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Multi-Area Unit Commitment with Bilateral Contract Approach in Deregulated Electricity Market

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Abstract – The eventual goal of this paper is to help the generating companies and load-serving entities to choose appropriate relative levels of interconnected system versus bilateral trades while considering risk, and economic performance. In competitive power markets, electricity prices are determined by balance between demand and supply in electric power exchanges or bilateral contracts. The problem formulation is bilateral contract incorporated into Multi-area unit commitment with import/export and tie-line constraints. This proposed method considers maximizing own profit or minimize the operating cost among the generating companies in multi-area system. The feasibility of the proposed algorithm has been demonstrated using IEEE system with four areas and experimental results shows that proposed method is reliable, fast and computationally efficient

Keywords: Bilateral contract, Dynamic Programming sequential combination, multi-area unit commitment, Multi-area economic dispatch

1. Introduction

D_j^k : Total load demand in area k at jth hour
L_j^k : Total import power to area k at jth hour
E_j^k : Total export power to area k at jth hour
$I_{i,j}^k$: Commitment state (1 on, 0 for off)
$Irlist$: List of committed units ascending priority order
i : Index for units
j : Index for time
λ_i : Marginal cost for unit
λ_{sys} : Marginal cost of supplying the last incremental energy to meet entire system demand
N_A : Total number of areas
N_k : Total number of units in area K
O_{plist} : List of uncommitted units in descending order
Pg_j^k : Power generation of area k at jth hour
$\underline{Pg_i^k}$: Lower limit of power generation of unit i in area k
$\overline{Pg_i^k}$: Upper limit of power generation of unit i in area k
$Pg_{i,j}^k$: Power generation of unit i in area k at jth hour
R_j^k : Spinning reserve of area k at jth hour
S_j^k : Total commitment capacity for area k at jth hour
SD_j^k : Total system demand at jth hour
t : Total time span in hours
T_i^{on} : Minimum up time of unit i
T_i^{off} : Minimum down time of unit i
τ_i : Time constant in start up cost function for unit i
W_j : Net power exchange with outside systems
$X_{i,j}^{on/off}$: Time duration for which unit i has been on/off at j^{th} hour

2. Introduction

An important goal behind the restructuring of the electricity industry is to bring more choice. In the way individual loads supply their needs, permitting them to buy either from a centralized spot market or directly from generators

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or marketers through pre-arranged bilateral contracts. These are typically of longer duration and tend to offer financial stability to generators and lower prices to loads when compared with the more volatile pool market prices. They can be of two types: either financial hedging agreement [1-2] or physical transactions directly affecting the generation and demand levels [3-4]. In the competitive environment, customers request for high service reliability and lower electricity prices, while generation companies (GENCOS) have to make their own profits. Thus, it is an important on to maximize own profit with high reliability and minimize overall operating costs. And meet demand contracts while satisfying relevant generation constraints and network constraints with respect to financial hedging contracts.

The Unit Commitment Problem (UCP) is a constrained optimization problem in which optimal turn-on and turn-off schedules need to be determined over a given time horizon for a group of power generation units under some operational constraints [5,6].The objective is to minimize the power generation costs while meeting the hourly forecasted power demands. The UCP is an important area of research which has attracted increasing interest from the scientific community due to the fact that even small savings in the operation costs for each hour can lead to major overall economic savings.In the economic dispatch problem, for each hour, the power outputs for the units scheduled to be online for that hour are obtained in such a way as to minimize the fuel costs while meeting the forecasted power demands for that hour. In this paper, a multi-area unit commitment is formulated while considering generator constraints, import/ export constraints and incorporating bilateral contract such as forward-contract, call and put options [8]

In deregulated market, the market price signal in each area can be modeled as a pseudo unit whose generation cost is the forecasted market prices. Financial hedging agreement, such as call or put options and forward contracts are proposed to the multi-area UC and ED.This paper proposes an alternative unit commitment approach, decision making via "bidding", which could encompass the merits of the DP based methods. Based on this approach, the sequential unit commitment method sequentially identifies, via "bidding", the most advantageous unit to commit until the system obligations are fulfilled. [9]

