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Congestion management coordination in the deregulated power market

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Abstract

This paper describes a coordination process between GENCOs and the ISO for congestion management and reducing the risk of failure to supply loads. The algorithm underlining the coordination technique is the security-constrained price-based unit commitment (SPUC) which is implemented in two stages. At first, GENCOs apply priced-based unit commitment (without transmission security constraints), schedule their generating units and submit their bids to the ISO for maximizing their profits. The ISO obtains transmission information as well from TRANSCOs via OASIS. The ISO executes congestion management and contingency analysis for minimizing line flow violations and the risk supplying loads. If transmission flow violations persist after the adjustments are made, the solution would provide a signal to GENCOs for modifying their initial bids. Accordingly, additional constraints will be introduced in GENCOs for rescheduling generating units and submitting modified bids to the ISO. Two 36 unit GENCOs are used to demonstrate the efficiency of the proposed algorithm.

Keywords: Risk management; Security-constrained price-based unit commitment; Congestion management; Transmission security; Contingency constraints; Deregulated power market

1. Introduction

NERC focused on the concept of control area responsibility to maintain sufficient ancillary services to maintain reliable system operation under $n-1$ contingency conditions.

The objective of security-constrained price-based unit commitment (SPUC) is the coordination between GENCOs and the ISO. SPUC schedules unit commitment based on generation bids to maximize GENCO's revenue while ensuring the transmission flow security in steady-state (congestion) and $n-1$ contingency cases. SPUC decomposes the problem into a master problem (GENCOs) and a subproblem (ISO) based on Benders decomposition [1,2]. The master problem solves a price-based unit commitment (PBUC) with all unit constraints. Then GENCOs submit their bids to the ISO (subproblem) which also obtains the transmission information from TRANSCOs via OASIS. Accordingly, the ISO will try to alleviate possible line flow violations (steady state and contingencies) by minimizing the cost of generation based on GENCOs' submitted generation and adjustment bids [3]. In the case the violations persist, the ISO will execute an optimization to minimize flow violations and create Benders cuts which represent the detected flow violations. With Benders cuts as additional constraints, the price based unit commitment (PBUC) in the master problem is solved again by GENCOs to provide a new schedule. The ISO will take further actions to secure the system regardless of the GENCOs' losses, if the GENCOs' resubmitted bids are not able to secure the system operation [3,4].

Ancillary services procured competitively in forward markets (day ahead or hour ahead) are regulation, spinning reserves, non-spinning reserves, and replacement reserves, which are traded hourly. Two other ancillary services, i.e. voltage support and black start, are procured on a long-term basis by the ISO. Due to this fact there is no need to study voltage violations

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while solving the infeasibility in congestion management.

In this paper, we model the interaction between GENCOs and the ISO as depicted in Fig. 1. The paper is organized as follows: Section 2 explains the congestion management. Section 3 discusses the global formulation based on Benders decomposition. Section 4 explains the application of decomposition to SPUC. The decomposition of Benders cuts between GENCOs to relief a violation is discussed in Section 5. Test cases and simulation results are given and discussed in Section 6, and conclusions are summarized in Section 7. The list of symbols is given in Appendix A in which bold letters identify vectors or matrices.

2. Congestion management

The section is intended to introduce an efficient procedure for the ISO that can include contingency limits during congestion mitigation, minimize the number of adjustments and increase efficiency of the system by eliminating interactions between inter- and intra-zonal subproblems and between each intra-zonal subproblem and other intra-zonal subproblems [5,6].

The contingency-constrained limits can be taken into consideration either during preferred schedule adjustments to mitigate congestion or after adjusting preferred schedules. In this paper, if the latter option is chosen, the ISO may have to modify the adjusted schedules.

At the beginning, the ISO checks schedules for inter- and intra-zonal congestion and try to minimize total congestion costs by possibly moving SCs and PXs away from their preferred schedules while keeping each SC or PX portfolio in balance, i.e. generation balances load. In this process, adjustment bids (incremental and decremental) represent the economic information on which the ISO will base its decisions to relieve congestion. Adjustment bids include suggested deviations from preferred loads and generation schedules provided by schedule coordinators and power exchange. At each bus, ranges of power deviations along with deviations in price are submitted to the ISO. Incremental bids may be different from decremental bids for the preferred schedule. Economically, these price-quantity values represent what each SC or PX is willing to pay to or receive from the ISO to remove congestion. Each schedule coordinator may trade transactions with others before submitting preferred schedules to the ISO; these parties may also trade power when preferred schedules are returned to them for revision.

