A Decentralized Dispatch Approach on AC/DC Hybrid Power Systems with Wind Power

Ming Zhou, *Member*, *IEEE*, Junyi Zhai, Gengyin Li, *Member*, *IEEE,* Jiahui Zhang, Yuan Wang
State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources
North China Electric Power University
Beijing, China
zhouming@ncepu.edu.cn

***Abstract*--This paper focuses on the day-ahead active power dispatch for interconnected power systems with wind power integration via HVDC tie-line. Considering the complex operating characteristics of HVDC tie-line, a decentralized dispatch model based on analytical target cascading (ATC) technique is proposed. The day-ahead power dispatch is divided into the master problem of the upper-level coordination dispatch and the subproblem of the lower-level regional dispatch. The upper-level dispatch center is responsible for coordinating the HVDC tie-line power flow between the interconnected areas, and the lower-level dispatch centers solve the security-constrained unit commitment (SCUC) problem of each area independently. Through the decomposition and coordination mechanisms, the economy of the entire interconnected system is achieved. A 12-bus two area system interconnected via HVDC tie-line is utilized to verify the effectiveness of the proposed model.**

***Index Terms*—AC/DC power system, HVDC transmission plan, wind power accommodation, decomposition and coordination, analytical target cascading technique.**

I. Introduction

By the end of 2015, the total installed capacity of wind power in China has exceeded 140GW, ranking first in the world. Most of these wind power is transferred to remote load center through hybrid HVAC and HVDC transmission. In fact, the cross-regional HVDC transmission capacity has exceeded 50 GW, which also ranks first in the world. A large-scale AC/DC hybrid interconnected power grid has been formed in China Southern Power Grid and East China Power Grid. This cross-regional HVDC interconnection and high penetration of wind power have brought big challenges to the dispatching operation of power system.

Segmented operation mode is widely used in the traditional cross-regional HVDC transmission. However, the transmission power is constant in each section, lacking the ability of responding to wind power fluctuations. Since the power flow of HVDC tie-line can be flexibly controlled, it is essential to make full use of the adjustment ability of HVDC tie-line to greatly promote wind power accommodation in the interconnected power grid.

In [1], the SCUC model considering the steady-state operation characteristics of AC/DC hybrid transmission system is established, and the Benders decomposition method is used to solve the problems. In [2], the unified optimization model of OPF for AC/DC interconnected power grid is established. In [3], a two-stage day-ahead generation scheduling model is proposed to optimize the regional HVDC tie-line transmission plan. These researches focus on the generation schemes in the centralized dispatch mode. For the AC/DC interconnected power grid, how to coordinately optimize the generation schemes and HVDC tie-line transmission plan is worthy of further researches.

Since the interconnected power grid is large in scale, it is unrealistic to carry on the centralized dispatch mode. However, the decentralized dispatch mode can reduce calculation complexity and maintain independent regional autonomy. The coordinated dispatch strategy of interconnected power grid under electricity market environment is studied in [4]. In [5], the augmented Lagrangian relaxation (ALR) algorithm is proposed to solve the multi-area OPF problem. In [6], the auxiliary problem principle (APP) algorithm is used to solve the OPF problem of large-scale power system. A decomposition and coordination algorithm is proposed in [7] and [8] for multi-area power systems using APP algorithm, in which a two-stage stochastic programing model is addressed to consider wind power uncertainty. A coordinated decentralized risk-based dispatch method based on analytical target cascading (ATC) technique is presented in [9]. However, the study only focuses on single interval, and the problem of dynamic coupling for multiple periods is not considered. In [10], a distributed SCUC model and a parallel calculation method are proposed to solve the large-scale SCUC problem based on ATC technique. These researches mentioned above have employed a decentralized manner to solve the multi-area active power dispatch, but fail to consider the coordination of HVDC tie-line transmission.

Considering the flexible operation characteristics of HVDC tie-line, we adopt a decomposition and coordination algorithm based on ATC technique [10] [12] to solve the day-ahead SCUC problem for interconnected power grid with wind power integration. Wherein, the upper-level dispatch center is responsible for coordinating the HVDC tie-line power flow between the interconnected areas, and the lower-level dispatch centers solve the SCUC problem of each area independently. Consequently, through the decomposition and coordination mechanisms, the economic operation of the entire interconnected system and the decentralized autonomy of regional power grid are achieved.

