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Intraday Two-Stage Hierarchical Optimal Scheduling Model for Multiarea AC/DC Systems with Wind Power Integration

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HIGHLIGHTS

- Based on analytical target cascading technology (ATC), we integrate the hierarchical control structure of decomposition-coordination into the model predictive control (MPC) method to achieve decentralized dispatch for multiarea AC/DC systems.
- A two-stage rolling coordinated scheduling model for the area subsystem considering the area coupling constraints based on the MPC is proposed.
- Based on the ATC and the area decomposition criterion of the AC/DC grid, an optimal scheduling model for the upper-level system is proposed.
- Flexible adjustment of the DC tie-line and decoupling scheduling of multiarea AC/DC systems are achieved.
- The hierarchical optimal scheduling model reduces the communication burden between the subsystems and ensures the efficiency of the solution algorithm.

ABSTRACT

To make full use of the flexible adjustment capability of DC tie-lines in multiarea AC/DC systems and to coordinate the generation resources and load demand of multiarea AC/DC systems, this paper presents an intraday two-stage hierarchical optimal scheduling model for multiarea AC/DC systems based on analytical target cascading (ATC). To avoid repeated adjustment and overadjustment of DC tie-lines after wind power integration, a two-stage rolling coordinated scheduling model for the area subsystem based on model predictive control (MPC) is proposed. The two-stage rolling coordinated scheduling method takes into consideration the influence of the predicted value in the future finite time domain and the latest measured DC tie-line power on the current scheduling state. Based on the ATC and the area decomposition criterion of the AC/DC grid, an optimal scheduling model for the upper-level system is proposed that takes into consideration the DC tie-line adjustment constraints and the area coupling constraints. The optimal scheduling model for the upper-level system formulates the two-stage DC tie-line plan for the multiarea AC/DC system, and the two-stage rolling coordinated scheduling model of the area subsystem solves the subproblems of the generation plan for each area subsystem in a parallel manner considering the area coupling constraints. The proposed method can achieve intraday two-stage decoupling scheduling of multiarea AC/DC systems and promote the cross-area consumption of large-scale wind power through flexible adjustment of the DC tie line. This approach also reduces the communication burden between the area subsystems and ensures the efficiency of the solution algorithm.

Keywords: Multiarea AC/DC systems; two-stage rolling coordinated optimal scheduling; area coupling constraints; analytical target cascading (ATC); model predictive control (MPC)

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1. Introduction

1.1. Background and motivation

To help achieve energy saving and emissions reduction goals, the inevitable choice of China's energy strategy is to vigorously develop new energy sources via wind power [1, 2]. The unbalanced development of wind power and load centres in China are such that a large amount of power is transmitted across areas through an AC/DC system consisting of a line commutated converter (LCC)-based high-voltage direct current (LCC-HVDC) and a voltage source converter (VSC)-based high-voltage direct current (VSC-HVDC). The power grid has been transformed into a hybrid AC/DC transmission system. A higher planned transmission power for the DC tie-line will increase the wind power consumption of the delivery subsystem. However, this will cause the receiving subsystem to have insufficient regulation capacity. To better utilize the power generation resources of each area subsystem, multiple factors should be considered simultaneously, and the transmission power of the DC tie-line should be optimized in a reasonable manner [3-5]. The key issues facing the scheduling of multiarea AC/DC systems with wind power integration are how to fully utilize the flexible adjustment of DC tie-lines in AC/DC systems, coordinate the generation resources and load demand of multiarea systems, and establish coordinated scheduling models to promote the consumption of wind power. Therefore, systematically studying the optimal scheduling for multiarea AC/DC systems with wind power integration is essential [6-8].

1.2. Literature review

Some scholars, when focusing on the new characteristics introduced by AC/DC systems, have investigated the optimal scheduling problem for AC/DC grids [9-14]. Mesanovic et al. [9] presented a robust optimal power flow algorithm for mixed AC and DC power transmission systems that takes into consideration uncertain renewable generation and/or load. The uncertain infeeds are assumed to lie inside a known norm-bounded set. The presented algorithm guarantees the satisfaction of various steady-state power system constraints for all uncertainties within this set. To further improve the robustness and economic efficiency of the conventional security-constrained unit commitment problem when confronting system uncertainties, Jiang et al. [10] presented a novel robust security-constrained unit commitment model taking into consideration the prompt and flexible controllability of HVDC in asynchronous interconnected systems. Unlike the conventional method, the proposed model minimizes the total cost of preday commitment for the base case and real-time dispatch under extreme uncertainties when guaranteeing that the generation units and high-voltage direct current can be adjusted adaptively and securely. By leveraging the congestion management capabilities of HVDC systems, Jiang et al. [11] presented a congestion-aware robust security constrained unit commitment model to preemptively address plausible congestion circumstances in a more adaptive way in the day-ahead market. In the presented model, the conventional uncertainty budget sets are modified by the proposed congestion-aware factors, where the typical operational characteristics of traditional corrective actions and high-voltage direct current regulations in the real-time market are adaptively formulated.

Doagou-Mojarrad et al. [12] presented an integrated framework that simultaneously employs different methods, including rescheduling, transmission expansion, and demand response, to manage AC/DC transmission congestion. Three different management approaches that take into consideration both the planning and operation phases were explored. The first management approach considered was to minimize the overall system cost, including both investment and operational costs. The second approach was to minimize the overall active power losses. The objective was to make a trade-off between these two approaches by simultaneously minimizing the system investment cost and operational loss as a multiobjective optimization problem. In [13] by Isuru et al., a two-stage optimization model was proposed for the joint scheduling of energy and reserve for hybrid AC/DC transmission grids. The optimal schedule, including the commitment, power dispatch, and reserve allocations, is computed subject to the feasibility of nonlinear AC and DC network constraints under a specified set of scenarios. Furthermore, the proposed decomposition approach transforms the second stage into a standard optimal power flow problem, which addresses the scalability issues observed with existing methods. A second-order cone relaxation is applied to nonlinear AC and DC network constraints to improve the computational tractability. Guzmán-Feria et al. [14] presented a novel modelling framework for unit commitment studies in multiterminal VSC-connected AC grids. Battery energy storage systems were also considered with an energy time-shifting strategy whose charge and discharge modes are defined within the 24-hour planning horizon to promote a high competition level of energy trading in the power grid. The entire transmission network was formulated by shift factors, and the power losses of AC/DC branches and VSC units were included via piecewise linear functions.

Research on the optimal scheduling of AC/DC power grids has achieved specific results [9-17]. However, most of the studies in the above literature concern centralized scheduling. Centralized dispatching faces many challenges: a unified dispatching center needs to collect global data and process all decision variables in a short period, which leads to high communication pressure, high security risks, and low operational efficiency of the power dispatching system. Therefore, based on the centralized dispatching model, it is necessary to find a method suitable for decentralized scheduling of multiarea AC/DC

systems [18, 19]. For the decentralized scheduling problem of a multiarea interconnected power system, the basic modeling idea is to decompose the multiarea scheduling problem into subsystem scheduling problems that can be solved independently. Decentralized scheduling can maintain the independent and autonomous operation of each subsystem's power grids and reduce the amount of data communication and the scale of computation [20]. Currently, decentralized scheduling algorithms for multiarea interconnected power systems mainly include the pairwise decomposition algorithm and the primitive decomposition algorithm. The pairwise decomposition algorithm solves the local optimization problem by solving the relaxation and coordinating the individual local optimization problems using dyadic variables. In contrast, primitive decomposition algorithms divide the decision variables of the whole scenario into local variables and coupling variables for solving [21]. Among these algorithms, the pairwise decomposition algorithm relaxes the coupling constraints into an objective function by constructing a partial Lagrangian function to obtain a decentralized solution; this can also be regarded as a variant of the Lagrangian relaxation method, and it is the earliest and currently most widely used decomposition algorithm. The ATC method is a decomposition and coordination algorithm based on the evolution of the alternating direction method of multipliers, which is a hierarchical and decentralized coordination optimization algorithm suitable for multi-layer systems. ATC decomposes the original optimization problem into a main problem and multiple regional subproblems by adding dummy variables.

In [22] by Liao et al., to study the impact of the interconnection of multiarea integrated energy systems on carbon emissions, a decomposition strategy for adjacent area integrated energy systems was constructed through flexible DC interconnections, and a decentralized and coordinated dispatch model of multiarea interconnected integrated energy systems was established based on the objective cascade method with the objective function of minimizing the sum of the fuel cost, carbon trading cost, contact line cost, and penalty for wind abandonment. Gan et al. [23] proposed a decentralized computation method for the robust operation of multi-area joint regional-district integrated energy systems with uncertain wind power. The interconnected multiple areas can cooperate for improved system flexibility and wind power integration capability. Using the decentralized method, the area operator optimizes its operation decisions independently without transferring its dispatch rights. The shared information is limited to exchanged energy flows. The proprietary information is thus preserved while the communication burden is significantly reduced. To solve the robust operation problem distributedly, the decentralized method is enhanced to cope with both deterministic and robust problems. A tri-level algorithm composed of the iterative alternating direction multiplier method and the column constraints generation method is utilized to realize the decentralized optimization. Zhai et al. [24] proposed different day-ahead robust scheduling frameworks for additional scheduling and control mechanisms. Decentralized and distributed scheduling frameworks were developed using analytical target cascading. In [25] by Zhao et al., a new spatiotemporal decomposition and coordination scheme was proposed for the load recovery problem in hybrid AC/DC transmission systems. A spatiotemporal decomposition framework for load recovery was established, and decoupling variables and spatiotemporal coordinators were defined, as well as two interaction blocks. In [26] by Wen et al., focused on the hierarchical multi-area power systems with multi-level dispatch centers, a coordinated decentralized risk-based dispatch approach based on the analytical target cascading technique was proposed. The upper- and lower-level dispatch problems were respectively formulated as a master problem and a set of sub-problems, where the master problem handles the coordination of exchange power flows across the tie-lines, while each sub-problem determines local dispatch solutions. The master problem was solved iteratively with the sub-problems until the convergence requirement was met. In [27] by Kargarian et al., a distributed security-constrained unit commitment algorithm to accelerate the generation scheduling of large-scale power systems was proposed. In this algorithm, a power system is decomposed into several scalable zones which are interconnected through tie lines. Each zone solves its own security-constrained unit commitment problem and a parallel calculation method is proposed to coordinate individual security-constrained unit commitment problems.

The existing decentralized scheduling models for multiarea AC/DC systems are more inclined to formulate day-ahead DC power delivery plans according to operation experience and delivery demand. However, the flexible role of the DC tie-line in intraday power flow regulation has been neglected. This approach is not conducive to dealing with the uncertainty of wind power and load forecast errors. Due to the significant forecast error for the day ahead and the low expectations of decision-makers charged with meeting the power balance and reserve constraints, the power balance requirements are appropriately relaxed at this time scale to avoid power overadjustment. This may lead to the infeasibility of day-ahead scheduling schemes, bringing new problems to the safe and reliable operation of power systems.

