# Generation Maintenance Scheduling in Restructured Power Systems

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***Abstract*—This paper addresses generation maintenance scheduling in a competitive electric energy environment. In a centralized setting, the system operator derives a maintenance scheduling plan that attains the desired reliability while minimizing cost and imposes it to all producers. In a competitive environment, this is not possible because the operator is still in charge of maintaining an adequate level of reliability, but the target of each producer is to maximize its own profits, which conflicts in general with the reliability objective of the operator. This paper proposes a technically sound coordinating mechanism based on incentives/disincentives among producers and the operator, which allows producers to maximize their respective profits while the operator ensures an appropriate level of reliability.**

***Index Terms*—Coordination, electricity market, generation maintenance, restructured power system.**

## NOMENCLATURE

The main mathematical symbols used throughout this paper are classified below for quick reference.

**Variables:**

$I(t,s)$ Reliability index in period $t$ and subperiod $s$.

$P_{Gij}(t,s)$ Power generated by unit $j$ of producer $i$ in period $t$ and subperiod $s$.

$v_{ij}(t,s)$ Online status for unit $j$ of producer $i$ in period $t$ and subperiod $s$ (1 if unit $j$ is on in subperiod $s$ of period $t$ and 0 otherwise).

$x_{ij}(t)$ Maintenance status for unit $j$ of producer $i$ in period $t$ (1 if unit $j$ is on maintenance in period $t$ and 0 otherwise).

$y_{ij}(t,s)$ Start-up status for unit $j$ of producer $i$ in period $t$ and subperiod $s$ (1 if unit $j$ is started up at the beginning of subperiod $s$ of period $t$ and 0 otherwise).

**Constants:**

$a$ Per unit constant $(0 < a < 1)$.

$C_{ij}^{\mathrm{FX}}$ Fixed cost (\$/h) of unit $j$ of producer $i$.

$C_{ij}^{\mathrm{M}}$ Maintenance cost (\$/MW) of unit $j$ of producer $i$.

$C_{ij}^{\mathrm{P}}$ Production cost (\$/MWh) of unit $j$ of producer $i$.

$C_{ij}^{\mathrm{SU}}$ Start-up cost (\$) of unit $j$ of producer $i$.

$D_{ij}$ Duration (# of time periods) of the maintenance outage of unit $j$ of producer $i$.

$D_{ij_1j_2}^{\max}$ Constant equal to $\max\{D_{ij_1}, D_{ij_2}\}$.

$D_{ij_1j_2}^{\min}$ Constant equal to $\min\{D_{ij_1}, D_{ij_2}\}$.

$I_\nu^{\mathrm{MP}}(t,s)$ Reliability index (per unit) in period $t$ and subperiod $s$ for the maximum-profit maintenance scheduling plan at iteration $\nu$.

$I^{\mathrm{MR}}(t,s)$ Reliability index (per unit) in period $t$ and subperiod $s$ for the maximum-reliability maintenance scheduling plan.

$O_{ij_1j_2}$ Number of time periods during which the maintenance of units $j_1$ and $j_2$ of producer $i$ should overlap.

$P_D(t,s)$ Power demanded (MW) in period $t$ and subperiod $s$.

$P_{Gij}^{\max}$ Capacity (MW) of unit $j$ of producer $i$.

$P_{Gij}^{\min}$ Minimum power output (MW) of unit $j$ of producer $i$.

$R^{\min}(t,s)$ Net minimum reserve (MW) in period $t$ and subperiod $s$.

$S_{ij_1j_2}$ Number of time periods required between the end of the maintenance outage of unit $j_1$ and the beginning of the maintenance outage of unit $j_2$ (both units owned by producer $i$).

$\alpha_\nu$ Constant (\$/MW) used by the ISO in iteration $\nu$.

$\delta_\nu(t,s)$ Quadratic difference (sign affected) of the reliability indices MR-MS and MP-MS in period $t$ and subperiod $s$ at iteration $\nu$.

$\lambda(t,s)$ Energy price estimate (\$/MWh) for period $t$ and subperiod $s$.

$\omega_\nu(t,s)$ Incentive/disincentive set up by the ISO for period $t$ and subperiod $s$ at iteration $\nu$ $(-1 < \omega_\nu < 1)$.

**Numbers:**

$I$ Number of producers.

$N$ Number of subperiods.

$N_i(t)$ Maximum number of units in maintenance for producer $i$ in period $t$.

$T$ Number of periods of time.

$T(t,s)$ Duration (# of hours) of subperiod $s$ in period $t$.

**Sets:**

$G_i$ Set of indices of generation units owned by producer $i$.

$\Omega_i^{\mathrm{E}}$ Set of pair of units of producer $i$ that satisfy the maintenance exclusion constraint.

$\Omega_i^{\mathrm{P}}$ Set of pair of units of producer $i$ that satisfy the maintenance priority constraint.

$\Omega_i^{\mathrm{S}}$ Set of pair of units of producer $i$ that satisfy the maintenance separation constraint.

$\Omega_i^{\mathrm{O}}$ Set of pair of units of producer $i$ that satisfy the maintenance overlap constraint.

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## I. Introduction

In a centralized electric power system, an appropriate generation maintenance scheduling is derived by the system operator and imposed to producers. The target in assembling such a plan is to achieve an appropriate blend between maximum reliability and minimum cost. Note that maintenance outages decrease reliability and increase operation cost. However, this centralized framework is not anymore valid in currently restructured electric energy systems. To guarantee reliability is still the duty of the operator, denominated in the new framework independent system operator (ISO), but producer/consumer profits or costs are not anymore its business.

