A Coordinated Dispatch Method for Receiving-end Grid Considering HVDC Power Characteristics

Shumei Jiao¹, Yuanyang Chen², Yijia Cao¹, Changfeng Liao¹*, Yi Tan¹, Yong Li¹, Zilong Zeng¹, and Siyuan Guo³

¹College of Electrical and Information Engineering, Hunan University, Changsha, Hunan 410082, China
²State Grid Hunan Electric Power Company Limited, Changsha, Hunan 410004, China
³State Grid Hunan Electric Power Company Limited Research Institute, Changsha, Hunan 410007, China

* Corresponding author’s e-mail: liaocf@hnu.edu.cn

Abstract. The power injection from the high-voltage direct current (HVDC) transmission system has a significant impact on the operation and scheduling of the receiving-end power system. In this paper, considering the unipolar blocking faults and the power characteristics of the traditional HVDC system (i.e., LCC-HVDC), a multi-period dispatch model is proposed for the receiving-end power system to achieve the coordinated optimization of various dispatchable resources such as the power injection of LCC-HVDC and the local generation. In the proposed model, the constraints such as those related to the number of LCC-HVDC power adjustments, branch power flow, bus voltage and the output of local generators are taken into account, and its objective is to minimize the total power purchase cost of the receiving-end power system. To solve the proposed model efficiently, the method for determining the time of changing LCC-HVDC power injection is first proposed, and then its results are used to further solve the proposed multi-period dispatch model of the receiving-end power system. The simulation results show that the dispatch method proposed in this paper can effectively deal with LCC-HVDC unipolar blocking faults, and reasonably optimize the power purchase cost of the receiving-end power system.

1. Introduction

The geographic distributions of the renewable energy and the load center often have a serious mismatch in power systems. Therefore, the large-scale and long-distance transmission of renewable energy has attracted extensive attention and research in power industry. And the traditional high-voltage direct current transmission technology (i.e., LCC-HVDC) has become one of the widely recognized solutions in that field due to its advantages of large transmission capacity, low operating loss, and good economy [1]. For example, the ±800kV Qishao ultra-high voltage direct current (UHVDC) transmission system in China operated in 2017 has significantly improved the long-distance transmission capacity of wind power [2].

At present, many relevant researches have been done on hybrid AC/DC systems and its dispatch problems. Reference [3] analyzed the complex instability problems caused by the coupling effects of the AC power system and the DC power system, as well as the HVDC technology based interconnection scheme for asynchronous power systems. Reference [4] considered the characteristics
of DC blocking faults, and proposed a deep learning based automatic creation method for the control strategies after DC blocking fault. Based on the idea of automatic cruise, reference [5] proposed a hybrid AC/DC power system dispatch framework and the corresponding core modules and technologies. Reference [6] proposed a practical economic dispatch method for the hybrid power system with VSC-HVDC by considering the power losses of the AC system, the DC grid and the power converter. Reference [7] comprehensively considered the characteristics of the wind farm and the daily load of the receiving-end system, and proposed an optimization method for exporting HVDC power which can improve the peak shaving capability of the receiving-end power system and reduce wind power abandonment. Reference [8] proposed a multi-objective dispatch method for the hybrid AC/DC system to minimize the network loss and the total fuel consumption of thermal generators.

The power injection from the LCC-HVDC system brings several challenges to the receiving-end power system. For example, the DC blocking due to continuous commutation failures of the converter will cause active power shortages in the receiving-end system. Also, the recovery process after commutation failure needs a lot of reactive generation which is easy to cause the voltage instability [9]. The wind power transmitted by the LCC-HVDC system also has the characteristics such as volatility. In addition, it is necessary to constrain the number of daily adjustments of LCC-HVDC power injection when considering the power system operational risks [10]. This will bring integer variables to the multi-period dispatch problem which greatly increases the difficulty of the operational dispatch. Therefore, it is necessary to fully consider the characteristics of LCC-HVDC power injection in day-ahead dispatch to realize the secure and economic operation of the receiving-end power system.

Based on the above analysis, this paper comprehensively considers the operational constraints of the LCC-HVDC power injection and the unipolar blocking faults, and proposes a multi-period coordinated dispatch method for the receiving-end power system with LCC-HVDC power injection. The effectiveness of the proposed dispatch method for receiving-end power system is verified through simulation analysis on a modified system.