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II. Centralized Dispatch Formulation

In the centralized dispatch framework, the upper-level dispatch center needs to obtain the characteristics of units of whole system and the topological information of power grid. Formula (1) shows the optimization goal of the traditional centralized dispatch model.

$$\min C=\sum_{t\in T}\left\{\sum_{i\in N_{\mathrm{G}}}[C_i(P_{it}^{\mathrm{G}},u_{it})+v_{it}C_i^{\mathrm{SU}}]+\sum_{j\in N_{\mathrm{W}}}(C^{\mathrm{WS}}P_{jt}^{\mathrm{WS}})\right\} \quad (1)$$

where N_{G}, N_{W} are the set of thermal units and wind turbines, $u_{i,t}$, P_{it}^{G} are the on-off states and output of thermal unit *i* at time *t*, C_i^{SU} is the start-up cost of thermal unit *i*, C^{WS} is the penalty cost coefficient of curtailed wind, P_{jt}^{WS} is the amount of curtailed wind of wind turbine *j* at time *t*.

III. Decentralized Dispatch Framework and Regional Decomposition Criterion

In this paper, the decentralized dispatch model is proposed for cross-regional interconnected power systems with multi-level dispatch centers. In our decentralized dispatch framework, each area is a lower-level dispatch center and has the autonomy ability. But the lower-level dispatch center is only responsible for scheduling their own generators, and the upper-level dispatch center is responsible for coordinating the HVDC tie-line power flow between the interconnected areas. Such that, there is no information interaction between lower-level dispatch centers.

We focus on the power exchange scheme of the HVDC tie-line, and the key to decomposing a large-scale system into a regional subsystem is to find a suitable coupling constraint. Considering that the method of phase angle difference is not suitable for analyzing the power flow of HVDC tie-line, therefore, the branch cutting method is adopted in our model to directly cut the HVDC tie-line. Regarding the power flow of HVDC tie-line as the shared variable, the interconnected area is divided into two isolated areas, furthermore, an equivalent generator is added to the HVDC tie-line bus in each isolated area. The regional decomposition technique is shown in Fig.1.

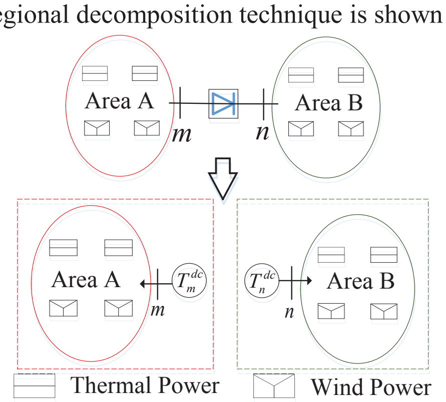

Fig. 1. Regional Decomposition Technique

The method of taking the power flow of HVDC tie-line as the shared variable has three advantages: 1) power flow of HVDC tie-line can be dealt with effectively, which can avoid the difficulty when using the method of phase angle difference, 2) only the power flow of HVDC tie-line and algorithm multipliers need to be exchanged between the upper-level and lower-level dispatch centers, reducing the communication burden, 3) it is not necessary to convey the phase angle information of boundary buses, and each area can set the slack bus independently.

In our decentralized dispatch model, the following regional coupling constraints must be satisfied:

$$T_m^{dc}+T_n^{dc}=0 \quad (2)$$

where T_m^{dc}, T_n^{dc} are the equivalent generator output of area A and area B, respectively.

IV. Decentralized Dispatch Model for Interconnected Power Grid via HVDC Tie-Line

A. The Subproblem of the Lower-level Regional Dispatch

Under the premise of satisfying cross-regional HVDC tie-line power exchange scheme, the exchange power of HVDC tie-line can be regarded as a variable to be optimized, that is to say, the output of equivalent generators in the HVDC tie-line buses are to be optimized. For the most part, the output constraints of equivalent generators are different from those of traditional generators, and their output constraints are more complex to reflect the operating conditions of HVDC tie-line. The operation constraints of equivalent generators in the HVDC tie-line bus are as follows:

1) Power adjustment direction constraints during adjacent periods

To protect the DC converter, the power adjustment direction of equivalent generators cannot be reversed during adjacent periods.