In fact, the ISO pursuing maximum social welfare seeks a generation maintenance annual plan that ensures similar reliability throughout the weeks of the year. However, every producer, pursuing its maximum profit, seeks to schedule the maintenance of its own units so that its lost of profit for maintenance outage is minimum. These objectives are clearly conflicting: the ISO strategy leads generally to schedule units for maintenance in low demand weeks while the independent strategies of the producers lead to schedule units for maintenance in low price weeks. The ISO is entitled to negotiate with producers a generation maintenance schedule that guarantees an appropriate level of system security. Analogously, by regulatory agreement, any generator must engage in the appropriate negotiation with the ISO to schedule its mandatory maintenance.

The algorithm presented in the paper is motivated by the electricity market of mainland Spain. However, it is not the one used in it. In the Spanish electricity market, a one-step mechanism is used for generator maintenance scheduling. That is, producers send their respective generator maintenance plans to the ISO, and then the ISO modifies the resulting maintenance plan for all units in the manner it considers appropriate to ensure security. This final maintenance plan is mandatory for all producers (see Operation Procedure P.O.2.5 [1]). Nevertheless, the proposed decentralized algorithm frames itself in an effort within the Power Industry in Spain to build maintenance scheduling tools appropriate for a competitive environment that may advantageously replace centralized tools.

This paper proposes an iterative procedure to coordinate maintenance scheduling among the ISO and the producers so that an appropriate degree of reliability is achieved throughout the weeks of the year in an acceptable manner for every producer. The iterative procedure relies on imposing a properly tuned-up incentive/disincentive to each week of the year for carrying out maintenance in it. This incentive/disincentive mechanism allows achieving a sufficient level of reliability in every week of the year.

A pool-based electricity market is considered. In such a market, producers submit to the market operator bids consisting in energy blocks and their corresponding minimum selling prices, while consumers submit energy blocks and their corresponding maximum buying prices. In turn, the market operator clears the market using an appropriate market clearing procedure, which results in hourly market clearing prices, and production and consumption schedules. Note, however, that the proposed maintenance scheduling procedure is valid for a market that includes bilateral contracts or consist only in bilateral contracts.

The considered time framework is one year divided by weeks and each week consists of six load subperiods. Subperiod demand block ordering is as follows: weekday peak, weekday shoulder, weekday valley, weekend peak, weekend shoulder and weekend valley. Considering hourly subperiods requires hourly price forecasts and hourly variables, which significantly increase both data uncertainty and computational burden. For one year in advance, the accuracy of daily price forecasts (peak, shoulder and valley) is significantly higher than the accuracy of hourly predictions. Therefore, our model embodies an adequate trade-off among modeling precision and data accuracy.

For the sake of simplicity, no uncertainty is considered, which means that appropriate demand and price forecasts are known and forced outage rates for the units are considered zero. Nevertheless, unit forced outage rates can be approximately taken into account derating their corresponding capacities.

The basic functioning of the proposed procedure comprises the three steps below:

Step 1) The ISO solves a maintenance scheduling problem involving all units, independently on which producer owns each unit, with the target of maximizing the reliability throughout the weeks of the year. Sufficiently accurate demand forecasts for the whole year are considered known. The load of each week is modeled using six demand blocks. This step results in a maximum-reliability maintenance scheduling (MR-MS) plan.

It should be noted that the ISO role is to ensure system security. Therefore, it must agree with producers on a generation maintenance plan that preserves system security. The maximum reliability plan from the ISO viewpoint is a convenient manner to establish an appropriate starting point for the negotiation among producers and the ISO on generation maintenance. However, any other plan agreed among market participants and the ISO, which ensures system security, is equally appropriate.

Step 2) Each producer solves independently its corresponding maintenance scheduling problem seeking to maximize its own profit. Note that all producers considered are price-taker, i.e., they have no capability of altering market clearing prices. Forecasts of market clearing prices are considered known. Unit costs include operating and start-up costs. Unit operating constraints include capacity and minimum power output. The joint consideration of the solution plans of all producers results in a maximum-profit maintenance scheduling (MP-MS) plan.

Step 3) The ISO compares MR-MS and MP-MS plans. If they are close enough in terms of reliability, the procedure concludes; if not, the ISO sets up weekly incentives/disincentives to encourage producers to modify their maximum-profit maintenance schedules so that the MP-MS plan approaches the MR-MS plan in terms of reliability.

The work reported in this paper frames itself in the large and rich body of literature on generation maintenance scheduling, which includes, among others, [2]–[15]. Within a competitive environment, this paper complements the pioneering work of Shahidehpour *et al.* [13]–[15]. For the unfamiliar reader, basic background on electricity markets can be found in [16]–[18].

The rest of this paper is organized as follows. In Section II, the problem of the ISO and the problems of the producers are formulated and analyzed. Then, the coordinating procedure proposed in this paper that uses revenue-neutral incentives/disincentives is described. Section III provides and discusses results from a real-world case study. In Section IV relevant conclusions are drawn.

## II. Problem Formulation

To adequately measure the degree of security throughout the weeks of the year, the reliability index below is defined for period $t$ and subperiod $s$

$$I(t,s) = \frac{\sum_{i=1}^{I}\sum_{j\in G_i} P_{Gij}^{\max}\left(1 - x_{ij}(t)\right) - P_D(t,s)}{\sum_{i=1}^{I}\sum_{j\in G_i} P_{Gij}^{\max} - P_D(t,s)}. \quad (1)$$

This reliability index is the net reserve divided by the gross reserve in period $t$ and subperiod $s$. The gross reserve in any subperiod is calculated as the difference between the sum of the capacity of all units and the power demand. The net reserve is calculated as the difference between the gross reserve and the power capacity in maintenance.