Once the inter-zonal congestion is solved, we move to intra-zonal congestion where we use inter-zonal flows as equality constraints. This assumption is to guarantee that inter-zonal line flows will not violate limits again and the solution will not swing between the two optimization subproblems. Another option for considering interactions between two subproblems is by assuming inter-zonal line flows as constant loads or generations (depending on the direction of flows in

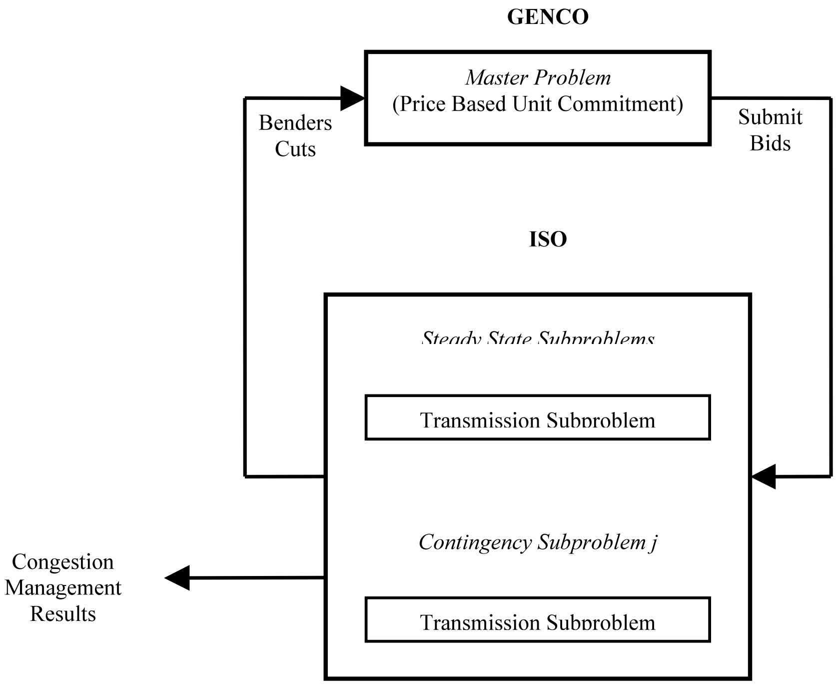

Fig. 1. SPUC hierarchy.

inter-zonal lines) at buses connected to inter-zonal lines. If generator or load at any bus in a zone is not involved in congestion management and do not submit inc/dec bids, then its minimum and maximum limits will be set to preferred schedules. Since small changes in variables may mitigate congestion, control devices such as phase shifters and tap transformers may play an important role in alleviating congestion. These control devices should be checked first as soon as congestion is detected to see if they can remove congestion without any adjustments in preferred schedules or adjusted schedules obtained from the solution of inter-zonal congestion. The ISO checks the first zone for congestion, if congestion is detected, it solves that congestion and then goes to the next zone and so on until all congested zones are done. If congestion in any zone is unsolvable, the ISO passes a signal to different parties to adjust preferred schedules. However, since the intention in each zone is to maintain preferred schedules, we try to solve congestion in each zone using less expensive options such as tap transformers and phase shifters, and if necessary solve the problem using expensive options such as power generation and loads close to congested intra-zonal lines.

If no congestion is detected in any zone or on inter-zonal lines, then the submitted preferred schedules are accepted as final real time schedules.

3. Benders decomposition

The composite SPUC problem can be written as follows:

$$\text{Max } \boldsymbol{ux}$$

$$\text{St.} \quad \mathbf{A}\boldsymbol{x} \geq \boldsymbol{b}$$

$$\mathbf{E}\boldsymbol{x} + \boldsymbol{Fy} \geq \boldsymbol{h} \tag{1}$$

where $\boldsymbol{x}$ represents generation bids and $\boldsymbol{y}$ represents unit generation control, phase shifter and tap transformer preventive controls and penalty variables. The composite formulation represents maximizing profit subject to two sets of constraints. The first set represents GENCO's generation constraints (unit commitment) and the second set represents the ISO's transmission security constraints based on the submitted bids. The formulation (1) is a standard form of Benders formulation [7] which is solved as follows:

i) In the GENCOs' master problem, bids $\boldsymbol{x}$ are determined as follows:

$$\text{Max } \boldsymbol{ux}$$

$$\text{St.} \quad \mathbf{A}\boldsymbol{x} \geq \boldsymbol{b}$$

$$w(\boldsymbol{x}) \leq 0 \tag{2}$$

where $w(\boldsymbol{x})$ is the cut which provides the information regarding the feasibility of the GENCOs submitted bids $\boldsymbol{x}$ in terms of transmission security constrains. The formulation of the Benders cut will be discussed later.