1.3. Knowledge gap

The latest studies still have two limitations:

(1) The existing multiarea AC/DC system decentralized scheduling models based on analytical target cascading technology (ATC) are mainly divided into two types: 1) Each area scheduling subsystem is responsible for formulating the transmission plan of the DC tie-line, and the upper-level scheduling system is only responsible for coordinating the transmission plan of the DC tie-line formulated by the area scheduling subsystem. 2) Each area scheduling subsystem is only responsible for formulating the power generation plan for its region, and then the upper-level scheduling system is responsible for formulating the transmission plan for the DC tie-line. If the area scheduling subsystem formulates the DC tie-line transmission plan, it will further increase the computational complexity of the area subsystem, while the computing power of the main problem of the

upper-level scheduling system is not fully utilized. Suppose the area scheduling subsystem is only responsible for formulating the power generation plan for this area. In that case, it does not consider the area coupling constraints between area subsystems. Each area subsystem operates completely in isolation, affecting the system's safe and economic operation. Therefore, it is worth further studying that the upper-level scheduling system is responsible for formulating the transmission plan of the DC tie-line while considering the area coupling constraints between area subsystems.

(2) The existing multiarea AC/DC system decentralized scheduling models are inclined to formulate day-ahead DC power delivery plans on the basis of operational experience and demand. However, the flexible role of the DC tie-line in intraday power flow regulation has been neglected. This approach is not conducive to dealing with the uncertainty of wind power and load forecast errors. To cope with large-scale wind power entering a grid, designing an intraday optimal scheduling model for multiarea AC/DC systems to better adapt to fluctuations in wind power output is a problem that warrants in-depth study.

To our knowledge, no researchers have published studies on these issues.

1.4. Main contributions of this paper

To make full use of the flexible adjustment capability of DC tie-lines in multiarea AC/DC systems and to coordinate the generation resources and load demand of multiarea AC/DC systems, we propose an intraday two-stage hierarchical optimal scheduling model for multiarea AC/DC systems based on the ATC. The upper-level scheduling system formulates the two-stage DC tie-line plan for the multiarea AC/DC system, and the area scheduling subsystem solves the subproblems of the generation plan in a parallel manner considering the area coupling constraints. The subsystem's optimal scheduling problem is a two-stage optimal scheduling model. Intraday rolling scheduling is based on the open-loop optimal control algorithm, and real-time rolling scheduling is based on model predictive control (MPC), which includes a lead rolling optimization segment and a lag feedback correction segment. The proposed method can reduce the communication burden between area subsystems, decrease the problem-solving scale, and improve the economic efficiency of wind power utilization and system operation. Moreover, this approach can enable repeated adjustments and overadjustments of DC tie-lines to be avoided, which is conducive to adapting to wind power fluctuations and stabilizing DC tie-line adjustments.

The main contributions of this paper compared with existing works are as follows:

(1) To achieve decentralized scheduling control of a multiarea AC/DC system after large-scale wind power access, based on the ATC and the area decomposition criterion of the AC/DC grid, an intraday two-stage hierarchical optimal scheduling model for a multiarea AC/DC system is proposed that takes into account the DC tie-line adjustment constraints and the area coupling constraints. The upper-level scheduling system formulates the two-stage DC tie-line plan for the multiarea AC/DC system, and the area scheduling subsystem solves the subproblems of the generation plan in a parallel manner considering the area coupling constraints. This approach can achieve intraday two-stage decoupling scheduling of multiarea AC/DC systems and promote cross-area consumption of large-scale wind power through flexible adjustment of the DC tie-line.

(2) To avoid repeated adjustment and overadjustment of DC tie-lines after wind power integration, a two-stage rolling coordinated scheduling model for the area subsystem is proposed. Intraday rolling scheduling is based on the open-loop optimal control algorithm. The real-time rolling scheduling is based on the MPC, including the lead rolling optimization and lag feedback correction segments. The two-stage rolling coordinated scheduling method takes into consideration the influence of the predicted value in the future finite time domain and the latest measured DC tie-line on the current scheduling state, which is conducive to adapting to wind power fluctuations and smoothing the DC tie-line adjustment.

(3) To improve the computational efficiency of the solution algorithm of the decentralized scheduling model, an optimal solution method for the intraday two-stage scheduling model of the multiarea AC/DC system based on ATC is proposed. The upper-level scheduling system formulates the intraday two-phase DC tie-line plan, and the area scheduling subsystem solves the subproblems of the generation plan independently in a parallel manner. The proposed method can reduce the communication burden between area subsystems and reduce the problem-solving scale. This approach can achieve intraday two-phase decentralized scheduling of a multiarea AC/DC system and ensure the efficiency of the solution algorithm.

1.5. Outline

The remainder of this paper is organized as follows: [Section 2](#) introduces the intraday two-stage optimal scheduling strategy for multiarea AC/DC systems. [Section 3](#) introduces the intraday two-stage optimal scheduling model for multiarea AC/DC systems. [Section 4](#) provides the methodology for solving our model. In [Section 5](#), two three-area AC/DC systems are simulated, and the numerical results are discussed. [Section 6](#) concludes this study.

2. Intraday two-stage optimal scheduling strategy for multiarea AC/DC systems

2.1. Hierarchical control for multiarea AC/DC systems

The basic idea of hierarchical control is to use the principle of "decomposition-coordination" to solve the optimal control problem of an extensive complex system in two steps to reduce the amount of computation of the control decision. Specifically, (1) a sizeable complex system is decomposed into several independent but interrelated subsystems.

Decentralized local controllers (DLC) implement local observation and control to achieve the subsystem's optimization goal. (2) An upper-level coordinator (ULC) is set up to implement each local controller's observation and control and coordinate the constraints between subsystems.

We use a hierarchical control technique (the ATC) [28-30] to solve the optimization of the intraday two-stage scheduling model for a multiarea AC/DC system. The upper-level coordinator develops the intraday two-stage transmission plan for the multiarea AC/DC tie-line and then issues it to the corresponding area controllers for execution. The area controllers solve the subproblems of each subsystem's generation plan independently in a parallel manner. This method can achieve the decentralized solution of the intraday two-stage scheduling model for a multiarea AC/DC system. The key to the decentralized solution of the intraday two-stage scheduling model for a multiarea AC/DC system based on the ATC is the division of the multiarea AC/DC system and the handling of the coupling variables among the multiareas. The decomposition strategy for the multiarea AC/DC system is given in Fig. 1. In this section, the DC tie-line power is directly used as an area coupling variable. The DC tie-line is cut to decompose the interconnected multiarea AC/DC system into several independent area subsystems.

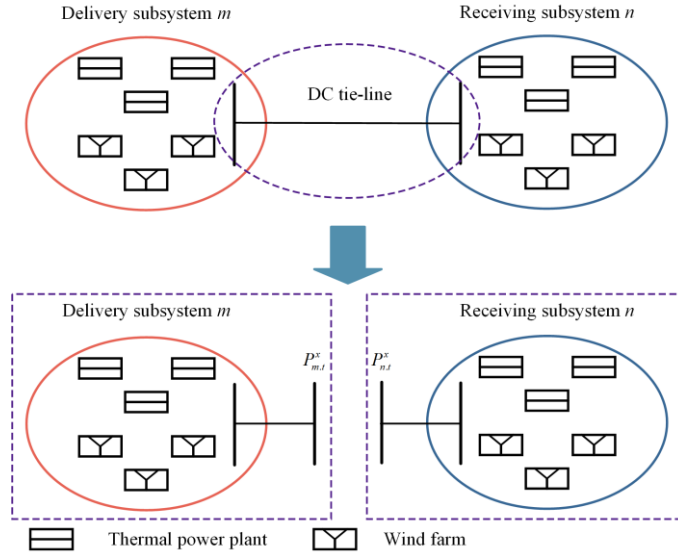


Fig. 1. Decomposition strategy for the multiarea AC/DC system.

To ensure the power balance between the delivery subsystem and receiving subsystem, the multiarea power system decomposition criterion should satisfy the area coupling constraints shown in Eq. (1).

$$P_{m,t}^x = P_{n,t}^x \quad (1)$$

where $P_{m,t}^x$ and $P_{n,t}^x$ are the active outputs of the converter stations of subsystems m and n in period t ; if x is L, this indicates that the converter type is LCC, and if x is V, this indicates that the converter type is VSC.

After decomposition, the general form of the area subsystem optimal scheduling problem for the delivery and receiving subsystems can be expressed as the following equation:

$$\begin{cases} \min_{\mathbf{z}, \mathbf{v}} \mathbf{h}(\mathbf{z}) = \mathbf{c}^T \mathbf{z} \\ \text{s.t. } \mathbf{F}\mathbf{z} + \mathbf{G}\mathbf{v} \leq \mathbf{r} \end{cases} \quad (2)$$

where $\mathbf{z}$ and $\mathbf{v}$ indicate the subsystems' decision variables and coupling variables, respectively. Here, $\mathbf{h}(\mathbf{z})$ is the objective function. $\mathbf{c}$ indicates the coefficient matrix of the objective function. $\mathbf{F}$ and $\mathbf{G}$ are the coefficient matrices associated with the subsystem's decision variables and coupling variables, respectively, in the constraints. $\mathbf{r}$ is the constant matrix of the constraints.

Due to the existence of the coupling variable $\mathbf{v}$, each of the area subproblems cannot be solved in isolation. To satisfy the need for decentralized solving, hierarchical optimization uses an area consensus constraint to describe the coupling variable. Furthermore, this constraint is relaxed to the subproblem objective function, thus allowing each subsystem scheduling problem to be solved independently and in parallel. After solving all the subproblems, the values of the coupling variables are updated and iterated until the convergence condition is satisfied. The relaxed area subproblem objective function is shown in Eq. (3), and the constraint is relaxed by augmenting the Lagrange equation.

$$\min_{\mathbf{z}, \mathbf{v}} \{ \mathbf{c}^T \mathbf{z} + \alpha^T (\hat{\mathbf{v}}^* - \mathbf{v}) + \beta^T (\hat{\mathbf{v}}^* - \mathbf{v})^2 \} \quad (3)$$

where α and β indicate the penalty factors corresponding to the linear and quadratic terms in the augmented Lagrangian equations, respectively. $\hat{v}^*$ indicates the target value of the power of the tie-line, which is determined by the upper-level scheduling centre and issued to the subsystem.

2.2. Intraday two-stage optimal scheduling framework for multiarea AC/DC systems

To achieve decentralized scheduling control for multiarea AC/DC systems after large-scale wind power integration, based on the ATC, we integrate the hierarchical control structure of decomposition-coordination into the MPC [31-33] method to achieve decentralized dispatch for multiarea AC/DC systems. The global coordinator is the upper-level scheduling system. The decentralized controller is the area scheduling subsystem. The upper-level scheduling system receives the DC tie-line plan and penalty factor uploaded from each area scheduling subsystem. The system also updates the DC tie-line power target value based on this information. It is subsequently issued to the corresponding area scheduling subsystem for the next iteration. The area scheduling subsystem receives the DC tie-line power target value from the upper-level scheduling system and optimizes the local generation resource output and the DC tie-line power reported in the next iteration. The area scheduling subproblem is a two-stage scheduling model.

In the proposed two-stage scheduling framework, the first stage is intraday rolling scheduling, and the second is real-time rolling scheduling. Intraday rolling scheduling is based on the open-loop optimal control algorithm, which rolls every 15 minutes to provide scheduling instructions for the next four hours. In intraday rolling scheduling, the power of thermal units and the DC tie-line are arranged to cope with the power deviation that the day-ahead scheduling scheme cannot compensate for. Intraday rolling scheduling aims to provide thermal unit output and DC tie-line power reference values for real-time rolling scheduling. The real-time rolling scheduling is based on the MPC, which includes a lead rolling optimization segment and a lag feedback correction segment. In real-time rolling scheduling, the latest thermal unit output and DC tie-line power measurement values are collected by the measurement system and used as inputs for real-time rolling scheduling. The real-time rolling scheduling is executed every 5 minutes, giving scheduling instructions for the next 15 minutes but only for the first scheduling period. The intraday two-stage hierarchical optimized scheduling framework based on the MPC is shown in Fig. 2.