Defining 0-1 integer variables x_{mt}, x_{mt}^{+}, x_{mt}^{-}, which represents whether the equivalent generator *m* adjusts the output, rumps up or rumps down at time *t*, respectively. Therefore, that the power adjustment direction cannot be reversed during adjacent periods can be expressed as:

$$\begin{cases} x_{mt}^{+}+x_{mt}^{-}=x_{mt}\le 1 \\ x_{mt}^{+}+x_{mt+1}^{-}\le 1 \\ x_{mt+1}^{+}+x_{mt}^{-}\le 1 \end{cases} \quad (3)$$

According to [11], x_{mt}^{+}, x_{mt}^{-} can be expressed by the change of equivalent generator output and the auxiliary 0-1 integer variables z_{mt}^{+} and z_{mt}^{-}, which are as follows:

$$\begin{cases} T_{mt}^{dc}-T_{mt-1}^{dc}\le M^{+}z_{mt}^{+} \\ T_{mt-1}^{dc}-T_{mt}^{dc}\le M^{-}z_{mt}^{-} \\ x_{mt}^{+}\ge z_{mt}^{+} \\ x_{mt}^{-}\ge z_{mt}^{-} \end{cases} \quad (4)$$

where M^{+} 、 M^{-} are constants which can make the equation valid.

2) Power adjustment rate constraints of the equivalent generator during adjacent periods

Different from the traditional generator's rump-up and rump-down rate constraints, we set the minimum power adjustment of equivalent generator which is greater than a fixed value to avoid the repeated adjustment of HVDC tie-line power in small amplitude during adjacent periods.

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$$x_{mt}\underline{\delta}_m^{dc} \le \left|T_{mt}^{dc} - T_{mt-1}^{dc}\right| \le x_{mt}\bar{\delta}_m^{dc} \tag{5}$$

where $\underline{\delta}_m^{dc}$, $\bar{\delta}_m^{dc}$ are the minimum and maximum power adjustment rate of equivalent generator m.

3) Minimum and maximum output constraints of equivalent generators

$$\underline{T}_m^{dc} \le T_{mt}^{dc} \le \bar{T}_m^{dc} \tag{6}$$

where $\underline{T}_m^{dc}$, $\bar{T}_m^{dc}$ are the minimum and maximum output of equivalent generator m.

4) Stepwise output constraints of equivalent generator

In order to keep the HVDC tie-line power as a stepwise state, the equivalent generator should keep the output constant at least one minimum time interval after one adjustment (rump-up or rump-down in single or multiple continuous time interval). We define 0-1 variables a_{mt}^+ , a_{mt}^- to represent whether the equivalent generator m is to start the adjustment, or to end the adjustment at time t.

$$a_{mt}^- + \sum_{\tau=t+1}^{\min(T,t+N_\mathrm{T})} a_{m\tau}^+ \le 1 \tag{7}$$

where N_T is the minimum number of time intervals.

According to [11], through the auxiliary 0-1 integer y_{mt} , the following constraints can be obtained:

$$\begin{cases} a_{mt}^+ \ge x_{mt+1} - y_{mt} \\ a_{mt}^- \ge x_{mt} - y_{mt} \\ y_{mt} \le x_{mt} \\ y_{mt} \le x_{mt+1} \\ y_{mt} \ge x_{mt} + x_{mt+1} - 1 \end{cases} \tag{8}$$

5) Total output constraints of the equivalent generator in the scheduling cycle

This constraint is to reflect that the HVDC tie-line transmission capacity is determined by the day-ahead contract.

$$(1-\rho)Q_m \le \sum_{t\in T} T_{mt}^{dc} \le (1+\rho)Q_m \tag{9}$$

where Q_m denotes the day-ahead planned transmission capacity of the HVDC tie-line, while ρ is the allowable deviation ratio of transmission capacity.