2. Dispatch Model of Receiving-end Power Grid with DC Feed-in

2.1. Objective Function

\[ \min \left\{ C_{HVDC} + C_{GEN} + C_{ESS} + C_{\text{Fload}} \right\} \]  

\[ C_{HVDC} = \sum_{j=1}^{T} \sum_{i=1}^{N} W_{j} p_{i,t}^{HVDC} \]  

\[ C_{GEN} = \sum_{j=1}^{T} \sum_{i=1}^{N} \alpha_{j} P_{i,t}^{G} \]  

\[ C_{ESS} = \sum_{j=1}^{T} \sum_{i=1}^{N} P_{i,t}^{\text{ESS}} \]  

\[ C_{\text{Fload}} = \sum_{j=1}^{T} \sum_{i=1}^{N} \gamma_{j} \Delta P_{i,t}^{\text{Fload}} \]  

where \( C_{HVDC} \) is the total cost of purchasing power via the LCC-HVDC transmission system, \( p_{i,t}^{HVDC} \) is the corresponding purchased power (i.e., LCC-HVDC power injection), \( W_{j} \) (\( \text{¥}/\text{kW} \cdot \text{h} \)) is the corresponding electricity price, \( T \) is the total number of sub-periods (\( T=96 \)) and each sub-period is 15 minutes; \( C_{GEN} \) is the total cost of the receiving-end power system purchasing electricity from the local thermal power plant, \( P_{i,t}^{G} \) is the active power output of the thermal power plant at the bus \( i \) at the sub-period \( t \), and \( \alpha_{j} \) (\( \text{¥}/\text{kW} \cdot \text{h} \)) is the electricity price of power supplied by thermal power plants at the bus \( i \). This paper assumes that the energy storage system has been sited and sized which means its investment cost is fixed. Therefore, only the operating cost of energy storage system (\( C_{ESS} \)) is
considered. The $P_{i,t}^{\text{ESS}}$ is the output of the energy storage system at the bus $i$ at the sub-period $t$. $P_{i,t}^{\text{ESS}}$ has a positive value for the status of discharging power. $\beta_{i}^{\text{ESS}}$ (¥/kW-h) is the unit operating cost of the energy storage system. $C_{\text{Float}}$ is the compensation cost of the flexible load, $\Delta P_{i,t}^{\text{Float}}$ and $\gamma_{i}^{\text{Float}}$ are the shed load and unit compensation cost of the flexible load at the bus $i$ at the sub-period $t$, respectively.

2.2. Normal Operation Constraints

2.2.1 LCC-HVDC Transmission System Constraints.

In this paper, we consider the scenario that external wind power and thermal power are fed into the receiving-end power system through the LCC-HVDC transmission system. In term of electric power, wind generation and thermal generation from external grids is equivalent to the equivalent power source at the AC side of the converter station, whose active power and reactive power are $P_{i,t}^{\text{HVDC}}$ and $Q_{i,t}^{\text{HVDC}}$, respectively. Due to the limitations of the transmission capacity and control capability of the LCC-HVDC transmission system, the following constraints need to be considered.

1) LCC-HVDC power constraint

$$\begin{align*}
    & P_{i,t}^{\text{HVDC}} \leq P_{i,t}^{\text{HVDC}} \leq P_{i,t}^{\text{max}} \\
    & P_{i,t}^{\text{HVDC}} \leq P_{\text{Sending}}^{i}
\end{align*}$$

(6)

where $P_{i,t}^{\text{HVDC}}$ and $P_{i,t}^{\text{HVDC}}$ are, respectively, the lower and upper limits of the active power that the HVDC system can transmit. Since this paper considers that external wind power and thermal power are fed into the receiving-end system through HVDC transmission system, the power injection at the converter station is also constrained by the maximum power supply ability of the sending-end power system, i.e., $P_{\text{Sending}}^{i}$.

Since the LCC-HVDC system absorbs reactive power from the AC system which is about 40% of its transmitted active power [11], this paper further considers the following simplified constraints:

$$Q_{i,t}^{\text{PV}} = \alpha P_{i,t}^{\text{PV}}$$

(7)

where $Q_{i,t}^{\text{PV}}$ is the consumed reactive power of the LCC-HVDC which is from the receiving-end power system, and $\alpha = 0.4$ is used.