### A. Problem of the ISO

The ISO solves a maintenance scheduling problem with the target of maximizing the reliability throughout the weeks of the year. The objective function of the ISO can be formulated as follow

$$\text{maximize } \frac{1}{T \times N}\sum_{t=1}^{T}\sum_{s=1}^{N} I(t,s). \quad (2)$$

The objective function (2) is the average value of the reliability index defined in (1). This is an appropriate objective function provided that a sufficiently large index value is ensured for every subperiod, which is done using constraint (3) below.

The set of constraints of the maintenance scheduling problem of the ISO are specified below. These constraints are illustrated using simple examples.

*1) Minimum Net Reserve:* Constraint (3) ensures a net reserve above a specified threshold for all periods and subperiods.

$$\sum_{i=1}^{I}\sum_{j\in G_i} P_{Gij}^{\max}\left(1 - x_{ij}(t)\right) - P_D(t,s) \geq R^{\min}(t,s), \quad \forall t, \forall s. \quad (3)$$

The constant right-hand side of (3) for period $t$ and subperiod $s$ is computed as the product of 1) a per unit constant, 2) the demand in the corresponding period and subperiod, and 3) a fraction calculated as the total gross reserve (summation over periods and subperiods) divided by the total energy demanded

$$R^{\min}(t,s) = aP_D(t,s)\frac{\sum_{t=1}^{T}\sum_{s=1}^{N}\left(\sum_{i=1}^{I}\sum_{j\in G_i} P_{Gij}^{\max} - P_D(t,s)\right)}{\sum_{t=1}^{T}\sum_{s=1}^{N} P_D(t,s)}.$$

The above minimum reserve constant ensures higher reserves in periods/subperiods with higher loads, which is an appropriate criterion.

*2) Maintenance Outage Duration:* The following constraint ensures for each unit that it is maintained the required number of time periods

$$\sum_{t=1}^{T} x_{ij}(t) = D_{ij}, \quad \forall i, \forall j \in G_i. \quad (4)$$

If the maintenance outage duration of unit $j$ of producer $i$ is 2, and the number of time periods of the planning horizon is 4, the equation above becomes $x_{ij}(1)+x_{ij}(2)+x_{ij}(3)+x_{ij}(4) = 2$, forcing that the unit is maintained exactly during 2 periods.

*3) Continuous Maintenance:* The constraint below ensures that the maintenance of any unit must be completed once it begins

$$x_{ij}(t) - x_{ij}(t-1) \leq x_{ij}(t+D_{ij}-1), \quad \forall i, \forall j \in G_i, \forall t. \quad (5)$$

Note that $x_{ij}(t) = 0; \forall t \leq 0, \forall t > T$.

If the maintenance outage of unit $j$ of producer $i$ lasts 2 periods, the equation above becomes $x_{ij}(t) - x_{ij}(t-1) \leq x_{ij}(t+1); \forall t$, which implies that 2 successive $x_{ij}(t)$ should take the value 1.

*4) Maximum Number of Units Simultaneously in Maintenance:* Constraint (6) limits the maximum number of units that producer $i$ can maintain at the same time

$$\sum_{j\in G_i} x_{ij}(t) \leq N_i(t), \quad \forall i, \forall t. \quad (6)$$

If producer $i$ owns 3 units and only 2 can be simultaneously maintained, the above equation implies $x_{i1}(t) + x_{i2}(t) + x_{i3}(t) \leq 2, \forall t$, which forces that only 2 units are simultaneously maintained.

*5) Maintenance Priority:* This constraint forces priority in maintenance for some units. Constraint (7) below expresses that unit $j_1$ must be maintained before unit $j_2$ (both owned by producer $i$)

$$\sum_{\tau=1}^{t} x_{ij_1}(\tau-1) - x_{ij_2}(t) \geq 0, \quad \forall i, \forall \{j_1, j_2\} \in \Omega_i^{\mathrm{P}}, \forall t. \quad (7)$$

Note that $x_{ij}(t) = 0, \forall t \leq 0$.

If unit 4 has to be maintained before unit 5, the (7) becomes $x_{i4}(1)+x_{i4}(2)+\ldots+x_{i4}(t-1)-x_{i5}(t) \geq 0, \forall t$, which forces the maintenance of unit 4 to take place before the maintenance of unit 5.

*6) Maintenance Exclusion:* This constraint enforces the impossibility of maintaining two prespecified units of the same producer at the same time.

$$x_{ij_1}(t) + x_{ij_2}(t) \leq 1, \quad \forall i, \forall \{j_1, j_2\} \in \Omega_i^{\mathrm{E}}, \forall t. \qquad (8)$$

If units 5 and 7 of producer $i$ cannot be simultaneously maintained, the equation above becomes $x_{i5}(t) + x_{i7}(t) \leq 1, \forall t$, which makes impossible the simultaneous maintenance of unit 5 and 7.

