THREE-LEVEL AUTOMATIC VOLTAGE CONTROL STRATEGY CONSIDERING THE OPERATIONAL BALANCE OF REACTIVE POWER COMPENSATION DEVICES

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Building upon an exploration of the imbalance in the operation of reactive power compensation devices within power systems characterized by high renewable energy penetration, this paper introduces an innovative Automatic Voltage Control (AVC) three-level voltage control strategy. Recognizing the limitations of traditional AVC strategies that primarily emphasize minimizing network losses while overlooking the disparities in the operational frequencies of reactive power compensation devices, this study augments the conventional approach by incorporating operational frequency balance as a key optimization objective. A multi-objective optimization model is formulated, which takes into account three primary goals: minimizing network losses, minimizing the average utilization rate of reactive power compensation devices, and achieving operational frequency balance. This holistic approach facilitates synergistic optimization across multiple objectives. To address the challenge posed by the coexistence of continuous and discrete variables in the reactive power optimization problem, a nonlinear mixed-integer programming method is adopted for solution finding, ensuring precision and reliability in the optimization outcomes. Simulations conducted on the IEEE 39-bus system reveal that the proposed strategy effectively alleviates the burden on frequently operated devices, thereby prolonging their service lifespan while keeping network losses within acceptable limits. From a cost-benefit analysis perspective, the new strategy demonstrates advantages in reducing device operational frequencies and maintenance expenses, with overall costs lower than those associated with traditional strategies. This research offers a fresh perspective on tackling the imbalance in the operation of reactive power compensation devices and provides insightful guidance for AVC strategies, holding substantial academic value and practical significance in the field of electrical engineering

Keywords: AVC control; reactive power compensation; operational balance; wind power penetration

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1. Introduction

With the transformation of the global energy structure and the advancement of the dual carbon goals, the proportion of renewable energy sources, such as wind power, in the electrical power system continues to increase [1]. However, the intermittent and unpredictable nature of wind power output introduces fresh challenges to grid stability, particularly exacerbating imbalances in reactive power flow distribution. This, in turn, leads to frequent and widely varying operations of reactive power compensation devices [2]. For instance, during the first half of May 2024, the reactive power compensation device at Station A in the Northern Hebei power grid was activated 262 times, whereas Station B's device was only activated 21 times, underscoring a substantial disparity in operational frequencies. Traditional three-level Automatic Voltage Control (AVC) strategies, which primarily emphasize economic objectives such as minimizing network losses, exhibit notable shortcomings in addressing these variations.

The use of capacitors for reactive power control involves considering numerous factors, such as the sinusoidal shape of the voltage and voltage fluctuations. After comprehensively considering factors like network loss and voltage quality, this paper proposes an Automatic Voltage Control (AVC) strategy. This strategy is a three-level AVC voltage control strategy that takes into account the balance of reactive power compensation capacitor operations. This strategy is applied to transmission grids, for instance, it is applied to transmission grids with a voltage level of 500KV. Building on traditional AVC control strategies, this approach indicatively incorporates operational frequency balance as a key optimization objective [3]. By developing a multi-objective optimization model and judiciously assigning weight coefficients, it achieves a synergistic optimization of network loss minimization and operational frequency balance. Furthermore, a nonlinear mixed-integer programming solution method is employed to adeptly manage continuous and discrete variables in the reactive power optimization problem, ensuring the precision and reliability of the optimization outcomes [4].

The research presented in this paper aims to offer novel insights and methodologies for tackling the issue of imbalanced reactive power compensation device operations in power systems with a high proportion of renewable energy [5]. Through simulation analysis and validation using actual grid data, the efficacy of the proposed strategy in alleviating the burden on frequently operated devices, prolonging equipment lifespan, and enhancing system economy is demonstrated. This not only holds paramount significance for elevating grid reactive power and voltage management levels but also provides invaluable references for the subsequent optimization and refinement of AVC strategies [6].

2. Traditional Three-Level Automatic Voltage Control (AVC) Strategy

The conventional Three-Level AVC strategy hinges on comprehensive optimization calculations of voltage and reactive power throughout the entire electrical network. This approach delves deeply into analyzing the current reactive power distribution within the grid, taking into full account the specific circumstances of power plants, substations, and regional dispatch centers regarding reactive power output and reserve capacity [7]. With a focus on minimizing network losses while ensuring grid voltage stability and adherence to power flow limits, the strategy employs optimization calculations to devise the optimal reactive power and voltage setting strategy for the entire network [8].