ii) Given $\hat{\boldsymbol{x}}$, the subproblem will minimize transmission flow violations as follows:

$$\text{Min } w(\hat{\boldsymbol{x}}) = \boldsymbol{dy}$$

$$\text{St.} \quad \boldsymbol{Fy} \geq \boldsymbol{h} - \mathbf{E}\hat{\boldsymbol{x}} \tag{3}$$

If the objective function $w(\hat{\boldsymbol{x}})$ is larger than zero in Eq. (3), Benders cuts will be submitted to Eq. (2) to reschedule generating units in the master problem. A linear approximation [8] of Benders cuts is given in Eq. (4) in which the coefficients of the linear approximation are the multipliers π_i associated with constraints in Eq. (3).

$$w(\boldsymbol{x}) = w(\hat{\boldsymbol{x}}) + \boldsymbol{\pi}(\boldsymbol{x} - \hat{\boldsymbol{x}}) \leq 0 \tag{4}$$

where, $w(\hat{\boldsymbol{x}})$ is the optimal solution of Eq. (3); $\hat{\boldsymbol{x}}$ is the solution for the master problem; $\boldsymbol{\pi}$ is the multiplier vector; $\pi_i = \partial w / \partial x_i$ is the multiplier in the subproblem

4. SPUC formulation

Based on the earlier discussion, we formulate GENCOs' master problem and the ISOs' subproblem for risk management.

4.1. Master problem (GENCO) formulation

The master problem (GENCO) solves price-based unit commitment without transmission security constraints [9,10]. The slope of the congestion management adjustment bid is determined by $(1+\lambda_1)$(marginal slope).

4.2. Subproblem formulation

The ISO executes security constraints (i.e. congestion management to find a feasible solution using the submitted bids. First, the ISO runs the inter-zonal congestion management between the zones then it runs the intra-zonal congestion management within the zones. In congestion management, the ISO will try to remove transmission violation by adjusting tap transformers, phase shifters, generation of the units and the load within the given limits.

However, if congestion persists, then line-flow infeasibilities would be represented by adding penalty variables to transmission flow constraints. Penalty variables are interpreted as the amount of transmission flow violations associated with the submitted bids. Therefore, the ISO defines the minimization of violations as its objective function $w(\hat{\boldsymbol{I}})$ at each hour.

In each subproblem, we try to retain the preferred schedule as much as possible. For that reason, we solve the subproblem using less expensive options such as tap transformers and phase shifters, before applying expensive options such as power generation and loads.

So, if congestion presists, the ISO will try to minimize transmission violation by adjusting tap transformers, phase shifters, generation of the units and the load within the given limits in the stead state case and the considered single contingency cases. So, if the congestion management is not feasible for the steady state and contingency cases then we have to solve the following congestion management infeasibility problem. This infeasibility congestion management subproblem takes into account both the steady state and the contingency state of operation.

$$w(\hat{\boldsymbol{I}}) = \mathrm{Min}\left\{\boldsymbol{F}^{\mathrm{s}} + \sum_{j=1}^{nc} \boldsymbol{F}^{\mathrm{c}}(j)\right\} \quad j = 1,\ 2,\ \ldots,\ nc \tag{5}$$

$$\text{St.}\quad \mathbf{A}\cdot\boldsymbol{P} + \boldsymbol{F}^{\mathrm{s}} \leq \boldsymbol{f}^{\mathrm{s}} \tag{6}$$

$$\mathbf{E}(j)\cdot\boldsymbol{P} + \boldsymbol{F}^{\mathrm{c}}(j) \leq \boldsymbol{f}^{\mathrm{c}}(j) \quad j = 1,\ 2,\ \ldots,\ nc \tag{7}$$

$$\boldsymbol{P}^{\min} \leq \boldsymbol{P} \leq \boldsymbol{P}^{\max} \tag{8}$$

We use linear sensitivity factors (LSFs) to formulate transmission constraints. Phase shifters are considered in calculating the LSFs.

