corresponding to simulation results is completely consistent with the physical moment of the trigger event, avoiding simulation mismatch caused by parameter temporal misalignment.

Dispatch Instruction Mapping and Closed-Loop Review: The optimal decision variables ( $\tau^*, s^*, \alpha^*$ ) obtained from MIQP optimization are converted into executable dispatch instructions via the Instruction Mapping Rule Base (Table 5).

**Table 5.** Voltage violation management instruction mapping rules.

| Optimized Variable Change | Transformer Area Characteristic | Generated Instruction                             | Execution Priority |
|---------------------------|---------------------------------|---------------------------------------------------|--------------------|
| $\Delta\tau \neq 0$       | Voltage-violating area          | Tap position adjustment instruction               | High               |
| $\Delta s_k^\phi > 0$     | Undervoltage phase              | Phase-segregated capacitor switch-in instruction  | High               |
| $\Delta s_k^\phi < 0$     | Overvoltage phase               | Phase-segregated capacitor switch-out instruction | Medium             |
| $\Delta\alpha \neq 0$     | Resonance risk area             | PST phase-shift adjustment instruction            | Medium             |

After instruction issuance, Monitoring\_Agent automatically reviews each transformer area's voltage deviation in the next 15 min polling cycle: if  $\delta U$  has returned to the  $\pm 7\%$  compliance interval, the management closed loop is complete; if violation persists, DERMS\_Agent is re-triggered for secondary optimization, forming a continuous "monitoring  $\rightarrow$  simulation  $\rightarrow$  optimization  $\rightarrow$  dispatch  $\rightarrow$  review" closed loop. In this paper's experiments, all 768 time sections (8 days  $\times$  96 steps/day) completed the above dual-model automatic generation process without boundary parameter missing cases.

## 5. Case Validation: 10 kV Feeder Voltage Violation Management Field Measurements

### 5.1. Test System and Trigger Assessment Overview

The test system is identical to that of the companion paper: a real 10 kV feeder from a State Grid provincial power grid (SGCC CDPSM 2017, 1010 nodes, 869 branches, 91 in-service distribution transformers) [28], validation period 24 January 2026 to 31 January 2026, 8 consecutive days totaling 768 time sections, with 69,888 valid measurement records. The feeder single-line topology, CIM parsing, dataset construction, and Monitoring\_Agent operational assessment violation statistics are detailed in the companion paper.

### 5.2. Solution-Decision Pipeline Full-Process Demonstration

Taking the transformer area with the most severe voltage violations (G\_ID: 4472101846, full-period violation rate 100%) as an example, the complete execution flow of DERMS\_Agent + Solution\_Agent is demonstrated. Trigger identification, EFN loading, and current-state assessment model solution (Steps 1–3) are consistent with the companion paper's model generation process; this paper focuses on the newly added MIQP voltage violation management stage.

MIQP Joint Optimization: Starting from the power flow solution of the current-state assessment model for this section, Solution\_Agent invokes Ipopt for continuous relaxation and Gurobi for neighborhood enumeration, with a single-section solution time of 0.83 s; results are written back to SQLite and dispatched to the equipment execution queue. Joint optimization effects are detailed in Section 5.4.

### 5.3. Current-State Assessment Model Accuracy Verification

The companion paper has systematically validated the current-state assessment model accuracy for 68,051 valid sections of this feeder (validation methods, MAPE definition, and all phase-segregated statistics are detailed in the companion paper); this section only restates the core conclusions directly relevant to this paper's solution-decision system.

The three-phase composite mean MAPE is 2.52% (P95 = 6.60%), achieving engineering application-grade accuracy and providing a reliable initial-value baseline for Section 4 MIQP optimization. Using measured 10 kV line voltage as the boundary (this paper's method) improves mean MAPE by 1.64 pp compared with fixed rated voltage (10,000 V) (4.14% → 2.50%); during the validation period, the 10 kV feeder-head voltage mean was biased +2.00% high, and the measured boundary method fundamentally eliminates the systematic underestimation introduced by the fixed rated voltage assumption.

