Security-Constrained Unit Commitment for Simultaneous Clearing of Energy and Ancillary Services Markets

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***Abstract*—This paper introduces a security-constrained unit commitment (SCUC) model with emphases on the simultaneous optimization of energy and ancillary services markets. Benders decomposition is used to decouple the SCUC into a unit commitment (UC) master problem and hourly network security checking subproblems. Lagrangian relaxation is used to decouple the UC problem into individual single-unit commitment problems. Dynamic programming is used to find the optimal commitment decision. A simultaneous marginal curve algorithm is proposed to find the optimal values of energy and ancillary services. A six-bus system with three units and the IEEE 118-bus system with 54 units are analyzed to illustrate the proposed model.**

***Index Terms*—Ancillary services, energy, security-constrained unit commitment (SCUC), transmission security.**

NOMENCLATURE

REGD	Regulation down.
REGU	Regulation up.
TMSR	Ten-minute spinning reserve.
TMNR	Ten-minute nonspinning reserve.
TMOR	Thirty-minute operating reserve.
AS	Ancillary services, including REGD, REGU, TMSR, TMNR, and TMOR.
i	Index for generating unit.
t	Index for time period (h).
x	Symbol for a single product (g for energy, d for REGD, u for REGU, s for TMSR, n for TMNR, and o for TMOR) or an integrated product (a combination of g, d, u, s, n, and o).
$I(i,t)$	Commitment status of unit i at t.
$P_g(i,t)$	Energy of generating unit i at t (in megawatthours).
$R_x(i,t)$	AS product x of generating unit i at t (in megawatts).
$f_{x,it}(\cdot)$	Bidding cost of unit i at t for product x (in dollars).
$s(i,t)$	Startup/shutdown cost of unit i at t (in dollars).
$P_{g\max}(i,t)$	Maximum generation bid of unit i at t (in megawatts).
$P_{g\min}(i,t)$	Minimum generation bid of unit i at t (in megawatts).
$P_{\max 1}(i,t)$	Maximum reachable generation of unit i with ramping constraints at t (in megawatts).
$P_{\max}(i)$	Maximum capacity of unit i (in megawatts).
$P_{\min}(i)$	Minimum capacity of unit i (in megawatts).
$R_{x\max}(i,t)$	Maximum AS bid of unit i at t (in megawatts).
$RR_{reg}(i)$	Ramping capability for regulation of unit i (in megawatts per hour).
$RR_{res}(i)$	Ramping capability for reserve of unit i (in megawatts per minute).
$RR_{op}(i)$	Ramping capability for operation of unit i (in megawatts per hour).
$QSC_{10}(i)$	10-min quick start capability of unit i (in megawatts).
$QSC_{30}(i)$	30-min quick start capability of unit i (in megawatts).
$D_x(t)$	System requirement for product x at t (in megawatthours for energy and megawatts for AS).
$\lambda_x(t)$	Lagrangian multiplier for product x at t.
$MC_{x,it}(\cdot)$	Marginal curve for a single product x or simultaneous marginal curve for an integrated product x of unit i at t.
$P_x^*(i,t)$	Optimal value for energy or an integrated product x that includes energy of unit i at t (in megawatthours).
$R_x^*(i,t)$	Optimal value for AS product x of unit i at t (in megawatts).

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I. INTRODUCTION

THE PROCESS of determining the startup or shutdown schedule of generating units is referred to as unit commitment (UC). In the traditional UC model, the objective is to minimize system operating costs for supplying the system load while satisfying various system and unit constraints [1]. In restructured power systems, security is enhanced by supplying sufficient spinning reserves in the system [2], [3]. In UC, security is explicitly taken into consideration by ensuring that transmission flows and bus voltages are within limits, which leads to the implementation of security-constrained unit commitment (SCUC). The basics of SCUC are discussed in [4]. The direct method for considering transmission flow constraints based on Lagrangian relaxation was employed to solve SCUC [5], [6]. In [7]–[9], Benders decomposition was employed to decompose SCUC into a UC master problem and hourly security checking subproblems, which were coordinated through Benders cuts. In [7], flow and voltage constraints were considered independently in SCUC and [8] applied SCUC with coupled flow and voltage constraints. In [9], contingency constraints were evaluated and included in the SCUC solution.

The objective for UC, which is executed by the independent system operator (ISO), could be to minimize the cost of supplying energy and ancillary services based on generating unit bids. However, in the proposed UC models, ancillary services are either not considered or only considered as constraints. In the latter case, the cost of supplying ancillary services is ignored. In [4]–[9], spinning and operating reserves were considered as constraints. However, none of those papers considered the cost of supplying ancillary services. References [10] and [11] considered a simultaneous optimal dispatch, rather than unit commitment, of energy and ancillary services.

This paper presents the formulation and solution of SCUC with simultaneous optimization of energy and ancillary services markets. In [4], we discussed the basics of ancillary service auction. Ancillary services considered in this paper include regulation down (REGD), regulation up (REGU), ten-minute spinning reserve (TMSR), ten-minute nonspinning reserve (TMNR), and thirty-minute operating reserve (TMOR). Regulation is the online synchronized generation capacity that is available to respond to the ISO's automatic generation control (AGC) signals on a second-by-second basis. Regulation capacity is procured separately for REGU and REGD. We adopt definitions of TMSR, TMNR, and TMOR given in [10]. TMSR is a resource capacity synchronized to the system that is 1) able to immediately begin to supply energy or reduce demand, 2) fully available within 10 min, and 3) able to be sustained for a period of at least 30 min to provide first contingency protection. TMNR/TMOR are resource capacities nonsynchronized to the system, which are 1) able to supply energy or reduce demand, 2) fully available within 10/30 min, and 3) able to be sustained for a period of at least 30/60 min to provide first/second contingency protection.

An important aspect of supplying ancillary services is their hierarchical nature that allows the substitution of a higher quality service with a lower quality one. Faster response reserves are graded as higher quality. For instance, TMSR can be used to satisfy TMNR requirements. Both the social efficiency and the rational procurement behavior promote such substitutions in restructured power systems [4].

The rest of this paper is organized as follows. Section II presents the SCUC formulation for simultaneous optimization of energy and ancillary services. Section III presents the solution methodology. Section IV introduces the application of a simultaneous marginal curve to optimizing energy and ancillary services. Section V illustrates the concept by examples. Section VI concludes the paper.

II. SCUC Formulation for Simultaneous Optimization of Energy and Ancillary Services

A. Objective

The SCUC objective in this paper is to determine an optimal commitment and dispatch of generating units for minimizing the ISO's cost of supplying energy and ancillary services. See (1) at the bottom of the page.

