AC Contingency Dispatch Based on Security-Constrained Unit Commitment

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***Abstract*—In this paper, an effective ac corrective/preventive contingency dispatch over a 24-h period is proposed based on security-constrained unit commitment (SCUC) model. The SCUC model includes unit commitment, ac security-constrained optimal power flow (SCOPF), and load shedding (LS) for steady state and contingencies. The objective of this SCUC model is to obtain the minimum bid-based system operating cost while maintaining the system security. The prevailing generation constraints, such as hourly power demand, system reserves, fuel and emission limits, ramp up/down limits, and minimum up/down time limits, are included in this model. In addition, system constraints such as time-limited emergency controls for a given contingency and ac network security limits are taken into account. The proposed ac solution for the hourly scheduling of generating units is based on Benders decomposition. Case studies with the six-bus system, the IEEE 118-bus test system, and 1168-bus system are presented in detail in this paper.**

***Index Terms*—AC corrective/preventive actions, ac security-constrained optimal power flow (SCOPF), ac security-constrained unit commitment, Benders decomposition, load shedding.**

NOMENCLATURE

b	Index for bus.
DR_i	Ramp-down rate limit of unit i.
$E_S^{\max}$	System emission limit.
$F_{ci}(.)$	Bid-based production cost function of unit i.
$F_{fi}(.)$	Fuel consumption function of unit i.
$F_{ei}(.)$	Emission function of unit i.
$F_{sk}(.)$	Load shedding cost function of virtual unit k.
$F_{FT}^{\min}$	Minimum fuel consumption (type FT).
$F_{FT}^{\max}$	Maximum fuel consumption (type FT).
FT	Index for fuel type.
i	Index for unit.
I_{it}	Commitment state of unit i at time t.
k	Index for virtual unit.
m	Index for contingency ($m = 0$ for steady state).
$MP_{b,1}, MP_{b,2}$	Slack variables for real power mismatch at bus $b (>= 0)$.
$MQ_{b,1}, MQ_{b,2}$	Slack variables for reactive power mismatch at bus $b (>= 0)$.
NB	Number of buses.
NG	Number of units.
NT	Number of periods under study (24 h).
NVG	Number of virtual units.
$P_{D,t}$	System demand at time t.
$P_{L,t}$	System losses at time t.
P_{it}	Generation of unit i at time t.
$P_{i,\min}$	Lower limit of real power generation of unit i.
$P_{i,\max}$	Upper limit of real power generation of unit i.
$Q_{i,\min}$	Lower limit of reactive power generation of unit i.
$Q_{i,\max}$	Upper limit of reactive power generation of unit i.
$R_{S,t}$	System spinning reserve requirement at time t.
$R_{O,t}$	System operating reserve requirement at time t.
$R_{S,it}$	Spinning reserve of unit i at time t.
$R_{O,it}$	Operating reserve of unit i at time t.
SU_{it}	Bid-based startup cost of unit i at time t.
SD_{it}	Bid-based shutdown cost of unit i at time t.
$SU_{f,it}$	Startup fuel consumption of unit i at time t.
$SD_{f,it}$	Shutdown fuel consumption of unit i at time t.
$SU_{e,it}$	Startup emission of unit i at time t.
$SD_{e,it}$	Shutdown emission of unit i at time t.
t	Index for time.
T_i^{off}	Minimum down time of unit i.
T_i^{on}	Minimum up time of unit i.
UR_i	Ramp-up rate limit of unit i.
VP_{kt}	Generation of virtual unit k at time t.
$VP_{k,\max}$	Upper limit of real power generation of virtual unit k.
X_{it}^{off}	OFF time of unit i at time t.
X_{it}^{on}	ON time of unit i at time t.
$\Delta_{\rm i}$	Permissible real power adjustment of unit i.
$\wedge$	Given variables.
$\mathbf{dP_0}$	Initial real power mismatch vector.
$\mathbf{dQ_0}$	Initial reactive power mismatch vector.
$\mathbf{\Delta P}$	Unit real power increment vector.
$\mathbf{\Delta Q}$	Unit reactive power increment vector.
$\mathbf{\Delta VP}$	Virtual unit real power increment vector.
$\mathbf{\Delta VQ}$	Virtual unit reactive power increment vector.

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$\mathbf{\Delta\delta}$	Bus phase angle increment vector.
$\mathbf{\Delta V}$	Bus voltage increment vector.
$\mathbf{\Delta T}$	Transformer tap increment vector.
$\mathbf{\Delta\gamma}$	Phase shifter angle increment vector.
$\mathbf{\Delta PL}$	Real line flow increment vector.
$\mathbf{\Delta PL_{min}}$, $\mathbf{\Delta PL_{max}}$	Lower and upper limit vector of real line flow increment.
$\mathbf{\Delta Q_{min}}$, $\mathbf{\Delta Q_{max}}$	Lower and upper limit vector of reactive power increment.
$\mathbf{\Delta V_{min}}$, $\mathbf{\Delta V_{max}}$	Lower and upper limit vector of bus voltage increment.
$\mathbf{TS}$	Vector of allowable range for adjusting transformer taps.
$\mathbf{\gamma S}$	Vector of allowable range for adjusting phase shifter angles.
$\mathbf{Y}$	Bus-unit incidence matrix.
$\mathbf{Z}$	Bus-virtual unit incidence matrix.
$\mathbf{H, N, E, F, M, J}$	Jacobian matrices.
$\mathbf{R, S, A, B, C, D}$	More Jacobian matrices.

I. INTRODUCTION

THE recent developments in restructured electric power systems provide an opportunity for electricity market participants, such as GENCOs, TRANSCOs, and DISCOs, to exercise least-cost or profit-based operations. However, the system security is still the most important aspect of the power system operation, which cannot be overlooked in the Standard Market Design (SMD). In restructured markets, including the PJM interconnection, the New York market, and the U.K. Power Pool, the ISO, as the key market entity, has the authority and responsibility to commit and dispatch system resources and curtail loads for maintaining the system security (i.e., balance load demands and satisfy fuel, environmental, and network security requirements). Consequently, the ISO must be equipped with powerful tools, such as the proposed approach, to fulfill unit commitment and dispatch in open markets by optimizing a set of objectives at steady state while satisfying pre- and post-contingency security constraints.

In this paper, an effective ac corrective/preventive contingency dispatch over a 24-h period is proposed based on the security-constrained unit commitment (SCUC) model. GENCOs will submit their bids to the ISO. The ISO will then use this model to minimize the bid-based system operating cost while maintaining the system security at both steady state and pre-defined contingency cases. Note that the same SCUC model can be applied to a vertically integrated utility system when the cost-based production, startup, and shutdown functions are used in the SCUC formulation.

The conventional optimal power flow (OPF) model would solve the economic dispatch (ED) problem while considering the network security constraints at steady-state [1], [2]. It is conceivable that in the event of a contingency, the steady-state setting of optimal operation would threaten the system security if the system state cannot be transferred quickly to a new steady-state operating point. In this sense, security-constrained optimal power flow (SCOPF) includes ac contingency dispatch to respond to the challenges of the conventional OPF.

