Coordination Between Long-Term and Short-Term Generation Scheduling with Network Constraints

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Abstract—**This paper discusses the coordination between long-term and short-term generation scheduling. The minimum energy reserve in the system is used as a performance index for short-term generation scheduling. If the short-term solution is unsatisfactory, the long-term schedule will be adjusted to satisfy the short-term scheduling requirements. The presence of network constraints impacts the scheduling solution. The proposed approach is tested on the IEEE RTS.**

Index Terms—**Coordination, long-term maintenance, Monte Carlo simulation, planning, short-term generation scheduling.**

I. Introduction

THE GENERATION scheduling function in a Genco may be divided into three stages of long-term, short-term and real-time as depicted in Fig. 1. The long-term scheduling (LTS) problem represents fuel allocation and budgeting, emission and production costing. The transmission lines in this model refer to local lines within a Genco. The model may also apply to cases where unit scheduling and transmission management are being handled by the ISO. The objective of short-term scheduling (STS) is to minimize the operation cost over hourly, daily or weekly horizon. STS is required to meet fuel supply and consumption limits, unit commitment requirements, transmission security constraints and hourly system demands. The third layer is the real-time economic dispatch with an objective of optimal dispatch for committed units to meet system requirements in the real-time operation.

LTS is not an independent problem. In LTS, maintenance scheduling is used to determine a specific window of time for generation maintenance scheduling. Using the given window, STS will determine the commitment of available units. The proper coordination between LTS and STS is imperative to ensure that the LTS output can be used to facilitate STS. In the literature, other analytical methods were suggested for the coordination between LTS and STS. Most of those methods focused on the fuel scheduling problem [1], [2]. This paper extends STS with network constraints to the LTS problem and introduces additional constraints in the problem formulation.

The paper consists of five major sections. Sections II and III outline LTS and STS formulation. The proposed coordination of LTS and STS is described in Section IV. Section V illustrates the results of applying the proposed method to the IEEE-RTS.

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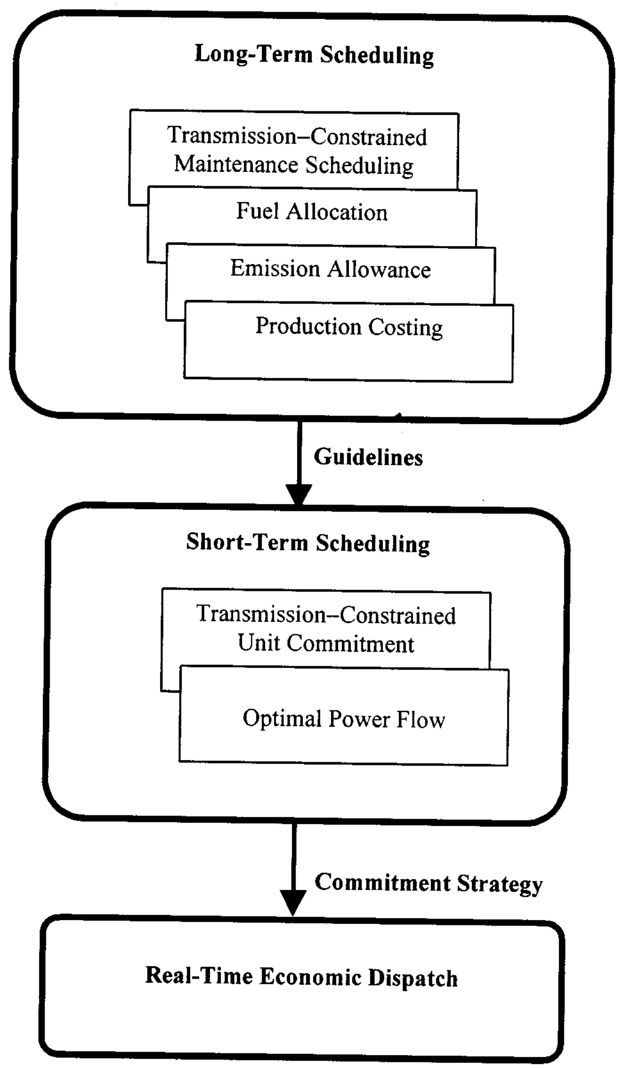

Fig. 1. Hierarchical structure of generation scheduling.

II. Long-Term Formulation

The interactions between fuel restrictions, allowable emission and system constraints increase the complexity of the LTS problem, resulting in a large optimization problem. The LTS problem has discrete decision variables for maintenance scheduling and continuous variables for fuel allocation and utilization of units.

The scheduling may involve a time horizon of one to two years which can be divided into window intervals (weeks). The best maintenance schedule given in those intervals must satisfy weekly fuel supply limits, short-term unit maintenance constraints, as well as network constraints. The formulation of LTS is given as follows.

