Security-Constrained Optimal Generation Scheduling for GENCOs

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***Abstract*—This paper presents an approach for maximizing a GENCO's profit in a constrained power market. The proposed approach considers the Interior Point Method (IPM) and Benders decomposition for solving the security-constrained optimal generation scheduling (SC-GS) problem. The master problem represents the economic dispatch problem for a GENCO which intends to optimize its profit. The formulation of the master problem does not bear any transmission network constraints. The subproblem will be used by the same GENCO to check the viability of its proposed bidding strategy in the presence of transmission network constraints. In this case if the subproblem does not yield a certain level of financial return for the GENCO or if the subproblem results in an infeasible solution of the GENCO's proposed bidding strategy, the GENCO will modify its proposed solution according to the Benders cuts that stem out of the subproblem. The study shows a more flexible scheduling paradigm for a GENCO in a competitive arena. The proposed approach proves practical for modeling the impact of transmission congestion on a GENCO's expected profit in a competitive environment.**

***Index Terms*—Benders decomposition, contingency, corrective action, interior point method, preventive action, restructuring, SC-GS.**

NOMENCLATURE

$P_i(t)$	Real power output of unit i.
N, M	Number of generating units, busses in the system.
$P_D(t)$	Forecasted system demand during hour t.
$P_i^{\max}(t)$	Upper generation limit of unit i during hour t.
$P_i^{\min}(t)$	Lower generation limit of unit i during hour t.
P_{di}	Forecasted demand at bus i.
$P_{\phi i}$	Equivalent power injection from phase shifter.
nc	Number of possible line outages in a contingency.
$\boldsymbol{A}$	Sensitivity coefficient matrix of steady state transmission constraints.
$\boldsymbol{E}(j)$	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 for line outage j.
$\boldsymbol{f^s}$	Steady state flow limit vector.
$\boldsymbol{f^c}(j)$	Flow limit vector for line outage j.
$w(\widehat{\boldsymbol{x}})$	Optimal solution of (3.3).
$w_s(\boldsymbol{P})$	Optimal solution of steady state subproblem.
$w_c(\boldsymbol{P}, j)$	Optimal solution of contingency subproblem.
$\widehat{\boldsymbol{x}}$	Solution for the master problem.
$\boldsymbol{\pi}$	Multiplier vector.
$\pi_i = (\partial w / \partial x_i)$	Multiplier in linear programming.
$\boldsymbol{P}$	Represents the real power generation.
$\widehat{\boldsymbol{P}}$	Represents the base-case unit power generation.
$\lambda_i(t)$	Forecasted market price at bus i and time t.
r_{ui}, r_{di}	Ramp up/down rate limit of unit i.
$\varepsilon_2, \varepsilon_1$	Power adjustment capability.

I. INTRODUCTION

In a restructuring paradigm, generation resources are planned and operated to compete in a volatile environment. The amount of power injected to or drawn from the busses within a control center is determined by the market clearing price. However, the competition in electricity market is constrained by available transfer capabilities and the level of transmission congestion in a market. The ISO plans hour-ahead and day-ahead schedules and determines the optimal allocation of generation resources based on the possible network congestion [1], [2].

The North American Electric Reliability Council (NERC) stressed the control area's responsibility to maintain sufficient ancillary services under n-1 contingency conditions. The SC-GS algorithm in such cases considers preventive solutions by imposing additional constraints to allow for a feasible state in the event of a contingency. SC-GS may also allow a post-contingency corrective rescheduling [1]–[3].

The proposed decomposition of SC-GS problem into two autonomous generation (GENCO) and transmission (TRANSCO) subproblems allows GENCOS to model the details of the transmission system more specifically. The decomposition allows GENCOS to model the transmission congestion and maximize their perceived profit based on locational marginal prices (LMPs) and financial transmission rights (FTRs). SC-GS

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performs additional sensitivity analyzes for considering the possible scenarios pertaining to the congestion in existing transmission systems.

In the SC-GS subproblem, the constrained power flow equations are solved based on steady state and contingency criteria at every successive linear programming (SLP) iteration [4]–[6]. The optimization process can be controlled or terminated at an earlier stage based on the user-specified accuracy. SLP requires 1) the linearization of the transmission subproblem by expressing the limits of constraints; 2) expressing the incremental variables in the vicinity of the current values of variables; 3) constructing and factorizing the network matrix; 4) solving the linearly-constrained transmission flow subproblem by an LP algorithm; and 5) updating the variables and solving the exact nonlinear power flow problem. The steps are repeated until changes in variables are below user-defined tolerances [7]–[9].