For the receiving-end power system with insufficient reactive power, large-scale reactive power compensation equipment is usually installed to ensure the security and stable operation of the LCC-HVDC system and the receiving-end power grid. Synchronous condenser (SC) is a large-capacity reactive power compensation device used to adjust the reactive power of the power system [12]. Considering that the SC consumes active power (about 3% of the rated capacity) due to its power loss [13], the following constraints of the SC power is taken into account:

$$\begin{align*}
    & P_{i,t}^{\text{SC}} = 0.03S_{i,t}^{\text{SC}} \\
    & Q_{i,t}^{\text{SC}} \leq Q_{i,t}^{\text{SC}} \leq Q_{i,t}^{\text{SC}}
\end{align*}$$

(8)

where $S_{i,t}^{\text{SC}}$ and $P_{i,t}^{\text{SC}}$ are the rated capacity and the active power of SC at the sub-period $t$, respectively; $Q_{i,t}^{\text{SC} \text{max}}$ and $Q_{i,t}^{\text{SC} \text{min}}$ are the upper and lower limits of the SC reactive power, respectively.

2) LCC-HVDC power adjustment constraints

Considering the operational stability of the LCC-HVDC transmission system, the following constraints on the number of LCC-HVDC power adjustments is further considered:
\[ \begin{align*}
|P_{i,t}^{\text{HVDC}} - P_{i,t-1}^{\text{HVDC}}| & \leq z_{\text{max}} \cdot k_t^{\text{HVDC}} \\
\sum_{t=1}^{T} k_t^{\text{HVDC}} & \leq N_{\text{max}}
\end{align*} \tag{9} \]

where \( z_{\text{max}} \) is the maximum daily variation of the LCC-HVDC power; the \( k_t^{\text{HVDC}} \) is a binary variable, \( k_t^{\text{HVDC}} = 1 \) means that the LCC-HVDC power at the sub-period \( t \) is different from the one at the previous sub-period, which means the LCC-HVDC power is changed; and \( k_t^{\text{HVDC}} = 0 \) means that the LCC-HVDC power is unchanged at the sub-period \( t \). \( N_{\text{max}} \) is the maximum allowable number of daily adjustments of LCC-HVDC power which is set to be 4 in this paper.

### 2.2.2 Power Flow Constraints of Receiving-end System

\[ \begin{align*}
P_{i,t} = V_{i,t} \sum_{j=1}^{N} V_{j,t} \left( G_{ij} \cos \theta_{ij,t} + B_{ij} \sin \theta_{ij,t} \right) \\
Q_{i,t} = V_{i,t} \sum_{j=1}^{N} V_{j,t} \left( G_{ij} \sin \theta_{ij,t} - B_{ij} \cos \theta_{ij,t} \right)
\end{align*} \tag{10} \]

where \( P_{i,t} \) and \( Q_{i,t} \) are the active power injection and reactive power injection at the bus \( i \) at the sub-period \( t \), respectively; \( V_{i,t} \) is the voltage magnitude at the bus \( i \) at the sub-period \( t \); \( G_{ij} \) and \( B_{ij} \) is the real and imaginary parts of the elements of the receiving-end power system admittance matrix; \( \theta_{ij,t} \) is the phase angle difference between bus \( i \) and \( j \) at the sub-period \( t \) in the receiving-end system. The \( N \) represents the number of buses in the receiving-end system. The \( P_{i,t} \) and \( Q_{i,t} \) can be formulated as follows:

\[ \begin{align*}
P_{i,t} = P_{i,t}^G + P_{i,t}^{\text{ESS}} + P_{i,t}^{\text{HVDC}} - P_{i,t}^{\text{Hx}} - P_{i,t}^{\text{Load}} + \Delta P_{i,t}^{\text{Flad}} \\
Q_{i,t} = Q_{i,t}^G + Q_{i,t}^{\text{ESS}} + Q_{i,t}^{\text{Hx}} - Q_{i,t}^{\text{HVDC}} - Q_{i,t}^{\text{Load}}
\end{align*} \tag{11} \]

where \( Q_{i,t}^G \) is the reactive power output of the thermal generator at the bus \( i \) at the sub-period \( t \). \( Q_{i,t}^{\text{ESS}} \) is the reactive power injected by the energy storage system at the bus \( i \) at the sub-period \( t \). The \( P_{i,t}^{\text{Load}} \) and \( Q_{i,t}^{\text{Load}} \), respectively, represent the active and reactive power loads of AC at the bus \( i \) at the sub-period \( t \); \( P_{i,t}^{\text{Hx}} \) is the active power consumed by SC at the bus \( i \) at the sub-period \( t \); \( Q_{i,t}^{\text{Hx}} \) is the reactive power injected by the SC at the bus \( i \) at the sub-period \( t \); \( Q_{i,t}^{\text{HVDC}} \) is the reactive power consumed by the converter station at the bus \( i \) at the sub-period \( t \).