In the ATC technique framework, each lower-level dispatch center should solve its own dispatch scheme using the shared parameters issued by upper-level dispatch center. Therefore, the optimization goal of traditional centralized dispatch model should be adjusted, that is to increase an augmented Lagrangian penalty function, so that the tie-line power obtained from the lower-level dispatch centers can approximate to the power issued by the upper-level dispatch center. The symbol $\circ$ represents the Hadamard product: a multiplication of two vectors. The sub optimization model of the lower-level dispatch center A (area A) is as follows:

$$\begin{aligned} \min \sum_{t\in T} \Bigg\{ & \sum_{i\in N_\mathrm{G}^A} [C_i(P_{it}^\mathrm{G}, u_{it}) + v_{it}C_i^\mathrm{SU}] + \sum_{j\in N_\mathrm{W}^A} C^\mathrm{WS}P_{jt}^\mathrm{WS}) \\ & + \sum_{m\in\Omega_{dc}^A} [\alpha_{mt}^{dc}(\tilde{T}_{mt}^{dc*} - T_{mt}^{dc}) + \left\|\beta_{mt}^{dc} \circ (\tilde{T}_{mt}^{dc*} - T_{mt}^{dc})\right\|_2^2] \Bigg\} \end{aligned} \tag{10}$$

$$\text{s.t.} \quad \sum_{i\in N_\mathrm{G}^A} P_{it}^\mathrm{G} + \sum_{j\in N_\mathrm{W}^A} (P_{jt}^\mathrm{W} - P_{jt}^\mathrm{WS}) + K\sum_{m\in\Omega_{dc}^A} T_{mt}^{dc} = \sum_{k\in\Omega_\mathrm{D}^A} D_{kt} \tag{11}$$

$$\begin{aligned} &\sum_{i\in N_\mathrm{G}^A} [\min(\bar{P}_i^\mathrm{G}, P_{it}^\mathrm{G} + RU_i)u_{it}] + \sum_{j\in N_\mathrm{W}^A} (P_{jt}^\mathrm{W} - P_{jt}^\mathrm{WS}) \\ &\qquad \ge \sum_{k\in\Omega_\mathrm{D}^A} D_{kt} - K\sum_{m\in\Omega_{dc}^A} \bar{T}_m^{dc} + R_t^{+A} \end{aligned} \tag{12}$$

$$\begin{aligned} &\sum_{i\in N_\mathrm{G}^A} [\max(\underline{P}_i^\mathrm{G}, P_{it}^\mathrm{G} - RD_i)u_{it}] + \sum_{j\in N_\mathrm{W}^A} (P_{jt}^\mathrm{W} - P_{jt}^\mathrm{WS}) \\ &\qquad \le \sum_{k\in\Omega_\mathrm{D}^A} D_{kt} - K\sum_{m\in\Omega_{dc}^A} \underline{T}_m^{dc} - R_t^{-A} \end{aligned} \tag{13}$$

$$R_t^{-A} = \omega_d \sum_{j\in N_\mathrm{W}^A} (\bar{P}_j^\mathrm{W} - P_{jt}^\mathrm{W}) \tag{14}$$

$$R_t^{+A} = \omega_u \sum_{j\in N_\mathrm{W}^A} P_{jt}^\mathrm{W} + \omega_D \sum_{k\in\Omega_\mathrm{D}^A} D_{kt} \tag{15}$$

$$\begin{aligned} &\Bigg| \sum_{i\in N_\mathrm{G}^A} H_{li}^\mathrm{G} P_{it}^\mathrm{G} + K\sum_{m\in\Omega_{dc}^A} H_{lm}^{dc} T_{mt}^{dc} + \sum_{k\in\Omega_\mathrm{D}^A} H_{lk}^D D_{kt} \\ &\qquad + \sum_{j\in N_\mathrm{W}^A} H_{lj}^\mathrm{W} (P_{jt}^\mathrm{W} - P_{jt}^\mathrm{WS}) \Bigg| \le \bar{F}_l \end{aligned} \tag{16}$$