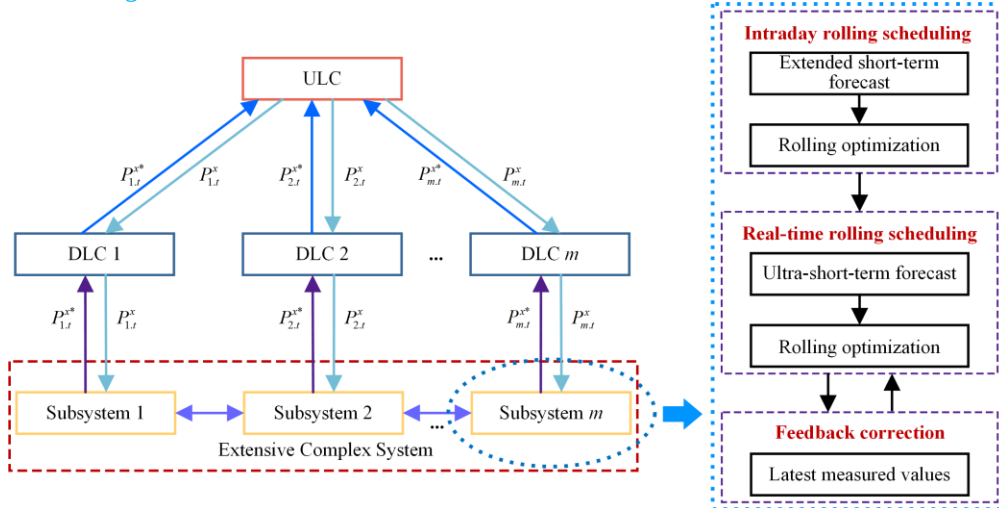


Fig. 2. Two-stage hierarchical optimization scheduling framework for multiarea AC/DC systems.

3. Intraday two-stage optimal scheduling model for multiarea AC/DC systems

3.1. DC tie-line adjustment constraints

(1) Upper and lower limits of the active output of the converter station constraints

$$P_{\min}^m \leq P_{m,t}^x \leq P_{\max}^m \quad (4)$$

where $P_{\min}^m$ and $P_{\max}^m$ are the minimum and maximum active outputs of the converter station of DC tie-line d .

(2) Adjacent-period adjustment direction constraints

$$\begin{cases} \kappa_{d,t}^m + \kappa_{u,t}^m \leq 1 \\ \kappa_{d,t}^m + \kappa_{u,t+1}^m \leq 1 \\ \kappa_{d,t+1}^m + \kappa_{u,t}^m \leq 1 \end{cases} \quad (5)$$

where $\kappa_{d,t}^m$ and $\kappa_{u,t}^m$ indicate whether the DC power of DC tie-line d climbs and slips in period t , respectively; $\kappa_{d,t+1}^m$ and

$\kappa_{u,t+1}^m$ indicate whether the DC power of DC tie-line d climbs and slips in period $t+1$, respectively. A value of 1 means yes, and 0 means no.

(1) Constraints on the number of output adjustments

$$\sum_{t=1}^{N_T} (\kappa_{d,t}^m + \kappa_{u,t}^m) \leq \psi \quad (6)$$

where ψ is the number of times the DC tie-line can be adjusted in a day.

(2) Adjacent period adjustment continuity constraints

$$\begin{cases} \kappa_{d,t}^m + \kappa_{d,t+1}^m \leq 1 \\ \kappa_{u,t}^m + \kappa_{u,t+1}^m \leq 1 \\ P_{m,t}^x - P_{m,t-1}^x \leq \nu_d \kappa_{d,t}^m \\ P_{m,t-1}^x - P_{m,t}^x \leq \nu_u \kappa_{u,t}^m \end{cases} \quad (7)$$

where $P_{m,t-1}^x$ is the active output of the converter stations of DC tie-line d in period $t-1$ and ν_d and ν_u are constants that ensure the inequality holds.

(3) Adjustment rate constraints

$$(\kappa_{d,t}^m + \kappa_{u,t}^m) \chi_{m,\min}^x \leq |P_{m,t+1}^x - P_{m,t}^x| \leq (\kappa_{d,t}^m + \kappa_{u,t}^m) \chi_{m,\max}^x \quad (8)$$

where $\chi_{m,\min}^x$ and $\chi_{m,\max}^x$ are the minimum and maximum DC adjustment powers of DC tie line d , and $P_{m,t+1}^x$ is the active output of the converter stations of DC tie line d in period $t+1$.

(4) Stair-like constraints

$$\begin{cases} \varpi_{u,t}^m + \sum_{t=t+1}^{t+T_{\min}^m} \varpi_{d,t}^m \leq 1 \\ \varpi_{u,t}^m \geq \kappa_{d,t+1}^m - \kappa_{d,t}^m \\ \varpi_{d,t}^m \geq \kappa_{d,t}^m - \kappa_{d,t+1}^m \end{cases} \quad (9)$$

where $\varpi_{u,t}^m$ and $\varpi_{d,t}^m$ represent whether the DC power of DC tie-line d begins to be adjusted and whether it stops being changed in period t , respectively; $T_{\min}^m$ is the minimum adjustment interval of DC tie-line d .

(5) The total transmission power constraints

$$(1-\rho)P_{mn} \leq \sum_{t=1}^{N_T} P_{m,t}^x \leq (1+\rho)P_{mn} \quad (10)$$

where P_{mn} is the transmission schedule of DC tie-line connected to subsystems m and n and ρ is the ratio of the allowed DC tie-line transmission deviation.

3.2. Upper-level scheduling model

The upper-level scheduling system receives the DC tie-line plan and penalty factor uploaded from each area scheduling subsystem. The system also updates the DC tie-line power target value based on this information. It is subsequently issued to the corresponding area scheduling subsystem for the next iteration. The upper-level scheduling system optimization model is shown in Eq. (11):

$$\begin{cases} \min \sum_{t \in \Omega_{NT}} \sum_{m,n \in \Omega_{ND}} \{ \alpha_{m,t} (P_{m,t}^x - P_{m,t}^{x*}) + [\beta_{m,t} (P_{m,t}^x - P_{m,t}^{x*})]^2 + \alpha_{n,t} (P_{n,t}^x - P_{n,t}^{x*}) + [\beta_{n,t} (P_{n,t}^x - P_{n,t}^{x*})]^2 \} \\ \text{s.t. Eq.(1), Eqs.(4) - (10)} \end{cases} \quad (11)$$

where Ω_{NT} and Ω_{ND} indicate the scheduling period and the set of DC tie-lines, respectively. $\alpha_{m,t}$, $\alpha_{n,t}$ and $\beta_{m,t}$, $\beta_{n,t}$ are the penalty factors corresponding to the linear and quadratic terms in the denoted augmented Lagrangian equation, respectively. The control variable in the objective function is the DC tie-line power objective value, $\alpha_{m,t}$, $\alpha_{n,t}$ and $\beta_{m,t}$.

3.3. Area scheduling model (Stage 1)

Taking the prediction's regularity and the prediction error's randomness into consideration, the wind power output is expressed as the sum of the determined prediction value and the uncertain error value. However, the prediction errors under different time scales have different standard deviations, which are expressed as the following equation:

$$P_{w,t}^{\text{actual}} = P_{w,t} + \varepsilon_{w,t} \quad (12)$$

where $P_{w,t}$ is the predicted output of wind farm w in period t , $P_{w,t}^{actual}$ is the actual output of wind farm w in period t , and $\varepsilon_{w,t}$ is the predicted error of wind farm w in period t .

It is assumed that wind power uncertainty affects only the system's reserve capacity requirements, which means that the thermal unit output can be dispatched based on the determined forecast values. While the spare capacity reserved for the system is used to balance the uncertain forecast error, the uncertainty variable is included only in the system spare constraint.

The area scheduling subsystem receives the DC tie-line power target value issued by the upper-level scheduling system and optimizes the local generation resource output with the DC tie-line power reported in the next iteration. The area scheduling subproblem is a two-stage optimization model. Stage 1 is intraday rolling optimization scheduling based on an open-loop optimization algorithm, which provides the output reference value for the Stage 2 problem. Stage 1 minimizes the system operating cost under the predicted wind power output condition. The intraday rolling optimal scheduling model is:

$$\min \sum_{t \in \Omega_{NT}} [\sum_{i \in \Omega_{NG}} a_i (P_{i,t})^2 + b_i P_{i,t} + c_i + \sum_{w \in \Omega_{NW}} \phi (P_{w,t}^{actual} - P_{w,t})] + \sum_{t \in \Omega_{NT}} \sum_{m,n \in \Omega_B} \alpha_{m,t} (P_{m,t}^x - P_{m,t}^{x*}) + [\beta_{m,t} (P_{m,t}^x - P_{m,t}^{x*})]^2 \quad (13)$$

where Ω_{NG} and Ω_{NW} indicate the number of thermal power units and the number of wind farms, respectively. $P_{i,t}$ is the active output of thermal power unit i in period t . a_i^m , b_i^m and c_i^m are the generation cost coefficients of thermal power unit i . ϕ is the penalty unit price of wind abandonment. The control variables in the objective function are the thermal and wind farm output, $\alpha_{m,t}$, $\alpha_{n,t}$ and $\beta_{m,t}$, and the DC tie-line power objective value.

(1) Power balance constraints

$$\sum_{i \in \Omega_{NG}} P_{i,t} + \sum_{w \in \Omega_{NW}} P_{w,t} + P_{m,t}^x = \sum_{l \in \Omega_{NL}} P_{l,t} \quad (14)$$

where $P_{l,t}$ is the predicted load l in period t and Ω_{NL} indicate the set of the number of the load.

(2) Upper and lower limits of thermal power unit output constraints

$$P_{i,\min} \leq P_{i,t} \leq P_{i,\max} \quad (15)$$

where $P_{i,\min}$ and $P_{i,\max}$ are the minimum and maximum active outputs of thermal power unit i , respectively.

(3) Thermal power unit climb and slip constraints

$$r_{di} \leq P_{i,t} - P_{i,t-1} \leq r_{ui} \quad (16)$$

where r_{di} and r_{ui} are the active output climb and slip limits of thermal power unit i , respectively, and $P_{i,t-1}$ is the active output of thermal power unit i in period $t-1$.

(4) Thermal power unit rotating reserve constraints

$$\begin{cases} 0 \leq s_{ui,t} \leq \min(P_{i,\max} - P_{i,t}, r_{ui}) \\ 0 \leq s_{di,t} \leq \min(P_{i,t} - P_{i,\min}, r_{di}) \\ \sum_{i \in \Omega_{NG}} (P_{i,t} + r_{ui}) + \sum_{w \in \Omega_{NW}} (P_{w,t}^{actual} - P_{w,t}) \geq \sum_{l \in \Omega_{NL}} P_{l,t} + P_{m,t}^x + s_{ui,t} \\ \sum_{i \in \Omega_{NG}} (P_{i,t} - r_{di}) + \sum_{w \in \Omega_{NW}} (P_{w,t}^{actual} - P_{w,t}) \leq \sum_{l \in \Omega_{NL}} P_{l,t} + P_{m,t}^x - s_{di,t} \end{cases} \quad (17)$$

where $s_{ui,t}$ and $s_{di,t}$ are the uprotating and downrotating reserves of unit i in period t , respectively.