The objective function in Eq. (5) is to minimize penalty variables. Eq. (6) represents steady state (congestion) flows and Eq. (7) represents contingency flows. Since we are interested in screening violations, line-flow equations are written in dc for simplicity. $\boldsymbol{P}$ represents generation bids (a function of unit commitment state $\boldsymbol{I}$) submitted by GENCOs. We have included transmission lines with inter- and intra-zonal congestion infeasibilities in these equations.

The controllable system quantities (e.g. generated MW, transformer taps, ... etc) are optimized within their limits so that no flow violations occur in either the steady state or contingency case system operating conditions [11,12].

We would now decompose Eq. (5) further into steady state (congestion) and contingency subproblems.

4.2.1. Steady state (congestion) subproblems

The formulation is as follows:

$$w_{\mathrm{s}}(\hat{\boldsymbol{I}}) = \mathrm{Min}\{\boldsymbol{F}^{\mathrm{s}}\} \tag{9}$$

$$\text{St.}\quad \mathbf{A}\cdot\boldsymbol{P} + \boldsymbol{F}^{\mathrm{s}} \leq \boldsymbol{f}^{\mathrm{s}} \tag{10}$$

$$\boldsymbol{P}^{\min} \leq \boldsymbol{P} \leq \boldsymbol{P}^{\max} \tag{11}$$

There are 24 inter-zonal congestion subproblems corresponding to the 24 h horizon. As explained above, the same model will be used for intra-zonal congestion management infeasibility. This means that we would have another 24 intra-zonal congestion subproblems.

4.2.2. Contingency subproblems

For each line outage j, the following subproblem is solved:

$$w_{\mathrm{c}}(\hat{\boldsymbol{I}},\ j) = \mathrm{Min}\{\boldsymbol{F}^{\mathrm{c}}(j)\} \quad j = 1,\ 2,\ \ldots,\ nc \tag{12}$$

$$\text{St.}\quad \mathbf{E}(j)\cdot\boldsymbol{P} + \boldsymbol{F}^{\mathrm{c}}(j) \leq \boldsymbol{f}^{\mathrm{c}}(j) \quad j = 1,\ 2,\ \ldots,\ nc \tag{13}$$

$$\boldsymbol{P}^{\min} \leq \boldsymbol{P} \leq \boldsymbol{P}^{\max} \tag{14}$$

There are $24 \times nc$ inter- and intra-zonal contingency subproblems that correspond to the 24 h horizon. Fig. 2 depicts the SPUC solution.

5. Distribution of Benders cuts among GENCOs

If a flow violation is detected in the ISO subproblem, the optimal values of $w_{\mathrm{s}}(\hat{\boldsymbol{I}})$ or $w_{\mathrm{c}}(\hat{\boldsymbol{I}},\ j)$ would be larger than zero. There are:

- 2×24 inter- and intra-zonal congestion subproblems which may generate up to 48 Benders cuts.
- $2 \times 24 \times nc$ inter- and intra-zonal transmission contingency subproblems which may generate up to $48 \times nc$ Benders cuts.

So, the total number of subproblems in each contingency case is $48 \times (1+nc)$. With such a large number of constraints added, the master problem would become bigger, more complicated with a larger CPU time. However, the linear representation of these constraints could minimize the required CPU time. The added constraints to the GENCOs' formulation are as follows:

$$w_{\mathrm{s}}^{i}(\hat{\boldsymbol{I}}) \leq 0.0 \quad i = 1,\ 2,\ \ldots,\ 48 \tag{15}$$

$$w_{\mathrm{c}}^{i}(\hat{\boldsymbol{I}},\ j) \leq 0.0 \quad i = 1,\ 2,\ \ldots,\ 48 \quad j = 1,\ 2,\ \ldots,\ nc \tag{16}$$

If the ISO detected a violation in the transmission security subproblem, it will generate Benders cut and will send it to that GENCO. If two or more GENCOs are involved, then the ISO will distribute the cuts among GENCOs as follows: assume the Benders cut at a certain hour involves n generating units in M GENCOs. The ISO Bender cut at that certain hour, based on Eq. (4), is given as follows:

$$\begin{aligned}&\pi_1 I_1 + \pi_2 I_2 + \pi_3 I_3 + \cdots + \pi_n I_n \\ &\quad \leq \pi_1 \hat{I}_1 + \pi_2 \hat{I}_2 + \pi_3 \hat{I}_3 + \cdots + \pi_n \hat{I}_n \\ &\qquad - w(\hat{I}_1,\ \hat{I}_2,\ \hat{I}_3,\ \ldots,\ \hat{I}_n)\end{aligned} \tag{17}$$