$$\text{(3)-(9)} \tag{17}$$

$$K \in \{-1,1\}, \forall t \in T, \forall l \in L^A$$

where Ω_{dc}^A , Ω_D^A are the set of HVDC tie-line buses and load buses in area A; $\tilde{T}_{mt}^{dc*}$ is the optimal output of equivalent generator m at time t issued by the upper-level dispatch center; T_{mt}^{dc} is the output of equivalent generator m at time t; α_{mt}^{dc} , β_{mt}^{dc} are the multipliers; K is the flag of rectified state and inverter state; P_{jt}^W is the wind power forecast of wind turbine j at time t; D_{kt} is the load of bus k at time t; $\underline{P}_{\mathrm{G}i}$, $\bar{P}_{\mathrm{G}i}$ are the minimum and maximum output of thermal unit i; RD_i , RU_i are the ramp-down and ramp-up rate of thermal unit i; ω_u , ω_d , ω_D are the demand coefficient of wind power up reserve, wind power down reserve and load; R_t^{+A} , R_t^{-A} are the required up and down reserve capacity of area A at time t; H_{li}^G , H_{lj}^W , H_{lm}^{dc} , H_{lk}^D are the power transfer distribution factor of thermal unit i, wind turbine j, HVDC tie-line equivalent generator m, load k, respectively; L^A is the internal lines of area A; $\bar{F}_l$ is the maximum transmission power of line l.

In the above model, the objective function in (10) is to minimize the total operating cost of area A, including generation cost and penalty cost of tie-line power differences. Equation (11) is the load balance constraint. Constraints (12)-(15) are the up and down reserve constraints, (16) is the network security constraint, (17) is the operation constraints of equivalent generators. The minimum/maximum output of thermal units, the ramp-up/-down rates, the minimum start/stop time constraint, and the start-stop states constraint are not described in detail.

After all lower-level dispatch centers acquire their own optimal dispatch schemes, the optimal HVDC tie-line power flow must be uploaded to the upper-level dispatch center for coordinated optimization.

B. Master Problem of the Upper-level Coordination Dispatch

The upper-level dispatch center is the coordinator of the whole interconnected power system, which is responsible for minimizing the power deviation of HVDC tie-line transmitted by all lower-level dispatch centers. The master optimization model of the upper-level dispatch center is as follows:

$$\min \sum_{m\in\Omega_{dc}^{A}} [\alpha_{mt}^{dc}(\tilde{T}_{mt}^{dc}-T_{mt}^{dc*})+\left\|\beta_{mt}^{dc}\circ(\tilde{T}_{mt}^{dc}-T_{mt}^{dc*})\right\|_2^2] + \sum_{n\in\Omega_{dc}^{B}} [\alpha_{nt}^{dc}(\tilde{T}_{nt}^{dc}-T_{nt}^{dc*})+\left\|\beta_{nt}^{dc}\circ(\tilde{T}_{nt}^{dc}-T_{nt}^{dc*})\right\|_2^2] \quad (18)$$

$$\text{s.t.} \quad \tilde{T}_{mt}^{dc}+\tilde{T}_{nt}^{dc}=0 \quad (19)$$

where $\tilde{T}_{mt}^{dc}$ ($\tilde{T}_{nt}^{dc}$) is the output of equivalent generator m (n) at time t of area A (B); T_{mt}^{dc*} (T_{nt}^{dc*}) is the optimal output of equivalent generator m (n) at time t uploaded by the lower-level dispatch center A (B). Equation (19) is the regional coupling constraint.

C. Global Convergence Criterion and Multiplier Updating Formula

The decomposition and coordination algorithm is composed of inner and outer loops. In the inner loop, a fixed penalty factor is used to solve the coupled sub problems. After the inner loop convergence, the multipliers are updated in the outer loop. The multiple cycle iterative is adopted in solving the master problem and sub problems until the convergence condition is satisfied.

The convergence condition of the decomposition and coordination algorithm is as follows:

$$\frac{\left|\tilde{T}_{mt}^{dc*}(\tau)-T_{mt}^{dc*}(\tau)\right|}{\bar{T}_{m}^{dc}} \le \varepsilon_{dc} \quad (20)$$

where ε_{dc} is the given convergence threshold.

The criterion (20) checks whether the tie-line power deviation among the power issued by upper-level dispatch center and the one calculated by lower-level dispatch centers satisfies the required precision in the τ th iteration.

