Research on HVDC Transmission Power Scheduling on the Background of Asynchronous Interconnection

Yiping Chen[1], Xiaodong Zheng[2], *Student Member, IEEE*, Haoyong Chen[2], *Senior Member, IEEE*, Yong Zhang[1], Jizhong Zhu[1], *Senior Member, IEEE*, Julong Chen[1], Zipeng Liang[2], Jingpeng Chen[1]

[1]China Southern Power Grid
Guangzhou, China
chenyiping@csg.cn, zhujz@hotmail.com

[2]School of Electric Power, SCUT
Guangzhou, China
eehychen@scut.edu.cn, z.xiaodong@mail.scut.edu.cn

***Abstract*—For asynchronous power systems which are interconnected only by HVDC transmission lines, the tie-line power scheduling becomes challenging due to the discrete characteristics of HVDC transmission power profile. Based on previous work on modeling HVDC transmission power, a feasible framework of constraints that fully describes the power characteristics is proposed. Moreover, a power scheduling model of HVDC transmission (DCPS) considering power and energy balance conditions, as well as operation limits of power plants and AC lines is developed. The model is decoupled into two subproblems and a high-performance solution is proposed. Real data of China Southern Power Grid is utilized to demonstrate that the method is efficient and reliable, and thus can be a competent approach for dispatching center to work out a HVDC transmission plan.**

***Index Terms*—Multiarea power system, HVDC tie-line, day-ahead power scheduling, mixed integer programming (MIP), Chebyshev approximation.**

I. INTRODUCTION

In China, several provincial grids are interconnected as a large-scale regional power grid. The dispatching center of a regional grid is obligated to carry out day-ahead tie-line power scheduling, which would be executed by provincial grids. The principles of transmission power scheduling include ensuring security and saving operation cost. However, current approach is empirical and manual, and thus cannot fully consider security and economic profit. Particularly, some provincial grids are now asynchronously interconnected such as in China Southern Grid, that is, tie-lines between these areas are all HVDC transmission lines [1], [2]. Due to the discrete characteristics of HVDC transmission power, it is challenging to formulating a reasonable transmission power plan.

Multiarea day-ahead generation and transmission scheduling can be generalized as an energy transaction constrained unit commitment problem. Although unit commitment is a general method for day-ahead power scheduling [3], [4], its application to China's regional grid may suffer some troubles. The reasons are manifold: *i*) the target or mode of scheduling varies with area and period, including equity, energy conservation, cost reduction or free market, which makes it hard to determine a unified objective; *ii*) the dispatching centers are hierarchically organized, which means that the higher level merely has to work out and distribute the power transmission plan, and unit commitment is the task for dispatching centers of provincial grids; *iii*) due to the discrete characteristics of HVDC transmission power, the multiarea day-ahead power scheduling problem should be specifically processed.

[5] presents a decentralized decision-making framework to determine an economical hourly generation schedule for a multi-area power system. The strength is that each area is self-governing and only limited data information needs to be exchanged, but the HVDC property is neglected in this model. [6] presents a hybrid scheduling mode for coordinated optimization of unit commitment and DC transmission power scheduling, but the dispatching interval should be 1 hour, which is not precise enough for DC transmission power scheduling, and if adopting 15-minute interval the scale of the model would be too large. Moreover, unit commitment is not inside the scope of dispatching center of regional grid but provincial grids.

To allocate hydro power to multi thermal systems, [7] choses minimizing the standard deviation relevant to the remaining load series for thermal systems as the objective, and produces satisfying effect of cutting down peak load. It's remarkable that by adopting a simple objective, the model's complexity is reserved for the other essential.

The discrete constraints of HVDC transmission power, including stair-like requirement, times limit of power level adjustment etc., are introduced to meet the reliability requirements for telemechanical apparatus, converter stations control etc. [8]. Modeling HVDC transmission power have been studied in several literatures [9]-[11], among which [11] develops a most delicate model to describe the property, but still cannot satisfy the requests of engineering practice. In [12] an ideal power cure is formulated firstly and then a stair-like curve is applied as an approximation. Approximation is a convenient and efficient method when error is controlled within permitted limits.