### 2.2.3 Branch Power Flow and Bus Voltage Constraints

\[ \begin{align*}
S_{ij,t} \leq S_{ij,t} & \leq S_{ij, \text{max}} \\
V_{i,t} \leq V_{i,t} & \leq V_{i, \text{max}}
\end{align*} \tag{12} \tag{13} \]

where \( S_{ij,t} \) is the transmission power of the branch \( ij \) at the sub-period \( t \) in the receiving-end power system; \( S_{ij,\text{min}} \) and \( S_{ij,\text{max}} \) are, respectively, the lower and upper limits of \( S_{ij,t} \). The \( V_{i,\text{min}} \) and \( V_{i,\text{max}} \) are, respectively, the lower and upper limits of the voltage at bus \( i \).

### 2.2.4 Power Generation Constraints

(1) Generator output constraint
where $P_{i,\text{min}}^G$ and $P_{i,\text{max}}^G$ are, respectively, the lower and upper limits of active generation at the bus $i$, $Q_{i,\text{min}}^G$ and $Q_{i,\text{max}}^G$ are, respectively, the lower and upper limits of reactive generation at the bus $i$.

(2) Ramping constraint

$$\begin{align*}
&\left\{ P_{i,t}^G - P_{i,t-1}^G \leq \Delta P_{i,t}^G, \quad \Delta P_{i,t}^G \leq \Delta P_{i,t}^{\text{max}}, \\
&\left\{ P_{i,t}^G - P_{i,t-1}^G \leq \Delta P_{i,t}^G, \quad \Delta P_{i,t}^G \leq \Delta P_{i,t}^{\text{max}},
\end{align*}$$

where $P_{i,\text{LASC}}^G$ and $P_{i,\text{LDS}}^G$ are, respectively, the ramping up and down limit of the active power of the generator at the bus $i$ at the sub-period $t$.

2.2.5 Energy Storage Operation Constraints [14]

$$\begin{align*}
&E_{i,t}^{\text{ESS}} + P_{i,t}^h \eta_{\text{ch}} \Delta t - \frac{P_{i,t}^{\text{dis}} \Delta t}{\eta_{\text{dis}}} = E_{i,t-1}^{\text{ESS}}, \quad \forall t \in \{1, 2, \ldots, T-1\} \\
&E_{i,T}^{\text{ESS}} + P_{i,T-1}^h \eta_{\text{ch}} \Delta t - \frac{P_{i,T-1}^{\text{dis}} \Delta t}{\eta_{\text{dis}}} = E_{i,0}^{\text{ESS}}, \quad t = T
\end{align*}$$

where $E_{i,t}^{\text{ESS}}$ is the stored electrical energy of the energy storage system at the bus $i$ at the sub-period $t$, $E_{i,\text{max}}^{\text{ESS}}$ is the energy capacity of the energy storage system at the bus $i$. The $\eta_{\text{ch}}$ and $\eta_{\text{dis}}$ are, respectively, the charging and discharging efficiencies of the energy storage system. The $P_{i,\text{max}}^h$ and $P_{i,\text{max}}^{\text{dis}}$ are, respectively, the upper limit of the charging power and the discharging power at the bus $i$.

2.2.6 Flexible Load Constraint

Flexible load can change its electricity consumption pattern (e.g., reducing or shifting the electricity demand for a certain period of time) by responding to electricity price strategy or incentive mechanism. Among the flexible loads, the interruptible load reduces its electricity demand during the peak period of the power grid based on their agreement with the power company [15]. In this paper, interruptible load is considered and the shed power and interruptible time are constrained as follows [16]:

$$\begin{align*}
&\left\{ \Delta P_{i,t}^{\text{load}} \leq \Delta P_{i,t}^{\text{load}}, \quad \Delta P_{i,t}^{\text{load}} \leq \Delta P_{i,t}^{\text{max}}, \\
&\left\{ \Delta P_{i,t}^{\text{load}} \leq \Delta P_{i,t}^{\text{load}}, \quad \Delta P_{i,t}^{\text{load}} \leq \Delta P_{i,t}^{\text{max}},
\end{align*}$$

where $\Delta P_{i,\text{min}}^{\text{load}}$, $\Delta P_{i,\text{max}}^{\text{load}}$ and $T_{i,\text{min}}^{\text{load}}$ are the minimum shed power, maximum shed power, and interruptible time of the interruptible load at the bus $i$; $T_{i,\text{min}}^{\text{load}}$ and $T_{i,\text{max}}^{\text{load}}$ are, respectively, the lower and upper limit of the interruptible time.