A. LTS Problem Description

LTS determines periods when generating units in a Genco are to be taken off line for planned preventive maintenance over the course of one to two year horizon so that the total operating cost is minimized while system energy, reliability as well as a number of other constraints are satisfied.

We impose local transmission line constraints on the maintenance scheduling problem. Local transmission lines refer to a network that may exist within a Genco and its exclusion could result in an optimistic generation maintenance scheduling.

B. LTS Constraints

LTS constraints may be categorized as coupling and decoupling constraints in time domain. The first set of coupling, or maintenance, constraints require that the units be overhauled regularly. This is necessary to keep their efficiency at a reasonable level, reduce forced outage rates and prolong the life of the units. This procedure is incorporated periodicity by specifying min/max times that a generating unit may run without maintenance.

The required time for overhauling a unit is generally given, hence, the number of weeks that a unit will be "down" is predetermined. It is assumed here that there is very little flexibility in the manpower usage and a limited number of units may be serviced at a given time. The available maintenance crew may be categorized by location and responsibility. The availability of the crew in each category will be specified in the formulation.

System constraints in each time period will be considered as decoupling constraints. The system can be represented as either the transportation model or a linearized power flow model. We choose the transportation model to represent flow constraints, peak load balance as well as generation and line capacity constraints.

C. LTS Problem Formulation

Mathematically, LTS can be formulated as (2-1). The list of symbols is given in Appendix A.

Min

$$\sum_t \sum_i \{C_i(1-x_{it}) + c_{it}P_{Git}\}$$

s.t.

maintenance constraints:

$$\begin{aligned} &x_{it}=1 && \text{for } 1 \le e_i \text{ or } t \ge l_i + d_i \\ &x_{it}=0 && \text{for } s_i \le t \le s_i + d_i \\ &x_{it}=0 \text{ or } 1 && \text{for } e_i \le t \le l_i \end{aligned} \qquad \text{(i)}$$

$$\begin{matrix} 1.\ \textit{crew availability} & 3.\ \textit{seasonal limitations} \\ 2.\ \textit{resources availability} & 4.\ \textit{desirable schedule} \end{matrix} \qquad \text{(ii)}$$

system constraints:

$$\boldsymbol{Sf} + \boldsymbol{P_G} + \boldsymbol{r} = \boldsymbol{d} \quad \forall\, t \qquad \text{(iii)}$$

$$\boldsymbol{P_G} \le \overline{\boldsymbol{P}}_{\boldsymbol{G}}.\boldsymbol{x} \quad \forall\, t \qquad \text{(iv)}$$

$$\boldsymbol{r} \le \boldsymbol{d} \quad \forall\, t \qquad \text{(v)}$$

$$|\boldsymbol{f}| \le \overline{\boldsymbol{f}} \quad \forall\, t \qquad \text{(vi)}$$

$$\sum_i \boldsymbol{r}_{it} \le \varepsilon \quad \forall\, t \qquad \text{(vii)}$$

(2-1)

The variable x_{it} is restricted to integer values, on the other hand, P_{Git} has continuous values. Therefore, the formulation corresponds to a mixed-integer programming problem. The objective in (2-1) is to minimize total maintenance and production costs over the operational planning period.

The first term of the objective function (2-1) is the maintenance cost of generators and the second term is the energy production cost.

Constraints i) represent the maintenance window stated in terms of "start of maintenance" variables (s_i). The unit must not be in maintenance before its earliest period of maintenance (e_i) and latest period of maintenance ($l_i + d_i$). Set of constraints ii) consists of crew and resources availability, seasonal limitations, desirable schedules, and other constraints such as fuel and environmental constraints.

Seasonal limitations are incorporated in e_i and l_i of constraint i). If we consider, for example, that units 1, 2 and 3 are to be maintained simultaneously, the set of constraints would be written as follows:

$$x_{1t} + x_{2t} + x_{3t} = 3 \quad \text{or} \quad x_{1t} + x_{2t} + x_{3t} = 0$$

If we consider that in each maintenance area we have limited resources and crew available, the set of constraints would be formed as follows:

$$\sum_{i \in A} \sigma_{mi}(1 - x_{it}) \le Z_{mt} \qquad \text{(2-2)}$$

In the case of resource constraint, Z_{mt} is the amount of resource m available in area A for each time t, and σ_{mi} is a percentage of this resource required for unit i. In the case of crew constraint, the corresponding Z_{mt} is the number of maintenance crew in area A and σ_{mi} is a percentage of this crew required for the maintenance of unit i.

Constraints iii)–vi) represent peak load balance and other operational constraints such as generation and transmission capacity limits of the system. Constraints vii) represent the allowable energy unserved in the system.

III. Short-Term Formulation

The difference between LTS and STS is the time horizon and the time increment. In LTS, the horizon of study is one to two years with increments of a week (Δt), but in STS the horizon of study is weeks with increments of an hour ($\Delta \tau$). The proper window for STS is determined by LTS. The LTS output, variables x, N and ϕ are passed on to STS and added to constraints in eq. (3-10), (3-13) and (3-14) below.