In the proposed approach, we cluster generation units into an area model in order to avoid the requirement for detailed information of each area, and optimize the inter-area power schedule with the object of minimizing the variation of generation power profile within an area. The 15-minute transmission power is then allocated onto each HVDC lines subject to operation constraints of relative components.

The paper is organized as follows. The framework of HVDC transmission power scheduling is depicted in Section

II. Mathematical model and solution is proposed in Section III. Test results on a realistic power system is presented in Section IV. Conclusions area given in Section V.

II. DCPS FRAMEWORK

The original HVDC transmission power scheduling problem (DCPS) can be generalized as problem (1) where f describes the economic profit of the system.

$$\begin{aligned} &\min f(\boldsymbol{P}_{\mathrm{G}}) \\ \text{s.t. } &\boldsymbol{g}_1(\boldsymbol{P}_{\mathrm{G}}, \boldsymbol{P}_{\mathrm{DC}}, \boldsymbol{x}_{\mathrm{DC}}) = \boldsymbol{0} \\ &\boldsymbol{g}_2(\boldsymbol{P}_{\mathrm{G}}, \boldsymbol{P}_{\mathrm{DC}}, \boldsymbol{x}_{\mathrm{DC}}) \le \boldsymbol{0} \end{aligned} \tag{1}$$

where, $\boldsymbol{P}_{\mathrm{G}}, \boldsymbol{P}_{\mathrm{DC}}, \boldsymbol{x}_{\mathrm{DC}}$ are decision variables, and represent the vectors of generation, power in HVDC tie-lines and discrete variables belonging to $\boldsymbol{P}_{\mathrm{DC}}$, respectively. $\boldsymbol{g}_1$ and $\boldsymbol{g}_2$ donate constraints on generation capacity, ramping rates, power flow limits, daily energy transaction contract, and discrete constraints on $\boldsymbol{P}_{\mathrm{DC}}$ etc.

The objective function of problem (1) tends to be nonlinear (always a quadratic function), and due to the discrete variables $\boldsymbol{x}_{\mathrm{DC}}$, problem (1) is a mixed integer nonlinear programming (MINP) with thousands of continuous and discrete variables and constraints. It is hard to solve this kind of problem directly, and the efficiency and reliability of the available solvers cannot meet the requirement of engineering application [13]. Therefore, a two-stage approach as shown in Fig.1 is proposed to tackle this problem.

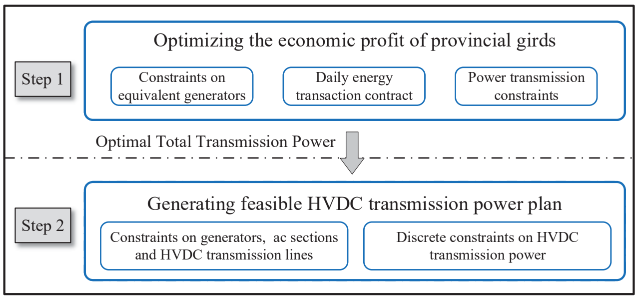


Figure 1. Framework of power scheduling of HVDC transmission.

Firstly, generators in a provincial grid are treated as an equivalent generator, tie-lines that connect a couple of grids are regard as a transmission channel, and discrete variables are omitted. Hence, the subproblem can be formulated as,

$$\begin{aligned} &\min f^{(1)}(\boldsymbol{P}_{\mathrm{Geq}}) \\ \text{s.t. } &\boldsymbol{g}_1^{(1)}(\boldsymbol{P}_{\mathrm{Geq}}, \boldsymbol{P}_{\mathrm{T}}) = \boldsymbol{0} \\ &\boldsymbol{g}_2^{(1)}(\boldsymbol{P}_{\mathrm{Geq}}, \boldsymbol{P}_{\mathrm{T}}) \le \boldsymbol{0} \end{aligned} \tag{2}$$

where, $\boldsymbol{P}_{\mathrm{Geq}}$ is the output of equivalent generators corresponding to each area, $\boldsymbol{P}_{\mathrm{T}}$ is the transmission power in the channels. Problem (2) is a quadratic programming (QP), which means it can be handled easily.