If the convergence condition is not satisfied in the τ th iteration, the multiplier of each lower-level dispatch center will be updated according to (21), and the τ+1 th iteration will be performed.

$$\begin{cases}\alpha_t^{dc}(\tau)=\alpha_t^{dc}(\tau-1)+2\beta_t^{dc}(\tau-1)^2[\tilde{T}_t^{dc*}(\tau-1)-T_t^{dc*}(\tau-1)] \\ \beta_t^{dc}(\tau)=\gamma\beta_t^{dc}(\tau-1)\end{cases} \quad (21)$$

where γ should be no smaller than one, and the initial value of α , β should be a smaller constant to get a converged solution [10][12].

V. Case Study

A. Case Data

The performance of the decentralized dispatch model is tested using two 6-bus systems to simulate area A and area B, and the two areas are interconnected by one HVDC tie-line. The DC converter is located in bus 5 of area A and bus 5 of area B, and a wind farm is located at bus 2 of area A. The thermal units data and line data can be found in [13]. The load of area B is 1.5 times of area A and the cost coefficients of thermal units in area B are twice of area A. In this way, we force power imports to area B. Assuming the transmission capacity deviation is not allowed (ρ =0%), the HVDC tie-line transmission limit is set to [50,150] MW, the day-ahead transmission plan of HVDC tie-line is 1700MWh, the output adjustment rate of equivalent generator is set to [5,20] MW, the penalty cost of curtailed wind is 100$/MW, the convergence threshold ε_{dc}=0.33% , the initial value of shared variables $\tilde{T}_{mt}^{dc*}$=$\tilde{T}_{nt}^{dc*}$=0 , and the initial value of multipliers $\gamma=1.05$, α_{mt}^{dc}=β_{mt}^{dc} = α_{nt}^{dc}=β_{nt}^{dc}=0.5 . The load and wind power of area A are shown in Fig.2.

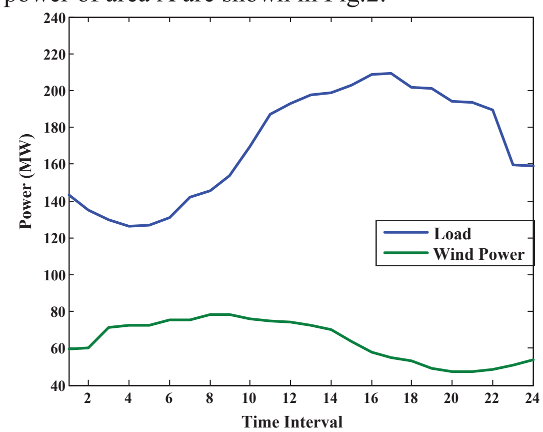

Fig. 2. Load and wind power

The mixed-integer quadratic programming (MIQP) problems are solved on a computer with 4 Quad-Core processors, 3.2 GHz and 8 GB of RAM, using Gurobi 6.0 under Yalmip.

B. Result Analysis

1) Comparison of HVDC tie-line transmission plan

In this paper, two HVDC transmission modes are selected for comparison. Mode 1 is the traditional constant power transmission mode used in the centralized dispatch model. Mode 2 has the same transferred electric energy, but is optimized by the proposed decentralized dispatch model, which considers the fact that the wind power in area A is sufficient and the load level in area B is high, so the power transmission of HVDC tie-line is uniformly optimized. Results are shown in Fig.3.

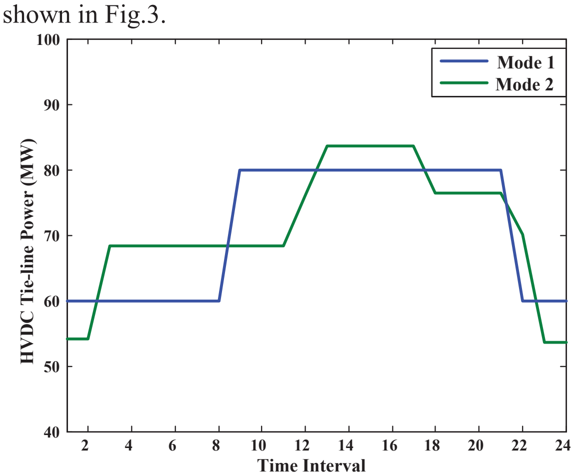

Fig. 3. HVDC tie-line power transmission plan

2) Comparison of wind power curtailment

The curtailed wind power of different tie-line transmission modes is shown in Tab.1, indicating that mode 2 is helpful for wind power accommodation.