The first part of (1) is the cost of supplying energy, REGD, REGU, and TMSR if the generating unit is on. The second part of (1) is the cost of supplying TMNR and TMOR. A generating unit may provide TMNR and TMOR whether the generating unit is on or off. The third part is the startup and shutdown costs, which are only incurred if the generating unit is turned on or off. In (1), $f_{x,it}(\cdot)$ represents the bidding cost of generating unit i at time t for product x. These generating unit i functions could be the same as the cost of generating unit i if the generating unit is bidding marginal. We have considered a more general case later in case studies.

The consideration of cost of supplying ancillary services is a significant departure from the existing SCUC formulation, which could complicate the commitment solution methodology. The final SCUC solution must satisfy many constraints, as discussed below, for the secure operation of power systems.

B. Power Balance Constraint

The power balance constraint of the system is given by (2). When necessary, power system losses could also be included, as discussed in [8]

$$\sum_i P_g(i,t) = D_g(t), \quad \forall t. \tag{2}$$

C. Ancillary Services Requirements

Power system requirements for REGD, REGU, TMSR, TMNR, and TMOR, are given by (3)–(7), respectively. The downward substitution of ancillary services is considered, which is the substitution of a higher quality service for a lower quality one. Accordingly, REGU can substitute for TMSR, TMSR for TMNR, and TMNR for TMOR. For instance, (5) shows that the extra REGU could be used to satisfy TMSR requirements

$$\sum_i R_d(i,t) \geq D_d(t), \quad \forall t \tag{3}$$

$$\sum_i R_u(i,t) \geq D_u(t), \quad \forall t \tag{4}$$

$$\sum_i R_u(i,t) + R_s(i,t) \geq D_u(t) + D_s(t), \quad \forall t \tag{5}$$

$$C = \sum_i \sum_t \left[f_{g,it}(P_g(i,t)) + f_{d,it}(R_d(i,t)) + f_{u,it}(R_u(i,t)) + f_{s,it}(R_s(i,t))\right] I(i,t) + \sum_i \sum_t \left[f_{n,it}(R_n(i,t)) + f_{o,it}(R_o(i,t))\right] + \sum_i \sum_t s(i,t). \tag{1}$$

$$\sum_i R_u(i,t) + R_s(i,t) + R_n(i,t) \geq D_u(t) + D_s(t) + D_n(t), \quad \forall t \tag{6}$$

$$\sum_i R_u(i,t) + R_s(i,t) + R_n(i,t) + R_o(i,t) \geq D_u(t) + D_s(t) + D_n(t) + D_o(t), \quad \forall t. \tag{7}$$

D. Unit Generation and Ancillary Services Constraints

When a generating unit is on, its generation and ancillary services are constrained by (8)–(18), $\forall i, t$. The generation dispatch given by (8) would comply with financial and physical limits. REGD and REGU given by (9) and (10) should also comply with financial and physical limits (e.g., ramping capability for regulation). TMSR, TMNR, and TMOR given by (11)–(13) are constrained by bidding limits. A generating unit has to reserve part of its capacity to provide REGD given by (14). The total REGU, TMSR, and TMNR given by (15) cannot exceed a generating unit's 10-min ramping capability for supplying reserves. The total REGU, TMSR, TMNR, and TMOR given by (16) cannot exceed a generating unit's 30-min ramping capability for supplying reserves. The total energy, REGU, TMSR, TMNR, and TMOR quantities given by (17) cannot exceed a generating unit's maximum operating limit. The ramping limit is specified by (18)

$$P_{\min}(i) \leq P_{g\min}(i,t) \leq P_g(i,t) \leq P_{g\max}(i,t) \leq P_{\max}(i,t) \tag{8}$$

$$0 \leq R_d(i,t) \leq R_{d\max}(i,t) \leq RR_{reg}(i) \tag{9}$$

$$0 \leq R_u(i,t) \leq R_{u\max}(i,t) \leq RR_{reg}(i) \tag{10}$$

$$0 \leq R_s(i,t) \leq R_{s\max}(i,t) \tag{11}$$

$$0 \leq R_n(i,t) \leq R_{n\max}(i,t) \tag{12}$$

$$0 \leq R_o(i,t) \leq R_{o\max}(i,t) \tag{13}$$

$$P_g(i,t) - R_d(i,t) \geq P_{\min}(i) \tag{14}$$

$$R_u(i,t) + R_s(i,t) + R_n(i,t) \leq 10RR_{res}(i) \tag{15}$$

$$R_u(i,t)+R_s(i,t)+R_n(i,t)+R_o(i,t) \leq 30RR_{res}(i) \tag{16}$$

$$P_g(i,t) + R_u(i,t) + R_s(i,t) + R_n(i,t) + R_o(i,t) \leq P_{\max}(i) \tag{17}$$

$$-RR_{op}(i) \leq P_g(i,t) - P_g(i,t-1) \leq RR_{op}(i). \tag{18}$$

When a generating unit is off, its generation and ancillary services are constrained by (19)–(23), $\forall i, t$. Accordingly, energy, REGD, REGU, and TMSR given by (19) would be zero. TMNR and TMOR given by (20) and (21) are constrained by bidding limits. TMNR given by (22) cannot exceed a generating unit's 10-min quick start capability. The total TMNR and TMOR quantities given by (23) cannot exceed a generating unit's 30-min quick-start capability

$$P_g(i,t) = R_d(i,t) = R_u(i,t) = R_s(i,t) = 0 \tag{19}$$

$$0 \leq R_n(i,t) \leq R_{n\max}(i,t) \tag{20}$$

$$0 \leq R_o(i,t) \leq R_{o\max}(i,t) \tag{21}$$

$$R_n(i,t) \leq QSC_{10}(i) \tag{22}$$

$$R_n(i,t) + R_o(i,t) \leq QSC_{30}(i). \tag{23}$$

E. Other Constraints

Other constraints included in SCUC are generating units' minimum on/off time constraints, generating units' fuel and emission constraints, and network security constraints. References [4], [8], and [9] provide a detailed formulation of other constraints of SCUC.