In terms of cross-regional collaboration in voltage and reactive power regulation, a comprehensive coordination control strategy is introduced for the North China and Northern Hebei power grids. Specifically, as depicted in Fig. 1, for 500kV main transformers, direct and precise control of reactive power is implemented on the low-voltage side, while collaborative scheduling of reactive power is executed on the medium-voltage side. This effectively harmonizes the resources and responsibilities of both the national and provincial dispatch centers [9]. This strategy delineates the regulatory scope of both entities, furnishing robust support for efficient collaboration in cross-regional voltage and reactive power regulation [10].

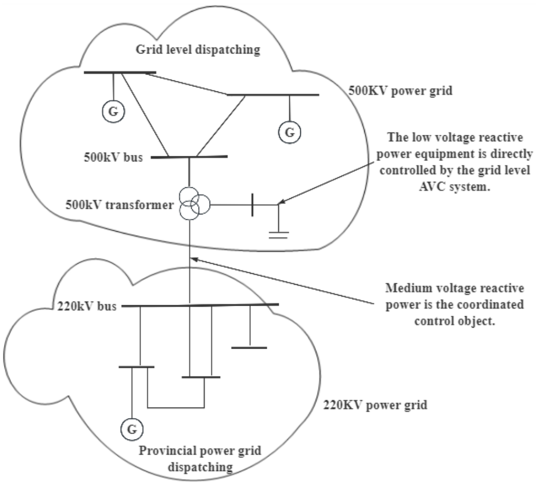

Fig. 1. Provincial-Level and Grid-Level Coordinated Control Scheme

3. Optimization Model

This research centers on mitigating the frequency of operations for frequently activated devices and achieving a balance in the operational frequencies of reactive power compensation devices across all nodes. To this end, an innovative three-level AVC voltage control strategy model is introduced. This model incorporates weighting coefficients λ1, λ2, and λ3 to comprehensively address three optimization objectives: minimizing network losses, minimizing the average usage rate of reactive power compensation devices, and ensuring operational frequency balance. Through simulation case studies, the significant benefits of this enhanced strategy in alleviating the burden on frequently activated devices, enhancing device utilization efficiency, and optimizing overall system performance are demonstrated.

3.1 Goals of Optimization Calculations

When developing the three-level AVC voltage control strategy model that accounts for the balance of reactive power compensation device operations, the following three core optimization goals are established. These goals aim to ensure system economic viability while effectively reducing the frequency of operations for frequently activated devices and achieving a balance in operational frequencies across all nodes:

Objective 1: Minimization of Network Losses. Traditional AVC (Automatic Voltage Control) strategies prioritize economic efficiency while ensuring adherence to system security constraints, facilitating the coordination of voltage and reactive power.

The frequency of operations of reactive power compensation devices at node i can be indicated by their utilization rate μi. Thus,

$$\mu_{\mathrm{i}} = \frac{N_{\mathrm{i0}} + N_{i\mathrm{k}}}{n * N_{i\max}} *100\% \tag{1}$$

Where Ni0 denotes the historical count of operations at node i, Nik represents the current count of operations at node i within the given time interval, n signifies the number of reactive power compensation devices at node i, and Nimax delineates the upper threshold for the number of operations of reactive power compensation devices at node i.

Objective 2: Minimization of the Average Utilization Rate of Reactive Power Compensation Devices. The average utilization rate of reactive power compensation devices reflects the overall level of switching operations across all devices. A reduction in the average number of operations indicates a decrease in the overall frequency of switching actions, which can extend the service life of frequently operated switching devices and reduce maintenance and replacement costs.

$$\overline{\mu} = \frac{1}{n_c} \sum_{i=1}^{n_c} \mu_i \tag{2}$$

Objective 3: Minimization of Disparities in Operation Frequency Utilization, i.e., Achieving Balance in Operation Counts.