2.2.7 Constraint about Unipolar Blocking

At present, the majority of LCC-HVDC transmission systems is a bipolar system [17]. When a pole is blocked due to a fault, the corresponding current in that pole becomes zero. When the transmission power of the LCC-HVDC system is large, the blocking of the LCC-HVDC system will have a serious adverse effect on the receiving-end systems [18-19]. Therefore, for the dispatch in the receiving-end
system, both the aforementioned constraints under normal operation and the security constraints about unipolar blocking should be considered.

When a DC unipolar blocking occurs, the active power injected by the LCC-HVDC system is reduced to a half of the original one [20]:

\[
P_{i,t,f}^{HVDC} = 0.5 P_{i,t}^{HVDC}
\]

(18)

\[
Q_{i,t,f}^{HVDC} = \alpha P_{i,t,f}^{HVDC}
\]

(19)

where the subscript \( f \) represents the DC unipolar blocking. When the unipolar blocking occurs at the sub-period of \( t_g \), the thermal generator, energy storage, SC and flexible load must be coordinated to keep the power balance in the safe operation as follows:

\[
\begin{align*}
& P_{i,t,f}^G - P_{i,t,f}^{Ac} \leq P_{i,t}^G \\
& P_{i,t-1}^G - P_{i,t,f}^{Ac} \leq P_{i,t}^G \\
& P_{i,t,f}^G \leq P_{i,t,f}^G \leq P_{i,t,f}^G \\
& P_{i,t,f}^G \leq P_{i,t,f}^G \leq P_{i,t,f}^G \\
& Q_{i,t,f}^G \leq Q_{i,t,f}^G \leq Q_{i,t,f}^G \\
& P_{i,t,f}^{ch} = \frac{P_{i,t,f}^{dis} \Delta t}{\eta_{dis}} \\
& 0 \leq E_{i,t,f}^{ESS} \leq E_{i,t,f}^{ESS} \\
& 0 \leq P_{i,t,f}^{ch} \leq P_{i,t,f}^{max} \\
& 0 \leq P_{i,t,f}^{dis} \leq P_{i,t,f}^{max} \\
& P_{i,t,f}^{Hx} = 0.03 S_{i,t,f}^H \\
& Q_{i,t,f}^{Hx} = Q_{i,t,f}^{Hx} \leq Q_{i,t,f}^{Hx} \\
& \Delta P_{i,t,f}^{Load} \leq \Delta P_{i,t,f}^{Load} \leq P_{i,t,f}^{max} \\
& \Delta P_{i,t,f}^{Load} \leq \Delta P_{i,t,f}^{Load} \leq P_{i,t,f}^{max} \\
\end{align*}
\]

(20)

Also, it should ensure that the bus voltage and branch power flow are within their limits after the unipolar blocking occurs. Therefore, it is necessary to further consider the post-contingency power flow constraints and security constraints as follows:

\[
\begin{align*}
& P_{i,t,f} = V_{i,t,f} \sum_{j=1}^{N} V_{j,t,f} \left( G_{ij} \cos \theta_{i,j,t,f} + B_{ij} \sin \theta_{i,j,t,f} \right) \\
& Q_{i,t,f} = V_{i,t,f} \sum_{j=1}^{N} V_{j,t,f} \left( G_{ij} \sin \theta_{i,j,t,f} - B_{ij} \cos \theta_{i,j,t,f} \right) \\
& P_{i,t,f} = P_{i,t,f}^G + P_{i,t,f}^{ch} + P_{i,t,f}^{HVDC} - P_{i,t,f}^{Hx} - P_{i,t,f}^{Load} + \Delta P_{i,t,f}^{Load} \\
& Q_{i,t,f} = Q_{i,t,f}^G + Q_{i,t,f}^{ch} + Q_{i,t,f}^{HVDC} - Q_{i,t,f}^{Hx} - Q_{i,t,f}^{Load} \\
& S_{i,t,f} \leq S_{i,t,f} \leq S_{i,t,f} \\
& V_{i,t} \leq V_{i,t,f} \leq V_{i,t}^{max} \\
\end{align*}
\]

(21)

3. Methodology

Due to the consideration of the constraints of the daily adjustments of LCC-HVDC power, the proposed coordination dispatch model is a large-scale mixed integer optimization model. In order to
efficiently solve the proposed model, this paper firstly proposes a method to determining the power adjustment time of LCC-HVDC while satisfying the constraints of the power adjustment number. After obtaining the time of the LCC-HVDC power being adjusted, the LCC-HVDC active power, thermal generator output, flexible load and the power of energy storage are optimized.