Dynamic programming is characterized by the forward and back path operations. Commitment of units progresses one hour at a time, and combinations of schedulable units are stored for each hour. Finally, the most economical schedule is obtained by backtracking from the combination with the least total cost at the final hour through the optimal path to the combination at the initial hour. Thus if there are 30 schedulable units in an hour, then there are 1, 073, 741, 824 (230) combinations to evaluate. Obviously, it is not practical to evaluate all of the combinations. Furthermore, many of the combinations are inadmissible due to inadequate available capacity and there is generally some pattern in starting order of the units so that it is not necessary to evaluate all possible unit combinations. The DP-SC method generates a subset of the combinations by turning each unit on in priority list sequence. Thus if there are 30 schedulable units, only 31 combinations will be evaluated. The first combination is all schedulable units off, assuming that all operation constraints are satisfied. Since many combinations are neglected, the optimal path may not be found. Proper ordering of the units in the priority list is expected to yield more economic schedules. This technique seems to be well suited when the system load is changing rapidly.

It is noted that the advantage of the DP–SC based methods corresponds with the disadvantage of the LR based methods and vice versa. This is quite logical considering that the primal decision space resembles a regulated decision environment and the dual decision space resembles decision environment with free competition. This observation suggests an alternative unit commitment approach, decision making via "bidding", which could encompass the merits of the DP based methods (primal feasibility) and the LR based methods (dual decomposition).Based on this approach, the sequential unit commitment method sequentially identifies, via "bidding", the most advantageous unit to commit until the system obligations are fulfilled.

In this paper dynamic programming sequential combination (DP-SC) method is applied to find the optimal generation scheduling in the multi-area system. In economic dispatch ,the lambda iteration method is used to determine optimum generation output for committed units [9,10].Numerical results have shown that generating companies is minimize the over all operating cost with forward contract and dispatch their generation unit effective manner in multi-area. The scope of this paper is restricted to forward bilateral contracts, financial agreement between a generator and load pair.

This paper first formulates the optimization problem of multi-area unit –commitment with forward contract and call and put options modeling is proposed in Section 2. Multi-area economic dispatch problem is explained in Section 3. Simulation results of IEEE test system for four areas are presented in section 4. Conclusion of the proposed approach is summarized in section 5.

3. Multi-area Unit -commitment with Bilateral Contract

Multi-area generation scheduling scheme which it provides proper unit commitment in each area, and effectively preserve the tie-line constraints. The objective of a multi-area generation scheduling problem is to coordinate area generations in order to minimize the operation cost [11-14]. The constraints are composed of the system power balance, spinning reserve requirements in every area, unit upper/ lower generation limits, unit minimum up/down times, tie line limitations and so on. Call and put options ,forward contracts ,and reliability must run contract are incorporated into multi-area UC and ED as a effective tool to procure the resource and supply the demand.A bilateral contract is an agreement between two parties to exchange electric power under a set of specified conditions such as MW amount, time of delivery, duration, and price. Bilateral contracts can take the form of futures or forward contracts, where the former are generally traded in an exchange, and can be traded continuously up until their time of delivery. In contrast, forward contracts are typically negotiated directly between the load and generator with the terms of the contract remaining fixed until the time of delivery [15].

The single area unit commitment problem is defined mathematically as a non-linear, non-convex, large-scaled mixed integer combinatorial optimization problem, often involving thousands of 0-1 decision values as well as continuous variables, and a wide spectrum of equality and inequality constraint. The optimal solution to such a complex combinatorial optimization problem can be obtained only by a global search technique. The following methods Priority List method, Simplex method, Branch and Bound method, Lagrangian relation method, Dynamic programming method have been proposed previously for solving single area unit commitment problem [5,6,16]. In this paper, DP-SC method is used to find the nearly optimal solution among the available generating units in the interconnected multi-area system with bilateral contract and minimize the total operating or production cost.

3.1 Bilateral Contracts

Bilateral transactions are usually long-term agreements determined through individual negotiations between a buyer and a seller. The price agreed to in a bilateral exchange is based on market forces and, other than under potential system security violations, the levels of the bilateral transactions are arrived at independently of any centralized pool optimal dispatch. In this paper, we assume that a set of bilateral contracts has been determined through some power exchange mechanism that facilitates such power contracts. In a competitive market, participantsoften employed power contracts to hedge their risks [17].