The balance in operation counts refers to minimizing the differences in utilization rates among reactive power compensation devices across various grid nodes, which is represented by the standard deviation of utilization rates.

$$\sqrt{\frac{1}{n_c\text{ -1}}\sum_{i=1}^{n_c}\left(\mu_i-\overline{\mu}\right)^2} \tag{3}$$

3.2 The Objective Function Segment of the Model

In the formulation of the comprehensive optimization function, a linear weighting approach is adopted. This involves assigning weight coefficients λ1, λ2, and λ3 to the aforementioned three objectives for a weighted summation. The assignment of these weight coefficients necessitates subjective empirical assessments, taking into account the actual conditions and specific demands of the power grid. By resolving the comprehensive optimization function, an optimized outcome that not only meets economic requirements but also balances operational equity can be attained. Owing to the disparate physical dimensions of the three objectives, the measurement parameters for the objectives are appropriately processed during model establishment. Specifically, the measurement parameter for Objective 1 is derived through the processing of network losses.

$$P_{\text{loss}}/P_{\text{load}} * 100\% \tag{4}$$

In the aforementioned formula, Ploss denotes the network loss, and Pload represents the total active power load of the network.

To summarize, the overall strategic objective function is formulated as follows:

$$\min\ F=\lambda_1F_1+\lambda_2F_2+\lambda_3F_3 \tag{5}$$

In the formula presented above, λ1, λ2, and λ3 represent the weights in the linear weighting method for multi-objective optimization. The objective function involves a weighted summation of three factors, with the weights serving to express the proportion of each factor in the final value.

$$F_1=P_{\text{loss}}/P_{\text{load}} * 100\% \tag{6}$$

$$F_2=\overline{\mu} \tag{7}$$

$$F_3 = \sqrt{\frac{1}{n_c\text{ -1}}\sum_{i=1}^{n_c}\left(\mu_i - \overline{\mu}\right)^2} \tag{8}$$

3.3 Constraint Component of the Model

3.3.1 Equality constraints

The equality constraints, illustrated in Equation 9, enforce the adherence of the power system to fundamental physical principles across all operating conditions, particularly the equilibrium of node power. This critical constraint ensures that, regardless of the operational state, the active and reactive power at each node within the power system can attain a balance between supply and demand, forming the bedrock of stable power system operation. By imposing these equality constraints on every node, we ensure that the overall power system consistently maintains power balance during the reactive power optimization process, thereby preserving system stability and ensuring safety, in line with the rigorous standards of electrical engineering academic discourse.

$$\begin{cases} P_{Gi} - P_{\mathrm{D}i} - V_i \sum_{j\in I} V_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) = 0 \\ Q_{Gi} + Q_{Ci} - Q_{\mathrm{D}i} - V_i \sum_{j\in I} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) = 0 \\ i = 1,\cdots,N_B \quad \theta_{\mathrm{s}} = 0 \end{cases} \tag{9}$$

In the aforementioned formula, NB stands for the total number of nodes, while θs signifies the phase angle of the slack node.

Vi and Vj: These symbols respectively represent the voltage magnitudes at nodes i and j.

Gijand Bij: They denote the conductance and susceptance between nodes i and j, respectively.

θij: This symbol represents the phase angle difference between nodes i and j.

PGi: It signifies the active power output of the generator at node i.

PDi: This indicates the active power load at node i.

QGi: It denotes the reactive power supplied by the generator at node i.

QDi: This represents the reactive power load at node i.

QCi: It signifies the reactive power provided by reactive power compensation devices (such as capacitors, reactors, etc.) at node i, which can be either positive (indicating the generation of reactive power) or negative (indicating the absorption of reactive power).

3.3.2 Inequality constraints

Inequality constraints play a crucial role in the reactive power optimization of power systems, ensuring that the system operates within a safe and stable range. These constraints primarily encompass limits on generator reactive power and node voltage ranges, with the inequality constraint expressed in Equation 10.

$$\begin{cases} Q_{Gi\min} \le Q_{Gi} \le Q_{Gi\max} & i = 1, \cdots, N_G \\ V_{i\min} \le V_i \le V_{i\max} & i = 1, \cdots, N_B \\ Q_{Ci\min} \le Q_{Ci} \le Q_{Ci\max} & i = 1, \cdots, N_{QC} \end{cases} \tag{10}$$

In the aforementioned equation, NG stands for the total count of power sources, NB denotes the overall number of nodes, and NQC signifies the total quantity of reactive power compensation capacitors.

QGimin and QGimax: These values respectively delineate the minimum and maximum reactive power outputs for the ith generator, ensuring its operation within a secure reactive power output range.

Vimin and Vimax: These values respectively define the minimum and maximum voltage magnitudes at the ith node, guaranteeing that the node voltage remains within a safe and stable limit.