The prices of wind power purchased by the receiving-end system through HVDC in some practical scenarios are low. In this paper, based on the wind power prices [21-22], the price of the HVDC power which is originally from the external wind power and generators is set to 0.29 ¥/kW·h and the price of local generation in the receiving-end system is set to 0.4 ¥/kW·h in this paper. In order to minimize the operational cost, the receiving-end system will purchase as much power as possible from the LCC-HVDC system due to the lower price. Therefore, the proposed method for determining the power adjustment time of LCC-HVDC in this paper is to maximize the LCC-HVDC active power as follows:

\[
\max \left\{ \sum_{t=1}^{T} \sum_{i=1}^{N} P_{\text{HVDC},i,t} \right\}
\]

\[
(P_{\text{HVDC},i,t} - P_{\text{HVDC},i,t-1}) \cdot (\sum_{i=1}^{N} P_{\text{Load},i,t} - \sum_{i=1}^{N} P_{\text{Load},i,t-1}) \geq 0
\]

\[
P_{\text{HVDC},i,t} \leq P_{\text{HVDC},i,t} \leq P_{\text{HVDC},i,t}
\]

\[
\left| P_{\text{HVDC},i,t} - P_{\text{HVDC},i,t-1} \right| \leq z_{\text{max}} \cdot k_{i,t} \text{HVDC}
\]

\[
\sum_{i=1}^{N} k_{i,t} \text{HVDC} \leq N_{\text{max}}
\]

The above model is a small-scale optimization model with discrete variables which is much easier to solve than the proposed model that is mentioned in Section 2. By using the proposed method for determining the power adjustment time, the LCC-HVDC active power can track the change trend of the total load in the receiving-end power system while meeting the constraints of the number of the LCC-HVDC power adjustment.

After obtaining the power adjustment time of LCC-HVDC, the (9) and binary variables can be removed from the proposed model that is mentioned in Section 2. Thus, the resulting model becomes an optimization model with sole continuous variables which is much easier to solve. The whole process of solving the proposed model that is mentioned in Section 2 is shown as follows:

Step1: Input the daily load and the basic parameters such as the generator parameters and transmission parameters of LCC-HVDC;

Step2: Solve the optimization model (22)-(23) to obtain the power adjustment time of LCC-HVDC by using commercial optimization software;

Step3: Import the power adjustment time of LCC-HVDC into the coordinated dispatch model proposed in Section 2 to yield an optimization model with sole continuous variables;

Step4: Solve the optimization model with sole continuous variables to obtain the optimal scheduling plan by commercial optimization software.

4. Case Study

In this section, an example of the receiving-end system with one infeed LCC-HVDC is constructed by modifying the IEEE 39 bus system. The parameters and specific modifications are shown as follows: 1) Bus 39 is connected with the LCC-HVDC and the adjustment range of the SC at the AC side of the converter station is -150Mvar~300Mvar; 2) The rated capacities of energy storage installed at bus 26 and bus 25 are 300MVA; 3) The loads at bus 8, bus 20 and bus 28 are treated as the flexible loads with up to 30% of the load being able to be shed at the sub-periods of 40-80. 4) the base power is set to
100MVA. In order to investigate the performance of the proposed method in different operating conditions, this paper will analyze the results of different load peak-valley ratios (i.e., the ratio of daily maximum load to the daily minimum load) while keeping the sum of the total loads in one day unchanged. In Figures 1-2, the forecasted load curves of the receiving-end power system and the transmittable power curve of the sending-end system are given, respectively. By using the proposed method in Section 3, the power adjustment time of LCC-HVDC are the ending time of the sub-periods 19, 59, 61, and 77 regardless of different daily load curves.

4.1. Dispatch Considering Unipolar Blocking

In order to demonstrate the effectiveness of the proposed method in presence of unipolar blocking, the following three different cases are analyzed:

- P1: The power system operates normally without unipolar blocking.
- P2: The unipolar blocking occurs at time 47.
- P3: The unipolar blocking occurs at time 67.

Figure 3 shows the active power of LCC-HVDC in different cases when the load peak-valley ratio is 1.4. As shown in Figure 3, the active power of LCC-HVDC in the cases P1 and P2 are very close. In contrast to P1 and P2, the active power of LCC-HVDC in P3 is significantly reduced in the sub-periods of 62-77. This is due to the follow reasons 1) the unipolar blocking is assumed to occur at the end of sub-period 67 in scenario P3, 2) the active power of LCC-HVDC is relatively large in periods 62-77 in the cases P1 and P2. If the active power of LCC-HVDC in P3 is the same as those in the other cases, the DC unipolar blocking will lead to a large decrease in active power supply in the receiving-end system which will cause power system security problems.