$$\begin{aligned}
L = & \sum_i \sum_t [f_{g,it}(P_g(i,t)) + f_{d,it}(R_d(i,t)) + f_{u,it}(R_u(i,t)) + f_{s,it}(R_s(i,t))] I(i,t) \\
& + \sum_i \sum_t [f_{n,it}(R_n(i,t)) + f_{o,it}(R_o(i,t))] + \sum_i \sum_t s(i,t) \\
& - \sum_t \lambda_g(t) \left[\sum_i P_g(i,t) - D_g(t) \right] \\
& - \sum_t \lambda_d(t) \left[\sum_i R_d(i,t) - D_d(t) \right] \\
& - \sum_t \lambda_u(t) \left[\sum_i R_u(i,t) - D_u(t) \right] \\
& - \sum_t \lambda_s(t) \left[\sum_i R_u(i,t) + R_s(i,t) - D_u(t) - D_s(t) \right] \\
& - \sum_t \lambda_n(t) \left[\sum_i R_u(i,t) + R_s(i,t) + R_n(i,t) - D_u(t) - D_s(t) - D_n(t) \right] \\
& - \sum_t \lambda_o(t) \left[\sum_i R_u(i,t) + R_s(i,t) + R_n(i,t) + R_o(i,t) - D_u(t) - D_s(t) - D_n(t) - D_o(t) \right].
\end{aligned} \tag{24}$$

III. SCUC Solution With Ancillary Services

As discussed in [8], the hierarchy for calculating SCUC utilizes a Benders decomposition, which decouples the SCUC into a UC master problem and network security check subproblems. UC is solved based on augmented Lagrangian relaxation (LR), which decomposes the UC into individual single-unit commitment (SUC) problems. SUC is solved by a dynamic programming (DP) approach, which determines a generating unit's optimal commitment schedule. Once converged, UC also solves an economic dispatch (ED) by linear programming (LP) to determine the dispatch of generating units. Then, the commitment and dispatch from UC are checked against ac network security constraints, and network security violations are minimized. If violations persist, certain constraints (Benders cuts) will be passed to the UC master problem for recalculating the UC solution. The iterative process will continue until all violations are eliminated, and a converged optimal solution is found.

For more details on the solution hierarchy, refer to [8]. A major difference between this paper and [8] is that in the SUC phase of this paper, dual optimal values for the five ancillary services, in addition to energy, are determined. The consideration of multiple ancillary services as well as their costs greatly complicates the determination of those dual optimal values. A Lagrangian function is presented next, and optimality conditions for dual optimal values at on and off cases are discussed.

A. Lagrangian Function

By relaxing system constraints such as power balance constraint (2) and ancillary service requirements (3)–(7) into the objective function (1), we form the Lagrangian function for the system, as in (24), shown at the bottom of the previous page.

The Lagrangian function for a single unit is given in (25), which is derived from (24) while ignoring constant terms. Then, we can decompose (25) as a function of time and use DP to find the minimum Lagrangian function. The key is to find optimality conditions for calculating energy and ancillary services, P_g, R_d, R_u, R_s, R_n, and R_o, that minimize the Lagrangian function. We discuss separately the optimality conditions for on status and off status. See (25) at the bottom of the page.

$$
\begin{aligned}
L(i) = &\sum_t \left[f_{g,it}(P_g(i,t)) + f_{d,it}(R_d(i,t)) + f_{u,it}(R_u(i,t)) + f_{s,it}(R_s(i,t))\right] I(i,t) \\
&+ \sum_t \left[f_{n,it}(R_n(i,t)) + f_{o,it}(R_o(i,t))\right] \\
&+ \sum_t s(i,t) \\
&- \sum_t \lambda_g(t) P_g(i,t) \\
&- \sum_t \lambda_d(t) R_d(i,t) \\
&- \sum_t \lambda_u(t) R_u(i,t) \\
&- \sum_t \lambda_s(t) \left[R_u(i,t) + R_s(i,t)\right] \\
&- \sum_t \lambda_n(t) \left[R_u(i,t) + R_s(i,t) + R_n(i,t)\right] \\
&- \sum_t \lambda_o(t) \left[R_u(i,t) + R_s(i,t) + R_n(i,t) + R_o(i,t)\right].
\end{aligned} \tag{25}
$$

B. Optimality Conditions for Single Unit Commitment When the Generating Unit is On

The Lagrangian function of an on unit at a single time period is given in (26), which is derived by regrouping (25)

$$
\begin{aligned}
L(i,t) = &f_{g,it}(P_g(i,t)) + f_{d,it}(R_d(i,t)) + f_{u,it}(R_u(i,t)) \\
&+ f_{s,it}(R_s(i,t)) + f_{n,it}(R_n(i,t)) + f_{o,it}(R_o(i,t)) \\
&- P_g(i,t)\lambda_g(t) \\
&- R_u(i,t)\left[\lambda_u(t) + \lambda_s(t) + \lambda_n(t) + \lambda_o(t)\right] \\
&- R_d(i,t)\lambda_d(t) \\
&- R_s(i,t)\left[\lambda_s(t) + \lambda_n(t) + \lambda_o(t)\right] \\
&- R_n(i,t)\left[\lambda_n(t) + \lambda_o(t)\right] \\
&- R_o(i,t)\lambda_o(t).
\end{aligned} \tag{26}
$$

Let

$$\lambda_{u1}(t) = \lambda_u(t) + \lambda_s(t) + \lambda_n(t) + \lambda_o(t) \tag{27a}$$

$$\lambda_{s1}(t) = \lambda_s(t) + \lambda_n(t) + \lambda_o(t) \tag{27b}$$

$$\lambda_{n1}(t) = \lambda_n(t) + \lambda_o(t). \tag{27c}$$

We have

$$
\begin{aligned}
L(i,t) = &f_{g,it}(P_g(i,t)) - P_g(i,t)\lambda_g(t) \\
&+ f_{d,it}(R_d(i,t)) - R_d(i,t)\lambda_d(t) \\
&+ f_{u,it}(R_u(i,t)) - R_u(i,t)\lambda_{u1}(t) \\
&+ f_{s,it}(R_s(i,t)) - R_s(i,t)\lambda_{s1}(t) \\
&+ f_{n,it}(R_n(i,t)) - R_n(i,t)\lambda_{n1}(t) \\
&+ f_{o,it}(R_o(i,t)) - R_o(i,t)\lambda_o(t).
\end{aligned} \tag{28}
$$

The optimality condition is satisfied by solving the following optimization problem:

$$\begin{aligned}&\min\ (28)\\ &\text{s.t. } (8)-(16)\\ &\quad P_g(i,t)+R_u(i,t)+R_s(i,t)+R_n(i,t)+R_o(i,t)\\ &\quad \le P_{\max 1}(i,t).\end{aligned} \tag{29}$$

In (29), $P_{\max 1}$ is the modified upper limit that incorporates ramping constraint (18), startup or shutdown ramping [12], and any other conditions that may limit P_g. There is no closed-form solution for the above optimization problem, and a simple priority order algorithm cannot handle quadratic or higher order cost functions. Although LP is a possibility for calculating optimal energy and ancillary services, the process could be time consuming in practical applications.