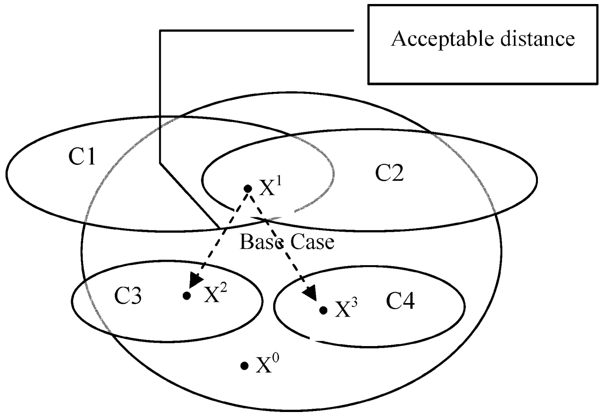

Fig. 1. Relationship between corrective and preventive actions.

Once the hourly commitment of units is calculated, SCOPF will consider the ac contingency dispatch represented by corrective (post-contingency) and preventive (pre-contingency) dispatch control actions. The ac contingency dispatch will result in minimizing the cost of system operation while satisfying the system security, fuel, and environmental constraints. A proper set of corrective and preventive control actions for managing contingencies could represent a trade-off between economics and security in restructured power systems.

Note that the preventive dispatch is very conservative and could be expensive and even infeasible for considering all potentially dangerous contingencies. In contrast, a corrective control action applies to allowable post-contingency control adjustments for eliminating *controllable* contingencies. A preventive dispatch based on *uncontrollable* contingencies will be included in the steady-state solution of SCOPF for maintaining the economics and the secure operation of a system in the event of a contingency [3]–[5].

Fig. 1 illustrates the relationship between corrective and preventive dispatch control actions. In this figure, feasibility regions for the steady state and four severe contingencies are shown. X^0 represents the optimal operating point at steady state; and X^1 represents the optimal base case solution with preventive action, which could mitigate violations at steady state as well as contingency 1 or 2 (i.e., C1 or C2). When contingency 3 or 4 (i.e., C3 or C4) occurs, the system will consider corrective actions within an acceptable distance so that it can safely and on time transfer from point X^1 to the new operating point X^2 or X^3, respectively.

The existing SCOPF studies in the literature do not take into account the impact of recalculating SCUC when security constraints are not satisfied. In other words, SCOPF is applied sequentially based on unit commitment results. Thus the traditional SCUC-SCOPF solution is an open-loop two-stage process. If SCOPF is unable to get a feasible solution based on the unit commitment at the first stage, additional security measures will have to be called upon. For instance, the system operator may be allowed to use heuristic methods to adjust unit commitment when SCOPF cannot obtain a satisfactory solution. However, such heuristic strategies will depend on the operator's experience and may not represent the least-cost solution. In this paper, we present a closed-loop approach for solving ac contingency dispatch based on SCUC. Accordingly, a new unit commitment solution could be sought when ac dispatch alone is unable to guarantee the convergence of SCOPF.

In order to focus on the description of the proposed functions, we resort to pre-defined contingencies. However, in practice, automatic contingency selection is applied to potential contingencies before submitting the contingency list to our algorithm for further analyzes. Automatic contingency selection methods fall into two classes: screening and ranking [6]–[9]. A common screening method is to use the results of the fast decoupled power flow (FDPF) algorithm for each contingency case. In addition, selection can be performed by various ranking schemes, which compute a scalar performance index (PI) for each contingency derived from the dc power flow solution for the contingency. Another selection approach is by bounding, which explicitly exploits localization. The effects of an outage diminish rapidly with electrical distance from the outage and beyond a certain tier of buses surrounding the outage become negligibly small for contingency analysis purposes. Further discussions on these contents are beyond the scope of this paper.

This paper is organized as follows. Section II provides an outline of the proposed model. Section III describes the formulations of SCUC and SCOPF based on ac network. Section IV presents and discusses test cases considering the prevailing constraints. The conclusion drawn from the study is provided in Section V.

II. MODEL OUTLINE

Fig. 2 depicts the flowchart of SCUC that encompasses SCOPF with ac contingency dispatch over the 24-h horizon. Benders decomposition [10]–[12] is used for solving the SCUC/SCOPF problem. SCUC includes UC as master problem and the entire SCOPF as subproblem. The SCOPF in Fig. 2 is also represented by a master problem that considers ac steady-state constraints and subproblems for contingencies. In essence, UC could provide to SCOPF a feasible and optimal commitment of generating units. If SCOPF cannot guarantee the system security at steady-state and critical contingencies, LS may be utilized for managing a feasible solution.

In our approach, augmented Lagrangian relaxation (ALR) is applied to solve UC. SCOPF utilizes the UC solution for calculating the optimal dispatch of generators, minimizing the bid-based operating cost at steady state, and preventing system violations when contingencies occur. A typical set of constraints in SCUC includes

1) power balance;
2) generating unit capacity;
3) system spinning and operating reserve requirements;
4) ramping up/down limits;
5) minimum up/down time limits;
6) maximum number of simultaneous on/offs in a plant;
7) maximum number of on/offs of a unit in a given period;
8) fuel and multiple emission limits;
9) limits on control variables, including real and reactive power generation, controlled voltages, tap-changing, and phase-shifting transformers;
10) ac network security constraints, including transmission flow and bus voltage limits;
11) time limited emergency control of contingencies.

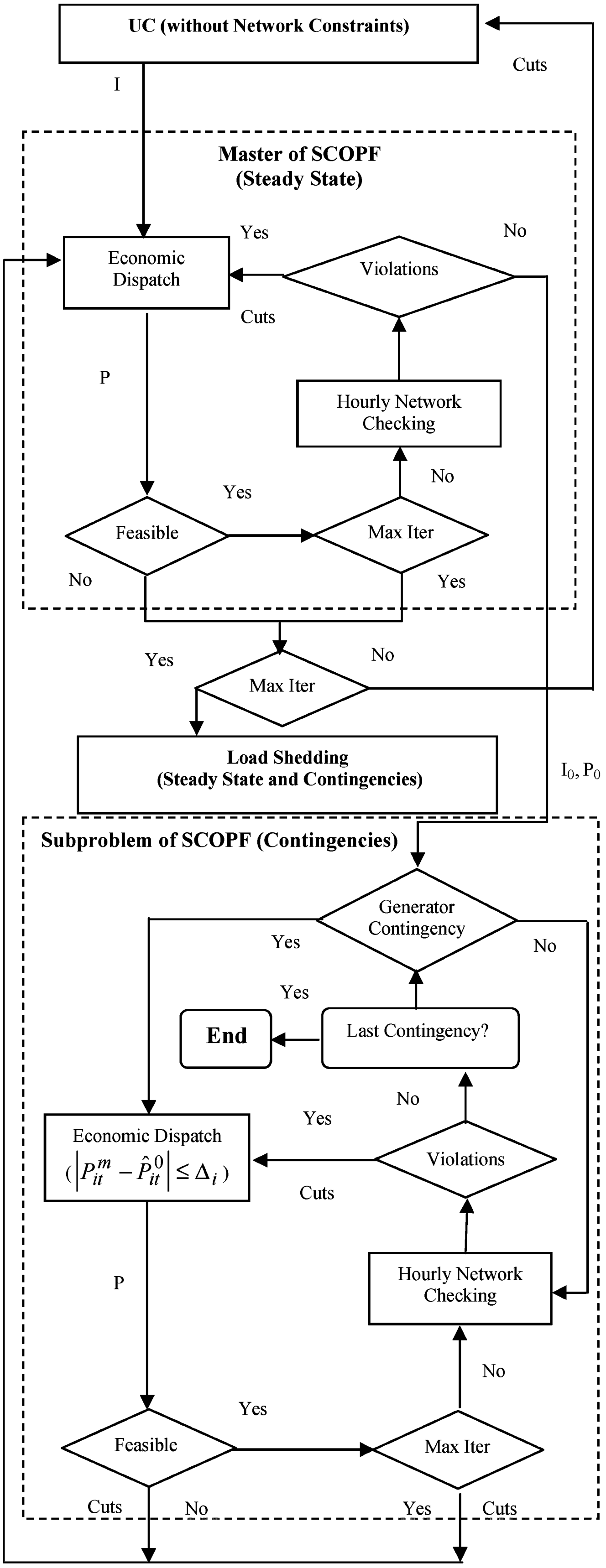

Fig. 2. SCUC with ac contingency dispatch.