The proposed SC-GS approach is based on the Benders decomposition and the predictor-corrector primal-dual Interior-Point method (IPM) [17]–[23]. The coordination between the master problem and the subproblems is via Benders cuts. The master problem solves the GENCO's economic dispatch by IPM. The solution of the master problem maximizes the GENCO's profit based on the forecasted market price for energy and the GENCO's prevailing constraints. Given the GENCO's generation schedule, the subproblems are solved by examining the feasibility of the GENCO's proposed generation schedule in a transmission-constrained system. Possible transmission overflows are minimized at steady state and n-1 contingency cases by adjusting phase shifters and utilizing adjustment bids based on the GENCO's original dispatch. If the GENCO's optimal solution is not feasible at the subproblem level, Benders cuts are generated for re-calculating the GENCO's optimal generation. GENCO's behavior has been modeled as a price-taker.

The master problem of the proposed SC-GS considers the dynamic scheduling of generating units. The subproblems consider corrective and preventive actions exclusively for transmission contingency analyzes. The proposed decomposition allows planners and analysts to modify and reinforce the individual formulation for TRANSCO and GENCO without modifying the entire solution process for SC-GS.

The SC-GS formulation is different from those of constrained dispatch stated earlier in [9], [14]. The model in this paper is price-based for GENCO's in restructured power markets, whereas the earlier models were cost-based for the vertically integrated power systems. Moreover, the earlier models were applicable to the ISO in restructured power markets in which the ISO does not get involved with the competition among entities. The objective function of SC-GS is to maximize the GENCOs' profit; however, the objective function in the earlier models was to minimize the ISO's cost of supplying the load. In [14], the simplex method was adopted to solve the cost-based problem. However, IPM is employed in this paper to solve the price-based problem.

The paper is organized as follows: Section II gives problem formulation. The solution methodology is presented in Sections III and IV. Different test cases are discussed in Section V. The paper is concluded in Section VI.

II. Formulation of SC-GS

A comprehensive framework for the adaptive short-term electricity price forecasting in restructure power markets was presented [1]. The electricity price forecasting factors including time, load, and historical price were analyzed in [1].

The proposed SC-GS is formulated as an optimization problem that maximizes the GENCO's profit as

$$\text{Max} \sum_{t=1}^{T} \sum_{i=1}^{N} [\lambda_i(t) P_i(t) - F_i(P_i(t))]. \tag{2.1}$$

Equation (2.1) represents the GENCO's profit which is the difference between the revenue (based on the forecasted market price of electricity) and the cost of power generation. The total cost $F_i(P_i(t))$ includes the start-up, shut-down and operating costs of a unit. The constraints in the optimization problem are

— GENCO's demand constraint

$$\sum_{i=1}^{N} P_i(t) \le P_D(t) \quad t = 1, 2, \dots, T \tag{2.2}$$

This inequality constraint shows that the total power generated by a GENCO should be less than or equal to the forecasted system demand. It is to be emphasized that a GENCO is not responsible for supplying the system demand which is the ISO's responsibility. A GENCO will supply a portion of the demand that maximizes its profit which will be determined by the optimization problem explained in this paper.

— Generating unit limits

$$P_i^{\min}(t) \le P_i(t) \le P_i^{\max}(t) \quad \text{where} \quad i = 1, \dots, N \quad t = 1, 2, \dots, T \tag{2.3}$$

— Ramp up/down constraints

$$P_i(t-1) - r_{di} \le P_i(t) \le P_i(t-1) + r_{ui} \quad \text{where} \quad i = 1, \dots, N \quad t = 1, 2, \dots, T \tag{2.4}$$

— Transmission flow limits from bus k to bus m

$$-P_{km}^{\max} \le P_{km}(t) = f(P_i(t), P_{\phi i}(t), P_{di}(t)) \le P_{km}^{\max} \quad \text{where} \quad t = 1, 2, \dots, T \quad i = 1, \dots, M \tag{2.5}$$