C. *Optimality Conditions for Single Unit Commitment When the Generating Unit is Off*

The Lagrangian function of off status for a single unit at a single time period is given by (30), which is derived by regrouping (25)

$$\begin{aligned}L(i,t) = {}& f_{n,it}(R_n(i,t)) + f_{o,it}(R_o(i,t))\\ &- R_n(i,t)\,[\lambda_n(t)+\lambda_o(t)]\\ &- R_o(i,t)\lambda_o(t).\end{aligned} \tag{30}$$

Let

$$\lambda_{n1}(t) = \lambda_n(t) + \lambda_o(t). \tag{31}$$

We have

$$\begin{aligned}L(i,t) = {}& f_{n,it}(R_n(i,t)) - R_n(i,t)\lambda_{n1}(t)\\ &+ f_{o,it}(R_o(i,t)) - R_o(i,t)\lambda_o(t).\end{aligned} \tag{32}$$

The optimality condition is derived by solving the following optimization problem

$$\begin{aligned}&\min\ (32)\\ &\text{s.t. } (19)-(23).\end{aligned}$$

IV. Application of Simultaneous Marginal Curves to Optimizing Ancillary Services

We offer a simultaneous marginal curve for calculating the optimal energy and ancillary services. The *marginal curve* for a product is the derivative of the Lagrangian function (28) or (32) with respect to the product quantity subject to lower and upper limits of the product. The *simultaneous marginal curve* (SMC) for an integrated product is the composition of marginal curves of individual products, as discussed later in this section. SMC represents a marginal change of Lagrangian function with respect to the change of the integrated product.

The optimal value of an integrated product corresponds to the point on its SMC that minimizes the Lagrangian function. For instance, if SMC crosses the x-axis, the intersection with the x-axis could be the optimal value of the integrated product. The following examples illustrate the concept of SMC.

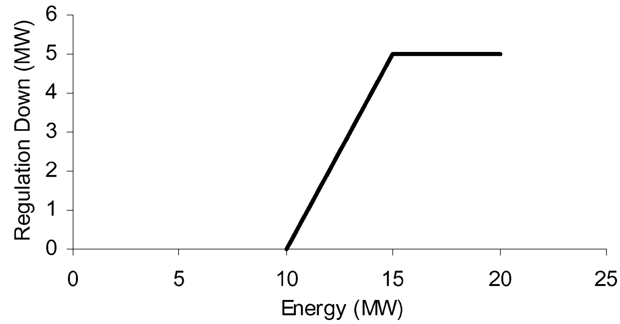

Fig. 1. Relationship between energy and regulation down.

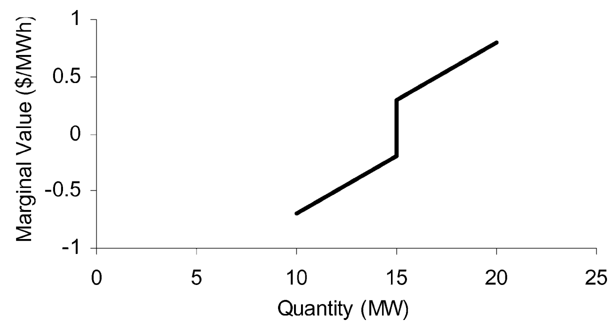

Fig. 2. Simultaneous marginal curve for energy and regulation down.

Example 1: Generating unit 1, with the following parameters, can provide energy and REGD: $P_{\min} = 10\ MW$, $P_{\max} = 20\ MW, R_{d\max} = 5\ MW, f_g(P_g) = 10P_g + 0.05P_g^2$, $f_d(R_d) = 0.5R_d$. Assume $\lambda_g = 11.2, \lambda_d = 1$. Find the optimal P_g, and R_d.

Solution: The marginal curve for energy is

$$MC_g(P_g) = 10 + 0.1P_g - 11.2 = -1.2 + 0.1P_g, \quad 10 \le P_g \le 20.$$

The marginal curve for REGD is

$$MC_d(R_d) = 0.5 - 1 = -0.5, \qquad 0 \le R_d \le 5.$$

Assume that the relationship between energy and REGD in Fig. 1 is given as

$$R_d = \begin{cases} P_g - 10, & 10 \le P_g \le 15\\ 5, & 15 \le P_g \le 20.\end{cases}$$

The composition of marginal curves for energy and REGD would be the SMC for integrated energy and REGD as follows. This is done by adding the y coordinates (marginal values) of $MC_g(P_g)$ and $MC_d(R_d)$ for the same x coordinates (P_g value)

$$MC_{gd}(P_g) = \begin{cases} -1.7 + 0.1P_g, & 10 \le P_g \le 15\\ -1.2 + 0.1P_g, & 15 \le P_g \le 20.\end{cases}$$

The SMC for integrated energy and REGD is illustrated in Fig. 2.

Based on SMC, the optimal energy and REGD are calculated as $P_g^* = 15, R_d^* = 5$. P_g^* is the P_g value on the SMC that corresponds to zero marginal values. R_d^* can be obtained from Fig. 1. Note that without providing REGD, the optimal energy would be $P_g^* = 12$. If we regard Lagrangian multipliers as market prices, since providing REGD is profitable, generating unit 1 would increase its generation up to 15 MW. At 15 MW, unit 1 would lose revenues for providing energy. However, the payoff

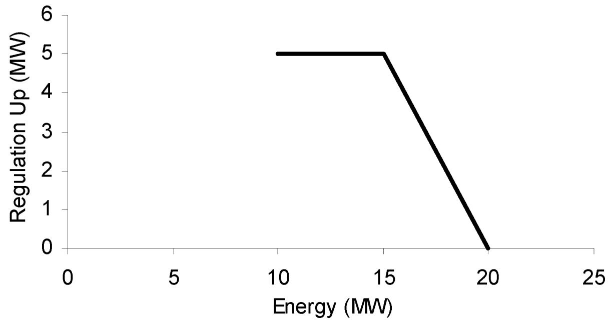

Fig. 3. Relationship between energy and regulation up.