A. SCOPF

SCOPF in Fig. 2 consists of the following two modules that utilize the UC solution.

1) Master of SCOPF (Steady State): The master of SCOPF represents the constrained ED at steady state. This section in Fig. 2 consists of ED as master problem and its subproblems for checking hourly network constraints. The ED is optimized by applying linear programming (LP), which includes committed units, power balance, reserve, fuel, and emission requirements. Then the subproblem (hourly network checking) checks network constraints in the hourly subproblems to find out whether the proposed ED solution can provide a converged ac power flow and meet network constraints (such as transmission flow and bus voltage limits). If a converged ac power flow solution is not obtained or violations persist, the steady-state subproblems will generate Benders cuts that will be added to ED for the next iteration. Furthermore, if the master of SCOPF is infeasible or the maximum number of iterations of the master of SCOPF is reached before identifying a feasible solution, cumulative Benders cuts will be introduced into the next UC calculation. The iterative process between UC and the master problem of SCOPF will continue until ac violations are eliminated or load shedding (LS) is prescribed to find a converged SCOPF solution at steady state. SCOPF could consider other objectives such as the minimization of losses. However, we confine the scope of this paper to constrained ED.

2) Subproblem of SCOPF With Contingencies: At this stage the converged SCOPF solution at steady state will be utilized for examining ac contingencies. Here we solve ED with additional constraints $|P_{it}^{m} - \hat{P}_{it}^{0}| \leq \Delta_i$ for each contingency in which Δ represents a time-based permissible adjustment of real power generation. Once a contingency is introduced, if violations are not eliminated within the emergency time by applying control variables such as real power generation P, tap transformers, and static capacitors, the contingency will be labeled as uncontrollable contingency. Accordingly, a pre-contingency operating point is sought for the uncontrollable contingency by recalculating the steady-state SCOPF and/or UC. The new operating point that includes preventive control actions can prevent system violations in the event of the uncontrollable contingency. Meanwhile, possible corrective dispatch controls within the given emergency time will eliminate system violations for any controllable contingencies.

B. LS

If violations resulting from uncontrollable contingencies cannot be mitigated by available control measures, LS will provide a feasible SCOPF solution based on decremental bids/contracts. The idea for applying LS is to add virtual generators at load buses where LS is allowed. The effect of a virtual generator is to shed local loads for removing any violations at steady state and contingencies. LS at a substation could represent several curtailment contracts. We provide the following five assumptions for implementing LS.

- In this proposed algorithm, demand bids are inelastic. LS is represented as an undesirable function, and LS contract prices are presumably higher than generating unit bids. LS is treated as the last resort when all other options fail in seeking a feasible solution.
- Virtual generators are considered for SCOPF at steady state and based on the hourly commitment of units.
- The LS calculated at the steady-state SCOPF could be subject to further curtailments during contingency evaluations.
- At each load bus, the ratio of curtailed reactive power to the total reactive load is the same as that of curtailed real power to the total real load. In essence we are assuming that the power factor of the load is constant.
- The ratio of system spinning/operating reserve requirement to the total load remains fixed.

C. Solution Procedure

The step-by-step procedure of SCUC/SCOPF solution in Fig. 2 with ac contingency dispatch is given as follows.

1) Solve UC.
2) Solve ED at steady state (in the master problem of SCOPF). If the ED solution is infeasible or the maximum number of iterations for solving ED is reached, go to step 6. Otherwise proceed to step 3.
3) Check the hourly ac flow dispatch at steady state. If the ac power flow is not converged, or network limits (transmission flows and bus voltages) are violated, form Benders cuts and go back to step 2 for recalculating ED. Otherwise, proceed to the next step.
4) Solve ED in the SCOPF subproblem with additional constraints $|P_{it}^{m} - \hat{P}_{it}^{0}| \leq \Delta_i$ for each contingency. Δ represents a physically acceptable time-limited adjustment of real power dispatch. If the ED solution is infeasible or if the maximum number of iterations is reached, label the contingency as uncontrollable, form Benders cuts based on the previous ED iterations for the uncontrollable contingency, add the cuts to master problem of SCOPF, and return to step 2 to obtain a pre-contingency dispatch with preventive actions for the uncontrollable contingency. Proceed to the next step if the ED solution in step 4 is feasible within the given number of iterations.
5) Check the hourly ac network for each contingency. If ac power flow is not converged or network (transmission flows and bus voltages) violations exist, form the corresponding Benders cuts and return to step 4. Otherwise, stop once the last contingency is considered.
6) If the maximum number of iteration between UC and the master problem of SCOPF is reached, use the feasible UC results at the previous iteration as the final and go to step 7 for the LS solution. Otherwise, go to step 1 for next UC calculation.
7) Add virtual generators to ED and obtain the LS solution at steady state.
8) Check the hourly ac network at steady state with virtual generators. If ac power flow is not converged or network (transmission flows and bus voltages) violations exist, form the corresponding Benders cuts and go back to step 7. Otherwise, continue.

9) Solve ED with additional constraints $|P^m_{it} - \hat{P}^0_{it}| \le \Delta_i$ and $V\hat{P}^0_{kt} \le VP^m_{kt} \le VP_{k,\max}$ and virtual generators for each contingency. Obtain the LS solution for each contingency.
10) Check the hourly ac network for each contingency with virtual generators. If ac power flow is not converged or network (transmission flows and bus voltages) violations exist, form the corresponding Benders cuts and return to step 9. Otherwise, stop once the last contingency is considered.

III. Problem Formulation

A. UC Calculation

UC can provide an hourly commitment of generating units with minimum bid-based dispatch cost. The objective function (1) is composed of bid-based fuel costs for producing electric power and startup and shutdown costs of individual units for the given period. The hourly UC constraints listed below include the system power balance (2), system spinning and operating reserve requirements (3), ramping up/down limits (4), minimum up/down time limits (5), and unit generation limits (6). Additional system-wide constraints such as fuel constraints (7) and emission limits (8) are included in this formulation for representing the market interdependencies. Note that the network constraints will be considered later in SCOPF

$$Min \quad \sum_{i=1}^{NG}\sum_{t=1}^{NT}\left[F_{ci}(P_{it})*I_{it}+SU_{it}+SD_{it}\right] \tag{1}$$

$$\text{S.T.} \quad \sum_{i=1}^{NG} P_{it}*I_{it} = P_{D,t}+P_{L,t} \quad (t=1,\cdots,NT) \tag{2}$$

$$\begin{aligned}&\sum_{i=1}^{NG} R_{S,it}*I_{it} \ge R_{S,t}\\ &\sum_{i=1}^{NG} R_{O,it}*I_{it} \ge R_{O,t} \quad (t=1,\cdots,NT)\end{aligned} \tag{3}$$