Through these inequality constraints, the optimization problem can ensure the safe and stable operation of the power system while satisfying the reactive power output limits of generators, the voltage limits at nodes, and the normal operating requirements of reactive power compensation equipment. During the solution process, it is imperative to strictly adhere to these constraints to guarantee the feasibility and practicality of the optimization results.

4. Solving Approach for Nonlinear Mixed-Integer Programming

The three-level voltage control strategy of the Automatic Voltage Control (AVC) system emphasizes comprehensive regulation of generator terminal voltages and reactive power compensation devices to ensure secure and stable power grid operation, while concurrently optimizing the equilibrium between active power losses and the frequency of reactive compensation device activation [11]. Due to the discrete nature of reactive power output from switchable shunt capacitor banks, the reactive power optimization problem inherently becomes a multi-objective nonlinear mixed-integer programming challenge encompassing both continuous and discrete variables [12].

The implementation of this strategy is segmented into two pivotal steps. Through iterative alternation between these steps, the strategy not only adeptly manages the interplay between continuous and discrete variables but also accomplishes the minimization of active power losses and the optimal balancing of reactive compensation device activation, all while adhering to power grid security constraints [13]. This enhances the control performance and operational efficiency of the entire AVC system [14].

When tackling the intricate issue of reactive power optimization in electrical systems, an initial strategic simplification is employed: temporarily disregarding the system's discrete constraints and transforming the original problem into a purely continuous nonlinear programming challenge [15]. This transformation facilitates a more straightforward solution using existing mathematical tools [16]. Subsequently, the interior point method, an optimization algorithm known for its proficiency in handling large-scale nonlinear issues, is utilized to interactively approach and seek the optimal solution. This step offers a preliminary, technically feasible solution to the reactive power optimization problem [17].

Subsequently, to address the distinct types of variables and constraints more meticulously, the optimization problem is divided into two sub-problems: continuous optimization and discrete optimization [18].

To achieve global optimization, an alternating solution approach is adopted [19]. This method involves continuously switching between the continuous optimization sub-problem and the discrete optimization sub-problem, striving for progress in both continuous and discrete dimensions during each iteration [20]. The iterative process persists until predefined convergence conditions are met or the maximum number of iterations is reached, ensuring that the final optimized result is comprehensive and reliable [21].

The calculation process of the strategy is as follows:

(a) Relax the discrete constraints and use a nonlinear interior point method to perform optimization calculations, obtaining the initial solutions $\boldsymbol{V}_G^{(0)}$ and $\boldsymbol{Q}_C^{(0)}$;

(b) Set $\boldsymbol{V}_G^0$ equal to $\boldsymbol{V}_G^{(0)}$ and initialize the iteration count k to 1;

(c) Keeping $\boldsymbol{V}_G^0$ constant, use a genetic algorithm to solve the discrete optimization sub-problem, obtaining $\boldsymbol{Q}_C^{*(k)}$*;*

(d) *Set* $\boldsymbol{Q}_C^0$ *equal to* $\boldsymbol{Q}_C^{*(k)}$;

(e) Keeping $\boldsymbol{Q}_C^0$ constant, use a nonlinear interior point method to solve the continuous optimization sub-problem, obtaining $\boldsymbol{V}_G^{*(k)}$*;*

(f) *Check if the convergence conditions are met, i.e., whether the number of iterations where the optimal solutions* $\boldsymbol{V}_G^{*(k)}$ and $\boldsymbol{Q}_C^{*(k)}$ *remain unchanged reaches the set value;*

(g) *If the convergence conditions in step (f) are met, the calculation ends; otherwise, set* $\boldsymbol{V}_G^0$ *equal to* $\boldsymbol{V}_G^{*(k)}$;

(h) Increment k by 1 and return to step (c).

5. Case Study Analysis

5.1 Wind Farm Output and Reactive Power Compensation Capacitor Parameter Settings

The wind farm is integrated into the IEEE39 system as a PQ node, replacing the conventional power plant at node 30. Based on the installed capacity, the wind power penetration rate is 14.91%. The active power output curve of the wind farm is depicted in Fig. 2, with a sampling interval of 15 minutes across 96 time points in a day. Node 31 is designated as the slack bus, while nodes 32 to 39 are configured as PV nodes. According to the net load illustrated in Fig. 3, the thermal power plants distribute their active power outputs proportionately to their installed capacities.