The transmission constraints given by (2.5) can be rewritten in terms of steady state and contingency constraints as follows:

1) Steady state constraints (no contingencies)

$$-P_{km}^{\max} \le P_{km}(t) = \sum_{i=1}^{M} A_{km}^{i} (P_i(t) + P_{\phi i}(t) - P_{di}(t)) \le P_{km}^{\max} \quad \text{where} \quad t = 1, 2, \dots, T \tag{2.6}$$

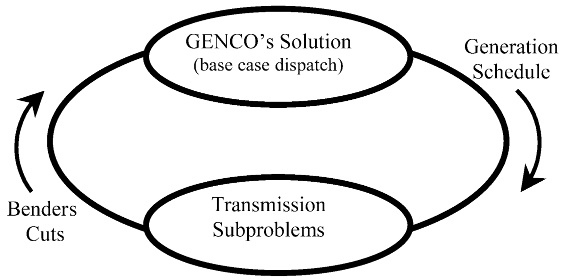

Fig. 1. SC-GS Problem.

2) Contingency constraints

$$-P_{km}^{\max} \leq P_{km}(j,t) = \sum_{i=1}^{M} E_{km}^{i}(j)(P_i(t) + P_{\phi i}(t) - P_{di}(t)) \leq P_{km}^{\max}$$
$$\text{where} \quad j = 1,2,\ldots,nc \quad t = 1,2,\ldots,T \quad (2.7)$$

Note that the total GENCO demand is less than or equal to the sum of all nodal demands:

$$\sum_{i=1}^{M} P_{di}(t) \leq P_D(t) \quad t = 1,2,\ldots,T \quad (2.8)$$

III. Bender's Decomposition

By representing the above transmission constraints in the SC-GS formulation, the problem can be rewritten as follows:

$$\begin{aligned} &\text{Max}\ \boldsymbol{u}x \\ &\text{St.}\quad \boldsymbol{A}x \geq \boldsymbol{b} \\ &\qquad \boldsymbol{E}x + \boldsymbol{F}y \geq \boldsymbol{h} \end{aligned} \quad (3.1)$$

where $\boldsymbol{x}$ represents the generation unit power generation, and $\boldsymbol{y}$ represents the penalty variable for satisfying unit generation control and phase shifters. $\boldsymbol{u}, \boldsymbol{d}, \boldsymbol{A}, \boldsymbol{b}, \boldsymbol{E}, \boldsymbol{F}$, and $\boldsymbol{h}$ are the associated constants which will be explained and formulated in Section IV. The decomposition is represented in Fig. 1.

The composite formulation represents the maximization of the profit minus the subproblem violation subject to two sets of constraints. The first set of inequalities represents real power constraints given in (2.2)–(2.4) and the second set represents transmission security constraints given in (2.5) which are rewritten as (2.6)–(2.7).

The formulation of (3.1) is a standard form of the Benders formulation that is solved as follows.

i) In the master problem, the unit power generation $\boldsymbol{x}$ is calculated as follows:

$$\begin{aligned} &\text{Max}\ \boldsymbol{u}x \\ &\text{St.}\quad \boldsymbol{A}x \geq \boldsymbol{b} \\ &\qquad \boldsymbol{w}(\boldsymbol{x}) \leq \boldsymbol{0} \end{aligned} \quad (3.2)$$

where $\boldsymbol{w}(\boldsymbol{x})$ is the cut which provides the information regarding the feasibility of the unit power generation $\boldsymbol{x}$ in terms of transmission security constraints. The formulation of the Benders cut will be discussed later.

ii) Given $\hat{\boldsymbol{x}}$, the subproblem is formulated as follows:

$$\begin{aligned} &\text{Min}\ w(\widehat{\boldsymbol{x}}) = \boldsymbol{d}s \\ &\text{St.}\quad \boldsymbol{F}y + \boldsymbol{d}s \geq \boldsymbol{h} - \boldsymbol{E}\,\widehat{\boldsymbol{x}} \end{aligned} \quad (3.3)$$

Here d is a user-specified weighting factor which could impact the security-constrained dispatch of units and s is the penalty variable for satisfying the network constraints. We assume the value of d is equal to 1 as we treat all violations equally. If the objective function $w(\widehat{\boldsymbol{x}})$ is larger than zero, we produce Benders cuts $w(\boldsymbol{x}) \leq 0$ based on the solution of subproblems. As discussed in [2]–[4], a linear approximation of the Benders cut is generated in which the coefficients of the linear approximation are the multipliers π_i associated with constraints in (3.2). The linear form of the Benders cut is

$$w(\boldsymbol{x}) = w(\widehat{\boldsymbol{x}}) + \pi(\boldsymbol{x} - \widehat{\boldsymbol{x}}) \leq 0. \quad (3.4)$$

Equation (3.4) represents the constraint added to the master problem.