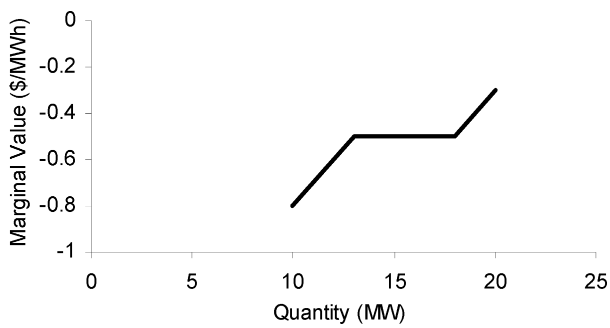

Fig. 4. Simultaneous marginal curve for energy and regulation up.

from providing REGD is larger than the loss incurred for providing energy. In essence, the maximum payoff of unit 1 occurs at 15 MW.

Example 2: Unit 2, with the following parameters, can provide energy and REGU: $P_{\min} = 10\ MW$, $P_{\max} = 20\ MW$, $R_{u\max} = 5\ MW$, $f_g(P_g) = 10P_g + 0.05P_g^2$, $f_u(R_u) = 0.5R_u$. Assume $\lambda_g = 11.8$, $\lambda_u = 1$. Find the optimal P_g and R_u.

Solution: The marginal curve for energy is

$$MC_g(P_g) = 10 + 0.1P_g - 11.8 = -1.8 + 0.1P_g, \quad 10 \le P_g \le 20.$$

The marginal curve for REGU is

$$MC_u(R_u) = 0.5 - 1 = -0.5, \qquad 0 \le R_u \le 5.$$

Assume the relationship between energy and REGU in Fig. 3, which is given as

$$R_u = \begin{cases} 5, & 10 \le P_g \le 15 \\ 20 - P_g, & 15 \le P_g \le 20. \end{cases}$$

The composition of marginal curves for energy and REGU is the SMC for integrated energy and REGU given as

$$MC_{gu}(P_{gu}) = \begin{cases} -1.8 + 0.1P_{gu}, & 10 \le P_{gu} \le 13 \\ -0.5, & 13 \le P_{gu} \le 18 \\ -2.3 + 0.1P_{gu}, & 18 \le P_{gu} \le 20 \end{cases}$$

where $P_{gu} = P_g + R_u$.

The composition is done by adding the x coordinates of $MC_g(P_g)$ and $MC_u(R_u)$ for the same y coordinates (marginal values). The SMC for integrated energy and REGU is illustrated in Fig. 4. Based on SMC, the optimal energy and REGU are $P_g^* = 15$, $R_u^* = 5$. Note that without providing REGU, the optimal energy is $P_g^* = 18$. Unit 2 would decrease its generation to 15 MW for offering the more profitable REGU.

According to the above examples, SMC captures the relationship between the integrated and individual products and provides information on marginal curves of individual products. Define three operations for curves:

YNEG operation of a curve: keep the segment of a curve with negative y (or cut the segment of curve with positive y)

YPLUS operation of two curves: add y coordinates of two curves for the same x coordinates

XPLUS operation of two curves: add x coordinates of two curves for the same y coordinates

In general, the steps for calculating SMC when a generating unit is on are listed as follows.

Step 1 *Form marginal curves for energy and individual ancillary services as*

$$MC_{g,it}(P_g(i,t)) = \frac{\partial f_{g,it}(P_g(i,t))}{P_g(i,t)} - \lambda_g(t)$$
$$P_{g\min}(i,t) \le P_g(i,t) \le P_{g\max}(i,t) \tag{33a}$$

$$MC_{d,it}(R_d(i,t)) = \frac{\partial f_{d,it}(R_u(i,t))}{R_d(i,t)} - \lambda_d(t)$$
$$0 \le R_d(i,t) \le R_{d\min}(i,t) \tag{33b}$$

$$MC_{u,it}(R_u(i,t)) = \frac{\partial f_{u,it}(R_u(i,t))}{R_u(i,t)} - \lambda_{u1}(t)$$
$$0 \le R_u(i,t) \le R_{u\min}(i) \tag{33c}$$

$$MC_{s,it}(R_s(i,t)) = \frac{\partial f_{s,it}(R_s(i,t))}{R_s(i,t)} - \lambda_{s1}(t)$$
$$0 \le R_s(i,t) \le R_{s\min}(i) \tag{33d}$$

$$MC_{n,it}(R_n(i,t)) = \frac{\partial f_{n,it}(R_n(i,t))}{R_n(i,t)} - \lambda_{n1}(t)$$
$$0 \le R_n(i,t) \le R_{n\min}(i) \tag{33e}$$

$$MC_{o,it}(R_n(i,t)) = \frac{\partial f_{o,it}(R_o(i,t))}{R_o(i,t)} - \lambda_o(t)$$
$$0 \le R_o(i,t) \le R_{o\min}(i). \tag{33f}$$

Step 2 *Form the simultaneous marginal curve for integrated energy and REGD as*

$$\begin{aligned} &MC_{gd,it}(P_g(i,t), R_d(i,t)) \\ &\quad = YNEG\{YPLUS\{MC_{g,it}(P_g(i,t)), \\ &\qquad YNEG\{MC_{d,it}(R_d(i,t))\}\}\} \\ &\qquad P_{g\min}(i,t) \le P_g(i,t) \le P_{g\max}(i,t) \\ &\qquad 0 \le R_d(i,t) \le RR_{reg}(i). \end{aligned} \tag{34}$$

Step 3 *Form the simultaneous marginal curve for integrated REGU, TMSR, TMNR, and TMOR*

a) Add marginal curves for REGU and TMSR as

$$\begin{aligned} &MC_{us,it}(R_u(i,t), R_s(i,t)) \\ &\quad = XPLUS\{YNEG\{MC_{u,it}(R_u(i,t))\}, \\ &\qquad YNEG\{MC_{s,it}(R_s(i,t))\}\} \\ &\qquad 0 \le R_u(i,t) + R_s(i,t) \le 10RR_{res}(i). \end{aligned} \tag{35}$$

b) Add marginal curves for REGU, TMSR, and TMOR as

$$\begin{aligned} & MC_{usn,it}(R_u(i,t), R_s(i,t), R_n(i,t)) \\ & = XPLUS\{MC_{us,it}(R_u(i,t), R_s(i,t)), \\ & \quad YNEG\{MC_{n,it}(R_n(i,t))\}\} \\ & \quad 0 \le R_u(i,t) + R_s(i,t) + R_n(i,t) \le 10RR_{res}(i). \end{aligned} \tag{36}$$

c) Add marginal curves for REGU, TMSR, TMNR, and TMOR as

$$\begin{aligned} & MC_{usno,it}(R_u(i,t), R_s(i,t), R_n(i,t), R_o(i,t)) \\ & = XPLUS\{MC_{usn,it}(R_u(i,t), R_s(i,t), R_n(i,t)), \\ & \quad YNEG\{MC_{o,it}(R_o(i,t))\}\} \\ & \quad 0 \le R_u(i,t) + R_s(i,t) + R_n(i,t) + R_o(i,t) \le 30RR_{res}(i). \end{aligned} \tag{37}$$