We use a security constrained unit commitment for short-term scheduling and apply *augmented* Lagrangian relaxation [6], [7] to solve the problem. The basic idea behind Lagrangian relaxation (LR) is to relax system constraints in the objective function by using Lagrangian multipliers. The relaxed problem is then decomposed into N sub-problems for each unit. The dynamic programming process is used to search optimal commitment for single unit. The Lagrangian multipliers are updated based on the violations of system constraints. The convergence criterion is satisfied if the duality gap in Lagrangian relaxation is within a given limit. To improve the unit commitment solution, augmentation is applied in this study to set up a convex objective function for unit commitment which will be differentiable at the optimal point and will reduce the duality gap. Unit commitment minimizes operating costs that include production cost and start up cost.

$$PC = \sum_i \sum_\tau [I_{i\tau} F_i(P_{Gi\tau}) + \delta_{i\tau}] \qquad (3\text{-}1)$$

The production cost $F_i(P_{Gi\tau})$ is calculated as the product of the heat rate (MBTU/Hr) and the unit's fuel cost ($/MBTU). The start up cost of a unit depends on how long the unit has been off and is defined as:

$$S_{i\tau} = I_{i\tau}[1 - I_{i(\tau-1)}] \left[\alpha_i + \beta_i \left(1 - \exp \frac{-X_{i\tau}^{\text{off}}}{\theta_i} \right) \right] \qquad (3\text{-}2)$$

Constraints of the optimization problem are:

a) System real power balance

$$\sum_i I_{i\tau} P_{Gi\tau} = P_D(\tau) \qquad \tau = 1, \cdots, t \qquad (3\text{-}3)$$

b) System spinning reserve requirements

$$\sum_i r_{si}(\tau) I_{i\tau} \geq R_s(\tau) \qquad \tau = 1, \cdots, t \qquad (3\text{-}4)$$

where, $r_{si}(\tau) = \min\{10 * \text{MSR}_i, \overline{P}_{Gi} - P_{Gi\tau}\}$. The spinning reserve requirement, $R_s(\tau)$, is typically defined as a base component plus a fraction of the load requirement and a fraction of the high operating limit of the largest on-line unit.

c) System operating reserve requirements

$$\sum_i r_{oi}(\tau) I_{i\tau} \geq R_o(\tau) \qquad \tau = 1, \cdots, t \qquad (3\text{-}5)$$

where,

$$r_{oi}(\tau) = \begin{cases} q_i, & \text{if unit } i \text{ is OFF} \\ r_{si}(\tau), & \text{if unit } i \text{ is ON} \end{cases}$$

Interruptible loads are usually added to the operating reserve capacity of units [left hand side of Eq. (3-5)]. The operating reserve requirement, $R_0(\tau)$, is commonly defined similar to $R_s(\tau)$ as a function of a base component plus a fraction of the load requirement and a fraction of the high operating limit of the largest on-line unit.

d) Unit generation limits

$$\underline{P}_{Gi} \leq P_{Gi\tau} \leq \overline{P}_{Gi} \qquad \tau = 1, \cdots, t \quad \forall i \qquad (3\text{-}6)$$

e) Thermal unit minimum start up/down times

$$(Z_{i(\tau-1)}^{\text{on}} - T_i^{\text{on}}) * (I_{i(\tau-1)} - I_{i\tau}) \geq 0 \qquad (3\text{-}7)$$

$$(Z_{i(\tau-1)}^{\text{off}} - T_i^{\text{off}}) * (I_{i(\tau-1)} - I_{i\tau}) \geq 0 \qquad (3\text{-}8)$$

f) Ramp rate limits

$$P_{Gi\tau} - P_{Gi(\tau-1)} \leq UR_i \qquad \text{as unit } i \text{ ramps up}$$
$$P_{Gi(\tau-1)} - P_{Gi\tau} \leq DR_i \qquad \text{as unit } i \text{ ramps down} \qquad (3\text{-}9)$$

g) Fuel constraints

$$FL \leq \sum_\tau \sum_{i\in A} f_{ci} * [I_{i\tau} F_i(P_{Gi\tau}) + S_{i\tau}] \leq \sum_{i\in A} \phi_{imt} \quad (3\text{-}10)$$

where $i \in A$ corresponds to all fuel-constrained units in group A. The first item $f_{ci} I_{i\tau} F_i(P_{Gi\tau})$ is operating fuel and $f_{ci} S_{i\tau}$ is additional fuel for start up.

h) System emission limit

$$\sum_\tau \sum_i H_i(P_{Gi\tau}) I_{i\tau} \leq EMS_t \qquad (3\text{-}11)$$

where several emission types (e.g. SO_2, NO_X) are considered.