Eq. (17) could be rewritten in a vector form as:

$$\begin{aligned}&\pi_{\mathrm{A}} \boldsymbol{I}_{\mathrm{A}} + \pi_{\mathrm{B}} \boldsymbol{I}_{\mathrm{B}} + \cdots + \pi_{\mathrm{M}} \boldsymbol{I}_{\mathrm{M}} \\ &\quad \leq \pi_{\mathrm{A}} \hat{\boldsymbol{I}}_{\mathrm{A}} + \pi_{\mathrm{B}} \hat{\boldsymbol{I}}_{\mathrm{B}} + \cdots + \pi_{\mathrm{M}} \hat{\boldsymbol{I}}_{\mathrm{M}} \\ &\qquad - w(\hat{\boldsymbol{I}}_{\mathrm{A}},\ \hat{\boldsymbol{I}}_{\mathrm{B}},\ \ldots,\ \hat{\boldsymbol{I}}_{\mathrm{M}})\end{aligned} \tag{18}$$

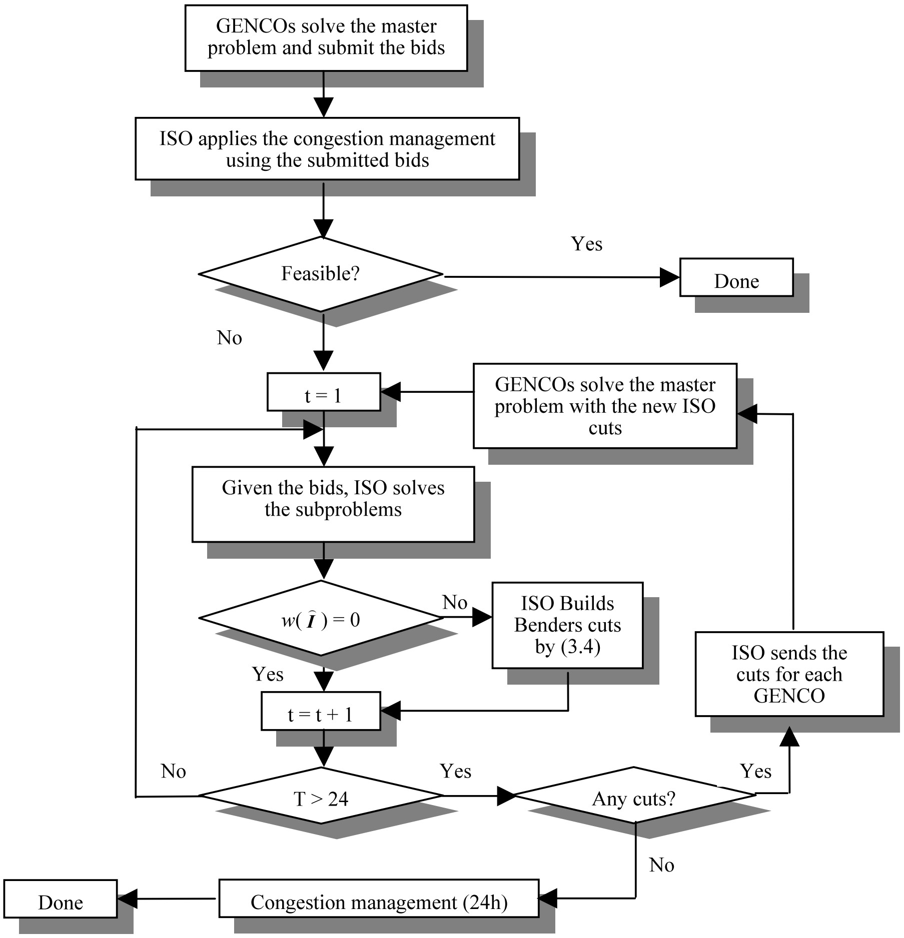

Fig. 2. Flowchart of SPUC.