Secondly, after problem (2) is solved, the total transmission power between two provincial grids is settled, and now the task is to allocate the total power to each tie-lines and generate a feasible HVDC transmission power plan, which can be described by the following model,

$$\begin{aligned} &\min f^{(2)}(\boldsymbol{P}_{\mathrm{DC}}) \\ \text{s.t. } &\boldsymbol{g}_1^{(2)}(\boldsymbol{P}_{\mathrm{G}}, \boldsymbol{P}_{\mathrm{DC}}, \boldsymbol{x}_{\mathrm{DC}}) = \boldsymbol{0} \\ &\boldsymbol{g}_2^{(2)}(\boldsymbol{P}_{\mathrm{G}}, \boldsymbol{P}_{\mathrm{DC}}, \boldsymbol{x}_{\mathrm{DC}}) \le \boldsymbol{0} \end{aligned} \tag{3}$$

where $f^{(2)}$ is an approximating function. Problem (3) can be converted to a mixed integer linear programming (MILP).

As an example of realistic system, Fig. 2 depicts the structure of China Southern Power Grid (CSG), among which YunNan Power Grid is asynchronously interconnected to the main grid. The day-ahead transmission plan of tie-lines should be carried out by the dispatching center of regional gird. According to the DCPS framework, the optimal sending power of YunNan grid should be determined in the first step, and the next step is about power scheduling of each HVDC transmission lines shown in the diagram with red lines.

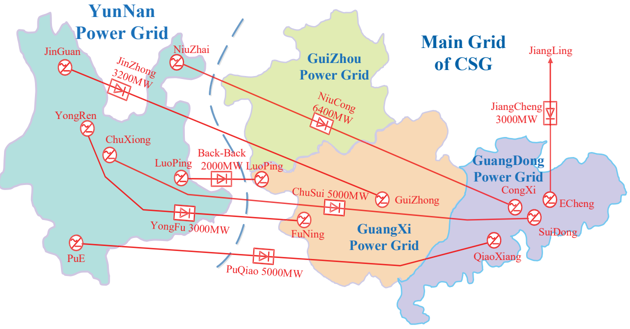


Figure 2. Diagram of China Southern Grid asynchronous system.

III. MODEL AND SOLUTION

In this section, a detailed model of DCPS is developed, and an efficient solution is proposed.

A. Optimizing Power in Transmission Channels

Intuitively, for an area the start-up cost and regulation cost of its thermal units can be reduced if the daily generation curve is smooth and steady [7], and this goal can be obtained by minimizing the standard deviation of generation series, or the Euclid norm of $\boldsymbol{P}_{\mathrm{Geq}} - \mathbf{A}\boldsymbol{P}_{\mathrm{Geq}}$, where $\mathbf{A}$ is a $NT \times NT$ matrix with all its elements be $1/NT$ (NT is 96 for 15-minute scheduling interval). Thus, problem (2) can be formulated as,

$$\min f(P_{\mathrm{Geq}i,t}) = \sum_{i\in R}\sum_{t\in T} w_i (P_{\mathrm{Geq}i,t} - \overline{P}_{\mathrm{Geq}})^2 \tag{4a}$$

$$\text{s.t.} \quad P_{\mathrm{Geq}i,t} - P_{\mathrm{T}i,t} - P_{\mathrm{L}i,t} = 0, \ \forall i \in R \cup S, \ t \in T \tag{4b}$$

$$\sum_{j\in S}(1-\rho_j)P_{\mathrm{T}j,t} + \sum_{i\in R} P_{\mathrm{T}i,t} = 0, \ \forall t \in T \tag{4c}$$

$$(1-\varepsilon)E_{i\mathrm{N}} \le 24/NT \sum_{t\in T}\left|P_{\mathrm{T}i,\ t}\right| \le (1+\varepsilon)E_{i\mathrm{N}}, \quad \forall i \in R \cup S, \ t \in T \tag{4d}$$

$$P_{\mathrm{Geq}i\,\min} \le P_{\mathrm{Geq}i,t} \le P_{\mathrm{Geq}i\,\max}, \quad \forall i \in R \cup S, \ t \in T \tag{4e}$$

$$P_{\mathrm{T}i\,\min} \le P_{\mathrm{T}it} \le P_{\mathrm{T}i\,\max}, \quad \forall i \in R \cup S, \ t \in T \tag{4f}$$