i) Area emission limit

$$\sum_\tau \sum_{i\in B} H_i(P_{Gi\tau}) I_{i\tau} \leq EMA_t \qquad (3\text{-}12)$$

where $i \in B$ corresponds to all units in the constrained emission area B where several emission types can be considered.

j) Maintenance constraints

$$I_{i\tau} \leq x_{it} \qquad \text{for } \tau \in t \qquad (3\text{-}13)$$

k) Transmission limits on line k (between buses i and j)

$$\underline{f}_k \leq f_{k\tau} \leq \overline{f}_k \qquad \text{for } \tau \in t \qquad (3\text{-}14)$$

where

$$f_{k\tau} = \sum_i \xi_{ki} P_{Gi\tau} I_{i\tau} - \sum_j \xi_{kj} P_{Dj}(\tau)$$
$$\text{for } j = 1, \cdots, NB \qquad (3\text{-}15)$$

Sensitivity coefficients ξ_{ki} and ξ_{kj} are determined based on contingency analyzes to represent the network security in unit commitment.

In the above constraints, (3-3)–(3-5) and (3-10)–(3-12) are system constraints which relate to each unit and are relaxed into the objective function (3-1) by Lagrangian multipliers. Eq. (3-6)–(3-9) are single unit constraints which are considered in the process of single unit dynamic programming.

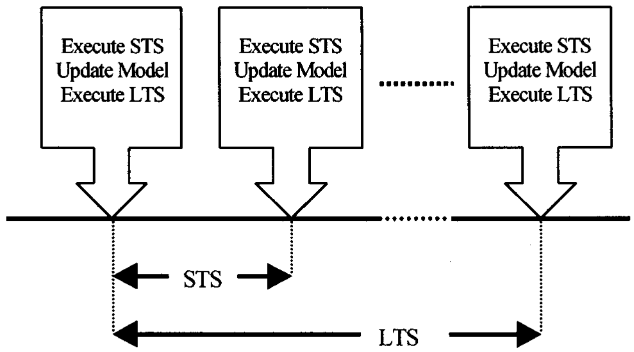

Fig. 2. Dynamic scheduling.

Constraint (3-13) links the maintenance variable x_{it} with the commitment state I. In order to set emission caps (EMA_t and EMS_t) in STS, emission caps of LTS are distributed proportional to weekly peak loads. The fuel scheduling problem is solved using a primal approach. This approach employs weekly targets as the coordination guidelines. LTS allocates weekly fuel target into a sequence of fuel constraints that can be directly used by STS. Constraint (3-10) limits the weekly fuel consumption, ϕ_{imt}, in STS. In the case of multiple constrained fuels, the dual coordination is preferable for fuel scheduling.

IV. Dynamic Scheduling

Facing the future uncertainty, the most effective coordination strategy may be implemented via dynamic scheduling. Based on this strategy, a scheduling decision is conditional upon its past realization and there is a possibility for adjusting the maintenance decision adaptively when additional information is made available. To account for additional information, LTS and STS activities are repeated in time as shown in Fig. 2. Based on past realizations, LTS determines the maintenance schedule for the next one-year horizon and STS determines unit commitment for the next one-week horizon.

In Fig. 2 each STS execution is preceded by LTS while in practice this may be deemed unnecessary at certain times. Whether this will be the case will depend on the system performance and new pieces of information that may become available in the course of the prior week.

LTS is dependent on many forecast parameters such as load demand as well as transmission line and generating unit availability. One can only have a perception of what these parameters might be in the future based on today's fact. Forced outage rates of generation units and lines should be updated according to the facts at the end of a week (STS planning horizon). In this paper, we use a two-state continuous-time Markov model for representing each generation and transmission.

For example, associated conditional probabilities for a component (i.e., generating unit or line) are:

$$p(\varphi_t = \text{up}|\varphi_{t=t_o} = \text{up}) = p + qe^{-(\mu+\lambda)(t-t_o)}$$
$$p(\varphi_t = \text{down}|\varphi_{t=t_o} = \text{up}) = q - qe^{-(\mu+\lambda)(t-t_o)}$$
$$p(\varphi_t = \text{up}|\varphi_{t=t_o} = \text{down}) = p - pe^{-(\mu+\lambda)(t-t_o)}$$