The pilot nodes for these four zones are nodes 2, 11, 16, and 29, respectively. Reactive power compensation capacitors are installed at nodes 3, 12, 16, and 29, with each node equipped with four 60MVar capacitors.

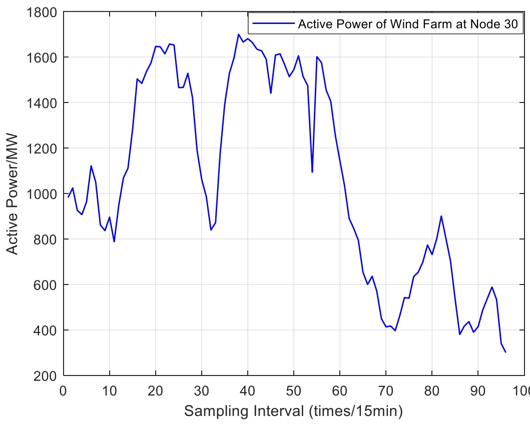

Fig. 2. Curve of Wind Farm's Active Power Output

Fig. 3. Curves of Net Load and Total Load

5.2 Cost of Losses under AVC Voltage Control Strategy

On one hand: Cost associated with the operation of reactive power compensation equipment

For frequently operated equipment with high utilization rates, replacement is required after 5000 operations. Hence, the cost of loss due to operations is calculated as 28056 USD / 5000 operations, i.e., 5.6112 USD per operation. This means that a reduction of one operation for frequently operated equipment results in a cost saving of 5.6112 USD.

For infrequently operated equipment with low utilization rates, if the number of operations does not reach 5000 but the equipment needs replacement due to reaching its service life, the loss due to the number of operations is negligible. Instead, the equipment's wear and tear are calculated based on time. For instance: 28056 USD / (2 years * 365 days * 24 hours) = 1.60120 USD per hour = 0.3998 USD per 15 minutes. This indicates that changes in the number of operations for infrequently operated equipment do not affect the cost savings.

In summary, when considering the strategy of operation balance, the cost savings derived from changes in the number of operations come from reductions in the number of operations for frequently operated equipment. When analyzing the cost savings of the strategy, it is important to distinguish whether the equipment is frequently operated or not.

On the other hand: Cost of network losses

In the transmission and distribution pricing table of the Jibei power grid, the energy price under the two-part tariff system is 0.0131 USD/KWh = 13.14 USD /MWh.

The cost of active power losses in the network is calculated as follows: Network loss cost = Network loss * Time * Electricity price = Ploss * 0.25h * 13.14 USD/MWh.

5.3 Analysis of Reactive Power Compensation Equipment Operations and Associated Loss Costs for a Singular Time Interval

Table 1

Comparative Table of Strategy Optimization Results

Index	Initial Reactive Power Compensation Capacity (MVar)				Current Time Slice Operation Frequency (Times)				Active Power Loss (MW)
	Node 3	Node 12	Node 16	Node 29	Node 3	Node 12	Node 16	Node 29	
1	60	0	60	0	3	0	0	0	40.7
2	60	0	60	0	0	1	0	1	41.38

In Table 1, entry number 1 represents the traditional AVC strategy, where the weight values for λ1, λ2, and λ3 are set to 1, 0, and 0, respectively. For the time cross-section labeled as number 1, nodes 3 and 16 exhibit frequent actions with respective frequencies of 3 times and 0 times, while nodes 12 and 29 show minimal activity, both with 0 actions.

Entry number 2 in Table 1 corresponds to the AVC strategy that takes into account action balance, with the weight values for λ1, λ2, and λ3 set to 0.1, 0.5, and 0.4, respectively. For the same time cross-section 1, nodes 3 and 16 both exhibit 0 actions, indicating a reduction in frequent activation. Meanwhile, nodes 12 and 29, which previously showed minimal activity, now each have 1 action, demonstrating an increase in their utilization.

The optimization results of the AVC strategy considering action balance reveal that the number of actions for frequently active nodes has decreased by 3, while the number of actions for less active nodes has increased by 2. This strategy has effectively reduced the frequency of actions for the more active nodes and enhanced the usage rate of the less active nodes. However, it has also resulted in a 0.68MW increase in active power loss during network transmission.