$$P_{\mathrm{Geq}i}^{-} \le P_{\mathrm{Geq}i,(t+1)} - P_{\mathrm{Geq}i,t} \le P_{\mathrm{Geq}i}^{+}, \quad \forall i \in R \cup S, \ t \text{ and } t+1 \in T \tag{4g}$$

where, $P_{\mathrm{Geq}i,t}$, $P_{\mathrm{T}i,t}$, $P_{\mathrm{L}i,t}$ are respectively generation, transferring power, and load demand of area i at period t; S, R, T are respectively set of indices of sending-end girds, receiving-end power girds and scheduling periods; ω_i is the weighting factor, ρ_j the loss factor, ε the daily energy trading error that is permitted and $E_{i\mathrm{N}}$ the energy trading plan. In this article, for variable x, $x_{\max}$ and $x_{\min}$ donate its upper bound and lower bound, while x^{+} and x^{-} donate its ramp up and ramp down limits and $\bar{x}$ the average. (4b)-(4c) are the power balance conditions for each area and for the total power exchange, respectively. (4d) is the energy transaction constraint. (4e)-(4g) are constraints on generation, tie-line power and ramping rate, respectively.

B. Power Scheduling of HVDC Transmission

Supposed that $\boldsymbol{P}_{\mathrm{T}}^{*}$ is the optimal transmission power in a channel, then for step 2, the sum of power in HVDC transmission lines belonging to the channel should be close to $\boldsymbol{P}_{\mathrm{T}}^{*}$. Our attempt to this is minimizing the maximum absolute deviation, or the Chebyshev norm of $\mathbf{B}\boldsymbol{P}_{DC} - \boldsymbol{P}_{\mathrm{T}}^{*}$ [14]. Thus, problem (3) can be formulated as

$$\min \Delta P_{\mathrm{T}} \tag{5a}$$

$$\text{s.t.} \quad P_{\mathrm{T}t} - \Delta P_{\mathrm{T}} \le \sum_{i\in DC} P_{\mathrm{DC}i,t} \le P_{\mathrm{T}t} + \Delta P_{\mathrm{T}}, \quad \forall\, t \in T \tag{5b}$$

$$(1-\varepsilon_{\mathrm{T}})E_{\mathrm{T}} \le 24/NT \sum_{i\in DC}\sum_{t\in T} P_{\mathrm{DC}i,t} \le (1+\varepsilon_{\mathrm{T}})E_{\mathrm{T}} \tag{5c}$$

$$P_{\mathrm{DC}i\min} \le P_{\mathrm{DC}i,t} \le P_{\mathrm{DC}i\max}\,, \quad \forall i \in DC,\ t \in T \tag{5d}$$

$$P_{\mathrm{G}j\min} \le P_{\mathrm{G}j,t} \le P_{\mathrm{G}j\max}\,, \quad \forall j \in G,\ t \in T \tag{5e}$$

$$P_{\mathrm{G}j}^{-} \le P_{\mathrm{G}j,(t+1)} - P_{\mathrm{G}j,t} \le P_{\mathrm{G}j}^{+}\,, \quad \forall j \in G,\ t \text{ and } t+1 \in T \tag{5f}$$

$$(1-\varepsilon_{\mathrm{G}j})E_{\mathrm{G}j} \le 24/NT \sum_{t\in T} P_{\mathrm{G}j,t} \le (1+\varepsilon_{\mathrm{G}j})E_{\mathrm{G}j}\,, \forall j \in G \tag{5g}$$

$$P_{\mathrm{L}k\min} \le P_{\mathrm{L}k,t} \le P_{\mathrm{L}k\max}\,, \quad \forall k \in L,\ t \in T \tag{5h}$$

$$P_{\mathrm{L}k} = \sum_{i\in DC} \pi_{i,k} P_{\mathrm{DC}i} + \sum_{j\in G} \pi_{j,k} P_{\mathrm{G}j}\,, \quad \forall k \in L \tag{5i}$$