*7) Separation Between Consecutive Maintenance Outages:* The constraints (9) and (10) below enforce that maintenance outages of unit $j_1$ and $j_2$ of producer $i$ are separated a specified number of time periods. It is considered that the maintenance outage of unit $j_1$ finishes before the one of unit $j_2$ begins

$$\sum_{\tau=1}^{t} x_{ij_1}(\tau - D_{ij_1} - S_{ij_1 j_2}) - x_{ij_2}(t) \geq 0, \quad \forall i, \forall \{j_1, j_2\} \in \Omega_i^{\mathrm{S}}, \forall t \qquad (9)$$

$$\sum_{\tau=1}^{t} \left[D_{ij_1 j_2}^{\min} x_{ij_1}(\tau - D_{ij_1} - S_{ij_1 j_2})\right] - \sum_{\tau=1}^{t} \left[D_{ij_1 j_2}^{\max} x_{ij_2}(\tau)\right] \leq 0, \quad \forall i, \forall \{j_1, j_2\} \in \Omega_i^{\mathrm{S}}, \forall t. \qquad (10)$$

Note that $x_{ij}(t) = 0, \forall t \leq 0$.

If 3 should be the number of time periods between the maintenance outages of units 2 and 6, whose maintenance durations are 1 and 2, respectively, the equations above become

$$x_{i2}(1) + \ldots + x_{i2}(t-4) - x_{i6}(t) \geq 0, \ \forall t$$

and

$$x_{i2}(1) + \ldots + x_{i2}(t-4) - 2x_{i6}(1) - \ldots - 2x_{i6}(t) \leq 0; \ \forall t.$$

The first of the equations above implies a temporal separation of at least 3 between the maintenance outages of units 2 and 6, while the second equation forces the separation to be exactly 3 periods.

*8) Overlap in Maintenance:* The constraints (11) and (12) below establish that the maintenance outages of units $j_1$ and $j_2$ of producer $i$ must overlap a specified number of time periods. It is considered that $j_1$ finishes the maintenance before $j_2$

$$\sum_{\tau=1}^{t} x_{ij_1}(\tau - D_{ij_1} + O_{ij_1 j_2}) - x_{ij_2}(t) \geq 0, \quad \forall i, \forall \{j_1, j_2\} \in \Omega_i^{\mathrm{O}}, \forall t \qquad (11)$$

$$\sum_{\tau=1}^{t} \left[D_{ij_1 j_2}^{\min} x_{ij_1}(\tau - D_{ij_1} + O_{ij_1 j_2})\right] - \sum_{\tau=1}^{t} \left[D_{ij_1 j_2}^{\max} x_{ij_2}(\tau)\right] \leq 0, \quad \forall i, \forall \{j_1, j_2\} \in \Omega_i^{\mathrm{O}}, \forall t. \qquad (12)$$

Note that $x_{ij}(t) = 0, \forall t \leq 0$.

If the maintenance outages of units 2 and 5, whose maintenance durations are 2 and 3, respectively, must overlap 1 time period, the equations above become

$$x_{i2}(1) + \ldots + x_{i2}(t-1) - x_{i5}(t) \geq 0, \quad \forall t$$

and

$$2x_{i2}(1) + \ldots + 2x_{i2}(t-1) - 3x_{i5}(1) - \ldots - 3x_{i5}(t) \leq 0, \quad \forall t.$$

The first of the equations above implies an overlap of at least 1 period between the maintenance outages of units 2 and 5, while the second equation forces the maintenance of unit 5 to begin in the corresponding period that produces an overlap of exactly 1 period of time.

### B. Problem of Each Producer

Each producer $i$ solves its corresponding maintenance scheduling problem seeking to maximize its own profit. The problem of producer $i$ can be formulated as follows:

$$\begin{aligned}\text{maximize} \quad & \sum_{j \in G_i} \sum_{t=1}^{T} \left[\sum_{s=1}^{N} \left[\left(\lambda(t,s) P_{Gij}(t,s) - C_{ij}^{\mathrm{P}} P_{Gij}(t,s)\right) T(t,s)\right]\right] \\ & - \sum_{j \in G_i} \sum_{t=1}^{T} \left[\sum_{s=1}^{N} \left[C_{ij}^{\mathrm{FX}} v_{ij}(t,s) T(t,s) + C_{ij}^{\mathrm{SU}} y_{ij}(t,s)\right]\right] \\ & - \sum_{j \in G_i} \sum_{t=1}^{T} \left[C_{ij}^{\mathrm{M}} P_{Gij}^{\max} x_{ij}(t)\right]. \end{aligned} \qquad (13)$$

The objective function (13) represents the profit of producer $i$, which is calculated as the difference between revenues and costs. Production, fixed, start-up and maintenance costs are considered. If needed, for a more detailed cost modeling can be used [19].

The set of constraints of the maintenance scheduling problem of producer $i$ are given below.

*1) Start-Up Logic:* The constraints (14) and (15) below enforce the logic of status change. The first constraint considers the change between the last subperiod of a period and the first subperiod of the following period. The second one considers the change between two consecutive subperiods of the same period

$$v_{ij}(t,1) - v_{ij}(t-1,N) \leq y_{ij}(t,1), \quad \forall j \in G_i, t = 2, \ldots, T \qquad (14)$$

$$v_{ij}(t,s) - v_{ij}(t,s-1) \leq y_{ij}(t,s), \quad \forall j \in G_i, \forall t, s = 2, \ldots, N. \qquad (15)$$

Using a time framework that includes six subperiods per week, units can be shut down during the weekend and restarted Monday morning. We introduce unit commitment variables to properly capture the shutting-down of units during the weekend.

Note that medium term constraints such as fuel limits, hydro energy limits, zonal transmission constraints, etc. could be considered in the model.