Table 1 shows the power changes of energy storage, flexible load and SC after unipolar blocking occurs at the end of sub-period 47 and sub-period 67. As shown in Table I, all flexible loads are in the
state of load shedding to alleviate the insufficient energy supply from LCC-HVDC after the unipolar blocking occurs. And energy storage quickly release all the stored energy to help maintain the power balance of the receiving-end power system. The total output of generators are also increased accordingly to meet the power demand of the receiving-end power system. Since the reactive power consumed by the LCC-HVDC system is related to its active power, the reactive power consumed by the LCC-HVDC during the blocking period is also decreased, resulting in a reduction of the reactive power output of the SC. In addition, the energy storage provides reactive power to compensate the reactive power deficit to realize the reactive power balance at the receiving-end power system.

Table.1 The data change of Cases P3 and P2 as compare to Case P1.

|        | P1  | P2   | P3   |
|--------|-----|------|------|
| PG     | \   | +334.1 | +1006.4 |
| PESS-16| \   | +48.75 | +100  |
| PESS-25| \   | +48.75 | +65.9 |
| PFL-8  | \   | +99.7  | +49.3 |
| PFL-16 | \   | +66.9  | +26.5 |
| PFL-25 | \   | +15.7  | +4.6  |
| QSC-8  | \   | -195.0 | -581.6 |
| QESS-16| \   | +94.6  | +239.0 |
| QESS-25| \   | +47.0  | +47.4 |

*a The unit of active power is MW, and the unit of reactive power is MVAR.*

-The "+" and "-" represent the increase and decrease of the power after the unipolar blocking occurs.

-**PG:** The total active outputs of local generators.

-**PESS-16, PESS-25:** The active powers of the energy storages at bus 16 and bus 25, respectively.

-**PFL-8, PFL-16, PFL-25:** The flexible loads at bus 8, bus 16 and bus 25, respectively.

-**QSC-8:** The reactive output of SC at bus 8.

-**QESS-16, QESS-25:** The reactive powers of the energy storages at bus 16 and bus 25, respectively.

4.2. The Impact of Load Peak-Valley Ratio on Dispatch

In this section, the three cases, i.e., the load peak-valley ratios of 1.4, 1.7 and 2, are analyzed. As shown in Figure 1, the peak load is the same in the three different cases, but the valley load is the smallest when the load peak-valley ratio is 2.0. The LCC-HVDC active power with different load peak-valley ratio is given in Figure 4. It can be seen from Figure 4 that the LCC-HVDC active power has a small difference during the peak load period regardless of the load peak-to-valley ratio. In contrast, when the load peak-valley ratio is 2.0, the LCC-HVDC active power is significantly reduced as compared to the ones of other load peak-valley ratios. This is mainly because the valley load in the case of the load peak-valley ratio equaling to 2.0 is significantly smaller than the ones in the other two load peak-valley ratios. Therefore, a very high peak-to-valley difference has a very significant impact on the LCC-HVDC active power that is injected into the receiving-end system.
4.3. The Impact of Energy Storage on Dispatch

In this section, the influences of the rated power of the energy storage on the receiving-end power system dispatch are analyzed. In this section, the load peak-valley ratio is set to 1.4 and the unipolar blocking is assumed to occur at sub-period 67. Figure 5 and Figure 6, respectively, show the results of LCC-HVDC and the SC when the energy storage capacities are 100MW and 200MW.

According to Figure 5 and Figure 6, there is a reduction of LCC-HVDC power during the sub-periods 20 to 77 when the rated power of the energy storage is 100MW. This is because the energy storage in the receiving-end system has a small power output capacity. In addition, the overall reactive output of the SC is decreased due to a reduction of LCC-HVDC power. Therefore, a larger rated power of energy storage can improve the ability of the receiving-end power system to consume the LCC-HVDC power.
5. Conclusion

In this paper, a multi-period dispatch model for the receiving-end power system is proposed to coordinate optimally various resources such as LCC-HVDC power, the local generation, flexible load, and the power of energy storage. A method to determine the adjustment time of LCC-HVDC power is proposed to eliminate the discrete variables in the original optimization model. Based on the analysis on the modified IEEE 39 bus system, it is shown that the proposed coordinated dispatch method can achieve the safe and economic multiple-period operation of the receiving-end power system in the presence of DC unipolar blocking and the LCC-HVDC power adjustment requirements.

Acknowledgments

This paper acknowledges financial support from the Science and Technology Project of State Grid Hunan Electric Power Company Limited under Grant 5216A518001L.