$$\begin{aligned}&P_{it}-P_{i(t-1)}\\ &\quad \le \left[1-I_{it}\left(1-I_{i(t-1)}\right)\right]UR_i+I_{it}\left(1-I_{i(t-1)}\right)P_{i,\min}\\ &P_{i(t-1)}-P_{it}\\ &\quad \le \left[1-I_{i(t-1)}(1-I_{it})\right]DR_i+I_{i(t-1)}(1-I_{it})P_{i,\min}\\ &\quad (i=1,\cdots,NG)(t=1,\cdots,NT)\end{aligned} \tag{4}$$

$$\begin{aligned}&\left[X^{on}_{i(t-1)}-T^{on}_i\right]*\left[I_{i(t-1)}-I_{it}\right]\ge 0\\ &\left[X^{off}_{i(t-1)}-T^{off}_i\right]*\left[I_{it}-I_{i(t-1)}\right]\ge 0\\ &\quad (i=1,\cdots,NG)(t=1,\cdots,NT)\end{aligned} \tag{5}$$

$$\begin{aligned}&P_{i,\min}I_{it} \le P_{it} \le P_{i,\max}I_{it}\\ &\quad (i=1,\cdots,NG)(t=1,\cdots,NT)\end{aligned} \tag{6}$$

$$\begin{aligned}F^{\min}_{FT} &\le \sum_{t=1}^{NT}\sum_{i\in FT}\left[F_{fi}(P_{it})*I_{it}+SU_{f,it}+SD_{f,it}\right]\\ &\le F^{\max}_{FT}\end{aligned} \tag{7}$$

$$\begin{aligned}&\sum_{t=1}^{NT}\sum_{i=1}^{NG}\left[F_{ei}(P_{it})*I_{it}+SU_{e,it}+SD_{e,it}\right]\\ &\quad \le E^{\max}_S.\end{aligned} \tag{8}$$

Also note that $\mathrm{P_{L,t}}$ in (2) is originally the estimated system loss at time t. However, following the iterations between UC and the master problem of SCOPF, the estimated $\mathrm{P_{L,t}}$ will be updated by its exact value obtained from the master problem of SCOPF. Also by enforcing (4) and (6), we assume that when unit i is starting up or shutting down at time t, the generation P_{it} or $P_{i(t-1)}$ will be equal to $P_{i,\min}$, respectively.

In order to solve UC, the ALR method is employed for relaxing power system constraints (2), (3), (7), (8). The relaxed problem is decomposed into N subproblems for each unit. Dynamic programming (DP) including ramp rate limits (4), and minimum up/down time limit (5) is used to search for the optimal commitment of a single unit over the entire study period. Lagrangian multipliers are updated based on violations of system constraints. The convergence criterion is satisfied if the duality gap between primal and dual solutions is within a given limit. The details of the LR solution procedure are described in [13]–[15].

B. SCOPF With Load Shedding

Once the hourly units are committed, SCOPF is calculated using a piecewise linear bid-based production cost function. The function is divided into NS straight-line segments in the conventional calculation of ED. The objective (9) is to minimize ED and LS costs (without network constraints) at steady state and when considering contingencies, based on UC results. Note that $m = 0$ represents steady state. The second term in the objective function is for modeling virtual generators that will be used if ED is infeasible. Constraints (10) and (11) represent the power balance and system spinning/operating reserve requirement. Note that the ratio of system spinning/operating reserve requirement to the total load should be fixed based on the above assumption for LS

$$Min \quad \sum_{i=1}^{NG}\sum_{t=1}^{NT}F_{ci}\left(P^m_{it}\right)*\hat{I}_{it}+\sum_{k=1}^{NVG}\sum_{t=1}^{NT}F_{sk}\left(VP^m_{kt}\right) \tag{9}$$

$$\begin{aligned}&\text{S.T.} \quad \sum_{i=1}^{NG}P^m_{it}*\hat{I}_{it}+\sum_{k=1}^{NVG}VP^m_{kt}=P_{D,t}+P_{L,t}\\ &\qquad (t=1,\cdots,NT)\end{aligned} \tag{10}$$

$$\begin{aligned}&\sum_{i=1}^{NG}R^m_{S,it}*\hat{I}_{it}\ge\frac{R_{S,t}}{P_{D,t}}\left(P_{D,t}-\sum_{k=1}^{NVG}VP^m_{kt}\right)\\ &\sum_{i=1}^{NG}R^m_{O,it}*\hat{I}_{it}\ge\frac{R_{O,t}}{P_{D,t}}\left(P_{D,t}-\sum_{k=1}^{NVG}VP^m_{kt}\right)\\ &\quad (t=1,\cdots,NT)\end{aligned} \tag{11}$$

$$\begin{aligned}&P^m_{it}-P^m_{i(t-1)}\\ &\quad \le\left[1-\hat{I}_{it}\left(1-\hat{I}_{i(t-1)}\right)\right]UR_i+\hat{I}_{it}\left(1-\hat{I}_{i(t-1)}\right)P_{i,\min}\\ &P^m_{i(t-1)}-P^m_{it}\\ &\quad \le\left[1-\hat{I}_{i(t-1)}(1-\hat{I}_{it})\right]DR_i+\hat{I}_{i(t-1)}(1-\hat{I}_{it})P_{i,\min}\\ &\quad (i=1,\cdots,NG)(t=1,\cdots,NT)\end{aligned} \tag{12}$$

$$\begin{aligned}&\sum_{t=1}^{NT}\sum_{i\in FT}\left[F_{fi}\left(P^m_{it}\right)*\hat{I}_{it}+\hat{SU}_{f,it}+\hat{SD}_{f,it}\right]\\ &\quad \le F^{\max}_{FT}\end{aligned} \tag{13}$$

$$\sum_{t=1}^{NT}\sum_{i=1}^{NG}\left[F_{ei}\left(P_{it}^{m}\right)*\hat{I}_{it}+S\hat{U}_{e,it}+S\hat{D}_{e,it}\right] \leq E_{S}^{\max}. \tag{14}$$

In addition, we use the following sets of constraints to represent steady state (15), (16) and contingencies (17), (18). Upper and lower limits on control variables (15), (16) are used at steady state

$$P_{i,\min}\hat{I}_{it} \leq P_{it}^{0} \leq P_{i,\max}\hat{I}_{it} \quad (i=1,\cdots,NG) \quad (t=1,\cdots,NT) \tag{15}$$

$$0 \leq VP_{kt}^{0} \leq VP_{k,\max} \quad (k=1,\cdots,NVG) \quad (t=1,\cdots,NT). \tag{16}$$

Constraints (17) and (18) are used when considering the contingency m in which variables marked with ^ are given values. Equation (17) shows the adjustment range for $\mathbf{P}$ in contingency m with respect to $\mathbf{P^0}$ at steady state. Equation (18) shows that the permissible LS in contingency m based on virtual generators

$$\left|P_{it}^{m}-\hat{P}_{it}^{0}\right| \leq \Delta_{i} \quad (i=1,\cdots,NG) \quad (t=1,\cdots,NT) \tag{17}$$

$$V\hat{P}_{kt}^{0} \leq VP_{kt}^{m} \leq VP_{k,\max} \quad (k=1,\cdots,NVG) \quad (t=1,\cdots,NT). \tag{18}$$