where ΔP_{T} is the decision variable used to convert the Chebyshev approximation problem to a linear programming; $P_{\mathrm{T}t}$ is the total transmission power between two provincial grids, E_T the transaction energy, and $E_{\mathrm{G}j}$ the daily energy contract of generator j; DC, G, L are respectively set of indices of HVDC transmission line, generators and AC lines; $P_{\mathrm{DC}i,t}$, $P_{\mathrm{G}j,t}$, $P_{\mathrm{L}k,t}$ are respectively power of HVDC transmission line i, generator j and AC line k at interval t; ε_{T} and $\varepsilon_{\mathrm{G}j}$ are the energy error permitted; $\pi_{i,k}$ and $\pi_{j,k}$ are power flow distribution factors. The combination of (5a)-(5b) is the Chebyshev approximation of total transmission power. (5c) is the energy transaction constraint. (5d), (5e) & (5h) are the capacity constraints. (5f) is the ramping limit condition. (5g) donates the energy transaction constraint of generators. (5i) is the power flow equation.

Some extra discrete constraints should be added in order to generate an executable HVDC transmission power plan.

- Power Flatting Constraint

In reality, power in HVDC transmission line stays unchanged in most of the time. That is, the power curve is flat except for several adjustments, and this can be expressed

$$x_{\mathrm{l}i,t}^{(1)} P_{\mathrm{DC}i}^{-} \le P_{\mathrm{DC}i,(t+1)} - P_{\mathrm{DC}i,t} \le x_{\mathrm{r}i,t}^{(1)} P_{\mathrm{DC}i}^{+}\,, \quad \forall i \in DC,\ t \text{ and } t+1 \in T \tag{6a}$$

$$\begin{cases} x_{\mathrm{l}i,t}^{(1)} + x_{\mathrm{r}i,t}^{(1)} \le 1 \\ \sum_{t\in T} (x_{\mathrm{l}i,t}^{(1)} + x_{\mathrm{r}i,t}^{(1)}) \le \mathrm{N}_{\max}^{(1)} \end{cases}, \quad \forall i \in DC \tag{6b}$$

where, $x_{\mathrm{l}i,t}^{(1)}$, $x_{\mathrm{r}i,t}^{(1)}$ are 0-1 integer variables; $\mathrm{N}_{\max}^{(1)}$ indicates the number of intervals during which the power level is changing.

- Reversed Regulation Constraint

Since up and down regulation is not only hard to realize, but also harm for the HVDC converters, following constraint is introduced to prevent sharp peak on the power curve

$$\begin{cases} x_{\mathrm{l}i,t}^{(1)} + x_{\mathrm{r}i,(t+1)}^{(1)} \le 1 \\ x_{\mathrm{l}i,(t+1)}^{(1)} + x_{\mathrm{r}i,t}^{(1)} \le 1 \end{cases}, \quad \forall i \in DC,\ t \text{ and } t+1 \in T \tag{7}$$

- Power Stages Constraint

The number of power stages is limited for realistic HVDC transmission lines. To ensure that the power stays at no more than 8 various levels, another constraint is needed

$$x_{i,t}^{(2)} P_{\mathrm{DC}i}^{--} \le P_{\mathrm{DC}i,(t+2)} - 2P_{\mathrm{DC}i,(t+1)} + P_{\mathrm{DC}i,t} \le x_{i,t}^{(2)} P_{\mathrm{DC}i}^{++}\,, \quad \forall i \in DC,\ t,\ t+1 \text{ and } t+2 \in T \tag{8a}$$

$$\sum_{t\in T} x_{i,t}^{(2)} \le \mathrm{N}_{\max}^{(2)}\,, \quad \forall i \in DC \tag{8b}$$

where, $x_i^{(2)}$ is 0-1 integer variable indicating whether the changing rate of power is switched; $\mathrm{N}_{\max}^{(2)}$ should be about 16 for the 8 stages as required.

C. Solution of DCPS

To acquire the final power plan, we only have to solve a QP and several MILP problems (the amount depends on the number of areas). For a realistic power system, the problems are always feasible. The MILP consumes most of the computing resources because of its NP-hard property and large scale. The set of indices of $x_{\mathrm{l}i,t}^{(1)}$, $x_{\mathrm{r}i,t}^{(1)}$, $x_{i,t}^{(2)}$ is $(i,t) \in DC \times T$, so for a provincial power grid with 6 HVDC transmission lines, the number of discrete variables would be $3 \times 6 \times 96 = 1728$. Thanks to the decoupling method, the scale of DCPS problem is significantly reduced, and the MILP problem can be independently or parallelly solved for each area.