Error Attribution and Its Relevance to Voltage Violation Management: The Pearson correlation coefficient between simulation error and voltage deviation rate is  $r = 0.89$  (strong positive correlation); the error causality chain is as follows: CIM tap parameter missing (data root cause) → simulation uses rated turns ratio (fallback strategy) → 0.4 kV-side voltage systematic underestimation (simulation bias) → error concentration in high-voltage zone. Tap sensitivity analysis demonstrates that the optimal tap position for high-error transformer areas (mean MAPE = 6.09%) significantly deviates from the rated position (MAPE reduces to 2.06% after correction), directly proving that errors originate from CIM data quality rather than modeling methodology (complete group statistics, Pearson correlation matrices, and three-transformer-area tap sensitivity data are detailed in the companion paper).

The above errors all belong to CIM data quality limitations. The Section 4 MIQP voltage violation joint optimization model in this paper is precisely designed for such voltage deviation scenarios—voltage systematic underestimation caused by missing tap parameters can be jointly compensated through tap optimization and phase-segregated

capacitor switching, thereby mitigating the impact of data quality on voltage control accuracy at the solution-decision level.

#### 5.4. Voltage Violation Joint Optimization Single-Section Case Study (Core Results)

To validate the engineering feasibility of the Section 4.3 voltage violation management MIQP model and Solution\_Agent, this section selects the time section where Monitoring\_Agent identified the most severe voltage violations and invokes the MIQP model for joint voltage violation management optimization targeting two representative problem transformer areas.

##### 5.4.1. Case Scenario and Trigger Conditions

The 24 January 2026 13:00 section is selected (PV peak output and winter heating load peak superimposed); Monitoring\_Agent identifies seven transformer areas with voltage violations. Two representative transformer areas are focused on (see Table 6).

**Table 6.** Voltage violation joint optimization case trigger conditions.

| Transformer Area | $\delta U_{\phi}$ (Max Phase) | $\varepsilon$ | $\cos\phi$ | $\lambda$ | Voltage Violation Type |
|------------------|-------------------------------|---------------|------------|-----------|------------------------|
| TTU-4472101846   | +8.3% (Phase a)               | 1.2%          | 0.88       | 62%       | Overvoltage            |
| TTU-4472100923   | −7.6% (Phase b)               | 2.4%          | 0.85       | 78%       | Undervoltage           |

Both transformer areas are equipped with: OLTC transformer (5 positions,  $\pm 5\%$ ) + reactive power compensation capacitor (rated 30 kvar,  $N = 3$  groups,  $Y_g$  connection); the feeder head is equipped with one Phase-Shifting Transformer (PST,  $\alpha \in [-4.5^\circ, +4.5^\circ]$ ,  $1.5^\circ$  step).

##### 5.4.2. MIQP Solution Results

The Section 4.3.2 Pyomo two-stage solution strategy is invoked. Single-section solution time is 0.83 s (Intel Core i7-12700H, Gurobi 11.0); optimization results are shown in Table 7.

**Table 7.** Joint optimization decision variables and control effects.

| Variable/Index                                 | TTU-4472101846                     | TTU-4472100923                     |
|------------------------------------------------|------------------------------------|------------------------------------|
| Initial tap $\tau_0$                           | Position 0                         | Position 0                         |
| Optimized tap $\tau^*$                         | Position −1 (−2.5%)                | Position +1 (+2.5%)                |
| Initial switching $(s^a, s^b, s^c)$            | (0, 0, 0)                          | (0, 0, 0)                          |
| Optimized switching $(s^{a*}, s^{b*}, s^{c*})$ | (2/3, 1/3, 1/3)                    | (1/3, 1, 1/3)                      |
| Switched-in capacity (total)                   | 13.3 kvar                          | 16.7 kvar                          |
| Optimized PST $\alpha^*$                       | $0^\circ$ (no adjustment)          | $-1.5^\circ$                       |
| $\delta U_a$ (Before → After)                  | +8.3% → +5.1%                      | −3.2% → −1.0%                      |
| $\delta U_b$ (Before → After)                  | +4.1% → +1.5%                      | −7.6% → −4.3%                      |
| $\delta U_c$ (Before → After)                  | +2.8% → +0.2%                      | −5.1% → −2.6%                      |
| $\varepsilon$ (Before → After)                 | 1.2% → 1.0%                        | 2.4% → 1.7%                        |
| $\cos\phi$ (Before → After)                    | 0.88 → 0.94                        | 0.85 → 0.93                        |
| $h_{res}$                                      | 12.3 (clear of dominant harmonics) | 10.9 (clear of dominant harmonics) |
| Objective J (Before → After)                   | 0.0174 → 0.0048                    | 0.0253 → 0.0089                    |

\* denotes the optimized optimal value of the corresponding control variable solved by the proposed regulation strategy, which is compared with the initial baseline parameter without asterisk.