(5) DC tie-line power constraints

$$P_{m,\min} \leq P_{m,t}^x \leq P_{m,\max} \quad (18)$$

where $P_{m,\min}$ and $P_{m,\max}$ are the minimum and maximum active outputs of DC tie-line, respectively.

(6) Abandoned wind constraints

$$0 \leq P_{w,t}^{actual} - P_{w,t} \leq P_{w,t}^{actual} \quad (19)$$

In addition, the Stage 1 constraints of the area scheduling optimization model also include DC tie-line adjustment constraints. Moreover, to satisfy the adjustment requirements of the Stage 2 problem, the decision variables in Stage 1 should also satisfy the Stage 2 constraints.

3.4. Area scheduling model (Stage 2)

The real-time rolling optimal scheduling for Stage 2 is modelled based on model predictive control. In the proposed real-time rolling optimal scheduling method, the latest thermal unit output power measurements are collected through an

actual measurement system as inputs to real-time rolling scheduling. The multistep dynamic rolling optimization and feedback correction strategies correct the power deviation in time. When power deviation occurs, the control mode with minimum power regulation ensures economy. Stage 2 adjusts the generation plan developed in Stage 1 according to the actual wind power output to ensure that the system does not experience wind power abandonment. The two stages of the problem can be solved together to achieve a balance between the economy and the safety of the system operation.

The ultrashort-term wind power forecasts are used as input variables. The latest thermal unit output and the measured value of the DC tie-line are taken as initial values. The increments of the thermal unit output and the DC tie-line in the next 15 minutes are taken as control variables.

$$\begin{cases} P_{i,t+k|t} = P_{i,t}^{initial} + \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t} \\ P_{m,t+k|t}^x = P_{m,t}^{x,initial} + \sum_{t \in \Omega_k} \Delta P_{m,t+\tau|t}^x \end{cases} \quad (20)$$

where $P_{i,t+k|t}$ is the active output of thermal unit i in future period $t+k$. $P_{m,t+k|t}^x$ is the active output of the DC tie-line in the future period $t+k$. $P_{i,t}^{initial}$ and $P_{m,t}^{x,initial}$ are the initial active outputs of thermal power unit i and the DC tie-line, respectively. $\Delta P_{i,t+k|t}$ and $P_{m,t+k|t}^x$ are the increases in the active outputs of thermal power unit i and the DC tie-line, respectively, in the future period. Ω_k is the set of prediction steps.

The reference values of the thermal units and the DC tie-line are determined based on intraday rolling scheduling. For the current scheduling moment, real-time rolling scheduling takes power deviation minimization as the objective, and the specific optimization model is:

$$\min \sum_{k \in \Omega_{NT}} \sum_{i \in \Omega_{NG}} \gamma_G |P_{i,t+k|t} - \hat{P}_{i,t+k}| + \sum_{k \in \Omega_{NT}} \sum_{i \in \Omega_{ND}} \gamma_D |P_{m,t+k|t}^x - \hat{P}_{m,t+k}^x| + \sum_{k \in \Omega_{NT}} \sum_{w \in \Omega_{NW}} \phi P_{w,t+k}^s \quad (21)$$

where γ_G and γ_D are the adjustment costs for thermal units and DC tie-lines in real-time rolling scheduling, respectively. $\hat{P}_{i,t+k}$ and $\hat{P}_{m,t+k}^x$ are the reference outputs of the thermal units and the DC tie-line determined by Stage 1. $P_{w,t+k}^s$ is the wind power abandoned in the real-time rolling scheduling.

This can be obtained by combining Eq. (20):

$$\min \sum_{k \in \Omega_{NT}} \sum_{i \in \Omega_{NG}} \gamma_G |P_{i,t}^{initial} + \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t} - \hat{P}_{i,t+k}| + \sum_{k \in \Omega_{NT}} \sum_{i \in \Omega_{ND}} \gamma_D |P_{m,t}^{x,initial} + \sum_{t \in \Omega_k} \Delta P_{m,t+\tau|t}^x - \hat{P}_{m,t+k}^x| + \sum_{k \in \Omega_{NT}} \sum_{w \in \Omega_{NW}} \phi P_{w,t+k}^s \quad (22)$$

(1) Power balance constraints

$$\sum_{i \in \Omega_{NG}} (P_{i,t}^{initial} + \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t}) + \sum_{w \in \Omega_{NW}} (P_{w,t+k} - P_{w,t+k}^s) + \sum_{m \in \Omega_{ND}} (P_{m,t}^{x,initial} + \sum_{t \in \Omega_k} \Delta P_{m,t+\tau|t}^x) = \sum_{l \in \Omega_{NL}} P_{l,t+k} \quad (23)$$

where $P_{w,t+k}$ is the predicted output of the wind farm in real-time rolling scheduling. $P_{l,t+k}$ is the predicted load in the real-time rolling scheduling.

(2) Upper and lower limits of the thermal unit output constraints

$$P_{i,\min} \leq P_{i,t}^{initial} + \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t} \leq P_{i,\max} \quad (24)$$

(3) Thermal unit climb and slip constraints

$$r_{di} \leq \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t} - \sum_{t \in \Omega_{k-1}} \Delta P_{i,t+\tau|t} \leq r_{ui} \quad (25)$$

(4) Thermal unit rotating reserve constraints

$$\begin{cases} 0 \leq s_{ui,t+k} \leq \min(P_{i,\max} - P_{i,t}^{initial} - \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t}, r_{ui}) \\ 0 \leq s_{di,t+k} \leq \min(P_{i,t}^{initial} + \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t} - P_{i,\min}, r_{di}) \\ \sum_{i \in \Omega_{NG}} (P_{i,t}^{initial} + \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t} + r_{ui}) + \sum_{w \in \Omega_{NW}} P_{w,t+k}^s \geq \sum_{l \in \Omega_{NL}} P_{l,t+k} + \sum_{m \in \Omega_{ND}} (P_{m,t}^{x,initial} + \sum_{t \in \Omega_k} \Delta P_{m,t+\tau|t}^x) + s_{ui,t+k} \\ \sum_{i \in \Omega_{NG}} (P_{i,t}^{initial} + \sum_{t \in \Omega_k} \Delta P_{i,t+\tau|t} - r_{di}) + \sum_{w \in \Omega_{NW}} P_{w,t+k}^s \leq \sum_{l \in \Omega_{NL}} P_{l,t+k} + \sum_{m \in \Omega_{ND}} (P_{m,t}^{x,initial} + \sum_{t \in \Omega_k} \Delta P_{m,t+\tau|t}^x) - s_{di,t+k} \end{cases} \quad (26)$$

where $s_{ui,t+k}$ and $s_{di,t+k}$ are the uprotating and downrotating reserves, respectively, of unit i in the real-time rolling scheduling.

(5) DC tie-line power constraints

$$P_{m,\min} \leq P_{m,t}^{x,\text{initial}} + \sum_{t \in \mathcal{I}_k^x} \Delta P_{m,t+\tau|t}^x \leq P_{m,\max} \quad (27)$$

When the increments of thermal units and DC tie-lines for the next 15 minutes are solved at the current scheduling moment, only the increments of thermal units and DC tie-lines at the 1st scheduling moment are executed. Thus, the output of the following scheduling moment can be obtained:

$$\begin{cases} P_{i,t+1|t} = P_{i,t}^{\text{initial}} + \Delta P_{i,t+1|t} \\ P_{m,t+1|t}^x = P_{m,t}^{x,\text{initial}} + \Delta P_{m,t+1|t}^x \end{cases} \quad (28)$$

3.5. Feedback correction strategy

The above rolling optimization model is based on the advanced control of the forecast value. However, under the current prediction accuracy, advanced control may lead to a power deviation between the actual and planned outputs of thermal units and DC tie-lines [34, 35]. Therefore, it is necessary to introduce a lagging feedback correction, i.e., at each scheduling moment, the latest measured values of the output of thermal units and the DC tie-line are used to correct the output plan formulated by the rolling optimization model. Thus, a closed-loop optimization is formed to compensate for the power deviation in time so that the power of the thermal units and DC tie-lines in the future scheduling moments are closer to the actual values.

At the next scheduling moment, a new round of rolling optimization strategies is executed. The latest thermal unit and DC tie-line output power measurements are set as the initial values, i.e.,

$$\begin{cases} P_{i,t+1}^{\text{initial}} = P_{i,t+1}^{\text{actual}} \\ P_{m,t+1}^{x,\text{initial}} = P_{m,t+1}^{x,\text{actual}} \end{cases} \quad (29)$$

where $P_{i,t+1}^{\text{actual}}$, $P_{m,t+1}^{x,\text{actual}}$ are the latest power output measurements of the thermal units and DC tie-lines collected by the measurement system for the next scheduling moment.

4. Solution algorithm

4.1 Convergence judgement and multiplier update

The solution flow of the intraday two-stage hierarchical optimal scheduling model based on the ATC is shown below:

(1) Initialization: the number of iterations $z=1$; the penalty factors $\alpha^{(1)}$ and $\beta^{(1)}$ for area scheduling subproblems; and the DC tie-line power objective value $\hat{v}^{(0)*}$.

(2) Each area scheduling subsystem solves its subproblems independently and in parallel to obtain the optimal scheduling strategy and DC tie-line power $\hat{v}^{(k)*}$ for the area and combines the values with $\alpha^{(k)}$ and $\beta^{(k)}$ uploaded to the upper-level scheduling centre.

(3) The upper-level scheduling system solves its optimization model to obtain the latest target power value of the DC tie-line and distributes the value to the area scheduling subsystems.

(4) Convergence judgement: if the convergence criterion in Eq. (30) satisfies the condition, the iteration stops, and the optimal scheduling plan is obtained. Otherwise, each area scheduling subsystem updates the penalty factor in parallel according to Eq. (31), sets $k=k+1$, and returns to step (2), where g_c in Eq. (30) is calculated by the difference between the coupling variables obtained by the upper-level scheduling system and the area scheduling subsystems; on the other hand, g_o is calculated by the change in the objective function of the area subproblem during two consecutive iterations, and ε_c and ε_o are the corresponding convergence criteria.

$$\begin{cases} g_c = \max | \hat{v}^{(k)*} - \hat{v}^{(k-1)*} | \leq \varepsilon_c \\ g_o = \left| \frac{h(z^{(k)}) - h(z^{(k-1)})}{h(z^{(k)})} \right| \leq \varepsilon_o \end{cases} \quad (30)$$

$$\begin{cases} \alpha^{(k+1)} = \alpha^{(k)} + 2(\beta^{(k)})^2 (\hat{v}^{(k)*} - \hat{v}^{(k-1)*}) \\ \beta^{(k+1)} = \gamma \beta^{(k)} \end{cases} \quad (31)$$

To ensure the algorithm's convergence, the preset constant γ should not be less than 1. During each iteration, the upper-level scheduling system and the area scheduling subsystems need to exchange only the DC tie-line power and the penalty factor. The communication burden is alleviated, and area information privacy is protected.