In this proposed method, bilateral contracts are incorporated into forward contracts and options. Forward contract holders are obligated to buy or sell power at a predefined price for a specified period which can be from an hour to years [5]. Unlike forward contracts, options give their option purchasers the right, but not the obligation, to buy (for call option) or sell (for put option) a fixed amount of power at a predefined strike price during the option term which is usually from months to a couple ofyears. We have considered option and forward contracts between internal generators and internal LSEs, between internal generators andexternal LSEs which is counted as sale transactions with the external system or between external generator and inter-nal LSE which is counted as purchase transactions with the external system [5,18].

1) Forward contract: When the forward contracts are exercised, the following procedures must be completed before the multi-area UC and ED problems are solved.

1.1) Forward Contracts between Internal Generators and Internal Load Serving Entities.

Step(1) : The generation requirements of areas where the designated source generating units are located at are increased by the amounts of power and in the periods specified in the contracts.

Step(2) : The generation requirements of the designated sink load areas are decreased by the amounts of power and in the periods specified in the contracts.Consequently, the adjusted generation requirements of the source areas are the demand of the source areas plus the contracted amounts of power and those of the sink areas are the demand of the sink areas minus the contracted amounts of power.

Step (3): The contracted amounts of power in the specified periods are counted against the export limits of the source areas and the import limits of the sink areas.

1.2) Forward Contracts between External Generators and Internal LSEs

The forward contracts between the external generators and the internal LSEs are considered as the purchase contracts with the external systems. When they are exercised, the generation requirements of the designated sink load areas need to be decreased by the amounts of power and in the periods specified in the contracts. The contracted amounts of power are then counted against the import limits of the sink areas.

1.3) Forward Contracts between Internal Generators and External LSEs

The forward contracts between the internal generators and the external LSEs are considered as the sale contracts with the external systems. When they are exercised, the generation requirements of areas where the designated source generating units are located at are increased by the amounts of power and in the periods specified in the contract. The contracted amounts of power are counted against the export limits of the source areas. Meanwhile, the designated source generating units are assigned their status as must-run with predefined minimum generation equal to the amounts specified in the agreement.

2) Options

The main difference between the forward contracts and options is that the holders of the forward contracts are obligated to buy and sell power while the holders of the options have the right to choose whether the contracts should be exercised.Once the call option or the put option is exercised, the procedures which must be completed before the multi-area UC and ED problems are solved. Finally, the tie line capacity limits must be adjusted with respect to flows contributed by contracted amounts of power.

3.2 Problem formulation for Multi-area Unit commitment

The cost curve of each thermal unit is in quadratic form

$$F(Pg_i^{\,k}) = a_i^k (Pg_i^{\,k})^2 + b_i^k (Pg_i^{\,k}) + c_i^k \text{ \$/hr };k=1\ldots N_A \qquad (1)$$

The incremental production cost is therefore

$$\lambda = 2a_i^k Pg_i^{\,k} + b_i^k \qquad (2)$$

(or)

$$Pg_i^{\,k} = \lambda - b_i^k / 2a_i^k \qquad (3)$$

The start up cost of thermal unit is an exponential function of the time that the unit has been off

$$S(X_{i,j}^{off}) = A_i + B_i(1 - e^{X_{i,j}^{off}}) \qquad (4)$$

The objective function for the multi-area unit commitment is to minimize the entire power pool generation cost as follows:

$$\min_{I,P} \sum_{k=1}^{N_A} \sum_{j=1}^{t} \sum_{i=1}^{N_k} [I_{i,j}^k F_j^k (Pg_{i,j}^k) + I_{i,j}(1 - I_{i,j-1}) S_i(X_{i,j-1}^{off}) \qquad (5)$$

and the following constraints are to be met for optimization

1) System power balance constraint where

$$\sum_k Pg_j^k = \sum_k Pg_{i,j}^k \qquad (6)$$

2) Spinning reserve constraints in each area

$$\sum_i \overline{Pg_i^k} \ge D_j^k + R_j^k + E_j^k - L_j^k \quad ;j=1\ldots t \qquad (7)$$

3) Generation limits of each unit

$$\underline{Pg}_j^k \le Pg_{i,j}^k \le \overline{Pg_j^k} \;;i=1\ldots N_k \;;j=1\ldots t\,;k=1\ldots N_A \qquad (8)$$

4) Minimum Up and Down time constraints

$$(X_{i,j-1}^{on} - T_i^{on}) * (I_{i,j-1} - I_{i,j}) \ge 0 \qquad (9)$$

$$(X_{i,j-1}^{off} - T_i^{off}) * (I_{i,j-1} - I_{i,j}) \ge 0 \qquad (10)$$

To decompose the problem in equation (5), it is rewritten as

$$\min_P \sum_{j=1}^{t} [F(Pg_{i,j})] \qquad (11)$$

Where $F(Pg_{i,j}) = \sum_{k=1}^{N_k} F^k (Pg_{i,j}^k)$ (12)

subject to the constraints of equation (6) and (8) and following constraints.