IV. Decomposition of SC-GS

The master problem and the subproblems are solved in two steps as follows: (1) Solve the GENCO's daily generation scheduling problem (master problem, (2.1)–(2.4) without transmission security constraints. (2) Test the transmission security violations in the subproblems (2.6)–(2.7) using the solution obtained in step (1). Benders cuts are produced for the GENCO's rescheduling of its dispatch solution if violations are detected. Fig. 2 depicts the flowchart of the approach.

A. Master Problem Using IPM

Previously, IPM was employed to solve several power system optimization problems such as network constrained security control, optimal reactive dispatch, state estimation, hydro scheduling, fuel planning, security constrained economic dispatch, var planning, and available transmission capability (ATC) [17]–[21].

In this study, we use PCx for IPM. The PCx software implements a variant of Mehrotra's predictor-corrector algorithm [22] with the higher-order correction strategy of Gondzio [23]. This primal-dual approach has proved to be the most efficient IPM for general linear programs. We use PCx to solve the GENCO's linearly-constrained economic dispatch through SLP.

There is a possibility that we encounter ramping violations at some hours, if we start the optimization process from $t = 1$, especially at those hours with peak demand. Therefore, we start ramping at the hour that corresponds to the peak demand. At that hour, the objective function is maximized without ramp rate constraints. Then we proceed by ramping forward and backward to optimize the generation schedule at other time intervals.

A GENCO intends to supply a portion of the system demand that maximizes its profit. The formulation of the master problem of SC-GS does not bear any transmission network constraints.

$$\text{Max} \sum_{t=1}^{T} \sum_{i=1}^{N} [\lambda_i(t) P_i(t) - F_i(P_i(t))] \quad (4.1)$$

St.

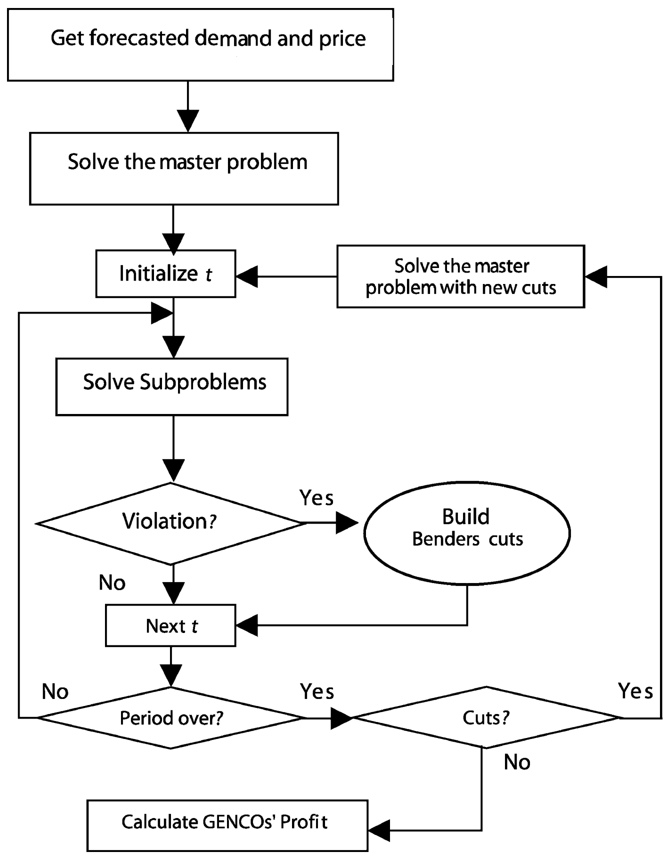

Fig. 2. Flowchart of the Benders Decomposition.