4.2 Optimization flow of the area scheduling model

Our proposed intraday two-stage optimal scheduling model, where the day-ahead scheduling model is coordinated with the intraday time scale in an equal time interval recursion-by-recursion manner, results in multi timescale optimal scheduling,

as shown in Fig. 3. The day-ahead time scale calculates the scheduling plan values for the next one-hour period. In the intraday two-stage rolling scheduling framework, the first stage is intraday rolling scheduling, and the second is real-time rolling scheduling. Intraday rolling scheduling is based on the open-loop optimal control algorithm, which rolls once every 15 minutes to provide scheduling instructions for the next four hours. The real-time rolling scheduling is based on the MPC, which includes a lead rolling optimization segment and a lag feedback correction segment. In real-time rolling scheduling, the latest thermal unit output and DC tie-line power measurement values are collected by the measurement system and used as inputs for real-time rolling scheduling. Real-time rolling scheduling is executed every 5 minutes to provide scheduling instructions for the next 15 minutes.

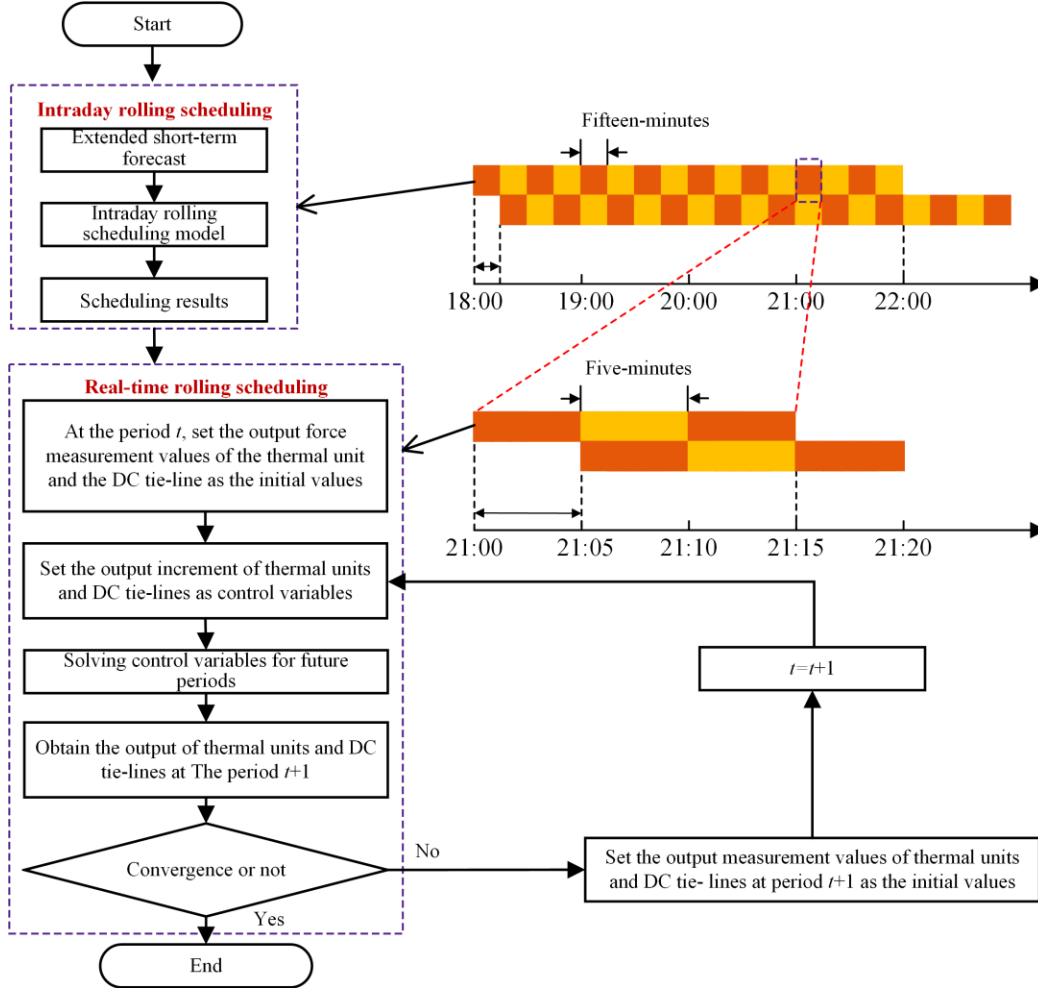


Fig. 3. Optimization flow of the area scheduling model.

5. Numerical experiments

To verify the effectiveness of the intraday two-stage hierarchical optimal scheduling model for multiarea AC/DC systems with wind power integration, we analyse two three-area AC/DC systems with wind power integration and set up four DC tie-line scheduling models for comparative analysis under the assumption that the same amount of power is transferred per day. A 64-bit desktop with a 3.40-GHz CPU and 16 GB of RAM was used to implement all the simulation tests. The four DC tie-line scheduling models were modelled and solved in MATLAB 2019b/YALMIP and CPLEX/Gurobi 9.0.

Model 1: Centralized scheduling: The DC tie-line power transmission model with fixed transmission power is adopted without taking into consideration the flexibility of the DC tie-line [36].

Model 2: Centralized scheduling: This is an intraday two-stage centralized optimal scheduling model for multiarea AC/DC systems that takes the adjustment constraints of DC tie-lines and area coupling constraints into consideration (centralized scheduling model corresponding to Section 3).

Model 3: Decentralized scheduling: Considering the flexibility and controllability of the DC tie-line, the transmission power of the DC tie-line is optimized together with the subsystem generator output, without taking area coupling constraints into consideration [36].

Model 4: Decentralized scheduling: This is an intraday two-stage hierarchical optimal scheduling model for multiarea AC/DC systems that takes into consideration the adjustment constraints of DC tie-lines and area coupling constraints (Section 3).

The intraday two-stage centralized optimal scheduling model corresponding to Section 3 is denoted Model 2. Based on Model 2, we present an intraday two-stage hierarchical optimal scheduling model for multiarea AC/DC systems as Model 4. The models in references [20, 36] (Model 1, Model 3) are selected for comparison with our method.

5.1. Case 1: 3-area 117-node AC/DC system

Case 1 concerns three New England 39-node systems (subsystems m , n , and o) [37]. Node 24 in subsystem m and node 24 in subsystem o are connected via a VSC-HVDC tie-line. Node 9 of subsystem m is connected to node 9 of subsystem n by an LCC-HVDC tie-line. Three identical wind farms are located at nodes 4, 21, and 27 of subsystem m . The predicted load of subsystem m and the predicted output of the wind farm of subsystem m are shown in Fig. 4. It is assumed that the extended short-term forecast error, and ultra-short-term forecast error for wind power are 15%, and 10% of the forecast value, respectively. To achieve cross-area power transmission from subsystem m to subsystems n and o , the generation cost coefficients of thermal units in subsystems m , n , and o are multiplied by 1, 2, and 2, respectively, and the predicted loads of subsystems m , n , and o are multiplied by 1, 1.2, and 1.2, respectively. The thermal unit climb and slip rates are set to 30% of the maximum output. The minimum and maximum active outputs of the LCC-HVDC and VSC-HVDC are set to [400, 1500] MW and [0, 1000] MW, respectively, and the transmission schedules of the DC tie-line are 20 GWh and 15 GWh, respectively. The minimum and maximum adjustment power of the LCC-HVDC and VSC-HVDC are [50, 500] MW and [10, 300] MW. The numbers of times the LCC-HVDC and VSC-HVDC DC tie lines can be adjusted in a day are 6 and 12, respectively. The minimum adjustment interval is 2. The penalty unit price of wind abandonment is 100\$/MW. The total number of scheduling periods is 24, and each scheduling period is set as one hour. In addition, the settings are $\alpha_{m,t} = \beta_{m,t} = \alpha_{n,t} = \beta_{n,t} = 0.02$, $\gamma = 1.2$, and $\varepsilon_c = \varepsilon_o = 1\%$. The initial power of the DC tie-lines is set to 0.

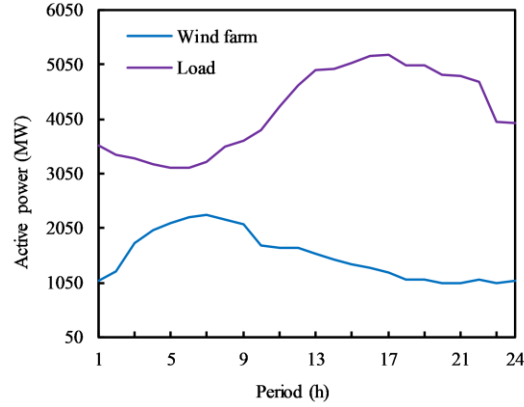


Fig. 4. The predicted output of the wind farm and the predicted load.

Table 1 compares the optimization results of the four scheduling models. The results of Model 2 and Model 4 are basically the same as those of Model 3, which indicates that the proposed model can obtain accurate results. The wind abandonment rate of the wind farm and the total cost for Model 1 are much higher than those of Model 2 and Model 4. This is because Model 1 does not consider the flexible control of the DC tie-line and adopts the transmission mode of fixed segmentation of the DC tie-line. Therefore, utilizing the flexible control of the DC tie-line can promote the cross-area consumption of wind power, reduce the peak adjustment pressure of the receiving subsystem, and improve the operation economy of the whole system.

Table 1
Comparisons of the scheduling results for Case 1.

DC tie-line power transfer models	Model 1	Model 2	Model 3	Model 4
Wind abandonment rate	12.3%	2.1%	2.1%	2.08%
Total cost (k\$)	4733	4190	4195	4194

The active power of the LCC-HVDC and VSC-HVDC tie-lines obtained by optimization is shown in Fig. 5 and Fig. 6. In Models 2, 3, and 4, which take the flexible control of the DC tie-line into consideration, the transmission power of the DC tie-lines increases during periods of high wind power generation and peak load periods, which indicates that flexible control of the DC tie-line transmission power helps transmit the surplus wind power of the delivery subsystem to the receiving subsystem, achieving cross-area consumption of wind power resources and improving the operation and economy of the whole system. In addition, by comparing Fig. 5 and Fig. 6, it can be found that the number of controls of the VSC-HVDC tie-line power is significantly higher than that of the LCC-HVDC, which is due to the more flexible control of the VSC-HVDC.

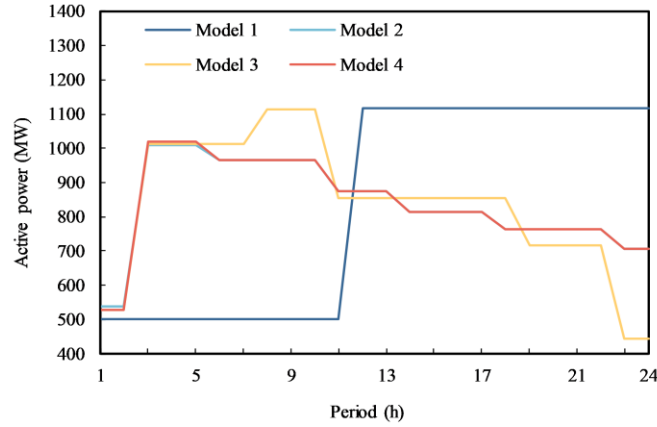


Fig. 5. LCC-HVDC tie-line active power for Case 1.

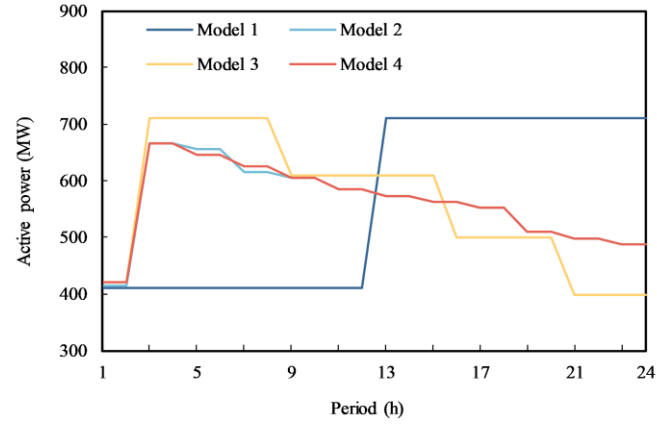


Fig. 6. VSC-HVDC tie-line active power for Case 1.