Table 2

Cost-Benefit Comparison Table

Index	Change in Current Time Slice Operation Frequency (Times)				Operation Cost (USD)	Active Power Loss (MW)	Active Power Loss Cost (USD)	Total Cost (USD)
	Node 3	Node 12	Node 16	Node 29				
1	3	0	0	0	16.83	40.70	133.74	150.58
2	0	1	0	1	0	41.38	135.98	135.98

In Table 2, entry number 1 corresponds to the traditional AVC strategy. The frequent action node experiences 3 actions, resulting in a reactive power compensation equipment operation cost of 16.83 USD (calculated as 3 actions multiplied by 5.61 USD per action). The network loss is 40.70MW, leading to a network loss cost of133.74 USD (calculated as 40.70MW multiplied by 0.25 and then by 13.14 USD per unit).

Entry number 2 represents the AVC strategy that considers action balance. In this case, the frequent action node experiences 0 actions, resulting in no reactive power compensation equipment operation cost. The network loss is 41.38MW, with a corresponding network loss cost of 135.98 USD.

When comparing the total costs, the AVC strategy that takes into account action balance incurs a total cost of 135.98 USD, which is lower than the 150.58 USD total cost of the traditional AVC strategy. This results in a cost savings of 14.60 USD.

Table 3

Cost-Benefit Comparison Table for Time Slice 38

Index	Change in Current Time Slice Operation Frequency (Times)				Operation Cost (USD)	Active Power Loss (MW)	Active Power Loss Cost (USD)	Total Cost (USD)
	Node 3	Node 12	Node 16	Node 29				
1	3	1	3	1	33.67	73.41	241.23	274.90
2	3	1	1	1	22.44	74.35	244.30	266.75

In the 38th time slice, the maximum active power output of wind energy is 1700MW. The voltage at nodes adjacent to the wind energy source drops significantly, indicating a substantial reactive power deficiency in these nodes. After optimization calculations that take into account equipment action balance, the reactive power compensation action frequency for node 3 remains at a maximum of 3 times, with no reduction in frequency. However, for the frequently active node 16, the action frequency decreases by 2 times.

A comparative analysis of the data from Table 3 reveals that the traditional strategy incurs a cost of 274.90 USD, while the strategy that considers action balance results in a cost of 266.75 USD. This comparison indicates a total cost savings of 8.15 USD.

In the 96th time slice, the minimum active power output of wind energy is 300MW. The voltage at nodes adjacent to the wind energy source remains stable, with no reactive power deficiency observed in these nodes. After optimization calculations that account for equipment action balance, no reactive power compensation actions occur at nodes 3 and 16. The total number of actions for frequently active nodes decreases by 2 times.

Table 4

Cost-Benefit Comparison Table for Time Slice 96

Index	Change in Current Time Slice Operation Frequency (Times)				Operation Cost (USD)	Active Power Loss (MW)	Active Power Loss Cost (USD)	Total Cost (USD)
	Node 3	Node 12	Node 16	Node 29				
1	1	1	1	0	11.22	48.08	157.98	169.20
2	0	1	0	1	0.00	48.16	158.26	158.26

A comparative analysis of the data from Table 4 shows that the traditional strategy incurs a cost of 169.20 USD, while the strategy that considers action balance results in a cost of 158.26 USD. This comparison indicates a total cost savings of10.95 USD.

Based on the data analysis from Tables 2 to 4, compared to the traditional AVC strategy, the strategy that takes into account action balance can reduce the action frequency of frequently active equipment and increase the utilization rate of less active equipment, thereby achieving a balanced distribution of action frequencies. Although the new strategy slightly increases network losses during the optimization process, it generally remains within an acceptable range. From a cost perspective, the new strategy demonstrates significant advantages in reducing equipment action frequencies and lowering maintenance costs, resulting in overall lower costs compared to the traditional strategy.

The following is an analysis of the reactive power compensation device operations and loss costs in the Tangshan-Qinhuangdao region of northern Hebei:

Based on the QS file from northern Hebei at 12:00 on July 23, 2024, the 500KV line grid structure of the Tangshan-Qinhuangdao region was extracted. Detailed information on the 500KV substations is shown in the Table 5 below.

Based on the QS file from the northern Hebei region at 12:00 on July 23, 2024, the upper and lower limits of the reactive power compensation device capacities on the low-voltage side of 500KV substations are extracted and presented in the Table 6 below.