5) Export/Import Constraints

Upper limits $\sum_i Pg_{i.j}^k \le D_j^k + E_{j\max}^k$ (13)

Lower limits $\sum_i Pg_{i,j}^k \ge \sum_k D_j^k - L_{j\max}^k$ (14)

Import/export balance $\sum_i E_j^k - \sum_k L_j^k + W_j = 0$ (15)

6) Area generation limits

$$\sum_i Pg_{i,j}^k \le \sum_i \overline{Pg_i^k} - R_j^k \;; \; k=1\ldots N_A \,; j=1\ldots t \qquad (16)$$

$$\sum_i Pg_{i,j}^k \ge \sum_i \underline{Pg_i^k} \;; \; k=1\ldots N_A \,; j=1\ldots t \qquad (17)$$

Each $F^k(Pg_{i,j}^k)$ for $k=1\ldots,N_A$ is represented in the form of schedule tables, which is the solution of the mixed variables optimisation problem

$$\min_{I,P} \sum_i [I_{i,j}^k F_i^k (Pg_{i,j}^k) + I_{i,j}(1 - I_{i,j-1}) S_i(X_{i,j}^{off}) \qquad (18)$$

Subject to constraints of equation (7),(9-10) and initial on/off condition of each unit.

The multi-area unit commitment problem is solved by Dynamic Programming Sequential Combination (DP-SC) method to form the optimal generation scheduling approach. Among the available generating units in the interconnected multi-area system, the proposed method sequentially identifies, via a procedure that resembles bidding, the most advantageous units to commit until the multi-area system obligations are fulfilled and this method has been explained [9].

3.3 Multi-Area Economic dispatch

The objective of Multi-area Economic Dispatch (MAED) is to determine the allocation of generation of each unit in the system and power exchange between areas so as to minimize the total production cost. The lamda –iteration method is implemented in the MAED to include area import and export constraints and tie-line constraints [16].

The objective is to select λ_{sys} every hour to minimize the operation cost.

$$Pg_j^k = D_j^k + E_j^k - L_j^k \qquad (19)$$

where $Pg_j^k = \sum_{i=1}^{N_k} Pg_{i,j}^k$

Since the local demand D_j^k is determined in accordance with the economic dispatch within the pool, changes of $P_{gj}^{\,k}$ will cause the spinning reserve constraint of equation (7) to change accordingly and redefine equation(18).

In this study, the iterative equal incremental cost method (λ method) was used to solve equation (11) and serve as a coordinator between unit commitments in various areas. With the λ iteration, the system would operate at an optimal point if λ for each unit is equal to a system incremental cost λ_{sys} .Units may operate in one of the following modes when commitment schedule and unit generation limits are encountered:

(a) Coordinate mode: The output of unit i is determined by the system incremental cost

$$\lambda_{\min,i} \le \lambda_{sys} \le \lambda_{\max,i} \qquad (20)$$

(b) Minimum mode: Unit i generation is at its minimum level.

$$\lambda_{\min,i} > \lambda_{sys} \qquad (21)$$

(c) Maximum mode Unit i generation is at its maximum level.

$$\lambda_{\max,i} < \lambda_{sys} \qquad (22)$$

(d) Shut down mode: Unit i *is* not in operation, Pg_i = 0.

Besides limitations on individual unit generations, in a multi-area system, the tie-line constraints in equation (9), (10) and (14) are to be preserved. The operation of each area could be generalized into one of three modes as follows:

(i) Area coordinate mode

$$\lambda^k = \lambda_{sys} \qquad (23)$$

$$D_j^k - L_{\max}^k \le \sum_i P_{i,j}^k \le D_j^k + E_{\max}^k \tag{24}$$

(or)

$$-L_{\max}^k \le \sum_i Pg_{i,j}^k - D_j^k \le E_{\max}^k \tag{25}$$

(ii) Limited export mode

When the generating cost in one area is lower than the cost in the remaining areas of the system, that area may generate its upper limit according to equation (13) or (16), therefore,

$$\lambda^k < \lambda_{sys} \tag{26}$$

λ^k is the optimal equal incremental cost which satisfies the generation requirement in each area k.