To verify the computational efficiency of the proposed method, the computational efficiencies of Models 1, 3, and 4 are compared, as shown in Table 2. The number of iterations and computation time needed for convergence in Model 1 is smaller than those in Models 3 and 4. Although the number of iterations and the computation time needed for convergence in Model 4 are higher than those in Model 2, the purpose of Model 4 is mainly to achieve area scheduling independence, promote the cross-area consumption of wind power in the AC/DC system, and ensure the privacy of area subsystem information rather than to improve computational efficiency. In addition, the number of iterations and computational time needed for the convergence of Model 4 are lower than those of Model 3.

Table 2
Comparisons of Computational Efficiency for Case 1.

DC tie-line power transfer models	Number of iterations	computation time (s)
Model 1	14	27.3
Model 3	16	114.5
Model 4	15	103.2

Table 3 summarizes the wind power abandonment rate and the total cost for Model 4 under different numbers of DC tie-line adjustments. As the number of adjustments increases, the operation mode of the DC tie-lines becomes more flexible. Therefore, the wind power abandonment rate and the total cost in Table 3 show a decreasing trend. Due to the flexible adjustment of VSC stations, VSC-HVDC tie-lines can undergo more frequent power adjustments to reduce the wind power abandonment rate and total cost. Therefore, to protect power electronic equipment, the power adjustment frequency of the LCC-HVDC tie-line can be set to 6. To further reduce the wind power abandonment rate and the total cost, the power adjustment frequency of the VSC-HVDC tie-line can be set to 12.

Table 3
Comparisons of Results Under Different DC Tie-Line Adjustment Times for Case 1.

DC tie-line adjustment times	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5	
	LCC	VSC	LCC	VSC	LCC	VSC	LCC	VSC	LCC	VSC
	0	0	3	3	3	6	6	6	6	12
Wind abandonment rate	11.9%		7.91%		6.49%		4.02%		2.08%	
Total cost (k\$)	4365		4315		4296		4256		4194	

Fig. 7 summarizes the transmission power of the DC tie-line under different adjustment times. Fig. 7 shows that the flexibility of DC tie-line adjustment decreases when the number of adjustments in Mode 3 compared to the maximum

number of adjustments (Mode 5). Therefore, the transmission power of the DC tie-line cannot be reduced according to the wind power output and load from 03:00 to 08:00. This also shows that an increase in the flexibility of the DC tie-line adjustment does not necessarily mean that the delivery subsystem transmits more power to the receiving subsystem but rather somewhat improves the system operation economy from a global perspective.

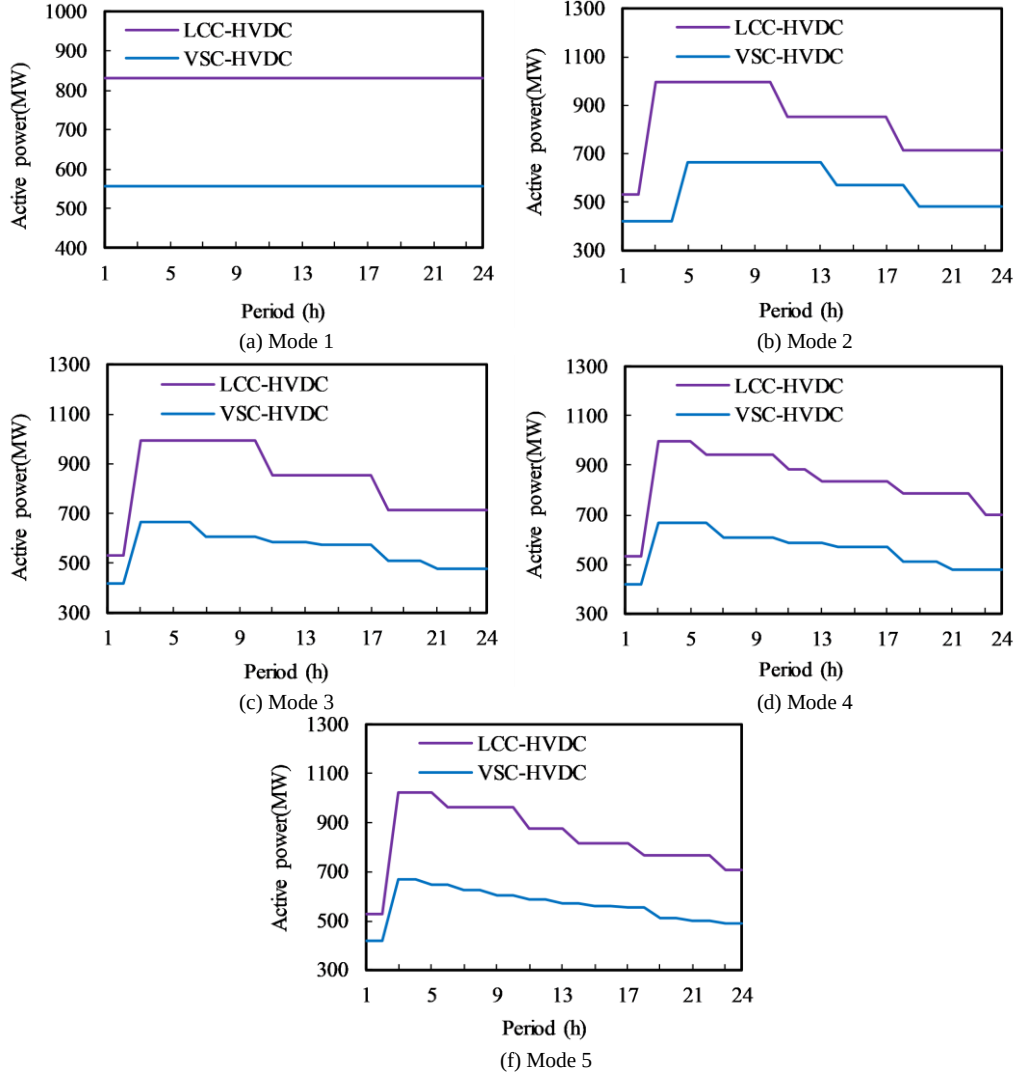


Fig. 7. DC tie-line transmission power under different adjustment times for Case 1

Fig. 8 summarizes the wind power abandonment under different numbers of DC tie-line adjustments. With the number of adjustments to the DC tie-line increasing, the operating mode of the DC tie-line becomes more flexible, resulting in a decreasing trend in the wind curtailment of the wind farm. The wind power consumption ratio obtained by adjusting Mode 5 is the highest, which means that increasing the number of adjustments to the DC tie-line can promote wind power consumption. This helps transmit surplus wind power from the delivery subsystem to the receiving subsystem, realizing the cross-area consumption of wind power resources.

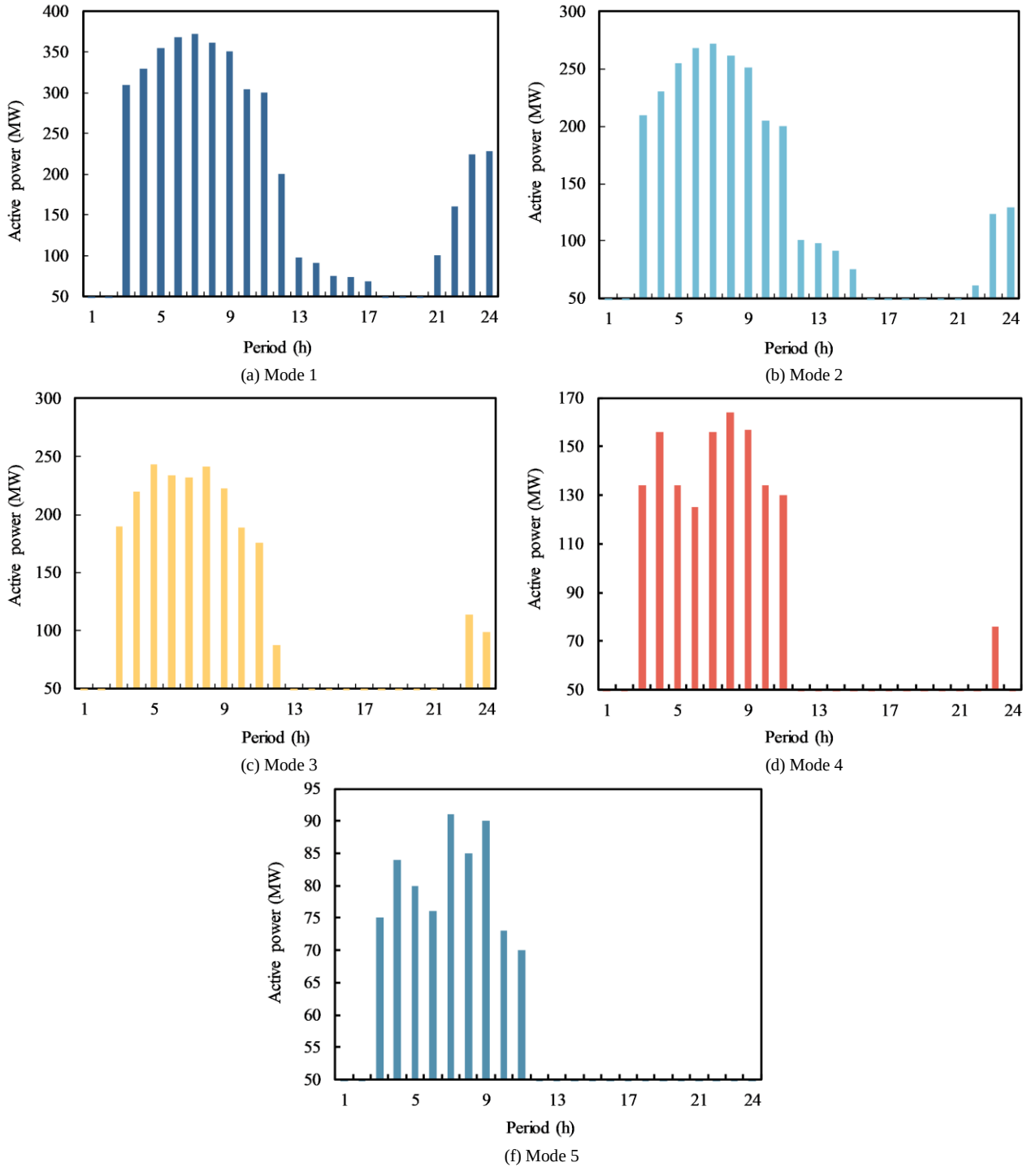


Fig. 8. Wind power abandonment under different numbers of DC tie-line adjustments for Case 1.

The DC tie-line power variance is selected to compare the smoothness of the DC tie-line power in Models 3 and 4. Fig. 9 shows that the DC tie-line power fluctuations in the day-ahead scheduling model are greater than those in our proposed intraday two-stage optimal scheduling model. The intraday two-stage optimal scheduling method can smooth the DC tie-line power and adapt well to fluctuations in the wind power output. Model 4 takes into consideration the effects of future predictions in the finite time domain and the latest measured DC tie-line power on the current scheduling state. This approach can avoid repeated adjustment and overadjustment of the DC tie-line power. It helps adapt to wind power fluctuations and make thermal unit outputs smoother. Therefore, intraday two-stage optimal scheduling can improve the operational reliability of multiarea AC/DC systems, indirectly reduce the mechanical loss of thermal units, and prolong working life.