TABLE I
WIND POWER CURTAILMENT RATE IN DIFFERENT MODE

	Mode 1	Mode 2
Wind Power Curtailment Rate	4.9%	1.3%

3) Algorithm convergence

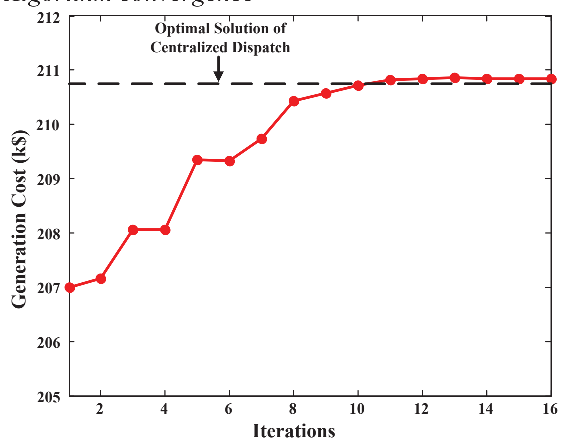

Fig. 4. Convergence curve of generation cost

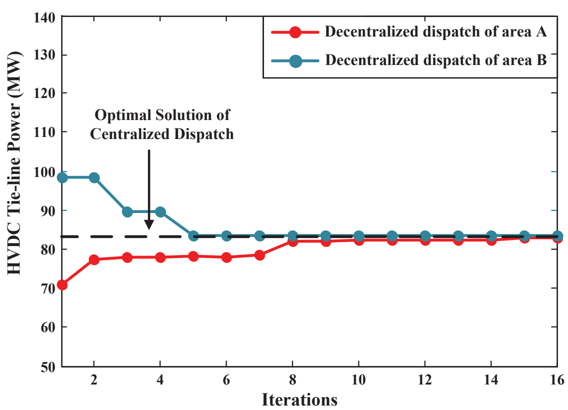

Fig. 5. Convergence curve of 16th period's HVDC tie-line power flow

Figure 4 shows the convergence curve of generation cost, and Fig.5 shows the convergence curve of the HVDC tie-line power flow at the 16th period. We can conclude that the proposed decomposition and coordination algorithm can converge to the global optimal solution at 16th iterations.

4) Calculation time and generation cost

The comparison about calculation time and generation cost between the centralized and decentralized dispatch models are shown in Tab.2, indicating that the generation cost of decentralized dispatch is very close to but slightly higher than that of centralized dispatch, and the cost error is 0.07%. Since the decomposition and coordination algorithm adopted in our paper is implemented on a single computer in series mode, the calculation time of centralized dispatch is less than that of decentralized dispatch. In the actual software system, the sub problems of lower-level dispatch are solved by different regional computers, and the solutions are sent to the master problem of upper-level dispatch center for coordination. That is, multi-machine distributed computing could greatly improve the solution efficiency, and what's more, the decentralized dispatch model is more feasible for a large-scale hierarchical power system with multiple dispatch centers.

TABLE II
COMPARISON BETWEEN CALCULATION TIME AND GENERATION COST OF CENTRALIZED AND DECENTRALIZED DISPATCH MODEL

	Calculation time (s)	Generation cost (k$)
Centralized dispatch model	14.2	210.687
Decentralized dispatch model	198.4	210.840

VI. CONCLUSIONS

This paper aims to research the day-ahead active power dispatch for interconnected power grid with wind power integration via HVDC tie-line. Considering the complex operating characteristics of HVDC tie-line, a decentralized dispatch approach based on ATC technique is proposed. The simulation on a 12-bus two area interconnected system shows that through the decomposition and coordination mechanisms, the economy of the entire interconnected system can be achieved, and the proposed decentralized dispatch model has the merit in wind power accommodation and cross-regional coordination of generation resources for AC/DC hybrid power systems.

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