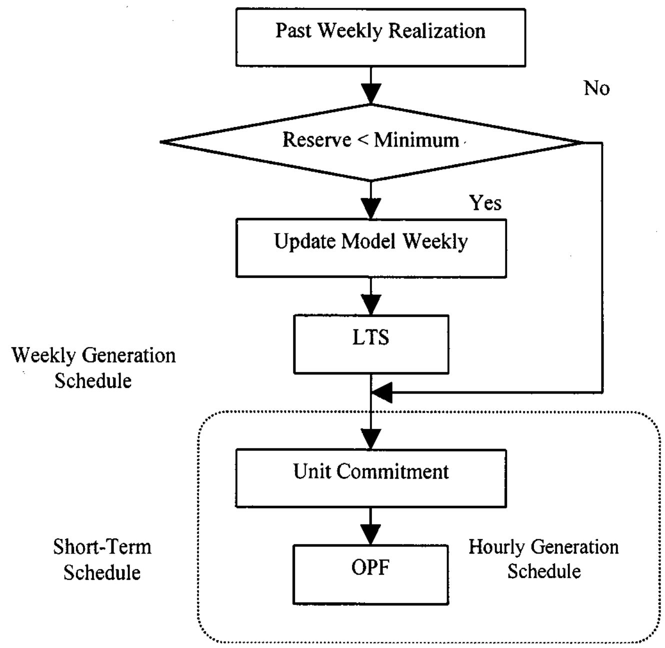

Fig. 3. Dynamic scheduling algorithm.

$$p(\varphi_t = \text{down}|\varphi_{t=t_o} = \text{down}) = q + pe^{-(\mu+\lambda)(t-t_o)} \quad (4\text{-}1)$$

In (4-1), p, q, μ, λ, represent the component's steady state availability, steady state unavailability, repair rate in (day)$^{-1}$ and failure rate in (day)$^{-1}$, respectively.

Accordingly, forces outage rates of all components in the system are calculated using (4-1) at weekly peak load. These updated values of forced outages are assigned to the set of network constraints for LTS calculation. Given any future scenario (i.e., described by the load and system state over the entire LTS horizon) the maintenance scheduling would be decided by LTS.

The proper scheduling of fuel is important in that it is desirable to burn appropriate amount of fuel required by contracts. Therefore, it is important to periodically update the fuel use schedule to allow for changes in demand. The weekly amount of constrained fuel burn is determined by prorating the amount of remaining constrained annual fuel by the ratio of the predicted weekly generation to the predicted annual generation.

The proposed dynamic scheduling algorithm for a coordination between LTS and STS is depicted in Fig. 3. In this paper, we use the system reserve energy as the coordination indicator. If the reserve energy is less than the minimum system requirement then LTS ought to be updated. We use (4-1) to calculate new probabilities before running the LTS again.

We use the Monte Carlo simulation in order to test the proposed dynamic scheduling approach. To simulate the actual system state realization, a conditional Monte-Carlo sampling (i.e. sequential sampling conditional on realization of past samples) is used to randomly generate various future scenarios. Each sample represents the availability of generating units and lines in a given week which are uncertain and conditional probabilities associated with this uncertainty are described by (4-1). The sequential sampling approach conveniently allows the dynamic scheduling strategy to take its course. In this application, 1000 randomly generated future scenarios

TABLE I
LTS PRIOR TO THE STS COORDINATION

Unit	Weeks on Maintenance
1	26,27
2	28,29
3	18,19
4	20,21
5	27,28

(i.e., each scenario specifies the realized system states over a 12-week study) are used to evaluate the dynamic maintenance schedule. The Monte Carlo sampling algorithm with generalized regression [8] is implemented in this study.

V. CASE STUDY

We apply the proposed method to the IEEE-RTS [5]. This system is made of 32 generating units, 20 demand sides, 23 buses and 38 transmission lines. A three-month study period of summer weeks of 18–29 is considered when generation facilities in a particular area need maintenance. We assume that the maintenance of a unit will take two weeks to be completed. The coverage of maintenance area is buses 1–10. For the purpose of STS, a typical hourly load data are listed in Table B1 of the Appendix. Generating unit data for unit commitment such as production cost function and minimum up/down time are listed in Tables B2 and B3.

The minimization of production and maintenance costs is used as the objective function of LTS. We apply a decomposition method to solve LTS [4] and the augmented LR method to solve STS [6], [7]. The minimum reserve energy requirement for the system is assumed 30 MWh.

The results of the following test cases are included to show the effect of dynamic scheduling on maintenance schedule and reserve energy of the system.

- Case 1: Maintenance schedule is not updated
- Case 2: Dynamic maintenance schedule is used

In Case 1, we assume a fixed LTS in the course of STS study. In other words, if the reserve energy in STS is less than 30 MWh, we do not return to LTS to modify the long term maintenance schedule to be able to retain the minimum 30 MWh reserve requirement. Using a Benders decomposition, the LTS solution is converged in two iterations. The decomposition separates coupling and decoupling constraints in (2-1). In the first iteration, LTS subproblems are infeasible in all periods. In iteration two, sub-problems ere feasible. The corresponding LTS solution for generator maintenance schedules is shown in Table I. In this table, the 12 week horizon is between weeks 18–29. Further discussions on LTS are beyond the scope of this paper and calculations are given in [4].

