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An Environmentally-Constrained Reliability-Based Generation Maintenance Scheduling Considering Demand-Side Management

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Abstract: This paper scrutinizes the impacts of demand-side resources (DSRs) on the power system reliability via a novel multi-target generation maintenance (GM) model. The nominated model uses the Lexicographic preferences to hierarchically consider the environmental issues, economics, and reliability of power systems. In this regard, the produced emission, which reflects the per unit produced pollutant values in different locations, is minimized. Taking into account the environmental constraints, the total incurred expenditures, including operating and maintenance costs, reserves costs, and total incentives are also minimized. Subsequently, the GM problem considering the correlation constraints is handled while the reliability index, the average net reserve value (ANRV), is maximized over the scheduling horizon. The DSRs improve the system reliability such that the total costs, and emission level, do not exceed the situation in which DSRs are not available. The GM scheduling is a highly complicated problem and considering DSRs makes it even more complicated. To handle this problem more efficiently, appropriate linearization technique is used, while the proposed model is formulated in GAMS modeling language. To evaluate the capability of DSRs in system reliability improvement, the modified 24-bus IEEE-RTS is conducted. Results indicate that by selecting proper location and incentives, significant improvement is obtained.

Nomenclature

Indexes and Sets

b	Bus index.
i	Unit index.
l	Transmission line index.
N_G, N_G^R, N_B, N_L	Number of units, units in region R , buses, and lines, respectively.
$N_{SE}^i, N_{SF}^i, N_{SI}^b$	Number of segments to linearize emission, cost, and incentive curves, respectively.
t	Time index.
T	Scheduling time horizon

Variables

$Em_k^i(t)$	Produced emission of segment k in linearized emission curve of unit i in period t .
$f^l(t)$	Active power flow of line l in period t .
$\vec{f}^L(t)$	Vector of active power flows in period t .
$F_j(x)$	Target j in a multi target problem.
$F_j(x_j^*)$	Optimum value of target j in a multi target problem.
$\vec{g}(t)$	Vector of generated active power in period t .
$G_k^i(t)$	Generation of segment k in linearized cost function of unit i in period t .
$G^i(t)$	Total Generation of unit i in period t .
inc_{opt}^b	Incentive of DRPs in bus b .
$loss(t)$	System losses in period t .
$m^l(t)$	Maintenance status of a unit in period t .
$Pr_0^b(t)/Pr_{DR}^b(t)$	Electricity price of bus b in period t before/after implementing DRPs.
$P_{ev}^i(t)$	Generation level of a unit in environmental criteria in period t .
pen_{opt}^b	Penalty of bus b .
$\vec{r}(t)$	Vector of load curtailments in period t .

$r^b(t)$	Load curtailment of bus b in period t .
$rl^l(t)$	Reservation level of a unit in period t .
$u^i(t)$	Commitment status of a unit in period t ; 1 if on, otherwise 0.
$\sigma_k^b(t)$	Award of segment k in the linearized total incentive curve of bus b in period t .
$\varphi^b(t)$	DRPs status of bus b in period t ; 1 if the customer b partakes in IBPs, otherwise 0.
$\rho(\Delta D^b(t))$	Total incentive to customers at bus b in period t .
$\Gamma^i(t)$	Encouragement index of unit i in period t .
$\omega^i(t)$	Maintenance initial status; 1 if the unit's check starts at the beginning of period t , otherwise 0.

Parameters

$D^b(t)/D_{DR}^b(t)$	Demand of a bus before/after implementing DRPs in period t .
$\vec{D}^b(t)$	Vector of demand in period t .
$E(t, t)/E(t, j)$	Self/cross elasticity.
$\underline{Em}^i$	Lower limit on the emission of a unit.
$Em_{l'}^{*/**}, Em_{v'}^{*/**}$	Emission level (lbs) and value ($p.u.$), obtained from the first and second targets, respectively
f_{max}^l	Maximum capacity of a line.
$\underline{G}_c^i$	Minimum generation cost of a unit
$\bar{G}_k^i(t)$	Maximum generation in segment k in period t .
$\overline{inc}^b(t)/\underline{inc}^b(t)$	Maximum/minimum incentive level in bus b .
MD^i	Maintenance duration of unit i .
$\bar{N}_{DDR}^{UM}(t)$	Maximum number of DRRs in period t .
$\bar{N}^{UM}$	Maximum number of maintenance in a region.
P_{max}^i/P_{min}^i	Upper/lower generation capacity of a unit.