— GENCO's demand constraint

$$\sum_{i=1}^{N} P_i(t) \leq P_D(t) \quad t = 1, 2, \ldots, T \tag{4.2}$$

— Generating unit limits

$$P_i^{\min}(t) \leq P_i(t) \leq P_i^{\max}(t)$$
$$\text{where} \quad i = 1, \ldots, N \quad t = 1, 2, \ldots, T \tag{4.3}$$

— Ramp up/down constraints

$$P_i(t-1) - r_{di} \leq P_i(t) \leq P_i(t-1) + r_{ui}$$
$$\text{where} \quad i = 1, \ldots, N \quad t = 1, 2, \ldots, T \tag{4.4}$$

B. Subproblem Formulation

Transmission constraints in SC-GS are represented by penalty variables corresponding to the GENCO's generation dispatch $\widehat{\boldsymbol{P}}$ submitted by the master problem. Therefore, we define the minimization of penalty variables as the objective of the subproblem $w(\widehat{\boldsymbol{P}})$, which is further decomposed into a steady state subproblem and contingency subproblems. The steady state subproblem formulation is as follows:

$$w_s(\boldsymbol{P}) = \text{Min}\{\boldsymbol{F}^s\} \tag{4.5}$$
$$\text{St. } \boldsymbol{A}P + \boldsymbol{F}^s \leq \boldsymbol{f}^s \tag{4.6}$$
$$\boldsymbol{P} = \widehat{\boldsymbol{P}}\,. \tag{4.7}$$

Here, (4.6) represents the steady state transmission flows. The penalty variables in the objective function may be multiplied by weighting factors in order to represent the importance of certain violations. (4.7) enforces the steady state solution provided by the master problem.

The contingency subproblems consider the corrective and preventive actions exclusively. The following subproblem represents the line outage j with a preventive action:

$$w_c(\boldsymbol{P}, j) = \text{Min}\{\boldsymbol{F}^c(j)\} \quad j = 1, 2, \ldots \text{nc} \tag{4.8}$$
$$\text{St.} \quad \boldsymbol{E}(j)\boldsymbol{P} + \boldsymbol{F}^c(j) \leq \boldsymbol{f}^c(j) \quad j = 1, 2, \ldots \text{nc} \tag{4.9}$$
$$\boldsymbol{P} = \widehat{\boldsymbol{P}}\,. \tag{4.10}$$

Here, (4.9) represents transmission flows in the case of a contingency. (4.10) is used as a constraint for preventive actions in which the steady state solution is maintained in the case of a contingency. In the contingency subproblem with corrective actions, (4.10) will be replaced by (4.11)

$$\text{Max}(\boldsymbol{P}_{\min}, \widehat{\boldsymbol{P}} - \varepsilon_1) \leq \boldsymbol{P} \leq \text{Min}(\boldsymbol{P}_{\max}, \widehat{\boldsymbol{P}} + \varepsilon_2). \tag{4.11}$$

Note that ε_1 and ε_2 are determined based on operating constraints. For instance if the operating constraint is enforced by the ramping of units, ε_1 denotes the ramp down capability of the unit for the allowable time to apply the corrective action once the contingency has occurred. Likewise, ε_2 represents the ramp up capability within the allowable time.

There are nc transmission contingency subproblems in SC-GS. The subproblems are solved using linear programming. In practice, we start the solution of subproblem by assuming that all contingencies can be treated by corrective actions. If the contingency cannot be treated by a corrective action, then we consider it for the preventive action in which the dispatch at steady state will be more expensive.

C. Benders Cuts and Complications

After solving each subproblem, if the optimal value of the objective function is larger than zero, we produce a Benders cut $w(\boldsymbol{P}) \leq 0$. A linear representation of the Benders cut is generated based on the subproblem results as

$$w(\boldsymbol{P}) = w(\widehat{\boldsymbol{P}}) + \pi(\boldsymbol{P} - \widehat{\boldsymbol{P}}) \leq 0. \tag{4.12}$$

For the nc possible single line outages in SC-GS, we consider: (a) T steady state transmission subproblem which may generate up to T Benders cuts, and (b) $T * \text{nc}$ contingency transmission subproblems which may generate up to $T * \text{nc}$ Benders cuts. So, the total number of subproblems in each contingency case is $T * (1 + \text{nc})$.