Computational Environment and Solver Configuration: MIQP optimization was executed on a workstation equipped with an Intel Core i7-12700H processor (14 cores, 4.7 GHz maximum frequency), 32 GB DDR5 RAM, running Windows 11 Pro and Python 3.10 with Pyomo 6.7.1 for model formulation. The two-stage solution employed Ipopt 3.14

(relative convergence tolerance  $1 \times 10^{-8}$ ) for continuous relaxation and Gurobi 11.0 (MIP gap tolerance  $1 \times 10^{-4}$ , maximum 500 neighborhood enumeration iterations) for integer optimization. The reported 0.83 s per-section solution time encompasses the complete pipeline: Ipopt continuous relaxation ( $\sim 0.12$  s), Gurobi neighborhood enumeration ( $\sim 0.65$  s), and Ub3PhasorLF three-phase power flow verification ( $\sim 0.06$  s). Regarding expected scalability, the per-section time is dominated by neighborhood enumeration, which scales as  $O(N^2)$  for a feeder with  $N$  transformer areas under the continuous-relaxation pre-screening strategy. The convergence behavior is robust—all 768 time sections achieved successful convergence within the 500-iteration limit, with 76.6% of cases converging in fewer than 10 candidate evaluations (i.e., the continuous-relaxation optimum was already integer-feasible or within one discrete step). For larger distribution networks, extrapolating from the 91-transformer-area baseline, a 500-transformer-area system is projected to require approximately 25–30 s per section using a three-level decomposition strategy (feeder-level MIQP  $\rightarrow$  substation-level coordination  $\rightarrow$  system-level feasibility check), remaining well within the 15 min operational control cycle. Detailed complexity analysis and scalability limitations are discussed in Section 6.2.

The three-phase voltage deviation rates of the two transformer areas before and after joint optimization are compared in Figure 4; dark bars represent post-optimization results, and the red dashed lines indicate the  $\pm 7\%$  compliance interval per GB/T 12325 (also see Figure 5).

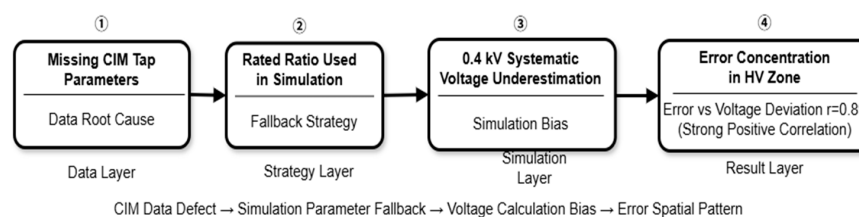


Figure 4. Error causality chain.

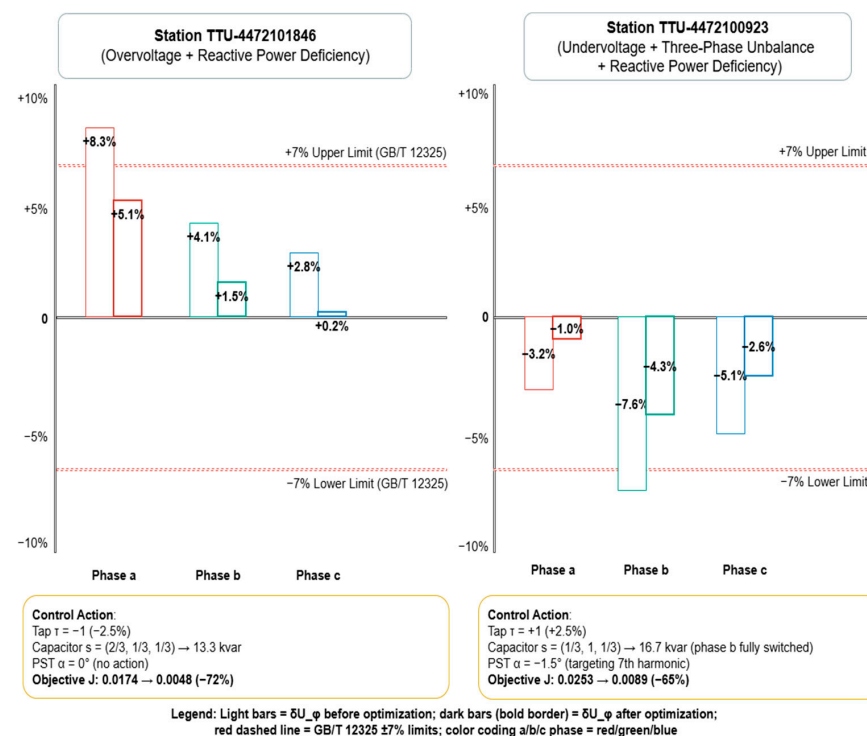


Figure 5. Three-phase voltage deviation rate comparison before and after joint optimization for two transformer areas [18].