(iii) Limited import mode

An area may reach its lower generation limit according to equation (14) or (17), because of the higher generation costs.

$$\lambda_{\min}^k > \lambda_{sys} \tag{27}$$

The proper generation schedule in multi-area will result by satisfying tie-line constraints and minimizing the system generation cost

3.4 Tie- line flow of four areas

An economically efficient area may generate more power than the local demand, and the excess power will be exported to the other areas through the tie-lines. As shown in Fig. 1, assume area 1 has excess power, the line flows would have directions from area 1 to other areas, and the maximum power generation for area 1 would be the local demand in area 1 plus the sum of all the tie-line capacities connected to area 1. If we fix the area 1 generation at its maximum level, then the maximum power generation in area 2 could be calculated in a similar way to area 1

Since tie-line imports power at its maximum capacity, this amount should be subtracted from the generation limit of area 2. According to the system power balance equation some areas must have a power generation deficiency, and require generation imports. The minimum generation level in these areas is the local demand minus all the connected tie-line capacities. If any of these tie lines is connected to an area with higher deficiencies, then the flow directions should be reversed. The tie-line flow details of four area and directional matrix were presented in [16]

Directional matrix: It indicates power flow direction from one area to another area.

$D_{l,k}$ =[1 when line flows from l to k l >k

[-1 when line flows from k to l

$D_{l,l} = 0, D_{l.k} = -D_{k,l}$ initial $D_{l.k}$ are zero

4. Test System and simulation results

The proposed MAUC algorithm has been implemented in C++ environment and tested extensively. Test results of a multi-area system are presented in this section. All simulations were performed on a PC with Intel processor (1.953 GHz) and 1012 MB of RAM.

As shown in Fig 1, a sample multi-area system with four areas, IEEE reliability test systems are used to test the speed of solving the multi-area UC and ED for a large-scale system with import/export , tie line constraints and real data from a market participants[15]. In the sample multi-area system, each area consists of 26 units. The total number of units tested is 104, and their characteristics are presented in [16]. There are identical thermal units in each area. The system contains five tie lines four area interconnections as shown in Fig.1, and area one is the reference area. Fig 2 shows the modified same load demand profile forecast used in all four areas. Bilateral contracts such as forward contract call and put options incorporated in to this problem.

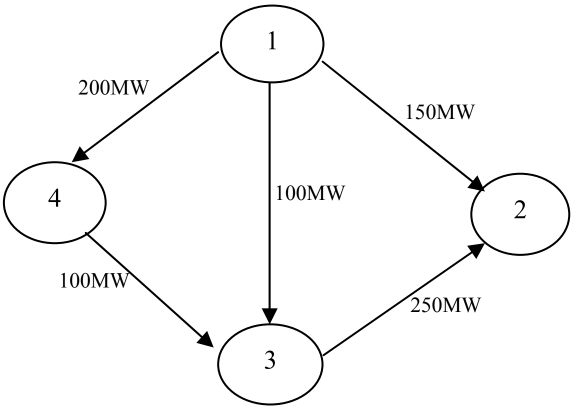

Fig. 1. Topological connections of four areas

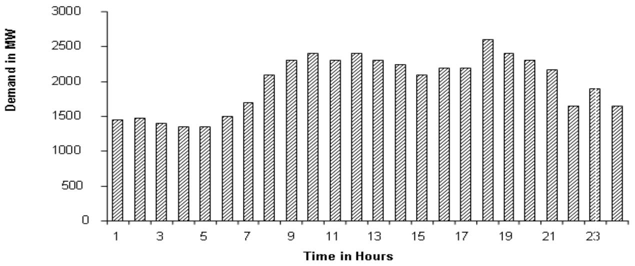

Fig. 2. Load demand profile for four area

1) Multi-area System with limited import /export limit: For base case multi-area unit commitment and economic dispatch is solved without contract but it includes import and export limit ,tie line constraints for same load at 24 –hour period. DP –SC method is used for committing the unit in each area and λ iteration method is used for importing and exporting power to other area and minimizes the operating cost. Areas with lower incremental fuel cost units may generate more power than their demand and export the excessive energy to the deficient areas; likewise, areas with higher incremental fuel cost units will generate less power than their demand and import the additional energy from other areas with surplus capacity. Simulation time of base case MAUC and ED is 2.1s.