The ED solution (9)–(18) in SCOPF is the linear program without network constraints. In the case of the generator contingency, if the initial ED solution is infeasible, the feasibility checking will be executed by replacing (9) with (19). The constraints (20)–(22) with positive slack variables $S1_t^m$, $S2_t^m$, $S3_t^m$, $S4_t^m$, and $S5_{it}^m$ replace (10), (11), and (17). The remaining constraints (12)–(14), (18) are also considered here as follows:

$$Min \quad v^{m}=\sum_{t=1}^{NT}\left(S1_{t}^{m}+S2_{t}^{m}+S3_{t}^{m}+S4_{t}^{m}\right)+\sum_{i=1}^{NG}\sum_{t=1}^{NT}S5_{it}^{m} \tag{19}$$

$$\text{S.T.} \quad \sum_{i=1}^{NG}P_{it}^{m}*\hat{I}_{it}+\sum_{k=1}^{NVG}VP_{kt}^{m}+S1_{t}^{m}-S2_{t}^{m} = P_{D,t}+P_{L,t} \qquad (t=1,\cdots,NT) \tag{20}$$

$$\begin{gathered}\sum_{i=1}^{NG}R_{S,it}^{m}*\hat{I}_{it}+S3_{t}^{m} \geq \frac{R_{S,t}}{P_{D,t}}\left(P_{D,t}-\sum_{k=1}^{NVG}VP_{kt}^{m}\right)\\ \sum_{i=1}^{NG}R_{O,it}^{m}*\hat{I}_{it}+S4_{t}^{m} \geq \frac{R_{O,t}}{P_{D,t}}\left(P_{D,t}-\sum_{k=1}^{NVG}VP_{kt}^{m}\right)\\ (t=1,\cdots,NT)\end{gathered} \tag{21}$$

$$\left|P_{it}^{m}-P_{it}^{0}\right|-S5_{it}^{m} \leq \Delta_{i}(i=1,\cdots,NG) \quad (t=1,\cdots,NT). \tag{22}$$

If $\hat{v}^m > 0$, the algorithm will form Benders cut (23) for 24 h, which is added to the next ED iteration as shown in Fig. 2

$$v^{m}(\mathbf{P^{0}},\mathbf{VP^{0}})=\hat{v}^{m}+\sum_{i=1}^{NG}\sum_{t=1}^{NT}\left.\frac{\partial v^{m}}{\partial P_{it}^{0}}\right|_{\hat{P}_{it}^{0}}\left(P_{it}^{0}-\hat{P}_{it}^{0}\right)+\sum_{k=1}^{NVG}\sum_{t=1}^{NT}\left.\frac{\partial v^{m}}{\partial VP_{kt}^{0}}\right|_{V\hat{P}_{kt}^{0}}\left(VP_{kt}^{0}-V\hat{P}_{kt}^{0}\right) \leq 0. \tag{23}$$

If the proposed Benders cut cannot solve the SCOPF at steady state (i.e., the maximum number that the iteration has reached), we add the following Benders cut to UC in Fig. 2

$$v^{m}(\mathbf{I},\mathbf{P^{0}})=\hat{v}^{m}+\sum_{i=1}^{NG}\sum_{t=1}^{NT}\left.\frac{\partial v^{m}}{\partial\left(P_{it}^{0}I_{it}\right)}\right|_{\hat{I}_{it},\hat{P}_{it}^{0}}\times\left(P_{it}^{0}I_{it}-\hat{P}_{it}^{0}\hat{I}_{it}\right) \leq 0. \tag{24}$$

C. Hourly AC Network Checks

At this stage, we check the viability of the ED solution for satisfying the network constraints. According to the Newton–Raphson method, the objective function (25) is introduced for minimizing real and reactive bus power mismatches for calculating a converged ac power flow solution subject to transmission flow and bus voltage limits. The load flow solution is based on UC and ED results. Similarly, $m = 0$ is for steady state.

In (25)–(32), slack variables $\mathrm{MP_{b,1}}$ and $\mathrm{MP_{b,2}}$ represent the real power mismatch at bus b, and $\mathrm{MQ_{b,1}}$ and $\mathrm{MQ_{b,2}}$ represent the reactive power mismatch at bus b. These values are introduced in the objective function to guarantee a feasible solution. From a physical viewpoint, slacks represent virtual generators that are added to each bus to balance mismatches. Equality constraints (26) are linearized real and reactive power balances in matrix form. $\mathbf{dP_0}$ and $\mathbf{dQ_0}$ represent mismatches between scheduled and calculated bus power injections. Inequality constraints (27)–(32) represent limits on transmission flows and bus voltages, real and reactive power generation, transformer taps, and phase shifter angles, respectively

$$Min \quad w_{t}(\hat{\mathbf{P}}^{\mathbf{m}})=\sum_{b=1}^{NB}(MP_{b,1}+MP_{b,2})+\sum_{b=1}^{NB}(MQ_{b,1}+MQ_{b,2}) \tag{25}$$

$$\text{S.T.} \quad \begin{bmatrix}\mathbf{Y}*\mathbf{\Delta P^{m}}+\mathbf{Z}*\mathbf{\Delta VP^{m}}\\ \mathbf{Y}*\mathbf{\Delta Q^{m}}+\mathbf{Z}*\mathbf{\Delta VQ^{m}}\end{bmatrix}-\begin{bmatrix}\mathbf{H}&\mathbf{N}&\mathbf{E}&\mathbf{F}\\ \mathbf{M}&\mathbf{J}&\mathbf{R}&\mathbf{S}\end{bmatrix}\times\begin{bmatrix}\boldsymbol{\Delta\delta}^{\mathbf{m}}\\ \mathbf{\Delta V^{m}}\\ \mathbf{\Delta T^{m}}\\ \boldsymbol{\Delta\gamma}^{\mathbf{m}}\end{bmatrix}+\begin{bmatrix}\mathbf{MP_{1}}\\ \mathbf{MQ_{1}}\end{bmatrix}-\begin{bmatrix}\mathbf{MP_{2}}\\ \mathbf{MQ_{2}}\end{bmatrix}=\begin{bmatrix}\mathbf{dP_{0}}\\ \mathbf{dQ_{0}}\end{bmatrix} \tag{26}$$

$$-\mathbf{\Delta PL_{max}} \leq \mathbf{\Delta PL^{m}}=[\mathbf{A}\quad\mathbf{B}\quad\mathbf{C}\quad\mathbf{D}]\begin{bmatrix}\boldsymbol{\Delta\delta}^{\mathbf{m}}\\ \mathbf{\Delta V^{m}}\\ \mathbf{\Delta T^{m}}\\ \boldsymbol{\Delta\gamma}^{\mathbf{m}}\end{bmatrix} \leq \mathbf{\Delta PL_{max}} \tag{27}$$

$$\mathbf{\Delta V_{min}} \leq \mathbf{\Delta V^{m}} \leq \mathbf{\Delta V_{max}} \tag{28}$$

$$\begin{aligned}
&\mathbf{\Delta P^m = 0} \quad \boldsymbol{\alpha} \\
&\mathbf{\Delta VP^m = 0} \quad \boldsymbol{\beta} && (29) \\
&\mathbf{\Delta Q_{min} \leq \Delta Q^m \leq \Delta Q_{max}} \quad \underline{\boldsymbol{\lambda}}, \overline{\boldsymbol{\lambda}} \\
&\mathbf{\Delta VQ^m = 0} && (30) \\
&|\mathbf{\Delta T^m}| \leq \mathbf{TS} && (31) \\
&|\boldsymbol{\Delta\gamma}^{\mathbf{m}}| \leq \boldsymbol{\gamma}\mathbf{S}. && (32)
\end{aligned}$$

We use LP for linearized constraints and apply the iterative method to calculate minimum bus mismatches according to the updated elements of Jacobian matrix and the initial mismatch vectors $\mathbf{dP_0}$ and $\mathbf{dQ_0}$ in (26). If the objective $\hat{w}$ is within an allowable tolerance, the current generation dispatch provides a feasible ac power flow solution and satisfies ac network security constraints. Otherwise, a positive $\hat{w}$ shows that ac power flow cannot converge as violations exist in the ac network. Thus, corresponding violation cuts (33) will be added to ED for the next iteration

$$\begin{aligned}
w_t(\mathbf{P^m}, \mathbf{VP^m}) = \hat{w}_t &+ \sum_{i=1}^{NG} \alpha_{it}|_{\hat{P}_{it}^m} \left(P_{it}^m - \hat{P}_{it}^m\right) \\
&+ \sum_{k=1}^{NVG} \beta_{it}|_{V\hat{P}_{it}^m} \left(VP_{it}^m - V\hat{P}_{it}^m\right) \leq 0. \qquad (33)
\end{aligned}$$

The addition of Benders cuts could reduce mismatches in the next iteration by modifying generating dispatch $\mathbf{P}$. All cuts from the previous $n = 1, 2, \ldots, N-1$ iterations will participate in the next iteration.