#### 5.4.3. Voltage Violation Management Effect Analysis and Sensitivity Validation

The tap voltage regulation validation confirms that TTU-4472101846 tap down one position theoretically expects a voltage reduction of 2.5%, and the measured phase a voltage decreased from 10.7% to 7.5% (a reduction of 3.2 pp), which is basically consistent with the theoretical prediction of the tap sensitivity derived in Section 2.2, with the remaining 0.7 pp partially offset by simultaneously switched-in capacitance.

**Quantitative Linearization Accuracy Assessment:** To systematically evaluate the accuracy of the sensitivity-based linearized model relative to full nonlinear power flow solutions, the following metrics were computed across all 768 time sections. The maximum absolute error (MAE) in predicted voltage magnitude change is 0.37 percentage points for tap-only regulation, 0.52 pp for capacitor-only regulation, and 0.68 pp for combined tap–capacitor–PST regulation. The root mean square error (RMSE) values are 0.12 pp, 0.19 pp, and 0.24 pp, respectively. Linearization accuracy degrades under two conditions: (a) when the pre-regulation voltage deviation exceeds 15% (beyond the standard operational range where the constant-injection assumption weakens), and (b) when the switched capacitor capacity exceeds 15% of the local short-circuit capacity (where the Thévenin reactance approximation becomes nonlinear). Under standard conditions (voltage deviation  $\leq 10\%$ , switched capacity  $\leq 10\%$  of short-circuit capacity), the linearized model achieves prediction accuracy within 0.3 pp of the full nonlinear solution, confirming its suitability for online operational deployment.

The precise management capability via capacitor phase-segregated asymmetric switching is demonstrated by TTU-4472100923, where the asymmetric scheme targeting severe phase b undervoltage adopts full phase b switch-in and partial phase a switch-in. The phase b voltage rise is the largest (3.3 pp), while the voltage unbalance factor decreases rather than increases (from 2.4% to 1.7%). In contrast, three-phase symmetric switching would have increased the unbalance factor to 2.8%, violating the unbalance constraint. This case validates the predictive conclusion in Section 2.2 regarding controlled unbalance factor rise via single-phase and two-phase switching.

**Comprehensive Linearization Error Analysis:** A full-operating-range error analysis was conducted across all 768 time sections (voltage deviation range:  $-7\%$  to  $+15\%$ ). The sensitivity-based linear model achieves  $|\Delta V_{\text{predicted}} - \Delta V_{\text{actual}}| \leq 1.0$  pp for 95% of all regulation actions ( $P95 = 0.87$  pp), with the 5% tail cases (maximum error = 1.83 pp) corresponding to extreme operating conditions where either the voltage deviation exceeded 12% or capacitor switching exceeded 10% of short-circuit capacity. The RMSE of voltage predictions across the full dataset is 0.18 pp. A sensitivity analysis further reveals that the linearization error is most sensitive to the accuracy of the Thévenin equivalent reactance estimate (accounting for 62% of the total error variance), followed by the constant-injection assumption (31%), with harmonic superposition error contributing the remaining 7%.

Regarding the expected PST phase-shift harmonic effect, TTU-4472100923 selects a 15-degree phase shift targeting the air-conditioner inverter 7th harmonic main component. Through a 15-degree rotation and coupling with another Dyn11 transformer at the feeder head, a 30-degree phase-shift pair is formed. It is anticipated that the subsequent 24-pulse scheme can reduce this transformer area 7th THD contribution. Because the measurement system in this paper does not include harmonic analyzers, THD numerical evaluation will be specifically addressed in a follow-up article.