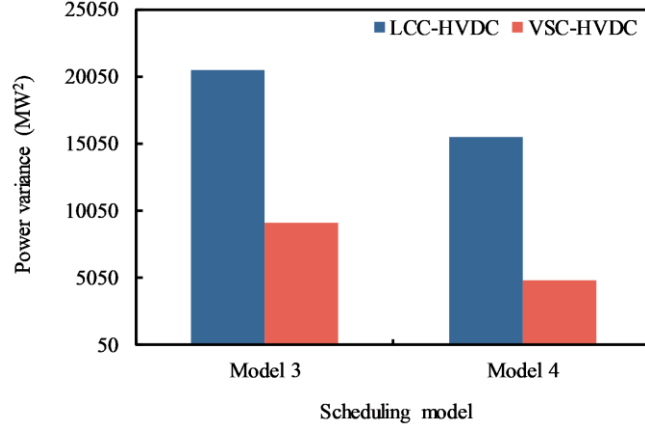


Fig. 9. DC tie-line power variance for Case 1

Fig. 10 illustrates the convergence process of hierarchical optimization. Fig. 10 shows that all the subsystems satisfy the convergence criterion after 15 iterations. Since each regional scheduling subsystem can solve its subproblems and update the penalty factors independently and in parallel during the iteration process, the solution time for each iteration is the sum of the maximum computation time of each subsystem and the computation time of the upper-level scheduling system. For this 117-node system, during each iteration, the area subsystems need to exchange only the power of the DC tie-line and the corresponding penalty factor at each moment with the upper-level scheduling system, which can significantly reduce the communication burden between subsystems.

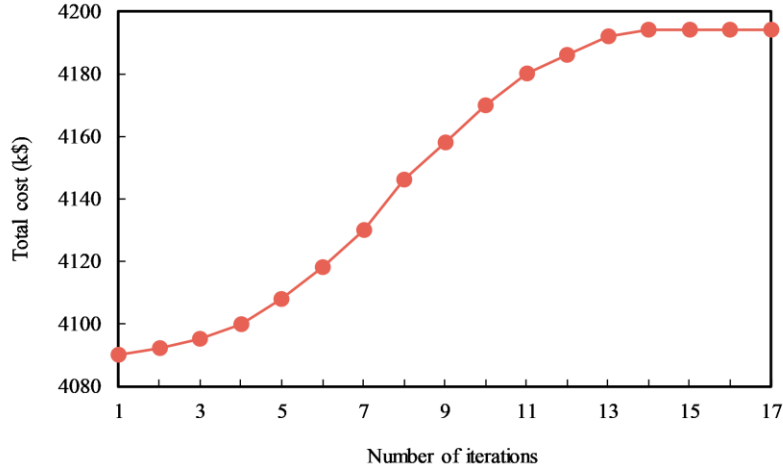


Fig. 10. Convergence process of ATC for Case 1

5.2. Case 2: 3-area 354-node AC/DC system

Case 2 concerns three 118-node systems (subsystems m , n , and o) [38]. Including 354 nodes, 558 internal lines, 162 thermal units, 5 wind farms, 273 load nodes, 1 LCC-HVDC tie-line, and 1 VSC-HVDC tie-line. Node 65 in subsystem m and node 65 in subsystem o are connected via a VSC-HVDC tie-line. Node 25 of subsystem m is connected to node 25 of subsystem n by an LCC-HVDC tie-line. Five identical wind farms are located at nodes 36, 38, 63, 68 and 77 of subsystem m . The predicted load of subsystem m is 1.3 times the daily load of subsystem m in Case 1, and the predicted output of the wind farm of subsystem m is 0.765 times the wind farm of subsystem m in Case 1. The minimum and maximum active outputs of the VSC-HVDC and LCC-HVDC are set to $[0, 1500]$ MW and $[0, 2000]$ MW, respectively, and the transmission schedules of the DC tie-line are 25 GWh. The other parameter settings are the same as in Case 1.

As the node size increases, to further verify the superiority of the flexible adjustment ability of DC tie-lines in promoting cross-area wind power consumption, similar to Case 1, 5 DC adjustment modes are set up for comparative analysis. The results are shown in Table 4 and Fig. 11. As the number of adjustments increases, the operation mode of the DC tie-lines becomes more flexible. Therefore, the wind power abandonment rate and the total cost in Table 4 show a decreasing trend. This again reflects the flexible adjustment of DC tie-lines with increasing node size, which is beneficial for improving wind power utilization and the overall operational economy of the system. Fig. 11 shows that the flexibility of DC tie-line adjustment decreases when the number of adjustments is in Mode 3 compared to the maximum number of adjustments (Mode 5). Therefore, the transmission power of the DC tie-line cannot be reduced according to the wind power output and load from 05:00 to 09:00. This also shows that an increase in the flexibility of the DC tie-line adjustment does not

necessarily mean that the delivery subsystem transmits more power to the receiving subsystem but rather somewhat improves the system operation economy from a global perspective.

Table 4

Comparisons of Results Under Different DC Tie-line Adjustment Times for Case 2.

DC tie-line adjustment times	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5	
	LCC	VSC	LCC	VSC	LCC	VSC	LCC	VSC	LCC	VSC
	0	0	3	3	3	6	6	6	6	12
Wind abandonment rate	10.57%		7.43%		5.93%		3.58%		1.53%	
Total cost (k\$)	21051		21048		21044		21038		21030	

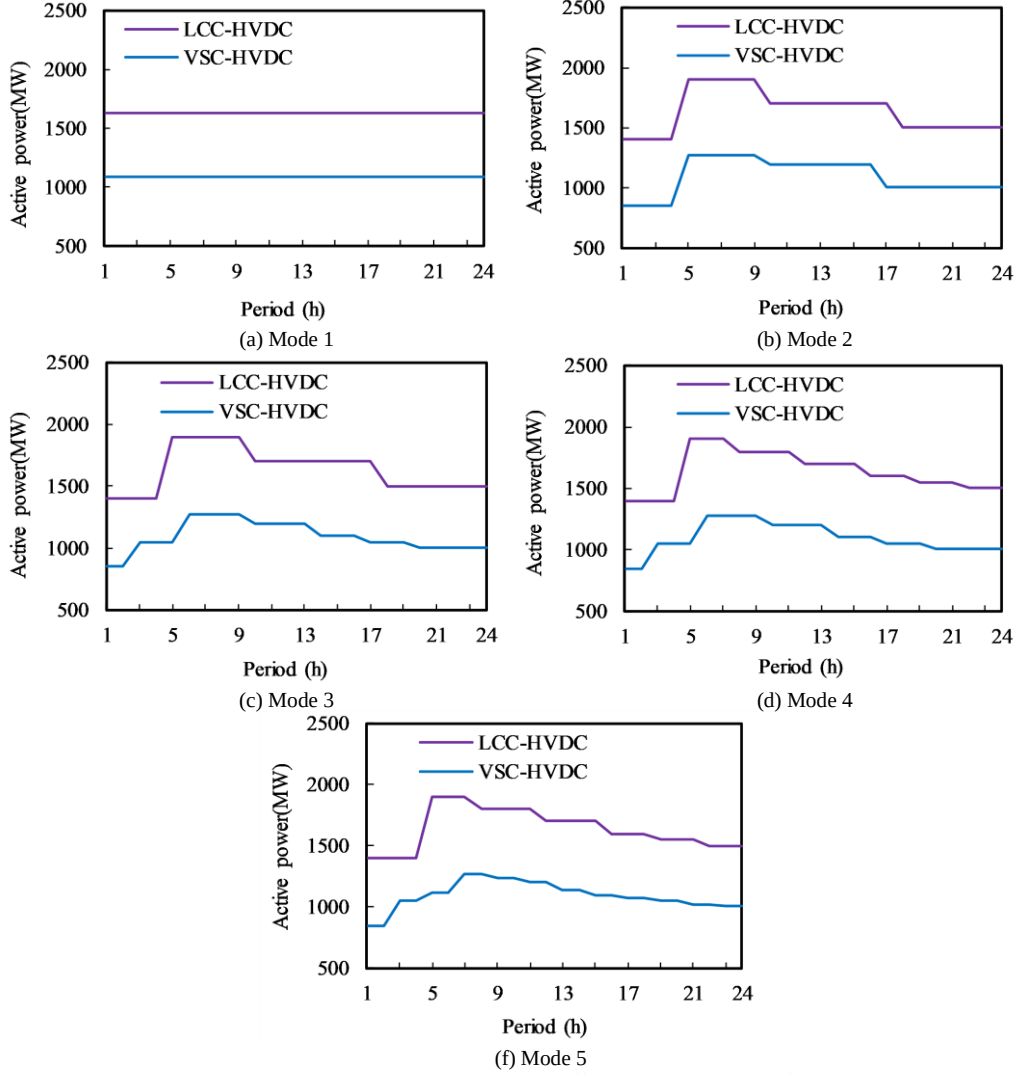


Fig. 11. DC tie-line transmission power under different adjustment times for Case 2

Fig. 12 summarizes the wind power abandonment under different numbers of DC tie-line adjustments as the node size increases. The number of adjustments to the DC tie-line is increasing, resulting in a decreasing trend in the wind power abandonment of the wind farm and the total cost. The wind power consumption ratio obtained by adjusting Mode 5 is the highest, which means that increasing the number of adjustments to the DC tie-line can promote wind power consumption—realizing the cross-area consumption of wind power resources.