The added constraints to the GENCO's formulation in the master problem are as follows:

$$w_s^i(\boldsymbol{P}) \leq 0.0 \quad i = 1, 2, \ldots 24 \tag{4.13}$$
$$w_c^i(\boldsymbol{P}, j) \leq 0.0 \quad i = 1, 2, \ldots 24 \quad j = 1, 2, \ldots \text{nc}. \tag{4.14}$$

The master problem of SC-GS could become more complex with the addition of constraints. However, this formulation allows a better reprehension of the actual GENCO's and TRANSCO's models in a competitive environment.

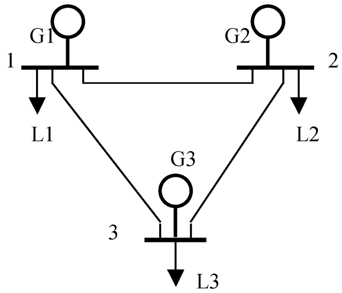

Fig. 3. Three-Bus System.

TABLE I
LOAD DISTRIBUTION

Generators and Lines	Steady State Line Flows (MW)	Line Contingency Flows (MW)		
		Line 2-3 Outage	Line 1-3 Outage	Line 1-2 Outage
G1	200.0	200.0	200.0	200.0
G2	84.0	82.0	82.0	84.0
G3	0.0	2.0	2.0	0.0
1-2	6.24	-25.0	30.0	0.0
2-3	32.96	0.0	55.0	30.0
1-3	23.72	55.0	0.0	27.0

TABLE II
GENERATORS DATA

Unit	Bus No.	Cost coefficients			$P_i^{\min}$ $P_i^{\max}$ (MW)	
		c_i (\$/h)	b_i (\$/MW)	a_i (\$/MWh^2)		
G3	3	118.82	37.89	0.01433	5.0	20.0
G2	2	218.33	18.10	0.00612	10.0	150.0
G1	1	142.73	10.69	0.00463	0.0	200.0

V. Case Studies

A. Three-Bus System

A three-bus system is used first for illustration. The time horizon T is considered to be 1 h for simplicity and discussion purposes. The system is shown in Fig. 3. Load distribution, characteristics of generators and transmission lines are given in Tables I–III, respectively. Line flow limits are 55 MW. The forecasted hourly market price is assumed to be 25 $/MWh.

1) GENCO's Economic Dispatch: The GENCO's master problem is solved with a total profit of $2732.5. As shown in Table IV, units G1 and G2 which are cheaper are scheduled for generation. Note that the marginal cost of unit G3 is higher than the forecasted price.

2) Subproblem Solution (With Transmission Constraints): We start with the steady state transmission constraints. Using the GENCO's schedule in Table IV as $\widehat{\boldsymbol{P}}$, we solve the transmission subproblem (4.5)–(4.7) to monitor transmission flow violations. If transmission violations persist, we introduce Benders cuts for recalculating the GENCO's solution. The final solution of the GENCO's dispatch is the same as that of Table IV. The total execution time is slightly higher than that of the master problem because of the transmission flow screening in the subproblem.

TABLE III
TRANSMISSION LINES PARAMETERS (BASE = 100 MVA)

Line	Resistance (p.u.)	Reactance (p.u.)
1-2	0.0	0.20
1-3	0.0	0.40
2-3	0.0	0.25

TABLE IV
GENCO'S DISPATCH (NO NETWORK CONSTRAINTS)

Generators and Lines	Steady State Generation and Line Flows (MW)
G1	200.0
G2	84.0
G3	0.0
1-2	6.177
2-3	33.163
1-3	23.817

TABLE V
GENERATION AND FLOWS WITH LINE 2–3 CONTINGENCY

Generators and Lines	Contingency Generation and Flows (MW)
G1	200.0
G2	82.0
G3	2.0
1-2	-25.0
2-3	0.0
1-3	55.0

Next, we consider the impact of transmission contingency constraints in the subproblem. We assume that the line 2–3 is on outage and solve the transmission subproblems (4.8), (4.9), (4.11) to minimize transmission flow violations (contingency cases). We have assumed that ε_1 and ε_2 are zero in this example. Since transmission violations persist after introducing the phase shifter control and generation adjustments for the corrective action in the subproblem, this contingency ought to be considered in the preventive action. We calculate the Benders cut and add it to the GENCO's master problem. The revised GENCO's dispatch is given in Table V.