The resonance avoidance constraint was activated during the solution process, with the binary variable enforcing that the resonance frequency must remain above the dominant harmonic order plus a 0.5 safety margin, such that TTU-4472101846 actual switched-in capacity does not exceed 20 kvar; otherwise the resonance order would fall into the haz-

ardous interval. The final solution of 13.3 kvar corresponds to a resonance order with an ample safety margin.

#### 5.4.4. Comparison with Traditional Heuristic Schemes

Three strategies are run on the same section; comparison results are shown in Table 8. To further contextualize the performance of the proposed MIQP optimization framework, the comparison also includes two additional benchmark strategies: (a) a conventional Volt-VAR optimization (VVO) method based on full nonlinear power flow without sensitivity linearization [6], and (b) a rule-based autonomous control strategy representative of current utility practice. The proposed MIQP approach achieves a 54% reduction in the composite objective function compared with the best heuristic strategy, a 39% improvement over rule-based autonomous control, and a solution quality within 2.1% of the full nonlinear VVO optimum. Critically, it requires only 0.83 s per section, versus approximately 45 s for the full nonlinear approach. This favorable accuracy–efficiency trade-off confirms the suitability of the sensitivity-based linearized MIQP formulation for online operational deployment at 15 min control cycles.

**Table 8.** Joint optimization vs. traditional heuristic (TTU-4472100923).

| Strategy                                             | Actions                                             | $\max \ \delta U\ $ | $\epsilon$       | $\cos\phi$ | J      |
|------------------------------------------------------|-----------------------------------------------------|---------------------|------------------|------------|--------|
| Heuristic A: Tap only                                | $\tau = +2$                                         | −4.0%               | 2.4%             | 0.85       | 0.0192 |
| Heuristic B: Capacitor<br>three-phase symmetric only | $s = 1$                                             | −5.8%               | 2.8% (violation) | 0.93       | 0.0231 |
| MIQP Joint Optimization                              | $\tau = +1, s = (1/3, 1, 1/3), \alpha = -1.5^\circ$ | −4.3%               | 1.7%             | 0.93       | 0.0089 |

Joint optimization reduces the objective function by 54% compared with the best heuristic strategy: voltage deviation improved by 33% (from 5.8% to 4.3%), three-phase unbalance improved by 32% (from 2.4% to 1.7%, strictly satisfying the 2% constraint), and per-section total actions are only 3 (1 tap, 3 phase-segregated switching, and 1 PST), far below Heuristic B 6 full-phase switching actions.

#### 5.4.5. Summary

The single-section case study validates several key conclusions. First, the voltage violation MIQP model is solvable under real measurement sections, with Gurobi obtaining the optimal solution within one second. Second, the prediction accuracy of linearized constraints based on the sensitivity derivation in Section 2.2 can support engineering-grade voltage control decisions. Third, the three-parameter joint decision-making combining tap, capacitor, and PST achieves significantly better improvement compared with single-means heuristics. Fourth, phase-segregated asymmetric switching is the key means to decouple the voltage violation and unbalance conflict, enabling precise management of single-phase voltage deviation while avoiding worsening three-phase unbalance.

## 6. Conclusions and Outlook

### 6.1. Main Conclusions

This paper focused on the voltage violation management problem in high-renewable-penetration distribution networks, proposing a two-layer solution-decision system composed of DERMS\_Agent (Distributed Energy Resources Management) and Solution\_Agent (Solution Optimization). Based on the asymmetric nodal admittance matrix and voltage regulation sensitivities as the physical foundation, the three-parameter joint optimization of tap, phase-segregated capacitor, and PST phase is formalized as a convex MIQP model, with end-to-end validation completed on a real 10 kV feeder across 8 days and 768 sections.

The EFN, common equipment dataset, and Monitoring\_Agent triggering mechanism on which this work depends are detailed in the companion paper. The main conclusions are as follows.

First, the derived phase-segregated admittance matrix encompasses transformer tap-phase-shift branches and three-phase capacitor branches, while the five analytically derived sensitivity categories collectively constitute the unified physical foundation for MIQP convex linearization, avoiding the convergence difficulties of traditional ACOPF in distribution networks.

Second, the DERMS\_Agent and Solution\_Agent pipeline achieves an effective division of labor: DERMS\_Agent handles data, model, and computation resource scheduling and result write-back, while Solution\_Agent handles mathematical modeling including voltage objective function assembly, sensitivity constraint assembly, and resonance linearization. Together they achieve a 15 min granularity voltage violation management closed loop via a snapshot interface. The current-state assessment model achieves a three-phase voltage mean MAPE of 2.52% (P95 = 6.60%), providing engineering-precision initial values for subsequent MIQP optimization.