The ISO will distribute this Benders cut among GENCOs A, . . ., M as follows:

$$\pi_A \boldsymbol{I}_A \le \left[\frac{\pi_A \hat{\boldsymbol{I}}_A}{\pi_A \hat{\boldsymbol{I}}_A + \cdots + \pi_M \hat{\boldsymbol{I}}_M}\right] \times [\pi_A \hat{\boldsymbol{I}}_A + \cdots + \pi_M \hat{\boldsymbol{I}}_M - w(\hat{\boldsymbol{I}}_A, \hat{\boldsymbol{I}}_B, \ldots, \hat{\boldsymbol{I}}_M)] \tag{19}$$

$$\pi_M \boldsymbol{I}_M \le \left[\frac{\pi_M \hat{\boldsymbol{I}}_M}{\pi_A \hat{\boldsymbol{I}}_A + \cdots + \pi_M \hat{\boldsymbol{I}}_M}\right] \times [\pi_A \hat{\boldsymbol{I}}_A + \cdots + \pi_M \hat{\boldsymbol{I}}_M - w(\hat{\boldsymbol{I}}_A, \hat{\boldsymbol{I}}_B, \ldots, \hat{\boldsymbol{I}}_M)]$$

The ISO will send these cuts to GENCOs for further consideration. With Benders cuts as additional constraints, the price based unit commitment in the master problem is solved again by GENCOs to provide a new schedule. GENCOs will then resubmit their bids. This is an iterative process that will be repeated up to three iterations and, if the convergent solution has not been reached at the end of the third iteration, will be terminated by the ISO. The ISO may take further actions (such as voluntary and mandatory load shedding) to secure the system, regardless of GENCOs' losses, if the GENCOs' resubmitted bids are not able to secure the system operation.

It is to be emphasized that the market structure in our model is not different from that of the existing power systems. The significance of our study is that Gencos will be required to resubmit their bids based on network security signals to scheduling coordinators or PX for market pricing.

6. Case study

We use two GENCOs each with 36 generating units and a network of IEEE 118-bus system, as shown in Fig. 3, to illustrate the proposed approach. The IEEE-118 bus network has 186-transmission lines each with a 300 MW capacity. We assume that the network represents one zone which means that we only discuss the intra-zonal congestion in this section. Generating units and transmission characteristics are given in [13]. A 350 MHz personal computer was used to test the proposed model.

Each GENCO first applies a price-based unit commitment and submit bids to the ISO. The unit commit-

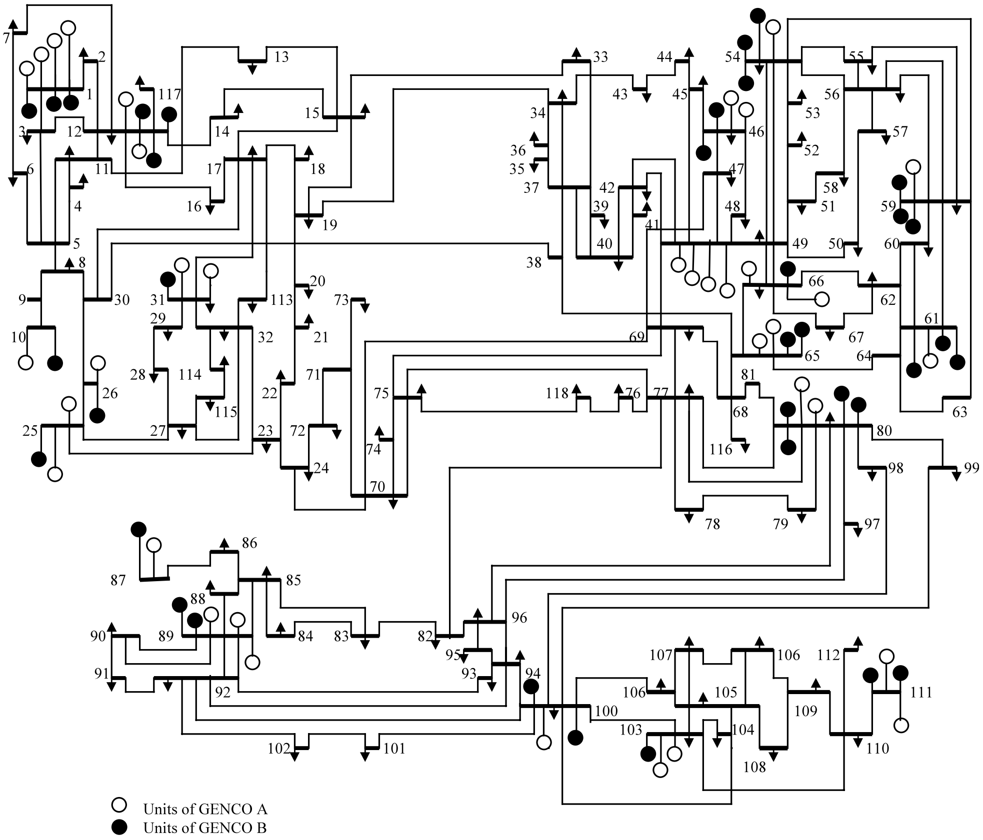

Fig. 3. The system.