If the proposed Benders cut cannot solve the SCOPF with contingencies (i.e., the maximum number that the iteration has reached), we introduce the following Benders cut given by (34), which is added to UC in Fig. 2

$$\begin{aligned}
w_t(\mathbf{I}, \mathbf{P^0}) = \hat{w}_t &+ \sum_{i=1}^{NG} \alpha_{it}|_{\hat{I}_{it}, \hat{P}_{it}^m} \left(P_{it}^0 I_{it} - \hat{P}_{it}^m \hat{I}_{it}\right) \\
&+ \sum_{i=1}^{NG} \overline{\lambda}_{it}|_{\hat{I}_{it}} Q_{i,\max}(I_{it} - \hat{I}_{it}) \\
&- \sum_{i=1}^{NG} \underline{\lambda}_{it}|_{\hat{I}_{it}} Q_{i,\min}(I_{it} - \hat{I}_{it}) \leq 0. \qquad (34)
\end{aligned}$$

From the above discussion, a positive w_t may be the result of a nonconverged power flow or violations of network security constraints. However, the solution of (25)–(32) cannot identify the real reason for the ill-condition. In case the reason for ill-conditioning is of interest, a two-stage approach can be applied to solve the hourly ac network check subproblem. In the first stage, we obtain a converged ac power flow without considering the network security constraints. If converged power flow solution does not exist, a corresponding Benders mismatch cut will be formulated. In the second stage, we check ac network security violations. If any violations exist, a corresponding Benders cut will be formulated. The detail of this two-stage approach is presented in [16]. The proposed approach in this paper and that of [16] will provide the same network results.

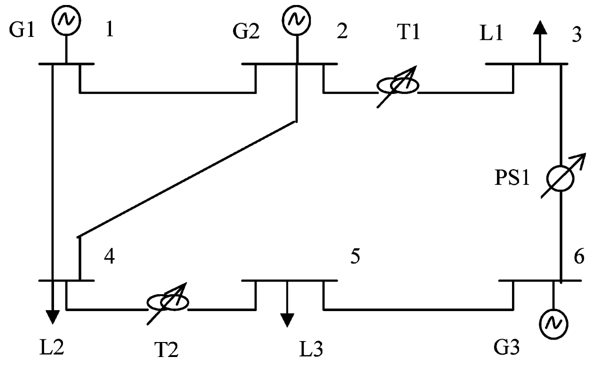

Fig. 3. Six-bus system.

IV. CASE STUDIES

The proposed model is applied to a six-bus test system, the IEEE 118-bus system, and the 1168-bus system to illustrate the performance of SCUC with ac corrective/preventive dispatch control actions. In order to focus on such discussions, only ac results are presented in this paper. The comparison between ac and dc results is thoroughly discussed in our previous paper [16].

A. Six-Bus System

The six-bus system depicted in Fig. 3 has three units, four transmission lines, two tap-changing transformers, and one phase shifter for MW control. The characteristics of generators, transmission lines, tap-changing transformers and phase shifter, and the hourly load distribution over the 24-h horizon are given in Tables I–IV, respectively. The magnitude of voltage at each bus must be between 0.85 and 1.15. In order to analyze the efficiency of the proposed method, we consider the following six case studies with corresponding constraints:

- Case 0) Base case (without network constraints);
- Case 1) Steady-state dispatch with ac network constraints;
- Case 2) Outage of line 3–6 (preventive dispatch);
- Case 3) Outage of unit 3 (preventive dispatch);
- Case 4) Outage of line 3–6 when line 1–4 has a new capacity of 115 MW (corrective dispatch);
- Case 5) Outage of line 5–6 with possible LS. Assume the LS contract is $1000/MWh for each load.

Case 0) We execute UC in which network constraints are not considered. The commitment schedule is shown in Table V in which 1 and 0 represent hourly on/off states of units, and hour 0 represents the initial condition. In addition, the daily bid-based generation dispatch cost (ED) given in Table VI is $101 598.18. In this case, the cheapest unit 1 supplies the base load. More expensive units 2 and 3 are not committed at certain hours to minimize the generation dispatch cost.

Case 1) The impact of ac constraints at steady state on SCUC and SCOPF is studied. If we use the UC results in Case 0 for SCOPF calculations, transmission flow violations will occur at steady state. Table VII shows overflows on line 1–4 at hours 12

TABLE I
GENERATOR DATA

Unit No.	Bus No.	Unit Cost Coefficients			Pmax (MW)	Pmin (MW)	Qmax (MVAR)	Qmin (MVAR)	IniState (hours)	Min Down (hours)	Min Up (hours)	Ramp (MW/Hr)
		a (MBtu)	b (MBtu/ MWh)	c (MBtu/ MW^2h)								
G1	1	176.9	13.5	0.0004	220	100	200	-80	4	-4	4	55
G2	2	129.9	32.6	0.001	100	10	70	-40	1	-3	2	50
G3	6	137.4	17.6	0.005	20	10	50	-40	-1	-1	1	20

and 15–19. Accordingly, six Benders cuts are generated for recalculating ED. We find that the UC in Case 1 is the same as that in Case 0. However, the optimal generation dispatch of SCOPF is changed as shown in Table VIII. The highlighted items in Table VIII show differences between Tables VI and VIII. Here the generation dispatch of the most economical unit 1 is decreased from 220 MW to about 204 MW for reducing the flow on line 1–4 to its capacity limits (given in Table II). The relatively expensive units 2 and 3 are dispatched more often to supply the system load. Accordingly, the daily cost of bid-based generation dispatch increases to $103 135.90.

Case 2) The outage of line 3–6, based on steady-state results of Case 1, will cause overflows on line 1–4 at hours 8 through 24. The addition of Benders cuts to the steady-state SCOPF for a preventive dispatch control will not provide a feasible dispatch solution. Then, a total of 17 Benders cuts are generated and added to UC for modifying the UC/SCOPF solution at steady state. Table IX shows the revised UC solution in which the uneconomical unit 2 is committed at hours 9–11 and 23, and unit 3 at hours 8, 9, 23, and 24. The new generation dispatch for preventing post-contingency violations in SCOPF is shown in Table X. The highlighted items in Table X show differences between Tables VIII and X. In this case, the bid-based generation dispatch cost increases to $119 525.00.