Step 4 *Form the simultaneous marginal curve for integrated energy and all ancillary services as*

$$\begin{aligned} & MC_{gdusno,it}(P_g(i,t), R_d(i,t), R_u(i,t), R_s(i,t), R_n(i,t), R_o(i,t)) \\ & = XPLUS\{MC_{gd,it}(P_g(i,t), R_d(i,t)), \\ & \quad MC_{usno,it}(R_u(i,t), R_s(i,t), R_n(i,t), R_o(i,t))\} \\ & \quad P_{g\min}(i) \le P_g(i,t) + R_u(i,t) + R_s(i,t) + R_n(i,t) \\ & \quad + R_o(i,t) \le \min\{P_{g\max}(i) + 30RR_{res}(i), P_{\max 1}(i,t)\}. \end{aligned} \tag{38}$$

The optimal quantities of integrated and individual products are calculated based on SMC. Note that the SMC for integrated energy and REGD is the result of YPLUS operation of marginal curves for energy and REGD. The SMC for other integrated products is the result of XPLUS operation of their marginal curves.

Similar to the on status, we propose the following steps for calculating the SMC for TMNR and TMOR when a generating unit is off, based on which the optimal TMNR and TMOR are calculated.

Step 1 *Form marginal curves for TMNR and TMOR as*

$$MC_{n,it}(R_n(i,t)) = \frac{\partial f_{n,it}(R_n(i,t))}{R_n(i,t)} - \lambda_{n1}(t), \quad 0 \le R_n(i,t) \le QSC_{10}(i) \tag{39a}$$

$$MC_{o,it}(R_n(i,t)) = \frac{\partial f_{o,it}(R_o(i,t))}{R_o(i,t)} - \lambda_o(t), \quad 0 \le R_o(i,t) \le QSC_{30}(i). \tag{39b}$$

Step 2 *Form the simultaneous marginal curve for integrated TMNR and TMOR as*

$$\begin{aligned} & MC_{no,it}(R_n(i,t), R_o(i,t)) \\ & = XPLUS\{YNEG\{MC_{n,it}(R_n(i,t))\} \\ & \quad YNEG\{MC_{o,it}(R_o(i,t))\}\}, \\ & \quad 0 \le R_n(i,t) + R_o(i,t) \le QSC_{30}(i). \end{aligned} \tag{40}$$

V. Case Studies

We present three case studies. Case 1 illustrates the concept of simultaneous marginal curves introduced in Section IV. For clarity, Case 1 is for a single period of time and a single unit. Different from the example in Section IV, the generating unit in this study has a quadratic cost function. Case 2 discusses a six-bus example with three generating units. Case 3 discusses the application to the IEEE 118-bus system with 54 generating units.

A. *Case 1: Quadratic Ancillary Services Cost Functions for a Single Unit at a Single Time Period*

The generating unit has the following parameters:

$$\begin{aligned} & P_{\min} = 10\text{ MW},\ P_{\max} = 100\text{ MW},\ RR_{reg} = 2\text{ MW/h}, \\ & RR_{res} = 0.8\text{ MW/min},\ P_{g\min} = 10\text{ MW},\ P_{g\max} = 100\text{ MW}, \\ & R_{d\max} = 2\text{ MW},\ R_{u\max} = 2\text{ MW},\ R_{s\max} = 8\text{ MW}, \\ & R_{n\max} = 8\text{ MW},\ R_{o\max} = 24\text{ MW},\ \text{and } P_{\max 1} = 100\text{ MW}. \end{aligned}$$

Cost functions for energy and ancillary services are given as

$$\begin{aligned} f_g(P_g) &= 100 + 10P_g + 0.05P_g^2 \\ f_d(R_d) &= 3.5R_d + 0.1R_d^2 \\ f_u(R_u) &= 4R_u + 0.1R_u^2 \\ f_s(R_s) &= 3R_s + 0.1R_s^2 \\ f_n(R_n) &= 2R_n + 0.1R_n^2 \\ f_o(R_o) &= R_o + 0.1R_o^2. \end{aligned}$$

Assume that Lagrangian multipliers for energy and ancillary services are $\lambda_g = 15$, $\lambda_d = 4$, $\lambda_u = 3$, $\lambda_s = 2$, $\lambda_n = 1$, and $\lambda_o = 3$. We follow the steps in Section IV for calculating optimal energy and ancillary services for the on status.

Step 1 *Form marginal curves for energy and individual ancillary services*

Marginal curve for energy

$$MC_g(P_g) = 10 + 0.1P_g - 15 = -5 + 0.1P_g, \ 10 \le P_g \le 100.$$

Marginal curve for REGD

$$MC_d(R_d) = 3.5 + 0.2R_d - 4 = -0.5 + 0.2R_d, \quad 0 \le R_d \le 2.$$

Marginal curve for REGU

$$\begin{aligned} MC_u(R_u) &= 4 + 0.2R_u - (3 + 2 + 1 + 3) \\ &= -5 + 0.2R_u, \quad 0 \le R_u \le 2. \end{aligned}$$

Marginal curve for TMNR

$$MC_s(R_s) = 3 + 0.2R_s - (2 + 1 + 3) = -3 + 0.2R_s, \quad 0 \le R_s \le 8.$$

Marginal curve for TMSR

$$MC_n(R_n) = 2 + 0.2R_n - (1 + 3) = -2 + 0.2R_n, \quad 0 \le R_n \le 8.$$

Marginal curve for TMOR

$$MC_o(R_o) = 1 + 0.2R_o - 3 = -2 + 0.2R_o, \quad 0 \le R_s \le 24.$$

Step 2 *Form the simultaneous marginal curve for integrated energy and REGD*

$$MC_{gd}(P_g) = \begin{cases} -7.5 + 0.3P_g, & 10 \le P_g \le 12 \\ -5 + 0.1P_g, & 12 \le P_g \le 50. \end{cases}$$

Step 3 *Form the simultaneous marginal curve for integrated REGU, TMSR, TMNR, and TMOR*

a) Add marginal curves for REGU and TMSR

$$MC_{us}(R_{us}) = \begin{cases} -5 + 0.2R_{us}, & 0 \le R_{us} \le 2 \\ -3.4 + 0.2R_{us}, & 2 \le R_{us} \le 8 \end{cases}$$

where $R_{us} = R_u + R_s$.