Given the maintenance schedule by LTS, STS is simulated using a Monte Carlo sampling to mimic the actual system realization. The sample which has the worst reserve energy can be seen in Fig. 4. The reserve energy drops below the minimum 30 MWh limit on week 20 and later on week 26. The reserve energy between weeks 22 and 25 is above 30 MWh because there is no unit on maintenance during these weeks (see Table I).

In Case 2, we apply dynamic scheduling to LTS in the course of the STS study as discussed in Section IV. Given the initial schedule in Table I, STS is simulated using the Monte Carlo sampling to mimic the actual system realization. Table II shows the rescheduling of generating units during simulations, and the final unit maintenance schedule is shown in Table III.

Table II shows the rescheduling process based on the LTS results. The second column shows the maintenance schedule of units 1–5 on week 18 (i.e., the initial schedule of the study). The reserve energy is depicted in Fig. 5. This figure shows that at the beginning of week 20, the initial schedule needs to be modified since the system reserve energy is below 30 MWh. As

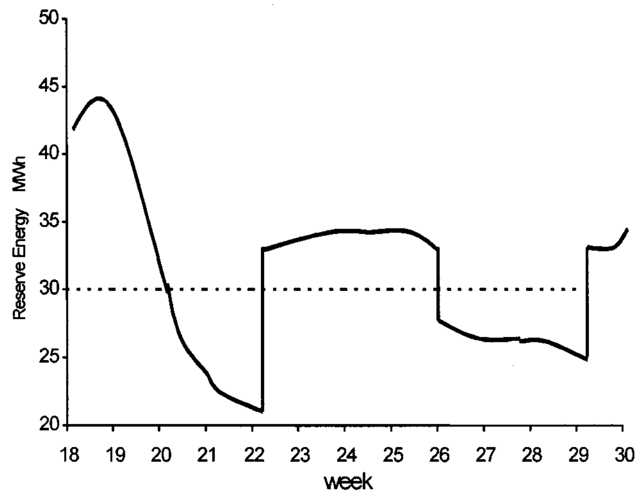

Fig. 4. Reserve energy without dynamic scheduling.

TABLE II
UNIT RESCHEDULING DURING SIMULATIONS

Unit	Rescheduled Week 18	20	24	25
1	26,27	**25,26***	25,26	25,26
2	28,29	28,29	**27,28**	27,28
3	18,19	**N/A**	**N/A**	**N/A**
4	20,21	**22,23**	**N/A**	**N/A**
5	27,28	**24,25**	**25,26**	**28,29**

*on week 20, unit 1 is rescheduled for maintenance on weeks 25,26

TABLE III
SCHEDULE USING DYNAMIC SCHEDULING

Unit	Weeks on Maintenance
1	25,26
2	27,28
3	18,19
4	22,23
5	28,29

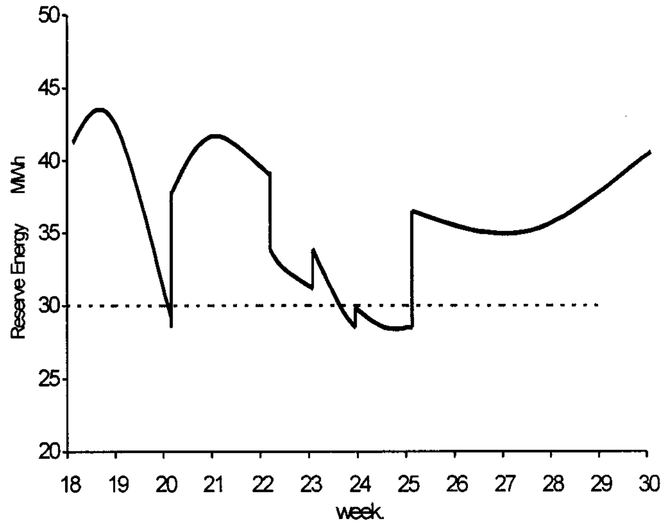

Fig. 5. Reserve energy with dynamic scheduling.

a result, we recalculate the LTS at the beginning of week 20 to reschedule the unit maintenance for the rest of the simulation. This updated schedule is given in the week 20 of Table II. Maintenance schedule of units 1, 4 and 5 which are shown in bold are changed accordingly. Unit 1 which was scheduled for maintenance on weeks 26, 27 is rescheduled for maintenance on weeks 25, 26. Units 4 and 5 are also rescheduled from weeks 20, 21 and 27, 28 into weeks 22, 23 and 24, 25. Unit 3 is not considered since its maintenance was completed during weeks 18 and 19.

The unit maintenance is rescheduled at the beginning of weeks 24 and 25 since the system reserve energy tends to drop below 30 MWh (see Fig. 5). On week 24, units 2 and 5 are rescheduled. On week 25, unit 5 is rescheduled. The peaking unit 5 is rescheduled more often because of its scheduling flexibility.