Case 3) The outage of generating unit 3, based on the steady-state results of Case 1, fails to supply loads at hours 10 through 22. Consequently, the SCOPF solution for this contingency will be infeasible, which requires Benders cut (see equation 24) for recalculating UC. Tables XI and XII show that the most expensive unit 2 replaces unit 3 at hours 10 and 11 to supply more loads at hours 10 through 23 at steady state. The highlighted items in Table XII show differences between Tables VIII and XII. Although the more expensive daily bid-based generation dispatch cost is $110 120.19, the outage of unit 3 will be manageable in this case and will not threaten the secure operation of the power system. In this example, we selected the outage of unit 3 in order to present the ability of our algorithm in handling generator contingencies. However,

TABLE II
TRANSMISSION LINE DATA

Line No.	From Bus	To Bus	R (pu)	X (pu)	Flow Limit (MW)
1	1	2	0.0050	0.170	200
2	1	4	0.0030	0.258	100
3	2	4	0.0070	0.197	100
4	5	6	0.0020	0.140	100

TABLE III
TAP-CHANGING TRANSFORMER AND PHASE SHIFTER DATA

Tap-Changers (T) and Phase Shifters (PS)	From Bus	To Bus	X (pu)	Max Tap/Angle	Min Tap/Angle
T1	2	3	0.037	0.98	0.95
T2	4	5	0.037	0.98	0.95
PS1	3	6	0.018	30	-30

TABLE IV
HOURLY LOAD DISTRIBUTION

Hr	Pd	Qd	Hr	Pd	Qd
1	178.69	50.37	13	247.03	69.63
2	168.45	47.48	14	248.47	70.03
3	161.84	45.62	15	253.83	71.55
4	157.83	44.49	16	260.90	73.54
5	158.16	44.58	17	261.12	73.60
6	163.69	46.14	18	251.68	70.94
7	176.86	49.85	19	250.89	70.72
8	194.21	51.06	20	242.10	68.24
9	209.67	53.71	21	242.05	68.23
10	221.54	59.50	22	231.68	66.89
11	233.18	65.73	23	205.07	56.33
12	240.82	67.88	24	200.69	56.23

TABLE V
SCUC WITHOUT NETWORK CONSTRAINTS (CASE 0)

Unit	Hours (0-24)
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 1
2	1 1 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 0 0
3	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0

when unit 1 is on outage, the remaining two units cannot supply the loads. Such a small network is definitely weak and subject to load shedding in certain contingencies cases as discussed in Case 5.

Case 4) Once we increase the capacity of line 1–4 to 115 MW, the steady-state SCOPF solution will be the same as that in Case 0 because no transmission line violations are encountered. However, when

TABLE VI
GENERATION DISPATCH (MW) IN CASE 0

Hour	U1	U2	U3
1	168.69	10.00	0.00
2	168.45	0.00	0.00
3	161.84	0.00	0.00
4	157.83	0.00	0.00
5	158.16	0.00	0.00
6	163.69	0.00	0.00
7	176.87	0.00	0.00
8	194.21	0.00	0.00
9	209.67	0.00	0.00
10	211.54	0.00	10.00
11	220.00	0.00	13.18
12	220.00	10.00	10.82
13	220.00	10.00	17.03
14	220.00	10.00	18.47
15	220.00	13.83	20.00
16	220.00	20.90	20.00
17	220.00	21.12	20.00
18	220.00	11.68	20.00
19	220.00	10.89	20.00
20	220.00	10.00	12.10
21	220.00	10.00	12.05
22	211.68	10.00	10.00
23	205.07	0.00	0.00
24	200.69	0.00	0.00

TABLE VII
FLOW ON LINE 1–4 AT VIOLATED HOURS (MW)

Hour	**12**	**15**	**16**
No Cuts	100.52	101.89	104.12
T-Cuts	98.16	98.29	98.27
Hour	**17**	**18**	**19**
No Cuts	104.19	101.21	100.96
T-Cuts	98.27	98.28	98.27

TABLE VIII
GENERATION DISPATCH (MW) IN CASE 1

Hour	U1	U2	U3
1	168.69	10.00	0.00
2	168.45	0.00	0.00
3	161.84	0.00	0.00
4	157.83	0.00	0.00
5	158.16	0.00	0.00
6	163.69	0.00	0.00
7	176.87	0.00	0.00
8	194.21	0.00	0.00
9	209.67	0.00	0.00
10	211.54	0.00	10.00
11	220.00	0.00	13.18
12	218.61	10.00	12.21
13	220.00	10.00	17.03
14	220.00	10.00	18.47
15	212.56	21.28	20.00
16	204.37	36.54	20.00
17	204.11	37.01	20.00
18	215.06	16.62	20.00
19	215.97	14.90	20.00
20	220.00	10.00	12.10
21	220.00	10.00	12.05
22	211.68	10.00	10.00
23	205.07	0.00	0.00
24	200.69	0.00	0.00

TABLE IX
UC WITH TRANSMISSION LINE CONTINGENCY IN CASE 2

Unit	Hours (0-24)
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 1
2	1 1 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
3	0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

TABLE X
GENERATION DISPATCH (MW) IN CASE 2

Hour	U1	U2	U3
1	168.69	10.00	0.00
2	168.45	0.00	0.00
3	161.84	0.00	0.00
4	157.83	0.00	0.00
5	158.16	0.00	0.00
6	163.69	0.00	0.00
7	176.87	0.00	0.00
8	184.21	0.00	10.00
9	187.44	10.00	12.23
10	185.44	16.11	20.00
11	174.65	38.53	20.00
12	167.57	53.25	20.00
13	161.81	65.21	20.00
14	160.48	67.99	20.00
15	155.51	78.33	20.00
16	148.95	91.95	20.00
17	148.75	92.37	20.00
18	157.50	74.17	20.00
19	158.24	72.65	20.00
20	166.39	55.71	20.00
21	166.43	55.63	20.00
22	176.04	35.64	20.00
23	185.07	10.00	10.00
24	190.69	0.00	10.00

TABLE XI
UC WITH GENERATOR CONTINGENCY IN CASE 3

Unit	Hours (0-24)
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 1
2	1 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
3	0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 0 0

line 3–6 is on outage, overloads will occur on line 1–4 at hours 12 through 21. In this case, the corrective dispatch shown in Table XIII is sufficient to mitigate violations and satisfy the system security in the event of line 3–6 outage. The daily bid-based generation dispatch cost of SCOPF for this contingency is $103 051.30.

Case 5) In this case, we retain the capacity of line 1–4 at 115 MW. After the second iteration between UC and SCOPF, we conclude that the violation on line 4–5 cannot be completely eliminated, because the transfer capacity at hours 15–18 is insufficient for supplying the load at bus 5 when line 5–6 is out. Thus, the last feasible UC solution is recorded in Table XIV. Meanwhile, three virtual generators are added at load buses 3–5 for LS. As a result, certain amount of load at bus 5 is curtailed at violated hours are shown in Table XV. The highlighted items in Table XV show differences between Tables VIII

TABLE XII
GENERATION DISPATCH IN CASE 3

Hour	U1	U2	U3
1	168.69	10.00	0.00
2	168.45	0.00	0.00
3	161.84	0.00	0.00
4	157.83	0.00	0.00
5	158.16	0.00	0.00
6	163.69	0.00	0.00
7	176.86	0.00	0.00
8	194.21	0.00	0.00
9	209.67	0.00	0.00
10	211.54	10.00	0.00
11	213.20	19.98	0.00
12	206.85	23.97	10.00
13	208.86	28.17	10.00
14	207.19	31.28	10.00
15	200.97	42.86	10.00
16	192.78	58.12	10.00
17	192.53	58.59	10.00
18	203.47	38.21	10.00
19	204.39	36.50	10.00
20	214.57	17.52	10.00
21	214.62	17.43	10.00
22	184.30	37.38	10.00
23	195.07	10.00	0.00
24	200.69	0.00	0.00