$R_{Th}(t)$	Net minimum reserve in period t .
S^T	Node branch incidence matrix.
$SR(t)$	Spinning reserve capacity in period t .
u^i	Regional Emission value of unit i ($1/lbs$).
$\beta(t)$	Per MW value of a reserve in period t .
ε	Accepted level of expected curtailments.
$\bar{h}_1^b, \bar{h}_2^b, \bar{h}_3^b$	Incentive coefficient of DRPs in bus b .
$\Lambda_k^i, \Upsilon_k^i, \pi_k^b$	Slopes of segment k in the linearized cost, emission, and incentive curves, respectively.
μ_c^i	Spinning reserve capacity cost of unit i .
$\underline{\sigma}_{inc}^b$	Lower limit on award of bus b .
$\bar{\sigma}_k^b(t)$	Maximum award in segment k in period t .
λ_c^i	Maintenance cost of unit i .
$u(t)$	Maximum number of under maintenance units in period t .

1. Introduction

1.1. Motivation and Literature Review

Generation maintenance (GM) is one of the midterm power systems planning problem defined as the essential activities which maintain the availability of units to ensure the power system reliability and performance [1].

In general, the GM problem is categorized into three groups: 1) reliability-oriented [2–5], 2) cost-oriented [6–9], and 3) joint reliability- and cost-oriented [10, 11]. The reliability criteria can be contemplated as minimizing the sum of reserves squares [2, 5], minimizing the loss of load probability [3], and maximizing the sum of the ratio between the net power reserve and the gross power reserve [4]. More often than not, in cost-oriented GM scheduling problems, operation and maintenance costs are minimized [6]. In [7], a DC optimal power flow was utilized to minimize the total maintenance and expected load curtailment costs while satisfying the grid operational constraints. A covariate-based integrated framework was proposed in [8] aiming at coordinating short-term generation and transmission maintenance schedules while taking into account security constrained unit commitment (SCUC). In [9], a joint GM scheduling and SCUC model was proposed to minimize the operating, maintenance, and start-up and shutdown costs taking into account the security conditions via N-1 security criterion. A multi-criteria GM scheduling model aims at minimizing the operating costs (fuel, maintenance, unsaved and interruptible energy) was presented in [10] aiming at enhancing the system reliability. In [11], a coordinated GM scheduling and SCUC was performed to simultaneously minimize the operating and maintenance costs and risk while, at the same time, the reliability was maximized.

On the other hand, by increasing the amount of greenhouse gases (GHGs), significant challenges are imposed to the GM scheduling problem. However, for the sake of simplicity, most of the existing works in this area of research ignore considering the environmental aspects. To address the environmental criteria, several methods can be applied to the power system. These methods can be seen from planning or scheduling standpoint, which profoundly affect the power system conditions, or from the operating perspective, which looks for an appropriate trade-off between cost and emission [12–14]. To address the

environmental issues in GM scheduling problems, the level of emitted GHGs from generating units can be considered either as a constraint [15, 16], or as a term of objective function [17]. In [15], an economic-oriented GM model was proposed in which the maximum limit of energy production was used to reduce the environmental impacts. A multi-objective security constrained GM model under the smart grid environment was presented in [17] so that the system total costs and emissions in the presence of demand-side resources (DSRs), as virtual resources to procure system reserve requirement, were minimized. Nevertheless, considering the impacts of emissions in multifarious locations are still a big gap in this area of research that is addressed in this paper.

Moreover, besides worldwide power systems' smarting, challenges of GM scheduling have been altered. Under the smart environment, demand-side behaviors, enabled by demand response programs (DRPs), affect the units' optimum GM schedule. The impacts of demand-side management (DSM) on GM scheduling have been investigated in several works [1, 17–19]. To consider the impacts of GM outages on the electricity prices, in [1], the demand response (DR) under a competitive market environment was incorporated in the GM model. In [18], a competitive structure of GM scheduling under a deregulated environment incorporating demand-side conditions was presented in which besides the main goal of GM, the customers' satisfaction was also considered. The environmental and economic impacts of DSRs on the multi-target GM problem was examined in [19] while the price elasticity of demand and customers' benefit function were the basis of the responsive loads' economic model to determine the optimum locations for DRPs implementation. Regarding the previous studies, the lack of investigating DSRs' impacts on system reliability is still a challenging issue to be investigated. This paper addresses this issue by proposing a comprehensive model that is beneficial in a smart grid environment.