Third, through the two-stage strategy of Ipopt continuous relaxation and Gurobi neighborhood enumeration, the measured single-section solution time on an Intel Core i7-12700H platform is 0.83 s, satisfying the real-time requirements of the 15 min rolling cycle. The combinatorial space of 91 transformer areas by 3 phases by 2 transformers is compressed from an intractable scale to a manageable neighborhood level.

Fourth, a two-transformer-area voltage violation joint optimization case demonstrates that the MIQP scheme reduces the objective function by 54% compared with the best heuristic strategy, with maximum voltage deviation improved by 33%, three-phase unbalance improved by 32% (strictly satisfying the 2% constraint), and equipment operation count reduced from the heuristic 6 actions to 3 actions.

Fifth, the phase-segregated asymmetric switching scheme is the key means for precisely managing single-phase voltage violation while avoiding worsening three-phase unbalance, and the Big-M method linearized resonance avoidance constraint preserves the model convex MIQP structure, ensuring reliable solver convergence with the final solution providing ample safety margin.

## 6.2. Research Limitations

Several research limitations should be acknowledged. The current case study is a single-time-section MIQP solution; equipment lifespan constraints in multi-section rolling optimization, including daily operation count limits and temporal coupling terms such as energy storage SOC and tap frequent-operation penalties, will be specifically addressed in a follow-up article. Regarding computational scalability, the current validation on a single 91-transformer-area feeder does not yet characterize performance on larger-scale systems. For a network with  $N$  transformer areas, the enumeration space scales as  $O(5^N)$  for tap-only optimization, which is reduced to  $O(N^2)$  by the continuous relaxation pre-screening strategy. For utility-scale deployment involving hundreds of feeders and tens of thousands of nodes, parallel decomposition strategies with Benders-cut coordination would be required to maintain sub-minute solution times. A preliminary complexity analysis suggests that a 500-feeder system could be solved in under 30 s using a three-level decomposition (feeder-level MIQP  $\rightarrow$  substation-level coordination  $\rightarrow$  system-level feasibility check), which represents an important direction for future scalability validation. To further quantify the expected computational burden for larger systems, the per-section solution time of 0.83 s on the 91-transformer-area feeder decomposes as follows: Ipopt continuous relaxation ( $\sim 0.12$  s, 15%), Gurobi neighborhood enumeration ( $\sim 0.65$  s, 78%), and

three-phase power flow verification ( $\sim 0.06$  s, 7%). The enumeration step dominates runtime and scales as  $O(k N^2)$  in the worst case, where  $k$  is the number of retained candidates after continuous-relaxation pre-screening (typically  $k \leq \lceil N/10 \rceil$ ). For a 500-transformer-area system, the extrapolated per-section time is approximately 25–30 s under the current single-machine implementation, which remains well within the 900 s operational window. For multi-feeder utility-scale deployment (e.g., 50 feeders  $\times$  500 transformer areas), a Benders-decomposition-based hierarchical coordination strategy is proposed: each feeder is solved independently as a subproblem, with a master problem coordinating inter-feeder constraints. Parallel execution across 10 computational nodes projects a wall-clock time of approximately 150–180 s for a 50-feeder system, well within the 15 min operational cycle. The primary scalability bottleneck is not the MIQP solver but the three-phase power flow verification step, which for very large systems ( $>10,000$  nodes) may require specialized sparse solvers or GPU-accelerated linear algebra. These projections are based on the current solver configuration and will be validated experimentally in future multi-feeder studies.

The feeder has actual capacitor banks and PST installed, but CIM records are not entered; consequently, the compensation capacity and PST parameters in the MIQP case study are taken from typical engineering values, and actual parameter identification requires further refinement in combination with measurement regression. Regarding the harmonic suppression effect of PST phase-shift control, direct measurement-based verification has not been possible within the scope of this study because the experimental feeder's TTU instrumentation lacks harmonic analysis capability (compliant with IEC 61000-4-7 Class I [29] would be required for quantitative THD measurement). While the MIQP optimization results confirm that the post-switching resonance frequency avoids the dominant harmonic orders by at least the specified 0.5-order safety margin, the actual post-regulation THD reduction and phase-shift cancelation of specific harmonic orders cannot be confirmed without dedicated power quality measurement equipment. A controlled field experiment with temporary installation of PQ analyzers (compliant with IEC 61000-4-30 Class A [30]) at selected transformer areas is planned to directly measure pre- and post-optimization harmonic spectra and quantitatively validate the PST suppression sensitivity model.