IV. CASE STUDY

The realistic data of CSG on Dec. 25th, 2016 is taken to verify the feasibility and effectiveness of DCPS. The QP and MILP problems are modeled on GAMS and solved by

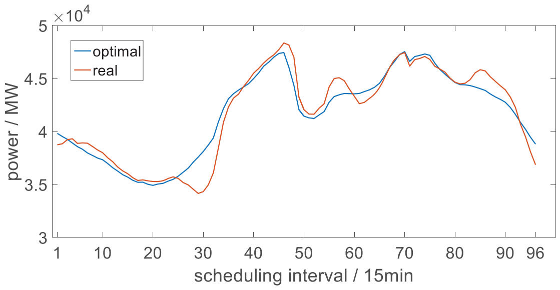
CPLEX. All runs were executed on an Intel i7 CPU machine running at 2.59 GHz and equipped with 8 GB of memory.

A. The Effect of Provincial Grid

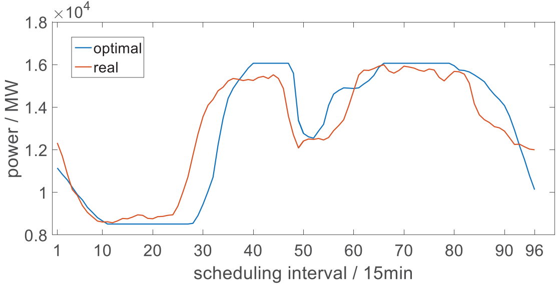
Within the regional grid CSG depicted by Fig. 2, two provincial grids are worth mentioning, namely YunNan Power Grid (YN) and GuangDong Power Grid (GD). YN is asynchronously connected to the main grid with more than 79% of its installed capacity be renewable energy, while GD is a load center with 86% of its installed capacity comes from thermal plants. About 33% of GD's load demand is supplied by power of YN transferred through the channel combined with 5 HVDC transmission lines, so it is potential to reduce GD's burden of peak load balance and frequency regulation, as well as improve the economic profit of operation by optimizing the transaction power between areas.

The effect of the first step of DCPS is shown in Fig. 3(a). Intuitively, the generation curve of GD is less fluctuant than the original one, which allows the dispatching center of GD provincial grid to work out unit commitment and power scheduling more easily. The power transaction plan in Fig. 3(b) is executable since certain constraints have been considered in the model.

Several indices are listed in table 1 to evaluate the improvement of power scheduling. By utilizing DCPS, the peak-valley difference of generation has decreased from 14200 MW to 12616 MW, and we have seen the standard deviation declined by 9.06 percent. Due to such improvements, the start-up cost and regulation cost of GD's thermal units can be reduced, and its burden of peak load and frequency regulation is reduced.



(a) Comparison on generation curve of GD



(b) Comparison on curve of receiving power of GD

Figure 3. Results of Guangdong power grid by optimizing transmission power.

TABLE 1. THE GENERATION CHARACTER OF GUANGDONG POWER GRID

MW

	Peak	Valley	Peak-valley Difference	Standard Deviation
DCPS	47535	34919	12616	3915
Real	48358	34157	14200	4305

B. HVDC Transmission Plan

For dispatching center of regional grid, the intent of power scheduling is to generate a transmission plan of tie-lines and a generation plan of several designated large units. The following is to verify the feasibility of HVDC transmission power plan taking YN asynchronous-interconnection system as an example.

YN is a sending-end system with great capacity of hydro resources, most of its power is delivered to GD through the HVDC transmission lines. As designed, each HVDC transmission line is corresponding to one or two hydro plants and responsible for their power delivery. The operation data of YN asynchronous system on Dec. 25th, 2016 is listed on table 2.