ment schedule is shown in Table 1 for GENCO A. The expected profits for GENCOs A and B are $622,207.3 and $356,223.5, respectively. The CPU computation time is 4–5 s. We considered different single contingency cases as shown in Table 2.

The maximum number of Benders cuts resulted from each ISO subproblem would be 24, however, the total number of the ISO subproblems is given in Table 3. Hours 11–22 represents the highest forecasted market prices and highest expected system demand which creates most of transmission violations and congestion management infeasibility as shown in Table 3.

Table 2
Contingency cases

Case	Single transmission line contingencies
1	109–110
2	109–110 or 82–96
3	109–110 or 95–96 or 69–77
4	109–110 or 95–96 or 69–77 or 19–20
5	109–110 or 95–96 or 69–77 or 19–20 or 56–58

Table 1
PBUC (with no subpronlem) for GENCO A

No.	Hours (0–24)																								
1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
2–7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8–11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
12	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
13–14	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
15–18	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
19–21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
22–24	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
25–26	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
27	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
28–36	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 3
Benders cuts and hours of congestion management infeasibility

Case	No. of ISO subproblems	GENCO A		GENCO B	
		Number of Benders cuts	Hours with infeasibility	Number of Benders cuts	Hours with infeasibility
Congestion management	1 × 24	5	15–19	11	5–6, 11–19
Contingency case 1	2 × 24	10	2 × (15–19)	22	2 × (5–6, 11–19)
Contingency case 2	3 × 24	15	3 × (15–19)	33	3 × (5–6, 11–19)
Contingency case 3	4 × 24	20	4 × (15–19)	51	2–7, 4 × (5–6, 11–19), 24
Contingency case 4	5 × 24	25	5 × (15–19)	68	1–6, 5 × (5–6, 11–19), 22, 2 × (24)
Contingency case 5	6 × 24	30	6 × (15–19)	87	1–6, 6 × (5–6, 11–19), 2 × (22), 3 × (24)

The ISO decomposes the resulting Benders cuts based on the formulation in Section 5 and submits them to GENCOs for re-formulation. GENCOs execute price-based unit commitment with added Benders cuts to calculate modified bids. Table 4 shows GENCOs' profits in various cases. Here, GENCOs' profit decreases as more possible outages are considered by the ISO to enhance the security. In Table 4, GENCOs' profit would not change when the added cut has no impact on the solution. This can be seen in cases 3, 4 and 5 for GENCO A. A similar situation applies to Genco B in cases of no contingency & 1 & 2 and with cases 4 and 5.

A typical SPUC solution for GENCOs A and B is shown in Table 5. In general, as more single line outages are considered, the more units are committed by GENCOs to relief the congestion management infeasibility. At hours 15–19, GENCO A commits more expensive units since the markets price and system demand are expected to be high. However, no changes are noted at other hours. GENCO B commits more expensive units at hours 1–7 and 11–19, however, some cheap units are decommitted at hours 1–7 to relief congestion infeasibility. In GENCO B, more expensive units are committed at hours 22 and 24 since the forecasted market prices are high and more congestion is expected to occur. The difference in GENCO solutions is due to Benders cuts and congestion management infeasibility.

A typical result for generated power, spinning reserve, power to be purchased and bidding schedules submitted to the ISO is shown in Table 6. There is no offered non-spinning reserve at any hours since the quick start units generation cost is much higher than the forecasted non-spinning market prices and the forecasted non-spinning market prices are almost similar to the forecasted spinning reserve market prices. In Table 6, GENCO A is bidding low at hours 1–20 and high at hours 21–24. However, GENCO B is bidding low always. The bids depend on GENCOs and factors such as unit characteristics, bilateral contracts, load forecasting, prices forecasting and others. In GENCO A, when more contingencies are considered, the generated power and offered spinning reserves are increased at hours 15–19. However, the purchased power is decreased. Also bids are slightly increased at hour 19 due to committing more units at high hourly forecasted market prices to cope with added ISO Benders cuts. As more contingencies are considered by the ISO, at hours 11–19 the generated power and the high bids of GENCO B are reduced while the offered spinning reserve is increased. The changes at other hours are due to changes in bidding strategies of GENCO B to cope with the added ISO Benders cuts at hours 11–19.