TABLE XIII
GENERATION SCHEDULE IN CASE 4

Hr	U1	U2	U3
1	168.69	10.00	0.00
2	168.45	0.00	0.00
3	161.84	0.00	0.00
4	157.83	0.00	0.00
5	158.16	0.00	0.00
6	163.69	0.00	0.00
7	176.87	0.00	0.00
8	194.21	0.00	0.00
9	209.67	0.00	0.00
10	211.54	0.00	10.00
11	220.00	0.00	13.18
12	216.33	10.00	14.49
13	216.96	10.07	20.00
14	215.63	12.84	20.00
15	210.65	23.18	20.00
16	204.10	36.80	20.00
17	203.90	37.22	20.00
18	212.65	19.03	20.00
19	213.38	17.50	20.00
20	216.47	10.00	15.63
21	216.46	10.00	15.59
22	211.68	10.00	10.00
23	205.07	0.00	0.00
24	200.69	0.00	0.00

TABLE XIV
UC WITH LOAD SHEDDDING IN CASE 5

Unit	Hours (0-24)																								
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	1
2	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
3	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

TABLE XV
GENERATION DISPATCH AND LOAD SHEDDING AT BUS 5 IN CASE 5

Hour	U1	U2	U3	LS
1	168.69	10.00	0.00	0.00
2	168.45	0.00	0.00	0.00
3	161.84	0.00	0.00	0.00
4	157.83	0.00	0.00	0.00
5	158.16	0.00	0.00	0.00
6	163.69	0.00	0.00	0.00
7	176.87	0.00	0.00	0.00
8	194.21	0.00	0.00	0.00
9	209.67	0.00	0.00	0.00
10	211.54	0.00	10.00	0.00
11	206.62	10.00	16.56	0.00
12	199.54	21.28	20.00	0.00
13	193.78	33.24	20.00	0.00
14	192.45	36.02	20.00	0.00
15	189.25	43.05	20.00	1.53
16	185.98	50.57	20.00	4.36
17	185.87	50.80	20.00	4.44
18	190.25	40.75	20.00	0.67
19	188.91	41.98	20.00	0.00
20	198.36	23.74	20.00	0.00
21	198.40	23.65	20.00	0.00
22	208.01	13.67	10.00	0.00
23	195.07	10.00	0.00	0.00
24	200.69	0.00	0.00	0.00

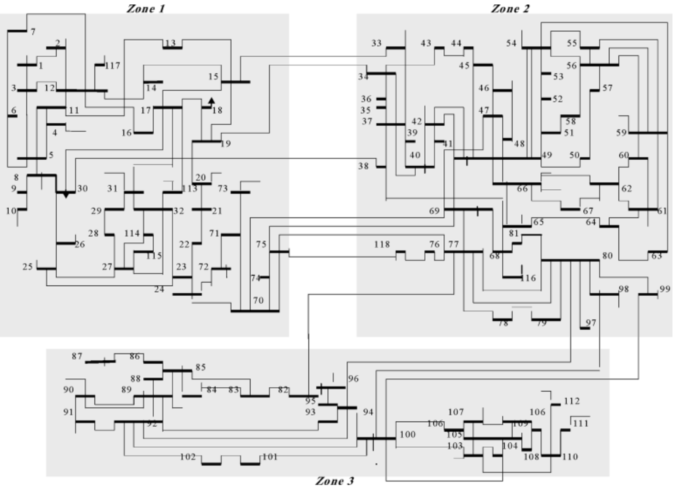

Fig. 4. One-line diagram of IEEE 118-bus system.

and XV. The daily bid-based dispatch cost is $119 069.80, including the generation dispatch cost of SCOPF at $108.056.67 and the LS cost at $11 013.12.

B. IEEE 118-Bus System

A modified IEEE 118-bus test system is used to study the SCUC with ac corrective/preventive dispatch action. The system has 76 units, 186 branches, 14 capacitors, nine tap-changing transformers, and 91 demand sides. The peak load of 7592 MW occurs at hour 21. The network structure with three zones is shown in Fig. 4, and the 118-bus system data are given on the web at http://www.motor.ece.iit.edu/data/SCUC_118. At first, we obtain solutions for UC and SCOPF dispatch at *steady state* for satisfying ac network constraints. Table XVI shows the

TABLE XVI
SCOPF VIOLATIONS AT STEADY STATE

Iteration No.	Cumulative Cuts	Hours with Violations
1	0	1,2,7-23
2	19	9,12,16,18-22
3	27	12,16,19,20
4	31	None

number of cumulative cuts and respective hours with violations at each iteration. In order to mitigate these violations, certain expensive units will be committed. Consequently, the daily bid-based generation dispatch cost of SCOPF will increase to $2 064 493 as compared with the base case cost of $2 062 314 without ac network constraints.

Next, we consider three contingencies that represent outages of unit 47, line 19–34, and line 56–59. These contingencies are denoted by CTGC1, 2, and 3, respectively. We consider the given contingencies individually. In this case, CTGC3 is a controllable contingency because the power system would shift to a new operating point by redispatching certain units. However, when CTGC1 or CTGC2 occurs, ac violations cannot be completely mitigated. We resort to a new UC calculation with Benders cuts provided by SCOPF for uncontrollable contingencies CTGC1 and CTGC2. SCOPF will then provide a new preventive control action with a higher bid-based generation dispatch cost of $2 065 532. Such preventive control actions can cope with the post-contingency operation of CTGC1 and CTGC2 without readjusting the generation dispatch of individual units.

C. 1168-Bus System

The proposed model is applied to a practical system with 169 generators, 1168 buses, 1474 branches, and 568 load sides. The top five contingencies are selected. The case is tested on a 1.8-GHz personal computer. Without considering contingencies, a typical CPU time for SCUC with ac network constraints is about 30 min. When considering contingencies, the CPU time increases to about 110 min. Note that the CPU time depends on system characteristics (i.e., load level, number of constraints and contingencies, and the robustness of system). According to our experience, the execution time increases rather linearly with the size of the scheduling problem.

V. CONCLUSIONS

We concluded that a balance of *economics* and *security* in restructured markets is essential for the operation of power systems. A conservative generation commitment and dispatch (e.g., commit all three units over 24 h in the six-bus test system) could result in an expensive operation, which will be ruled out by the proposed method. Likewise, a merely economical solution may result in a less than secure operation of power systems. The numerical tests show the effectiveness of the proposed method for satisfying economic and security constraints in a constrained power system. The proposed method could solve both SCUC and SCOPF modules based on ac constraints and devise a set of corrective/preventive control actions for the secure and economical operation of power systems. It would be possible to introduce this model to the long-term SCUC [17].

In this paper, the notion of controllable and uncontrollable contingencies is proposed when SCOPF is executed at every iteration. Such classification of contingencies is dynamic, depends on the current unit commitment solution, and may change at the next iteration. It will be possible to improve the performance of the proposed method by applying parallel calculations because SCUC and SCOPF modules are composed of many subproblems.

The proposed SCUC and contingency analyzes are executed as a day-ahead strategy. The SCOPF model proposed in this paper could further be used for analyzing last-minute outages. We recognize that the look-ahead outage planning could affect any day-ahead solution. However, the discussion of outage planning strategies is beyond the scope of this paper and will be studied in our future papers.

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