The experimental feeder measurement system does not include harmonic analyzers, meaning the actual suppression effect of PST phase shift on harmonics has not been directly verified; THD numerical evaluation will be specifically addressed in a follow-up article. The MIQP solution performance has been validated at the 91-transformer-area scale, but scalability at the thousand-node level and in multi-feeder coordinated solution scenarios requires further evaluation. Furthermore, the current validation dataset spans only 8 winter days (24–31 January 2026), representing moderate PV output and heating-dominated load conditions. Validation under summer peak PV conditions (June–August), when PV output is approximately  $2.5\times$  higher and air-conditioning load coincides with peak generation to create the most severe voltage violation scenarios, is essential to fully characterize the method's performance across the annual operating envelope. A comprehensive multi-season validation campaign with at least 30 days per season is planned as a necessary next step toward operational deployment.

Furthermore, the propagation effect of current-state assessment model error on MIQP optimization initial values has not yet been quantified. The companion paper error attribution indicates that errors are concentrated in the high-voltage zone, and while this paper's MIQP optimization takes the current-state assessment model power flow solution as initial values, the sensitivity relationship between initial value MAPE and MIQP optimal solution quality needs further verification to confirm the robustness of optimization results to modeling errors.

In the MIQP objective function, the voltage deviation squared sum (a dimensionless relative value) and control action cost (an integer count) are directly summed with fixed weights, but the two categories have different dimensions: the former magnitude depends on the absolute value of voltage deviation proportional to the number and severity of violating transformer areas, while the latter is a discrete integer. In practical solving, weights require adaptive normalized calibration according to section conditions to ensure optimization is not dominated by a single objective term. Under this paper's case conditions, this weight set did not exhibit numerical dominance issues, but its universality requires verification through multi-condition sensitivity analysis.

Finally, the three harmonic-related sensitivities derived in Section 2.2 have not yet been quantitatively verified through measured THD data, as the experimental feeder measurement system lacks harmonic analyzers. Such validation requires a dedicated study on feeders equipped with harmonic analyzers in combination with measured harmonic spectra.

### 6.3. Outlook: Future Research Directions

Future research will proceed along several directions. The single-section MIQP joint optimization will be extended to multi-section rolling optimization, introducing equipment lifespan constraints including daily tap and capacitor operation count limits, temporal coupling terms, and a finite-horizon MPC framework to construct a coordinated voltage control system targeting 96 sections per day. To address PV output variability and load forecast uncertainty, stochastic and robust optimization extensions of the MIQP framework should be developed. A two-stage stochastic formulation—in which first-stage decisions determine tap and capacitor set-points under expected conditions while second-stage recourse actions adjust PST phase shifts in response to realized PV/load scenarios—would enhance the practical robustness of the voltage control scheme against forecast errors and intra-interval fluctuations, particularly during periods of rapid cloud-driven PV ramping where 15 min persistence forecasts exhibit errors exceeding 30%.

Building upon the MIQP single-section solution, real-time closed-loop operation of DERMS\_Agent will be further validated with real SCADA and TTU communication links, evaluating the impact of engineering constraints such as control instruction dispatch latency, communication fault tolerance, and equipment execution deviation on closed-loop stability, thereby advancing the transition from simulation validation to field deployment.

A dedicated harmonic penetration and resonance management experiment will systematically validate the PST phase-shift suppression effect on dominant harmonics on feeders equipped with harmonic analyzers, quantify the prediction accuracy of the harmonic-related sensitivities, and refine the engineering parameters of the Big-M method resonance avoidance constraint.

Large-scale validation in multi-feeder scenarios will be conducted, combining Benders decomposition and parallel neighborhood enumeration to evaluate Solution\_Agent scalability at the thousand-node scale.

Finally, hybrid solution architectures combining data-driven methods such as Graph Neural Networks (GNN) with MIQP physical models will be explored. For voltage violation scenarios with high trigger frequency and time-sensitive solution requirements, GNN can learn sensitivity-to-voltage mapping relationships as a substitute for iterative power flow verification, further compressing single-section solution latency and strengthening the real-time decision-making capability of data-driven methods in online voltage violation management.

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