As more contingencies are considered, at hour 16 GENCO B generated more power and offered more spinning reserve in the market, however, both quantities decreased most of the time. At hours 2–7, the purchased power increased due to the reduction in the generated power since some of the cheap units are decommitted at these hours. This is due to the added Benders cuts since more congestion is expected at hour 16 when forecasted

Table 4
GENCOs' profits

Case	GENCO A ($)	GENCO B ($)
No Benders cuts	622,207.3	356,223.5
With Benders cuts for congestion management	621,462.5	333,872.9
With Benders cuts for congestion management and contingency case 1	621,006.0	333,872.9
With Benders cuts for congestion management and contingency case 2	619,750.8	333,872.9
With Benders cuts for congestion management and contingency case 3	619,750.1	270,284.4
With Benders cuts for congestion management and contingency case 4	619,750.1	261,371.1
With Benders cuts for congestion management and contingency case 5	619,750.1	261,371.1

Table 5
SPUC for GENCO A (case 1)

No.	Hours (0–24)																								
1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
2–3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
8–11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
12	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
13–14	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
15–18	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
19–21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
22–24	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
25–26	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
27	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
28–36	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

market prices are the highest. At hour 16, one more unit is committed.

7. Conclusions

This paper presents new model to generate Benders cuts by the ISO in case of any congestion management infeasibility is detected. Also, it explains how to include transmission security Benders cuts in the GENCOs' price-based unit commitment problem in a deregulated power market structure. The proposed model can be used in deregulated power markets such as New England, California, Australia and New Zealand power markets where GENCOs are taking the risk of committing their units and the ISO is responsible for the system security. The test on the 36 unit GENCOs shows the effectiveness of the proposed model in solving the

Table 6
GENCO A's schedule in case 1 (MW)

Hour	Generated power	Spinning reserve	Purchased power	Lagrangian multiplier λ_1
1	2250.0	730.2	1850.0	−0.232
2	2263.9	728.2	1584.0	−0.179
3	2213.8	694.8	1434.1	−0.155
4	2210.5	694.8	1281.3	−0.138
5	2210.2	694.8	1271.6	−0.137
6	2619.9	401.5	450.6	−0.046
7	2620.5	405.5	455.1	−0.046
8	2766.1	495.6	514.5	−0.052
9	2907.3	964.2	1292.8	−0.117
10	2945.4	1010.5	1962.7	−0.18
11	3053.6	1010.5	2455.7	−0.174
12	3080.5	1010.5	2527.1	−0.177
13	3113.8	1010.5	2450.8	−0.163
14	3115.7	1010.5	2274.1	−0.146
15	3123.0	1017.2	2140.8	−0.137
16	3127.0	1020.5	2139.2	−0.137
17	3123.2	1020.5	2527.9	−0.171
18	3047.8	1020.5	2860.0	−0.253
19	3060.8	1020.5	2860.0	−0.244
20	2963.7	873.0	2600.0	−0.246
21	3632.5	0.0	0.0	1.265
22	3400.0	0.0	0.0	1.117
23	3400.0	0.0	0.0	1.245
24	3050.0	0.0	0.0	1.141

problem of infeasibility in congestion management through a cooperative process between the ISO and the GENCOs.

Appendix A: List of symbols

$\mathbf{A}$	sensitivity coefficient matrix of steady state transmission constraints
$\mathbf{E}(j)$	sensitivity coefficient matrix of contingency transmission constraints for line outage j
$\boldsymbol{F}^{s}$	penalty vector for steady state flow constraints
$\boldsymbol{F}^{c}(j)$	penalty vector for contingency flow constraints in case of line outage j
$\boldsymbol{f}^{s}$	steady state flow limit vector
$\boldsymbol{f}^{c}(j)$	flow limit vector for line outage j
$\boldsymbol{P}^{\min}$	lower limit for the congestion management bid (inc/dec bid)
$\boldsymbol{P}^{\max}$	upper limit for the congestion management bid (inc/dec bid)

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