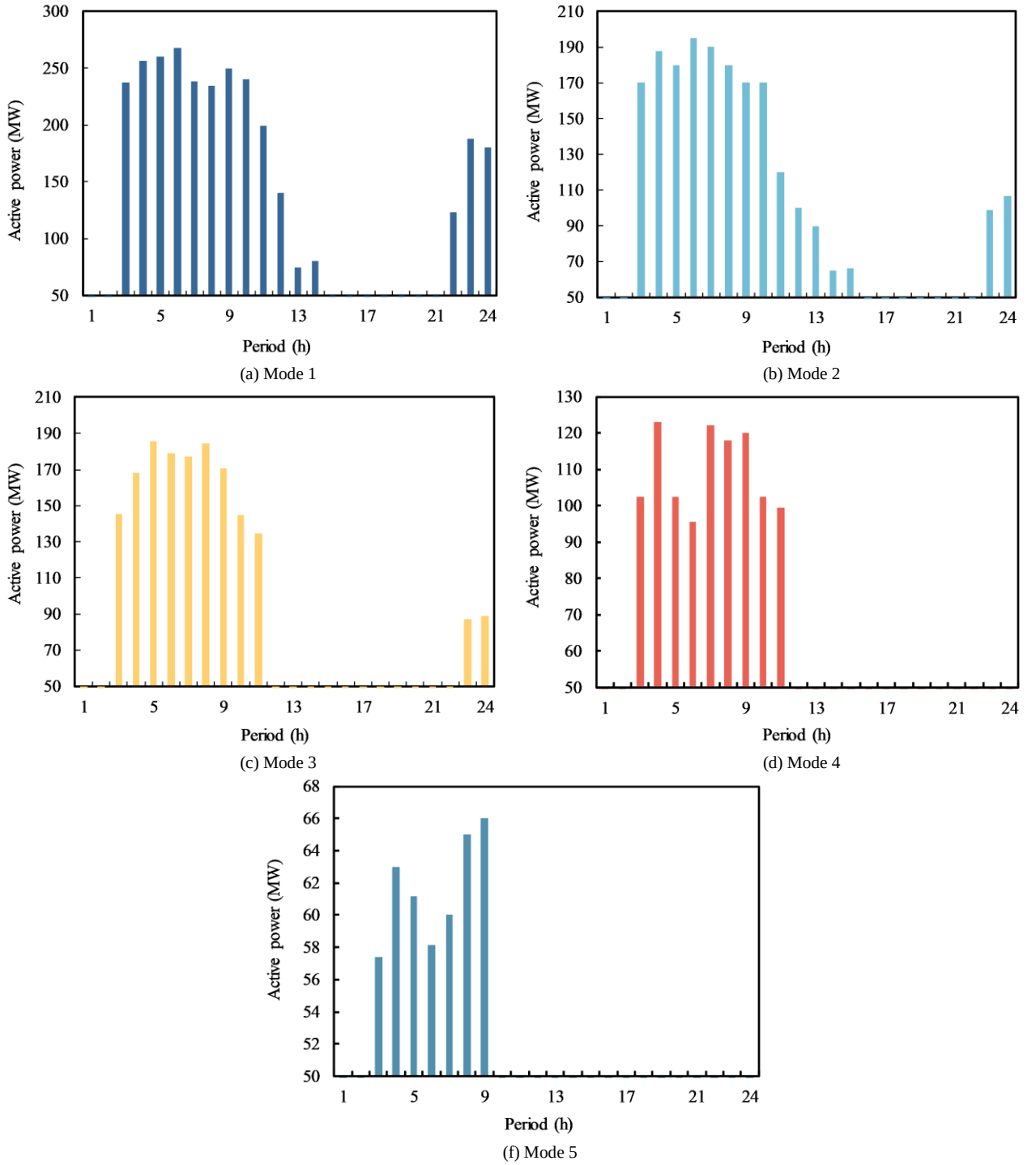


Fig. 12. Wind power curtailment under different numbers of DC tie-line adjustments for Case 2.

Fig. 13 illustrates the convergence process of hierarchical optimization. **Fig. 13** shows that all the subsystems satisfy the convergence criterion after 16 iterations. Since each regional scheduling subsystem can solve its subproblems and update the penalty factors independently and in parallel during the iteration process, the solution time for each iteration is the sum of the maximum computation time of each subsystem and the computation time of the upper-level scheduling system. For this 354-node system, during each iteration, the area subsystems need to exchange only the power of the DC tie-line and the corresponding penalty factor at each moment with the upper-level scheduling system, which can significantly reduce the communication burden between subsystems.

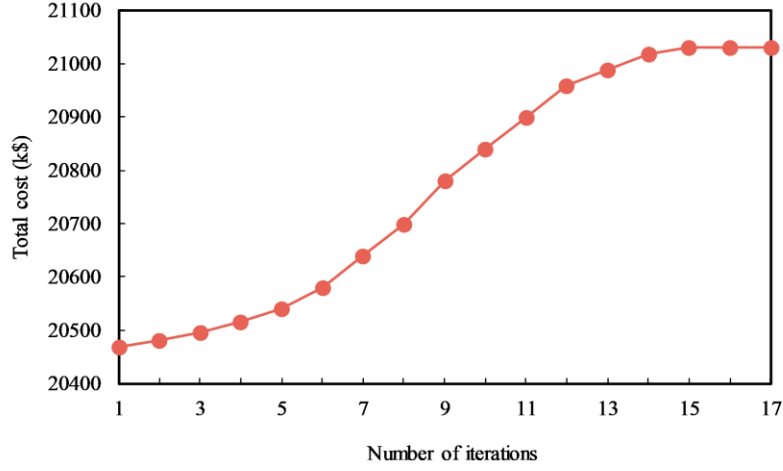


Fig. 13. Convergence process of ATC for Case 2

5.3. Optimization analysis under communication failures

Communication failures influence the information interactions between subsystems. We conduct Models 2, 3, and 4 optimizations to illustrate the effectiveness and superiority of the proposed approach in dealing with communication failures. Comparisons are conducted in four communication failure scenarios, and the optimal results are also compared with those in the nominal scenario without failure (i.e., Scenario 4), as shown in Table 5. The frameworks with communication failures are shown in Fig. 14, and Table 6 reports the optimal objectives.

Table 5
Scenario setting.

Scenarios	Settings
Scenario 1	Subsystem m loses information interaction with the upper-level due to subsystem m .
Scenario 2	The communication centre of subsystem m fails.
Scenario 3	The communication centre of the upper-level malfunctions
Scenario 4	The nominal scenario without failure

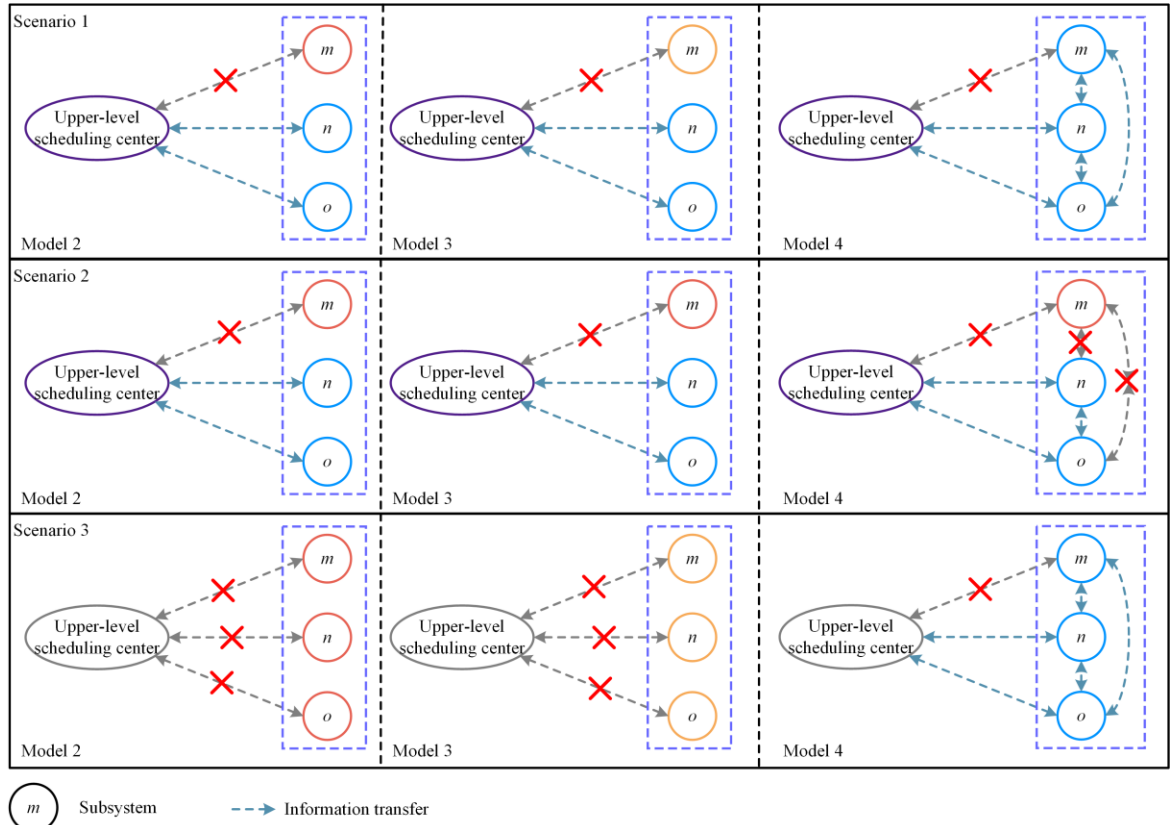


Fig. 14. Frameworks with different communication failures.

Table 6
Comparison analysis of communication scenarios

Scenarios	Models	Case 1		Case 2	
		Total cost (k\$)	Wind abandonment rate	Total cost (k\$)	Wind abandonment rate
1	Model 2	4296	8.15%	21148	7.39%
	Model 3	4271	6.53%	21118	5.33%
	Model 4	4217	2.62%	21052	1.74%
2	Model 2	4296	8.15%	21148	7.39%
	Model 3	4271	6.53%	21118	5.33%
	Model 4	4351	13.51%	21208	11.9%
3	Model 2	4468	19.32%	21325	17.5%
	Model 3	4398	16.36%	21267	14.95%
	Model 4	4271	2.62%	21052	1.74%
4	Model 2	4190	2.1%	21032	1.62%
	Model 3	4195	2.1%	21040	1.62%
	Model 4	4194	2.08%	21030	1.53%

Table 6 and Fig.14 indicate that the multiarea AC/DC system loses some of the coordinated interactions of DC tie-lines under communication failures, resulting in greater operational costs than in Scenario 4. For Scenario 1, subsystem m is independently dispatched in Models 2 and 3; thus, the total cost of the multiarea AC/DC system without external coordination is high. In Model 4, subsystem m , without interactions with the upper-level scheduling centre, still communicates with subsystem n and subsystem o , such that coordinated scheduling of subsystem m , subsystem n , and subsystem o is maintained. In Models 2 and 3, for Scenario 3, the upper-level coordinator's control command cannot be updated. For Scenario 2. In Models 2, 3, or 4, subsystem m loses all the information interactions with other subsystems.

The above analysis shows that Model 4 can still guarantee partial communications in different failure scenarios. Compared with Model 2 and Model 3, Model 4 can effectively mitigate communication failures and provide more economical plans for all subsystems in the multiarea AC/DC system.

6. Conclusion

To make full use of the flexible adjustment capability of DC tie-lines in multiarea AC/DC systems and to coordinate the generation resources and load demand of multiarea AC/DC systems, we propose an intraday two-stage hierarchical optimal scheduling model for multiarea AC/DC systems based on analytical target cascading technology (ATC). The main conclusions are as follows:

(1) Based on the ATC and the area decomposition criterion of AC/DC systems, the intraday two-stage hierarchical optimal scheduling model for multiarea AC/DC systems takes into consideration the DC tie-line adjustment constraints and the area coupling constraints. The proposed method can achieve decoupling scheduling of multiarea AC/DC systems and ensure the efficiency of the solution algorithm in real time. By fully utilizing the flexible control of the DC tie-line, the capacity for large-scale wind power consumption can be improved.

(2) Based on the open-loop optimal control algorithm and the MPC, the two-stage rolling coordinated scheduling method takes into consideration the influence of the predicted value in the future finite time domain and the latest measured DC tie-line on the current scheduling state, which is conducive to adapting to the wind power fluctuations and smoothing the DC tie-line adjustment.

(3) Under communication failures, the proposed method can guarantee partial communications in different failure scenarios, can effectively mitigate the impact of communication failures and provide more economical plans for all subsystems in the multiarea AC/DC system.

In this paper, Considering the flexible control characteristics of DC tie-lines and to reduce computational complexity, we specifically only considered multiarea AC/DC networks with DC interconnection. However, in actual power grids, there may be operating scenarios where AC and DC tie-lines coexist, which will be the focus of our next research.

CRedit authorship contribution statement

Dong Yu: Conceptualization, Methodology, Software. **Shan Gao:** Supervision. **Xin Zhao:** Visualization, Investigation. **Yu Liu:** Data curation, Project administration. **Haiteng HAN, Chuanshen Wu:** Writing - review & editing. **Tiancheng E. Song:** Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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