Case studies 2, 3, and 4 are performing with base

MAUC-ED but import capabilities of areas 2, 3, and 4 are limited to 250, 300, and 200 MW respectively. Area 1, 3, 4 are limited to export power of 250,300 and 200MW in case studies 5-7 respectively.Both import/export capability of area 1, 2, 4 is limited to 50 MW in case studies 8-10.Table-I shows comparison result of total operating cost.

Bilateral Contract with Multi-area System: In this case studies 11-18, future contract, call and put options are incorporated in to MAUC-ED with tie-line constraints. The impact of bilateral contract, production cost of multi-area system is reduced. Table II shows case studies of 11-19 and Table-III shows comparison result of total operating cost. In this paper bilateral can enable the power producers like GENCO's and LSEs to establish a firm transaction to hedge against the price volatility in the spot market although some transactions may incur more total production cost. Integrating the market operation components into the multi-area UC and ED creates the flexibility in planning the operation and market strategies. For example, multiple bilateral contracts can be exercised in order to buy power at low prices and sell it at high prices. In addition, the profit can be maximized through exercising the market operation components

Table 1. Cost Comparison of multi-area UC and ED with Limited import and export constraints

Case study	Import /export limit	Total operating cost($)
1	Unlimited import/export capability	2510587.50
2	Area 2 of import power is 250 MW	2485955.75
3	Area 3 of import power is 300 MW	2478300.75
4	Area 4 of import power is 200 MW	2487192.25
5	Area 1 of export power is 250 MW	2535111.50
6	Area 3 of export power is 300 MW	2536156.25
7	Area 4 of export power is 200 MW	2531894.50
8	Area 1 of import/ export power is 50 MW	2514552.00
9	Area 2 of import /export power is 50 MW	2505149.25
10	Area 4 of import/ export power is 70 MW	2517275.25

Table 2. Case Studies of Bilateral Contract

Case Study	Contract	Source	Sink	Power MW	Rate ($/MWh)	Hour
12	Put Options	Unit 31 in area 2	External LSE's	50	34	2-16
13	Put Options	Unit 58 in area 3	External LSE's	50	34	2-16
14	Forward Contract	Unit 84 in area4	External LSE's	100	34	10-14
15	Forward Contract	Unit 104 in area4	External LSE's	100	34	10-14
16	Put Options	Unit 4 in area1	External LSE's	20	50	8-11
17	Put Options	Unit 4 in area1	External LSE's	20	100	8-11
18	Call Options	Unit 31 in area 2	Unit 56 in area 3	100	25	18-22

Table 3. Cost Comparison of multi-area UC with Bilateral Contract

Case	MAUC & ED Cost result ($)	Cost of purchase ($)	Cost of revenue ($)	Total Cost ($)
1	2510587	0	0	2510587
11	2534090	0	-26250	2507840
12	2534090	0	-49500	2484590
13	2511158	0	-17000	2494158
14	2511158	0	-20550	2490608
15	2506081	0	-3000	2503081
16	2502033	0	-6000	2496033
17	2513969	36000	0	2549969
18	2530963	0	-60000	2470963

5. Conclusion

Bilateral Contract coordination of multi-area unit commitment is formulated as an operating cost minimization subject to tie-line constraints .The ultimate goal of this strategy is to suggest relative levels of interconnected system versus bilateral commitments by load serving entities and Genco's that offer a good balance between economics and risk. Among the available generating units in the interconnected system, the proposed DP-SC method sequentially identifies, via a procedure that resembles bidding, the most advantageous units to commit until the multi-area system obligations are fulfilled. In this proposed method, multi-area unit commitment is solved with bilateral contract in addition to power balance and spinning reserve constraints, area import/export constraints and tie-line constraints. Test results have demonstrated that the proposed method of multi-area unit commitment with bilateral contract is efficient and simultaneously reduces operating cost.

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