*2) Maintenance and Online Status:* This constraint enforces that a unit cannot be on line if it is in maintenance

$$x_{ij}(t) + v_{ij}(t,s) \leq 1, \quad \forall j \in G_i, \forall t, \forall s. \qquad (16)$$

*3) Capacity and Minimum Power Output:* The power generated for each online unit must be within a certain range represented by its minimum power output $P_{Gij}^{\min}$ and its capacity $P_{Gij}^{\max}$

$$v_{ij}(t,s) P_{Gij}^{\min} \leq P_{Gij}(t,s) \leq v_{ij}(t,s) P_{Gij}^{\max}, \ \forall j \in G_i, \forall t, \forall s. \qquad (17)$$

*4) Maintenance Constraints:* The maintenance constraints are (4)–(12), as previously explained, but particularized for the considered producer $i$.

### C. Coordinating Procedure

The following procedure allows achieving a generation maintenance plan that satisfies producer maximum-profit criteria while achieving a sufficient level of reserve in each week of the year and therefore ensuring an appropriate security level. This procedure works as follows.

1) The ISO solves the maintenance scheduling problem explained in Section II-A, with the target of maximizing the reserve throughout the weeks of the year. This problem results in the MR-MS plan.
2) Each producer solves independently its maintenance scheduling problem explained in Section II-B, with the target of maximizing its own profit. The solutions of these problems result in the MP-MS plan.
3) The ISO compares the MP-MS and the MR-MS plans. If they are close enough in terms of reliability, the procedure concludes; otherwise, it continues in step 4.
4) The ISO sets up incentives/disincentives for each period and subperiod (identical for all producers) that encourage producers to modify their maintenance scheduling so that the MP-MS plan approaches the MR-MS plan in terms of reliability. The incentives and disincentives are calculated as follow:

   Maintaining the sign, the quadratic difference between the reliability index for both maintenance plans in period $t$, subperiod $s$ and iteration $\nu$ is given by

$$\delta_\nu(t,s) = \left[I^{\rm MP}_{\nu-1}(t,s) - I^{\rm MR}(t,s)\right]\left|I^{\rm MP}_{\nu-1}(t,s) - I^{\rm MR}(t,s)\right|. \tag{18}$$

   It should be noted that $\delta_\nu(t,s)$ cannot be either all positive or all negative. The reason follows. All $\delta_\nu(t,s)$ positive/negative means that in the corresponding iteration the security indices of all periods improve/deteriorate, which requires less/more units in maintenance throughout the year, which contradicts the fact that all units should be maintained during the year.

   The normalized penalty parameter is then computed as

$$\omega_\nu(t,s) = \frac{\delta_\nu(t,s) + |\delta_\nu(t,s)|}{\sum_{t=1}^{T}\sum_{s=1}^{N}\left[\delta_\nu(t,s) + |\delta_\nu(t,s)|\right]} - \frac{|\delta_\nu(t,s)| - \delta_\nu(t,s)}{\sum_{t=1}^{T}\sum_{s=1}^{N}\left[|\delta_\nu(t,s)| - \delta_\nu(t,s)\right]}. \tag{19}$$

   Note that penalty neutrality is achieved, i.e., $\sum_{t=1}^{T}\sum_{s=1}^{N}\omega_\nu(t,s) = 0$ and that the penalty $\omega_\nu(t,s)$ is not restricted in sign. The first term of the right hand side of (19) is zero for negative quadratic differences, while the second term is zero for positive quadratic differences. Therefore, positive and negative penalties are normalized independently so that their corresponding signs are preserved.

   Note that the above penalty parameter is appropriate for two reasons: a) it allows approaching the yearly security target pursued by the ISO, and b) it results in a security margin that is proportional to the demand in each subperiod.
5) Each producer, solving the problem stated in II-B, calculates its new maintenance scheduling including incentives/disincentives in the objective function. The new objective function for producer $i$ is then
6) 

$$\sum_{j\in G_i}\sum_{t=1}^{T}\left[\sum_{s=1}^{N}\left[\left(\lambda(t,s)P_{Gij}(t,s) - C^{\rm P}_{ij}P_{Gij}(t,s)\right)T(t,s)\right]\right] - \sum_{j\in G_i}\sum_{t=1}^{T}\left[\sum_{s=1}^{N}\left[C^{\rm FX}_{ij}v_{ij}(t,s)T(t,s) + C^{\rm SU}_{ij}y_{ij}(t,s)\right]\right] - \sum_{j\in G_i}\sum_{t=1}^{T}\left[\sum_{s=1}^{N}\left[C^{\rm M}_{ij} - \alpha_\nu\omega_\nu(t,s)\right]P^{\max}_{Gij}x_{ij}(t)\right]. \tag{20}$$

   In the above equation the penalty parameter $\omega_\nu(t,s)$ has been multiplied by $\alpha_\nu$ to express it in cost units per MW. The parameter $\alpha_\nu$ is selected using a subgradient-type technique. This parameter, which must be positive, is selected as small as possible but large enough to influence producer maintenance schedules. The values of $\omega_\nu(t,s)$ are computed through (19) and represent normalized deviations with respect to subperiod security targets.

   Note that each producer maximizes objective function (20) subject to constraints (4)–(12) and (14)–(17) in each iteration.
7) The ISO compares the new maintenance scheduling plan provided by the producers and the MR-MS plan in terms of reliability. The iterative procedure concludes once the percentage reliability index in all subperiods is above a prespecified percentage value. Otherwise, it continues in step 4.

The problem of the ISO and the problem of each producer are formulated as standard mixed-integer linear programming problems that can be solved using commercially available software [20]. The computational complexity of these problems is illustrated in Table I for the realistic case study of Section III.