The final unit maintenance schedule is given in Table III for the five units that are considered for maintenance during the 12-week period. The schedule satisfies both LTS and STS requirements.

VI. Conclusions

This paper presents a coordination approach between long-term maintenance and short-term generation scheduling. A Monte Carlo simulation is used to mimic the behavior of system and possible forced outage scenarios in long-term maintenance scheduling. The proposed long-term scheduling is submitted to the short-term scheduling module to make sure that the short-term unit and network constraints will be satisfied. A 32 generating unit system is studied and the system reserve energy is used as an indicator of a satisfactory short-term solution. A less than minimum required reserve energy indicates that the long-term solution ought to be modified to accommodate short-term conditions. The example shows that a coordination will be necessary to present a feasible solution for generation maintenance scheduling.

Appendix A
List of Symbols

C_{it}	Generation maintenance cost for unit i at time t.
c_{it}	Generation cost of unit i at time t.
x_{it}	Unit maintenance status, 0 if unit is off-line for maintenance.
s_i	Period in which maintenance of generating unit i starts.
e_i	Earliest period for maintenance of generating unit i to begin.
l_i	Latest period for maintenance of generating unit i to begin.
d_i	Duration of maintenance for generating unit i.
$\boldsymbol{r}$	Vector of dummy generators which corresponds to energy not served at time period t.
$\overline{\boldsymbol{f}}$	Maximum line flow capacity in matrix term.
$\boldsymbol{f}$	Active power flow in vector term.
$\overline{\boldsymbol{P}}_{\boldsymbol{G}}$	Maximum generation capacity in vector term.
$\boldsymbol{P_G}$	Vector corresponding to (P_{Git}) power generation of unit i at time t.
$\boldsymbol{d}$	Vector of the demand in every bus at time t.
$\boldsymbol{S}$	Node-branch incidence matrix.
ε	Acceptable level of expected energy not served.
DR_i	Ramp down rate of unit i (MW/hr).
UR_i	Ramp up rate of unit i, (MW/hr).
EMA	Emission cap for area emission in the study period.
EMA_t	Emission cap for area emission in week t.
EMS	Emission cap for system emission in the study period.
EMS_t	Emission cap for system emission in week t.
f_{ci}	Fuel cost of unit i.
$F_i(P_{Gi\tau})$	Fuel cost if unit i when generating power is $P_{Gi\tau}$.
$\underline{FL}$	Lower fuel constraint for a group of units.
$\overline{P}_{Gi}$	Upper real power limit of unit i.
$\underline{P}_{Gi}$	Lower real power limit of unit i.
$P_{Gi\tau}$	Real power output of unit i at hour τ.
$H_i(P_{Gi\tau})$	Emission function of unit i.
MSR$_i$	Maximum sustain ramp rate of unit i, (MW/min).
$P_D(\tau)$	Total system real power load demand at hour τ.
$P_{Dj}(\tau)$	Load demand at bus j at hour τ.
PC	STS production cost.
q_i	Quick start capability unit of i.
$r_{si}(\tau)$	Contribution of unit i to spinning reserve at hour τ.
$R_o(\tau)$	System operating reserve requirement at hour τ.
$R_s(\tau)$	System spinning reverse requirement at hour τ.
$S_{i\tau}$	Start up cost of unit i at hour τ.
$T_i^{\mathrm{on/off}}(\tau)$	Minimum up/down time of unit I.
α_i	Integrates labor starting up cost and equipment maintenance cost of unit i.
β_i	Starting up cost of unit I from cold conditions.
θ_i	Time constant that characterizes unit i cooling speed.
$X_{i(t-1)}^{\mathrm{off}}$	Number of weeks that unit i has been on maintenance at the end of the week $t-1$.

$Z_{i(\tau)}^{\text{on/off}}$ Time for which unit i has been on/off at hour τ.
ϕ_{imt} MBtu of fuel from the mth contract (fuel m) allocated to unit i during time t.
Ini Initial condition (hours).

APPENDIX B
IEEE-RTS TEST SYSTEM DATA

TABLE B1
HOURLY PEAK LOAD IN PERCENT OF DAILY PEAK

Hour	Winter Weeks 1-8 Wkdy	Winter Weeks 44-52 Wknd	Summer Weeks 18-29 Wkdy	Summer Weeks 30 Wknd	Spring/Fall Weeks 9-17 Wkdy	Spring/Fall Weeks 31-43 Wknd
12-1am	67	78	64	74	63	75
1-2	63	72	60	70	62	73
2-3	60	68	58	66	60	69
3-4	59	66	56	65	58	66
4-5	59	64	56	64	59	65
5-6	60	65	58	62	65	65
6-7	74	66	64	62	72	68
7-8	86	70	76	66	85	74
8-9	95	80	87	81	95	83
9-10	96	88	95	86	99	89
10-11	96	90	99	91	100	92
11-Noon	95	91	100	93	99	94
Noon-1pm	95	90	99	93	93	91
1-2	95	88	100	92	92	90
2-3	93	87	100	91	90	90
3-4	94	87	97	91	88	86
4-5	99	91	96	92	90	85
5-6	100	100	96	94	92	88
6-7	100	99	93	95	96	92
7-8	96	97	92	95	98	100
8-9	91	94	92	100	96	97
9-10	83	92	93	93	90	95
10-11	73	87	87	88	80	90
11-12	63	81	72	80	70	85