b. Add marginal curves for REGU, TMSR, and TMNR

$$MC_{usn}(R_{usn}) = \begin{cases} -5 + 0.2R_{usn}, & 0 \le R_{usn} \le 2 \\ -3.4 + 0.2R_{usn}, & 2 \le R_{usn} \le 7 \\ -2.7 + 0.1R_{usn}, & 7 \le R_{usn} \le 8 \end{cases}$$

where $R_{usn} = R_u + R_s + R_n$.

c. Add marginal curves for REGU, TMSR, TMNR, and TMOR

$$MC_{usno}(R_{usno}) = \begin{cases} -5+0.2R_{usno}, & 0 \le R_{usno} \le 2 \\ -3.4+0.2R_{usno}, & 2 \le R_{usno} \le 7 \\ -2.47+0.0667R_{usno}, & 7 \le R_{usno} \le 8.5 \\ -3.6+0.2R_{usno}, & 8.5 \le R_{usno} \le 18 \end{cases}$$

where $R_{usno} = R_u + R_s + R_n + R_o$.

Step 4 *Form the simultaneous marginal curve for energy and ancillary services*

$$MC_{gdusno}(P_{gdusno}) = \begin{cases} -7 + 0.2P_{gdusno}, & 10 \le P_{gdusno} \le 12 \\ -8.1 + 0.3P_{gdusno}, & 12 \le P_{gdusno} \le 14 \\ -5.2 + 0.1P_{gdusno}, & 14 \le P_{gdusno} \le 22 \\ -4.467 + 0.0667P_{gdusno}, & 22 \le P_{gdusno} \le 37 \\ -3.48 + 0.04P_{gdusno}, & 37 \le P_{gdusno} \le 39.5 \\ -4.53 + 0.0667P_{gdusno}, & 39.5 \le P_{gdusno} \le 68 \end{cases}$$

where $P_{gdusno} = P_g + R_u + R_s + R_n + R_o$.

Based on SMC, optimal values of energy and ancillary services are $P_g^* = 50$, $R_d^* = 2$, $R_u^* = 2$, $R_s^* = 5.5$, $R_n^* = 0.5$, and $R_o^* = 10$.

Fig. 5 illustrates the simultaneous marginal curve calculated in Step 4. Also illustrated in Fig. 5 is the simultaneous marginal curve with $\lambda_o = 10$. Comparing the two curves, we see that larger Lagrangian multipliers (λo) would result in lower simultaneous marginal curves. Table I compares optimal energy and ancillary services in two cases as a function of Lagrangian multipliers.

B. Case 2: Six-Bus, Three-Unit, 24-hr System

We apply the proposed model to a six-bus system with input data given in *http://motor.ece.iit.edu/data/JEAS_6bus.doc* and [8]. Table II shows major generator data with a quadratic generation cost function of $a + bP_g + cP_g^2$, where a is in dollars, b in \$/MW, and c is in \$/MW^2.

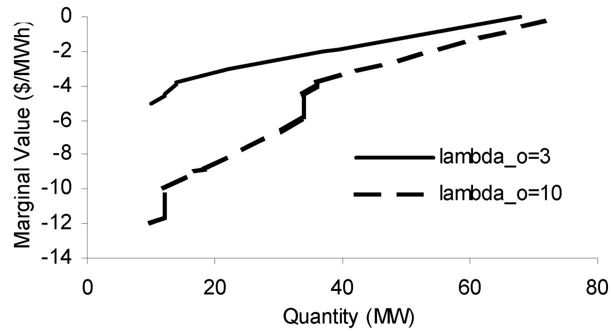

Fig. 5. Simultaneous marginal curve of energy and ancillary services.

TABLE I
OPTIMAL ENERGY AND ANCILLARY SERVICES

MW	λo=3	λo=10
Energy	50	50
REGD	2	2
REGU	2	2
TMSR	5.5	5.5
TMNR	0.5	0.5
TMOR	10	16

Table III shows the hourly load data. REGD, REGU, TMSR, TMNR, and TMOR are 0.5%, 0.5%, 1%, 2%, and 5% of the system load, respectively.

We assume quadratic cost functions for ancillary services and consider the following two cases for ancillary services to study the effect of substitutions.

1) *Case 2-1*

$$\begin{aligned} f_d(R_d) &= 3.5R_d + 0.01R_d^2 \\ f_u(R_u) &= 4R_u + 0.01R_u^2 \\ f_s(R_s) &= 3R_s + 0.01R_s^2 \\ f_n(R_n) &= 2R_n + 0.01R_n^2 \\ f_o(R_o) &= R_o + 0.01R_o^2. \end{aligned}$$

2) *Case 2-2*

$$\begin{aligned} f_d(R_d) &= 3.5R_d + 0.01R_d^2 \\ f_u(R_u) &= 4R_u + 0.01R_u^2 \\ f_s(R_s) &= R_s + 0.01R_s^2 \\ f_n(R_n) &= 2R_n + 0.01R_n^2 \\ f_o(R_o) &= 3R_o + 0.01R_o^2. \end{aligned}$$

In Case 2-1, higher quality ancillary services are more expensive than lower quality ones. In Case 2-2, we assume TMSR (higher quality) is cheaper than TMNR (lower quality), which, in turn, is cheaper than TMOR (further lower quality). Presumably, there would be no substitutions in Case 2-1, while substitutions could occur in Case 2-2. Table IV compares surpluses (+) and deficiencies (−) of REGU, TMSR, TMNR, and TMOR for Cases 2-1 and 2-2.

The results verify our presumption that no substitution would occur in Case 2-1. Substitution occurs in Case 2-2 at all hours. For instance, dispatched TMSR at Hour 1 (i.e., 14.02

TABLE II
GENERATOR DATA FOR SIX-BUS SYSTEM

U	Bus No.	Cost Coefficients			Pmax (MW)	Pmin (MW)	Qmax (MVAR)	Qmin (MVAR)	Ini. State	Min Off	Min On	Ramp (MW/h)	Start Up($)
		a	b	c									
G1	1	100	10.00	0.050	220	100	200	-80	4	4	4	55	100
G2	2	162	40.66	0.001	100	10	70	-40	2	3	2	50	200
G3	6	171	22.06	0.006	20	10	50	-40	-1	1	1	20	0

TABLE III
HOURLY LOADS FOR SIX-BUS SYSTEM

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Load (MW)	175.2	165	158.7	154.7	155.1	160.5	173.4	177.6	186.8	207	228.6	236
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Load (MW)	242.2	244	248.9	255.8	256	246.7	246	237.4	237.3	232.7	195.9	196