The algorithm proposed embodies a subgradient type convergence mechanism. Once deviations are computed (with respect to target reliability levels), i.e., $\omega_\nu(t,s)$, numerical incentives proportional to the deviations (through parameter $\alpha_\nu$) are computed and incorporated as costs of rewards for the next iteration. The algorithm is heuristic and therefore no formal convergence proof can be developed. However, numerical simulations using different electric energy systems show appropriate (subgradient-type) convergence behavior.

The rationale behind the proposed algorithm is as follows. Given the initial proposal of generator maintenance outages provided by the producers, the purpose of the proposed algorithm in to orderly encourage “moving maintenance outages” from periods of low reliability to periods of high reliability, so that a reasonably reliability level is attained throughout the year. This maintenance outage movement should be encouraged in a

TABLE I
COMPUTATIONAL COMPLEXITY OF PROBLEMS

| | Number of continuous variables | Number of binary variables | Number of constraints |
|---|---|---|---|
| ISO problem | $TN$ | $JN$ | $TN + J + T(J + I) + T(P + E + 2S + 2O)$ |
| Problem of producer $i$ | $J_i TN$ | $J_i T(1 + 2N)$ | $J_i[(T-1) + T(N-1)] + 2J_i TN + J_i(1+T) + T + T(P_i + E_i + 2S_i + 2O_i)$ |

ordered manner so that a flip-flop effect is avoided. That is, if maintenance in low reliability periods is highly penalized while maintenance in high reliability periods is encouraged through high incentives, a major reallocation of maintenance may take place, and a flip-flop effect is generated if incentives/disincentives are reversed. On the contrary, to promote an ordered reallocation of maintenance outages, the minimum incentives (high reliability periods)/disincentives (low reliability periods) that originate an actual maintenance reallocation are generated. Then, the new maintenance schedule is evaluated and a new set of minimal incentives/disincentives are generated. The procedure continues until an acceptable generator maintenance schedule for the ISO and the producers is achieved.

The maximum reliability problem solved by the ISO is a mixed-integer linear programming problem whose numbers of variables and constraints are characterized in Table I. Analogously, the maximum profit problem solved by each producer is a mixed-integer linear programming problem whose numbers of variables and constraints are characterized in Table I. The heuristic iterative procedure to attain a final maintenance schedule acceptable for the ISO and the producers requires typically $n$ (usually below 10) iterations to converge, and therefore it requires one solution of the ISO problem and $n$ solutions of the problem of every producer.

In Table I, $J$ is total number of units in the system and $J_i$ is the number of units owned by producer $i$; $P$, $E$, $S$ and $O$ represent the numbers of pairs of units that satisfy the maintenance priority, exclusion, separation and overlap constraints, respectively, for all producers, and $P_i$, $E_i$, $S_i$ and $O_i$ for producer $i$.

Once the procedure has converged at iteration $\nu = n$, the rescheduling cost involved (payment to producers) in achieving the final maintenance plan is computed as

$$C = \sum_{i=1}^{I} \sum_{j \in G_i} \sum_{t=1}^{T} \sum_{s=1}^{N} \alpha_n \omega_n(t,s) P_{Gij}^{\max} x_{ij}(t). \qquad (21)$$

This rescheduling cost (payment to producers) is allocated to time periods and subperiods and consumers pro rata. The amount corresponding to subperiod $s$ of time period $t$ is

$$C(t,s) = \frac{P_D(t,s)}{\sum_{t=1}^{T} \sum_{s=1}^{N} P_D(t,s)} C \qquad (22)$$

which is allocated pro rata to consumers summing up demand $P_D(t,s)$.

It should be noted that C is usually very small with respect to total consumer payment (see the case study below).

TABLE II
COMPUTATIONAL COMPLEXITY OF PROBLEMS OF THE CASE STUDY

| | Number of continuous variables | Number of binary variables | Number of constraints |
|---|---|---|---|
| ISO problem | 312 | 3900 | 6679 |
| Larger producer | 4368 | 9464 | 14144 |

The payment for maintenance scheduling adjustments to each producer are

$$RP_i = \sum_{j \in G_i} \sum_{t=1}^{T} \sum_{s=1}^{N} \alpha_n \omega_n(t,s) P_{Gij}^{\max} x_{ij}(t). \qquad (23)$$

We assume that payments for maintenance scheduling adjustments to producers take place once a year, after the appropriate agreement among producers and the ISO has been reached. However, this payment can be distributed throughout the year. Total payment is provided by (21) and (23) provides the payment to each producer.

## III. Case Study

Results for a realistic case study based on the generating system of mainland Spain [21] are reported in this section. The number of units considered is 75, owned by nine producers. Total capacity is about 36 GW, while maximum and minimum demands are approximately 27 and 14 GW, respectively. The capacity shares of the producers are 17, 16, 15, 14, 13, 12, 6, 4 and 3%, respectively. Demand and price data for year 2002 are obtained from [22]. Maximum and minimum prices are respectively 108 and \$3/MWh. The analysis considers 52 time periods corresponding to the weeks of year 2002. Each period (week) is divided in six subperiods (peak, shoulder and valley for weekdays and weekend, respectively). The computational complexities of the ISO problem and the larger producer problem for the case study are illustrated in Table II.

The iterative procedure concludes once the percentage reliability index in all subperiods is above 0.15%. The value of $\alpha_n$ used for this case study is 8050.

Figs. 1–3 illustrate plans 1) MR-MS, 2) initial MP-MS, and 3) final MP-MS, respectively.

Figs. 4–6 illustrate the evolution of the reliability index (1) throughout the weeks of the years for plans 1) MR-MS, 2) initial MP-MS, and 3) final MP-MS.