TABLE B2
GENERATING UNIT DATA

No	P^{max}	P^{min}	a_i	b_i	c_i	$1/f_c$	$S_i(t)$
1	12.	2.40	0.02533	25.5472	24.3891	1.0	0.
2	12.	2.40	0.02649	25.6753	24.4110	1.0	0.
3	12.	2.40	0.02801	25.8027	24.6382	1.0	0.
4	12.	2.40	0.02842	25.9318	24.7605	1.0	0.
5	12.	2.40	0.02855	26.0611	24.8882	1.0	0.
6	20.	4.00	0.01561	37.9637	118.9083	1.0	30.
7	20.	4.00	0.01359	37.7770	118.4576	1.0	30.
8	20.	4.00	0.01161	37.9637	118.9083	1.0	30.
9	20.	4.00	0.01059	38.7770	119.4576	1.0	30.
10	76.	15.20	0.00962	13.5073	81.8259	1.0	80.
11	76.	15.20	0.00876	13.3272	81.1364	1.0	80.
12	76.	15.20	0.00895	13.3538	81.2980	1.0	80.
13	76.	15.20	0.00932	13.4073	81.6259	1.0	80.
14	100.	25.00	0.00623	18.0000	217.8952	1.0	100.
15	100.	25.00	0.00599	18.6000	219.7752	1.0	100.
16	100.	25.00	0.00612	18.1000	218.3350	1.0	100.
17	100.	25.00	0.00588	18.2800	216.7752	1.0	100.
18	100.	25.00	0.00598	18.2000	218.7752	1.0	100.
19	100.	25.00	0.00578	17.2800	216.7752	1.0	100.
20	155.	54.25	0.00481	10.7367	142.7348	1.0	200.
21	155.	54.25	0.00473	10.7154	143.0288	1.0	200.
22	155.	54.25	0.00481	10.7367	143.3179	1.0	200.
23	155.	54.25	0.00487	10.7583	143.5972	1.0	200.
24	197.	68.95	0.00259	23.0000	259.1310	1.0	300.
25	197.	68.95	0.00260	23.1000	259.6490	1.0	300.
26	197.	68.95	0.00263	23.2000	260.1760	1.0	300.
27	197.	68.95	0.00264	23.4000	260.5760	1.0	300.
28	197.	68.95	0.00267	23.5000	261.1760	1.0	300.
29	197.	68.95	0.00261	23.0400	260.0760	1.0	300.
30	350.	140.00	0.00150	10.8416	176.0575	1.0	500.
31	400.	100.00	0.00194	7.4921	310.0021	1.0	800.
32	400.	100.00	0.00195	7.5031	311.9102	1.0	800.

TABLE B3
GENERATING UNIT OPERATING DATA

No	T_i^{on}	T_i^{off}	Ini	UR	DR	Bus
1	1	-1	-1	12.0	12.0	15
2	1	-1	-1	12.0	12.0	15
3	1	-1	-1	12.0	12.0	15
4	1	-1	-1	12.0	12.0	15
5	1	-1	-1	12.0	12.0	15
6	1	-1	-1	20.0	20.0	1
7	1	-1	-1	20.0	20.0	1
8	1	-1	-1	20.0	20.0	2
9	1	-1	-1	20.0	20.0	2
10	3	-2	3	38.0	38.0	1
11	3	-2	3	38.0	38.0	1
12	3	-2	3	38.0	38.0	2
13	3	-2	3	38.0	38.0	2
14	4	-2	5	50.0	50.0	7
15	4	-2	5	50.0	50.0	7
16	4	-2	5	50.0	50.0	7
17	4	-2	-3	50.0	50.0	7
18	4	-2	-3	50.0	50.0	7
19	4	-2	-3	50.0	50.0	7
20	4	-2	-3	50.0	50.0	7
21	5	-3	5	77.5	77.5	15
22	5	-3	5	77.5	77.5	16
23	5	-3	5	77.5	77.5	23
24	5	-4	-4	98.5	98.5	22
25	5	-4	-4	98.5	98.5	22
26	5	-4	-4	98.5	98.5	22
27	5	-4	-4	98.5	98.5	22
28	5	-4	-4	98.5	98.5	22
29	5	-4	-4	98.5	98.5	22
30	8	-5	10	175.0	175.0	23
31	8	-5	10	200.0	200.0	21
32	8	-5	10	200.0	200.0	18

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