The reactive power and voltage optimization calculations were carried out separately according to the traditional AVC strategy and the AVC strategy considering equipment operation balance as described in the previous sections. The number of reactive power compensation device operations at each substation is presented in the Table 7 below.

Under the traditional AVC strategy, the network loss is 31.26MW, while under the AVC strategy considering the balance of reactive power device operations, the network loss is 31.66MW.

Table 5

List of 500KV Substations in the Tangshan-Qinhuangdao Region

Seq. No.	Substation Name	Voltage Level	Topology Node No.
1	Yufeng	500	2730
2	Caofeidao	500	2945
3	Angezhuang	500	132
4	Diantou	500	2490
5	Wangtan	500	522
6	Tangshandong	500	2052
7	Jiangjiaying	500	318
8	Taiping	500	917
9	Tangshanxi	500	1011
10	Yangle	500	1508
11	Tianma	500	452
12	Changli	500	5947
13	Leting	500	2569

Table 6

Reactive Power Compensation Capacity Range Table for Substations

Substation Name	Upper Limit of Reactive Power Compensation Capacity /MVar	Lower Limit of Reactive Power Compensation Capacity /MVar
Yufeng	240	-120
Angezhuang	480	-240
Diantou	360	-120
Tangshandong	360	-120
Jiangjiaying	480	-360
Taiping	480	-240
Tangshanxi	240	-240

Table 7

Number of Reactive Power Compensation Device Operations at Substations

Substation Name	Traditional AVC Operation Times	AVC Operation Times Considering Balance
Yufeng	1	0
Angezhuang	4	1
Diantou	3	1
Tangshandong	2	1
Jiangjiaying	1	1
Taiping	6	2
Tangshanxi	1	1
Yangle	3	1
Tianma	1	0
Changli	2	1
Leting	5	1

According to the historical data analysis of AVC operation status, Yufeng, Angezhuang, Yangle, and Tianma are frequent operation nodes, accounting for 821.7 points. The network loss and equipment operation cost under the traditional AVC strategy is 153.23 USD, while under the AVC strategy considering the balance of reactive power device operations, the network loss and equipment operation cost is 115.27 USD, saving 37.96 USD compared to the traditional AVC strategy.

6. Conclusion

To address the limitations of traditional Automatic Voltage Control (AVC) strategies, which overlook the variability in the operation of reactive power compensation devices within high-penetration renewable energy power systems, an enhanced three-level AVC strategy is introduced. This strategy not only focuses on optimizing network losses but also gives special attention to balancing the operation of reactive power compensation devices. Its objective is to alleviate the burden on frequently activated devices, prolong their service life, and enhance the overall system operational efficiency.

A multi-objective optimization model is established, incorporating three objectives: minimizing network losses, minimizing the average utilization rate of reactive power compensation devices, and balancing the frequency of device operations. By introducing weight coefficients $\lambda 1$, $\lambda 2$, and $\lambda 3$ for a weighted summation, this strategy effectively tackles the issue of uneven device operation frequencies while maintaining system economic viability. A nonlinear mixed-integer programming approach is adopted to handle both continuous and discrete variables in the reactive power optimization problem, ensuring the accuracy and reliability of the optimization outcomes.

Simulation analysis conducted on the IEEE 39-bus system reveals that, in comparison to the conventional AVC strategy, the proposed strategy notably reduces the operation frequency of frequently activated devices and increases the utilization of less frequently used devices, achieving a balanced distribution of operation frequencies. Although the new strategy results in a slight increase in network losses during optimization, these remain within an acceptable range. From a cost perspective, the new strategy demonstrates significant advantages in reducing device operation frequencies and lowering maintenance expenses, leading to overall reduced costs compared to the traditional approach.

To further substantiate the efficacy of the proposed strategy, simulations using real-world power grid data are planned. These will assess its adaptability and robustness in complex power grid environments, a crucial step for translating theoretical research into practical applications. This will contribute to enhancing reactive power and voltage management in power grids and provide valuable insights for future optimization and refinement of AVC strategies.

In summary, the proposed three-level AVC strategy, which accounts for the balancing of reactive power compensation capacitor operations, presents novel ideas and methodologies for addressing the challenge of unbalanced reactive power compensation device operations in high-penetration renewable energy power systems. This strategy holds considerable practical application value in the field of electrical engineering.

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