TABLE 2. MAJOR INFORMATION OF YUNNAN POWER GRID

	Transmission Power Limits (MW)	Relative Plants and Scheduled Energy (MWh)	AC Section Limits (MW)
ChuSui	5000, 500	XiaoWan, 28956 JinAnQiao, 17505	-1600, 1600
NiuCong	6400, 640	XiLuoDu, 65075	-1000, 800
PuQiao	5000, 500	NuoZhaDu, 68125	-800, 2400
JinZhong	3200, 320	LiYuan, 13218 AHai, 11720	-500, 500
YongFu	3000, 300	GuanYinYan, 20640	-500, 500
LuoPing	2000, 200	none	none

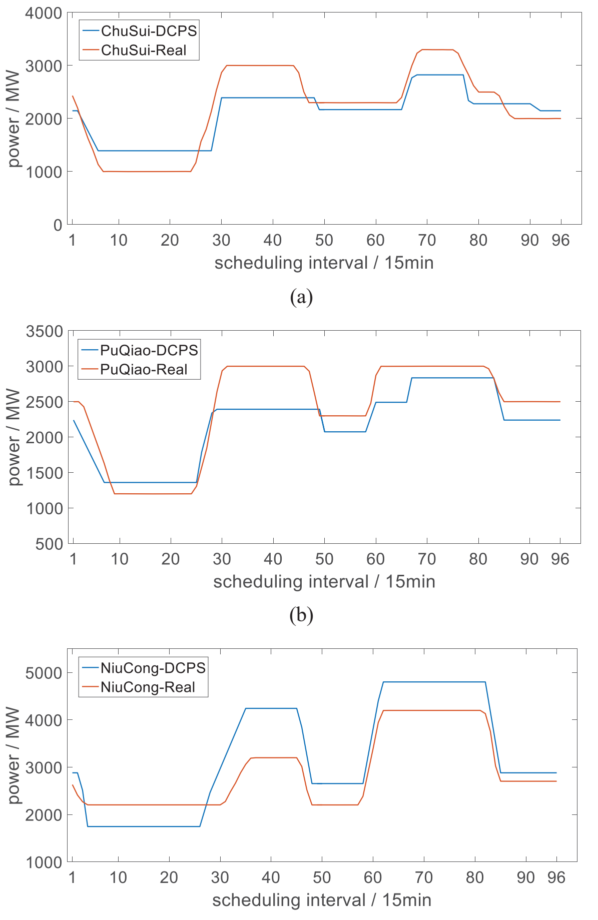
Adopting the total transaction power acquired from solving the QP problem, the MILP problem is solved in this step and then we get the HVDC transmission power plan as shown in Fig. 4. It is obviously that the power curves obtained by DCPS possess similar characteristics with the real ones drawn up manually, and this means that the plan complies with the operation request of HVDC transmission.

Moreover, DCPS has some advantages compared with current method.

1) *Security constraint:* DCPS fully considers the limits of both AC and dc transmission lines, thus the results meet the security requirements. For example, in actual operation, the AC section related to ChuSui HVDC transmission line reached up to 2300 MW, exceeding the up-limit with 700 MW, while in the case of DCPS, power is strictly within limits.

2) *Flexibility:* The objectives in both of the problems can be changed as needed. For instance, the object function in step 1 can be minimizing the cost when given equivalent generation cost; the objective in step 2 can be altered if we need to reduced transmission loss, and the former approximation formula can be dealt with as a constraint.

3) *Reliability and efficiency:* Dozens of cases have been tested, and it is definite that for any reasonable base data (like daily energy trading etc.), DCPS is able to generate a near-optimal HVDC transmission power plan in reasonable CPU times, which allows it to be implemented in the dispatching automation system.



(a)

(b)

(c)

Figure 4. Transmission power plan of (a) ChuSui; (b) PuQiao; and (c) NiuCong.

V. CONCLUSION

Inspired by the requirement of HVDC transmission power scheduling from dispatching center of large-scale regional power grid, this paper propose a hierarchical approach (DCPS model), in which, the total transmission power of each area is determined at the first step, and an executable HVDC transmission power plan is formulated at the second step. Discrete variables and relative constraints are introduced to fully consider the characteristics of HVDC transmission power, and thus makes the power plan suitable for interconnected power grid with HVDC tie-lines, especially for asynchronous interconnection.

We apply the DCPS to a realistic large-scale power grid in southern China. Experiment results demonstrate that DCPS can generate a HVDC transmission power plan using permitted computing and time resources. Besides, security constraints like AC power flow limit are satisfied. In summary, the DCPS method proposed in this paper show appealing advantages of reliability and theoretical guarantees on feasibility, and it is promising in practical applications of dispatching center of regional power grid.

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