References

[1] Xiuqiang, He.; Hua, Geng.; Geng, Yang.; et al. Coordinated Control for Large-Scale Wind Farms with LCC-HVDC Integration. Energies 2018, 11(9), 2207.
[2] Wang, Can.; LUO, Jianbo.; Ning, Zhihao.; et al. Model of ±800kV Qesun UHV DC transient electromagnetic field based on PSCAD/EMTDC [J]. Hunan electric power, 2017, 37(06), 1-4.
[3] Rao, Hong.; Wu, Wei.; Zhou, Baorong.; et al. Study on the Mutual influence and Asynchronous networking Scheme between Yunnan Power Grid and the main AC/DC system of Southern Grid [J]. Chinese journal of electrical engineering, 2020, 40(11), 3470-3477.
[4] Yang, Xiaonan.; Sun, Bo.; Lang, Yansheng. Intelligent scheduling decision of uhvdc lock-up fault based on deep learning [J]. China electric power, 2020, 53(06), 8-17.
[5] Zhao, Jinquan.; Zhang, Yikang.; Su, Dawei.; et al. Automatic cruise Architecture and Key Technologies for AC and DC large power grid dispatch [J]. Automation of electric power systems, 2019, 43(22), 187-193+216.
[6] Luis, M.; Castro, J.H.; Tovar-Hernández, N.; González-Cabrera.; et al. Real-power economic dispatch of AC/DC power transmission systems comprising multiple VSC-HVDC equipment. International Journal of Electrical Power & Energy Systems. 2019, 107, 140-148.
[7] Cui, Yang.; ZHAO, Yu.; QIU, Lijun.; et al. Coordinated Dispatch of UHVDC external supply air and fire to improve peak Adjustment margin at receiver end grid [J]. Power System Automation. 2012, 42(15), 126-132+219-220.
[8] Lu, Wentian.; Lin, Shunjia.; LIU, Mingbo.; et al. A provincial Coordinated Active Power Scheduling Optimization method for AC-DC interconnection power system network including wind power plants [J]. Power system automation. 2015, 39(07), 89-96.
[9] Weichen, Yang.; Shihong, Miao.; Shixu, Zhang.; et al. A commutation failure risk analysis method considering the interaction of inverter stations. International Journal of Electrical Power & Energy Systems. 2020, 120.

[10] Yang, Xiaonan.; Sun, Bo.; Lang, Yansheng. Intelligent scheduling decision of uhvdc lock-up fault based on deep learning [J]. China electric power. 2020, 53(06), 8-17.

[11] Cui, Ting.; Shenyang, Wu.; Zhang, Bin.; et al. A research on the influence of 300MVar level synchronous adjusting cameras on power grid stability in hunan province [J]. Hunan electric power. 2016, 36(03), 1-4+8.

[12] Ehsan, Karami.; Gevork, B.; Gharehpetian.; Hassan, Moradi, CheshmehBeigi.; et al. A hybrid active load and ideal synchronous condenser-based model for STATCOM applied to power flow studies. Energy Systems Integration. 2019, 1(4), 229-235.

[13] Puyu, Wang.; Yongkun, Wang.; Ningqiang, Jiang.; et al. A comprehensive improved coordinated control strategy for a STATCOM integrated HVDC system with enhanced steady/transient state behaviors. International Journal of Electrical Power & Energy Systems. 2020, 121.

[14] Peng, Kang.; Wei, Guo.; Weigang, Huang.; et al. Two-Stage Stochastic Programming Scheduling Model for Hybrid AC/DC Distribution Network Considering Converters and Energy Storage System. Applied Sciences. 2019, 10(1).

[15] Minhan, Yoon.; Gilsoo, Jang. System-Level Vulnerability Analysis for Commutation Failure Mitigation in Multi infeed HVDC Systems. Journal of Electrical Engineering & Technology. 2018, 13(3), 1052-1059.

[16] Lei, Liu.; Sheng, Lin.; Kai, Liao.; et al. Extinction angle predictive control strategy for commutation failure mitigation in HVDC systems considering voltage distortion. IET Generation, Transmission & Distribution. 2019, 13(22), 5171-5179.

[17] He, Jian.; ZHANG, Jian.; GUO, Qiang.; et al. Calculation of the peak power fluctuations of two area AC tie line under the impact of DC commutation failure [J]. Chinese journal of electrical engineering. 2015, 35(04), 804-810.

[18] Luan, Chunpeng.; Zhu, Xiaodong.; Pang, Jianye. Multi-objective Optimization of wind-thermal Power generation Right Trading considering dynamic Cost [J]. Dianli Dianli. 2017(11), 65-69.