This generation schedule includes the dispatch of more expensive unit G3. The proposed GENCO's solution satisfies all the constraints in the master problem as well as those in the subproblem. The hourly profit is $2694.90 which is lower than that of the base case due to the scheduling of unit G3. According to Fig. 3, when line 2–3 is on outage, L3 is larger than the capacity of line 1–3, so unit G3 will be scheduled additionally for supplying L3 even though the marginal cost of G3 is higher than the forecasted market price.

Using the unit generation schedule in Table IV as $\widehat{\boldsymbol{P}}$, we solve (4.8)–(4.11) for the single outage of other lines as well. Again we treat the individual constraints in a corrective action and if the violation persists, then we form the Benders cut for a preventive action to minimize individual transmission flow violations. The results are given in Table VI. Table VI indicates that flow violations will persist and require Benders cuts when either line 2–3 or line 1–3 is on outage. The GENCO's revised power generation and the resulting line flows in Table VII satisfy the corresponding limits.

TABLE VI
PROFIT AND TRANSMISSION VIOLATIONS

Line on Outage	Profit ($)	Number of Bender's Cuts
2-3	2,694.9	1
1-3	2,694.9	1
1-2	2,732.5	0

TABLE VII
GENERATION AND LINE FLOWS

		Line Contingency Flows (MW)		
		Line 2-3 Outage	Line 1-3 Outage	Line 1-2 Outage
G1	200.0	200.0	200.0	200.0
G2	84.0	82.0	82.0	84.0
G3	0.0	2.0	2.0	0.0
1-2	6.24	-25.0	30.0	0.0
2-3	32.96	0.0	55.0	30.0
1-3	23.72	55.0	0.0	27.0

TABLE VIII
PROFIT AND TRANSMISSION VIOLATIONS

Case	Profit ($)	Number of Bender's Cuts
I	2,694.9	1
II	2,694.9	2

TABLE IX
UNIT SCHEDULES WITH TRANSMISSION CONSTRAINTS

Generators	Generation Schedules (MW)	
	Case I	Case II
G1	200.0	200.0
G2	82.0	82.0
G3	2.0	2.0

We now include the impact of all single contingencies in the GENCO's generation solution. Consider the following security cases:

Case I $(\mathrm{nc}=2)$: line 1–2 or 2–3 on outage

Case II $(\mathrm{nc}=3)$: line 1–2 or 2–3 or 1–3 on outage.

In Case II, 3 independent single line outages are included in the constrained dispatch. This case will require the solutions of 3 transmission contingency subproblems. Using the unit generation schedule in Table IV as $\widehat{\boldsymbol{P}}$, we solve subproblem (4.8)–(4.11) for each case to minimize transmission flow violations. The resulting constraints (4.13), (4.14) are added to the master problem and the GENCO's profit optimization problem is solved again. The solution is given in Table VIII.

In Table VIII, the profit is the same in both cases and is lower than the base profit due to the scheduling of more expensive units to enforce possible preventive actions. In essence the Benders cut in Case I (line 2–3) is the decisive one for the constrained generation scheduling in Table VIII. Table IX shows the GENCO's schedules for the two cases. As the number of possible outages increase, the number of Benders cuts may increase which further complicates the optimization problem.

Next we consider the impact of our proposed method on the IEEE 118-bus system.

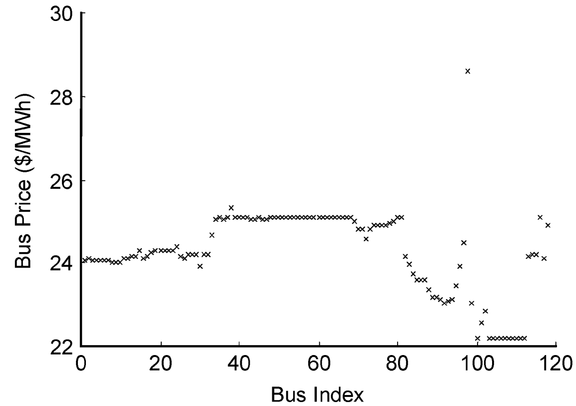

Fig. 4. Price Profile for IEEE 118-bus System (at hour 18).