TABLE IV
DISPATCH SURPLUSES OR DEFICIENCIES FOR SIX-BUS SYSTEM

Hour	REGU (MW)		TMSR (MW)		TMNR (MW)		TMOR (MW)	
	Case 2-1	Case 2-2	Case 2-1	Case 2-2	Case 2-1	Case 2-2	Case 2-1	Case 2-2
1	0	0	0	12.27	0	-3.50	0	-8.76
2	0	0	0	5.52	0	2.74	0	-8.26
3	0	0	0	5.62	0	2.32	0	-7.93
4	0	0	0	5.68	0	2.06	0	-7.74
5	0	0	0	5.67	0	2.08	0	-7.75
6	0	0	0	5.60	0	2.43	0	-8.02
7	0	0	0	5.40	0	3.27	0	-8.67
8	0	0	0	5.15	0	4.37	0	-9.52
9	0	0	0	4.91	0	5.36	0	-10.28
10	0	0	0	9.74	0	-4.34	0	-5.40
11	0	0	0	14.56	0	-4.57	0	-10.00
12	0	0	0	14.46	0	-4.72	0	-9.73
13	0	0	0	14.19	0	-4.84	0	-9.34
14	0	0	0	12.74	0	-4.87	0	-7.88
15	0	0	0	7.41	0	-4.98	0	-2.43
16	0	0	0	14.17	0	-5.12	0	-9.04
17	0	0	0	14.16	0	-5.12	0	-9.04
18	0	0	0	9.56	0	-4.93	0	-4.62
19	0	0	0	10.34	0	-4.92	0	-5.43
20	0	0	0	14.45	0	-4.75	0	-9.70
21	0	0	0	14.45	0	-4.75	0	-9.70
22	0	0	0	15.90	0	-4.54	0	-11.36
23	0	0	0	4.98	0	5.07	0	-10.05
24	0	0	0	5.05	0	4.78	0	-9.84

MW) is enough to satisfy the TMSR requirement of 1.75 MW and requirements for both TMNR and TMOR (i.e., 3.50 and 8.76 MW, respectively). At Hour 2, dispatched TMSR and TMNR have 5.52 and 2.74 MW surpluses, respectively. These surpluses, which amount to 8.26 MW, will satisfy the TMOR requirement of 8.26 MW; thus, no extra TMOR will be dispatched.

C. Case 3: IEEE 118-Bus, 54-Unit, 24-hr System

The IEEE 118-bus system data are given in *http://motor.ece.iit.edu/data/JEAS_IEEE118.doc*. Table V shows the hourly system load. REGD, REGU, TMSR, TMNR, and TMOR are 1%, 1%, 2%, 2%, and 5% of the system load, respectively. Cost functions for ancillary services are

$$\begin{aligned} f_d(R_d) &= 3.5R_d + 0.01R_d^2 \\ f_u(R_u) &= R_u + 0.01R_u^2 \\ f_s(R_s) &= 2R_s + 0.01R_s^2 \\ f_n(R_n) &= 3R_n + 0.01R_n^2 \\ f_o(R_o) &= 4R_o + 0.01R_o^2. \end{aligned}$$

Since higher quality ancillary services are more expensive than lower quality ones, it is again expected that the substitution could occur. Different from Case 2-2, which had no REGU substitution for other ancillary services, REGU could substitute for TMSR, TMNR, or TMOR here since it is the least expensive entity.

Table VI lists surpluses (+) and deficiencies (−) of REGU, TMSR, TMNR, and TMOR for Case 3 in which surpluses and deficiencies are balanced for the entire system. For instance, at Hour 1, surpluses of REGU, TMSR, TMNR (i.e., $26.8 + 176 + 7.17 = 210$ MW) are balanced with the deficiency of TMOR, which is 210 MW; at Hour 2, surpluses of REGU and TMSR (i.e., $37.2 + 196 = 233.2$ MW) are balanced with deficiencies of TMNR and TMOR (i.e., $35.15 + 198 = 233.2$ MW).

VI. CONCLUSION

The SCUC formulation and solution with simultaneous optimization of energy and ancillary services are presented in this paper. Optimality conditions for calculating energy and ancillary services are discussed in detail. SMCs are proposed to calculate the optimal values of energy and ancillary services for finding the optimal single-unit commitment. The substitutability of ancillary services is illustrated for a six-bus system and the IEEE 118-bus system. The consideration of the cost of supplying ancillary services complicates the SCUC problem and inevitably increases computation time. However, applications of the proposed SMCs could circumvent the time-consuming LP and quadratic programming computations, while the SMCs do not compromise the optimality conditions. Experiments on the IEEE 118-bus system show that the application of SMCs increases the computation time by 20% compared with the cases when the cost of supplying energy alone are considered. If LP

TABLE V
HOURLY LOADS FOR 118-BUS SYSTEM

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Load (MW)	4200	3960	3480	2400	3000	3600	4200	4680	4920	5280	5340	5040
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Load (MW)	4800	4560	5280	5400	5100	5340	5640	5880	6000	5400	5220	4920

TABLE VI
DISPATCH SURPLUSES OR DEFICIENCIES FOR 118-BUS SYSTEM

Hour	REGU (MW)	TMSR (MW)	TMNR (MW)	TMOR (MW)
1	26.8	176	7.17	-210
2	37.2	196	-35.15	-198
3	42	201.59	-69.6	-174
4	72.8	95.2	-48	-120
5	46.8	163.18	-60	-150
6	40.8	203.2	-64.04	-180
7	26.8	176	7.17	-210
8	52	269.5	-87.53	-234
9	49.6	213.6	-17.21	-246
10	46	206.4	11.67	-264
11	45.4	205.2	16.41	-267
12	48.4	211.2	-7.61	-252
13	50.8	229.34	-40.11	-240
14	53.2	266	-91.2	-228
15	48	214.4	1.67	-264
16	46.8	212	11.22	-270
17	49.8	218	-12.84	-255
18	47.4	213.2	6.44	-267
19	23.6	207.2	51.24	-282
20	21.2	202.4	70.37	-294
21	20.99	200	79	-300
22	46.8	212	11.24	-270
23	48.6	215.6	-3.14	-261
24	49.6	213.6	-17.21	-246

is employed, in place of the proposed method, the computation time will increase by about 100%. If quadratic programming is employed, the computation time will increase by about 150%. These experiments demonstrate the effectiveness of the proposed method. Our future work will consider the application of the proposed method to larger power systems with more complicating constraints.

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