First of all, note that the MR-MS plan (see Fig. 1) schedules most units for maintenance during weeks 12–23 and 32–34, which are the weeks with the lowest loads. Its reliability profile is depicted in Fig. 4. However, the initial MP-MS plan (see Fig. 2) schedules most units for maintenance during weeks 12–14, 32, 33 and 46–52, which are the weeks with the lowest average energy prices. Its reliability profile is depicted in Fig. 5. The final MP-MS plan and its reliability profile are illustrated in Figs. 3 and 6. The final MP-MS plan approaches in terms of reliability the MR-MS plan (see Figs. 4 and 6) ensuring a sufficient degree of security throughout the weeks of the year. This is achieved by moving maintenance outages from the last weeks of the year to weeks 9–25, as can be concluded from Figs. 2 and 3.

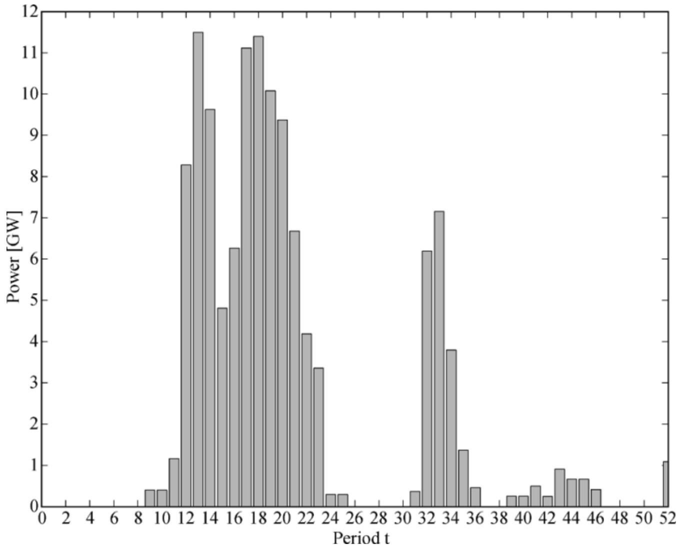


Fig. 1. Maximum-reliability maintenance scheduling plan.

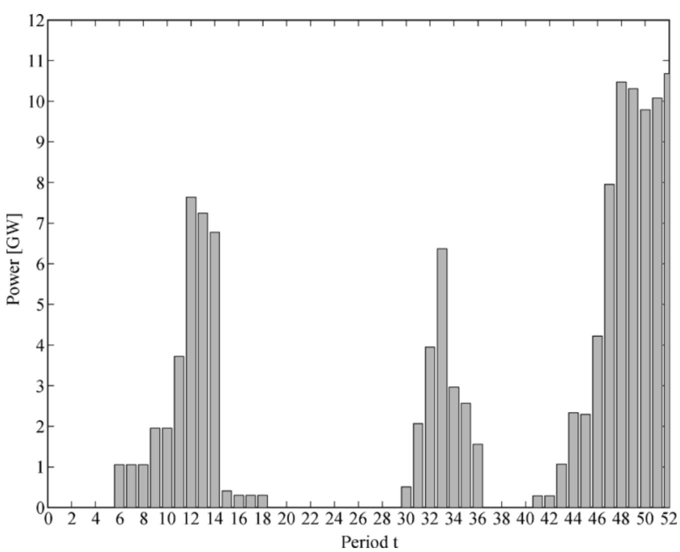


Fig. 2. Initial maximum-profit maintenance scheduling plan.

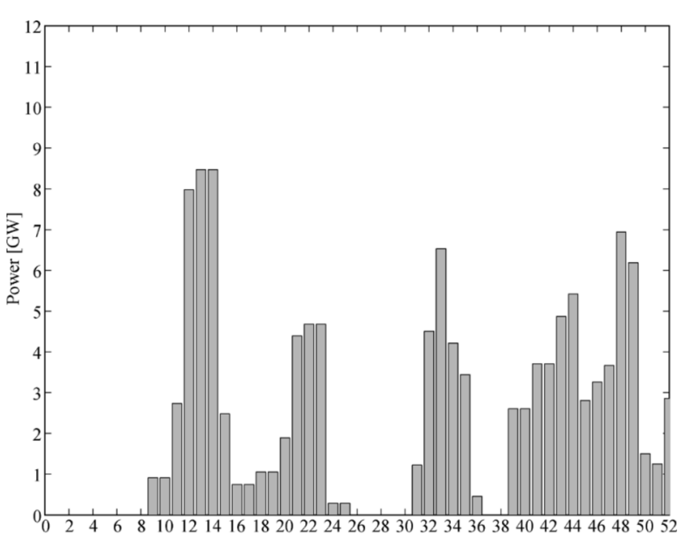


Fig. 3. Final maximum-profit maintenance scheduling plan.

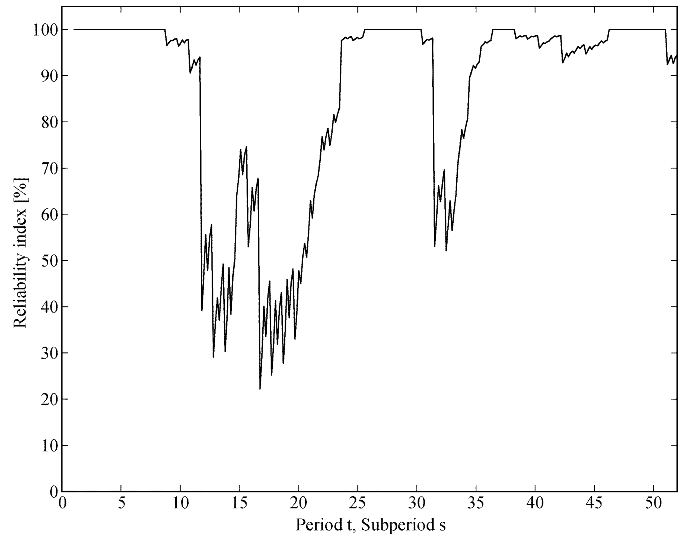


Fig. 4. Evolution of the reliability index of the MR-MS plan.