B. IEEE 118-Bus System

We test the SC-GS solution for the IEEE 118-bus network [1], [2], [24]. Here the GENCO has 36 generating units and the network consists of 186 transmission lines. The details of the system and its one-line diagram are given in [1], [2]. We assume transmission lines have a 300 MW capacity. Fig. 4 depicts forecasted bus prices for the 118-bus system at hour 18.

As in the three-bus system, we determine the GENCO's generation dispatch and then examine the viability of the proposed generation schedule in the transmission market. The time horizon is considered to be 24 h to represent the day-ahead market.

GENCO's Economic Dispatch: The GENCO's solution of the master problem has a profit of $424 388.7 with an execution time of 4 s on a Pentium III processor. In this case, generating units 28–36 constitute the base load units.

Impact of Transmission Constraints: First we consider the steady state transmission case. There will be 14 Benders cuts at hours 10–23 that are added to the revised master problem. The revised GENCO's solution has a profit of $403 250.2 due to the scheduling of more expensive generating units such as 7, 12, 16, 17, 18, 25, and 26. The execution time is a couple of seconds higher than that of the original GENCO's schedule. Next, we consider contingency constraints in the transmission subproblems.

For contingency, we consider the loss of line 109–110 in SC-GS. Since the corrective action cannot remove the constraint, we form the Benders cuts. Here the GENCO's profit will decrease to $395 665.2 with an execution time of 8 s. There are 24 Benders cuts for hours 1–24 for the contingency case in addition to 14 Benders cuts for the steady state case.

Table X shows the GENCO's profit and the corresponding number of Benders cuts for each possible line outage.

We now study the impact of several single outages of individual lines on the GENCO's schedule. Consider the following security cases:

Case I $(\mathrm{nc}=2)$: line 109–110 or 82–96 on outage

Case II $(\mathrm{nc}=3)$: line 109–110 or 82–96 or 69–77 on outage

Case III $(\mathrm{nc}=4)$: line 109–110 or 82–96 or 69–77 or 19–20 on outage

TABLE X
PROFIT AND BENDERS CUTS

Lines on outage	Profit ($)	Number of Bender's Cuts
109-110	395,665.2	24
82-96	391,210.0	24
69-77	383,742.7	17
19-20	376,175.5	24
56-58	392,952.1	14

TABLE XI
PROFITS AND CUTS FOR TRANSMISSION CONTINGENCIES

Contingency	Profit ($)	Number of Bender's Cuts
I	389,142.1	62
II	380,988.4	79
III	367,756.6	103
IV	363,229.0	117

Case IV $(\mathrm{nc}=5)$: line 109–110 or 82–96 or 69–77 or 19–20 or 56–58 on outage.

Table XI shows the results for these cases. However, we can extend the results to many more outages. The results indicate that the number of cuts increase as we consider more outages for the inclusion in the master problem. Accordingly, the cost of supplying the load will increase as more expensive units may be committed. In Table XI the corresponding profit drops as more cuts are included in the master problem.

The intriguing issue about the application of Benders cut in SC-GS is that it calculates the impact of outages simultaneously in various subproblems and provides a single hourly Benders cut for the master problem. Hence, it is suited for parallel processing, which can provide the results for a very large network within a very short period of time.

The results show that the proposed approach can provide more flexible scheduling results in less than 50% of the computation time when a simplex method was adopted [14].

VI. CONCLUSION

The proposed SC-GS method considers the impact of transmission constraints on generation scheduling in a competitive market. The approach is based on IPM and Benders decomposition to solve SC-GS. An efficient predictor-corrector primal-dual IPM is used since it is faster and more efficient to solve the linearized subproblem. The contingencies are modeled in the subproblem based on corrective and preventive actions. The steady state generation schedules are adjusted to accommodate the transmission constraints. Two different size systems are used to demonstrate the effectiveness of the proposed SC-GS approach for GENCO's. The proposed approach could help GENCO's identify the transmission system bottlenecks based on the operating schedules, and adjust their generation bids accordingly for maximizing their profits. The SC-GS profits could be lower when contingency constraints are imposed because the system would be operated in a more conservative manner. The results show that the proposed approach can provide more flexible scheduling results in less time.

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