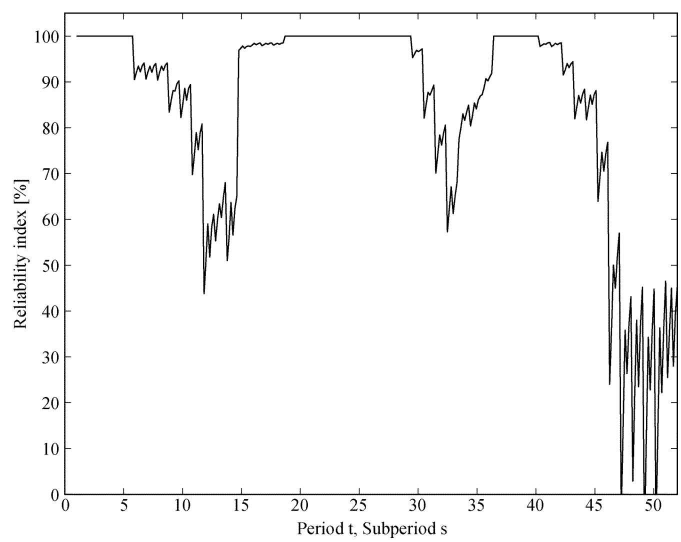


Fig. 5. Evolution of the reliability index of the initial MP-MS plan.

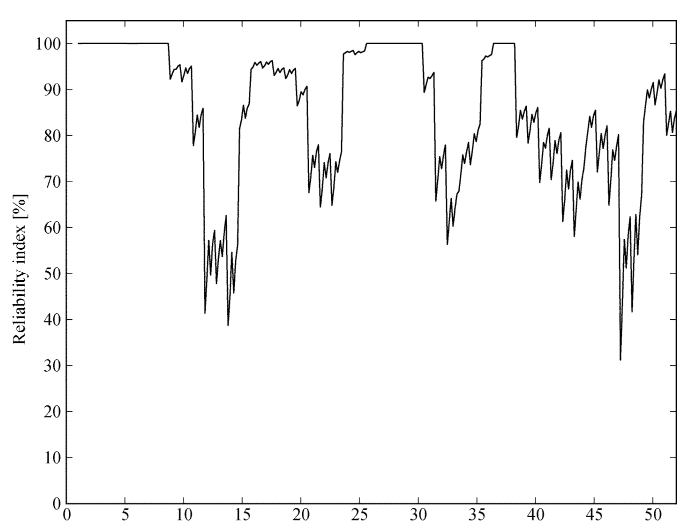


Fig. 6. Evolution of the reliability index of the final MP-MS plan.

TABLE III
PRODUCER PROFITS AND RESCHEDULING PAYMENTS TO PRODUCERS

| Producer | Producer Profits: Initial MP-MS [M$] | Producer Profits: Final MP-MS [M$] | Reschedule Payment [M$] |
|---|---|---|---|
| 1 | 606.191 | 607.929 | 10.231 |
| 2 | 1223.881 | 1212.941 | -7.505 |
| 3 | 1009.893 | 995.115 | 2.543 |
| 4 | 1049.331 | 1034.243 | 2.045 |
| 5 | 384.408 | 390.512 | 8.308 |
| 6 | 701.391 | 697.075 | 2.506 |
| 7 | 161.151 | 160.803 | 2.250 |
| 8 | 102.772 | 102.943 | 0.420 |
| 9 | 79.635 | 80.542 | 1.428 |
| Total | 5318.653 | 5282.103 | 22.226 |

The model is implemented using CPLEX 8.1 under GAMS [23] on a computer equipped with dual Xeon processors clocking at 1.60 GHz with 2 GB of RAM. The number of iterations needed to attain convergence is 2 and the CPU time required to attain the solution is 14 min.

Table III illustrates the profit obtained by the seven producers (information not available to the ISO) and the reschedule payments to producers. Column 2 provides profits associated to the initial maximum-profit maintenance schedule; the third column, profits associated to the final maximum-profit maintenance schedule; and the fourth column provides the payment to producers for altering their initial maintenance schedules. A negative figure indicates that the producer transfers money to the ISO to preserve its preferred maintenance schedule.

It should be noted that producers receive the payments stated in the last column of Table III, which are computed using (23). The payment received by any given producer depends on its ability to reallocate the maintenance outage of their units and to take advantage of reallocation incentives. Rescheduling payments made to producers ($22 226 000) are allocated *pro rata* to demands as a cost to achieve the desired level of reliability. Note that rescheduling payments are below 0.42% of total profits made by producers.

## IV. CONCLUSION

This paper sets up an appropriate coordinating mechanism that allows achieving a generation maintenance plan that satisfies producer maximum-profit criteria while achieving a sufficient level of reliability in each week of the year. The coordination mechanism considers the perspectives of both producers and the ISO, so that an acceptable solution for both is achieved. The proposed procedure is simple to implement in practice, and requires a reasonably small amount of computing time and a small amount of data communication. This coordinating procedure is illustrated in a real-world case study that is based on the generating system of mainland Spain.

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