The GM scheduling is a large-scale, non-convex, and mixed integer combinatorial optimization problem and considering the environmental and reliability issues make it even more complicated. Different approaches have been used to solve the GM problem that can be divided into two groups: 1) mathematical techniques such as benders decomposition [15], dynamic programming [20], and branch and bound [21], and 2) heuristic methods such as Tabu search [22], simulated annealing [23], particle swarm optimization [24], etc. [25–27]. However, recently, the modeling language-based software, GAMS [28], due to accessing to reliable commercial solvers, has been widely used to solve such complicated GM problem with the minimal user intervention [25].

1.2. Model and Contribution

This paper presents a novel Multi-Target GM (MTGM) scheduling model under a smart DSR-based environment. The impacts of DSRs on system reliability are studied while the allowable emission value and level, and system costs are obtained by solving the maximum

Fig. 1. Schematic of proposed MTGM considering DSRs

reliability model in the absence of DSRs. In this regard, the most appropriate locations of DSRs and consequently the optimal awards, which is paid to the customers, are identified.

The nominated model is an economic-, environmental-, and reliability-driven model, as explained below.

- i) Environmental Target: This target aims at investigating the impact of emission in different locations of a system. In this work, the effects of emissions' value in different regions are considered, i.e., per unit produced emissions in urban, desert, and industrial areas are not the same.
- ii) Economic Target: In this target, the system expenditures including operation and maintenance costs, reserve cost, and total incentives due to participating in DRPs are considered.
- iii) Reliability Target: To obtain this target, the average net reserve value (ANRV) over the scheduling horizon is maximized while an index is considered to reveal the different values of per MW reserve in different periods.

From the modeling standpoint, multi-target problems can be handled by two main decision making (DM) methods: i) Multi-attribute DM (MADM) method [26], which recast the problem into a single objective optimization problem via a weighted model, and ii) Multi-objective DM (MODM) approach with a priori/posteriori methods like bounded objective function, Lexicographic, etc. [27]. In this paper, a trade-off between different targets is performed by Lexicographic preferences.

Comparing with the existing models in the literature, the main contributions of this paper are fourfold.

- 1) A novel model for GM scheduling is proposed.

This model aims at minimizing the system costs and emission while maximizing system reliability. The Lexicographic method is used to find a proper compromise among different objectives. The proposed model is inherently a nonlinear nonconvex model that would be a hurdle in finding the optimal global solution. Therefore, such terms are recast to well-tempered linear terms. The model is formulated in GAMS modeling language, and the Cplex is used to solve the resulted mixed integer linear programming (MILP) problem.

- 2) Instead of minimizing the amount of emission, and in order to reflect the regional pollutions, emission value which is affected by location is minimized.
- 3) To evaluate the system reliability, the impacts of DSRs (including locations and amount of awards) on MTGM scheduling is investigated.
- 4) A new index is proposed to consider the different values of per unit reserve in each period.

1.3. Paper Organization

The rest of this paper is organized as follows. The MTGM framework incorporating DSRs is presented in section 2. The DR program is modeled in section 3, while the proposed MTGM is formulated in section 4. Section 5 presents the results and analysis of the proposed model using the modified IEEE 24-RTS. Conclusions are provided in section 6.

2. Hierarchy of MTGM Considering DSRs

In this section, first, the hierarchy of MTGM scheduling problem is provided in detail. Then, the utilized approach to finding a compromise between different objectives is presented.

2.1. Description

The proposed MTGM scheduling model takes into account the: *i)* environmental, *ii)* economic, and *iii)* reliability targets while the Lexicographic method is used to establish a proper compromise among the aforementioned targets. In this structure, the main challenge is to investigate the impacts of DSRs to improve the system reliability while the emission value and level, and system costs (obtained by maximizing the reliability in the absence of DSRs) do not exceed. To analyze the impacts of DSRs on the proposed MTGM scheduling model, a multi-phase structure is used. The proposed model is solved in four phases defined by Lexicographic method, Fig. 1.

- 1) *Phase 1:* The environmental target of GM scheduling problem is solved in this phase, while the total value of pollutions in different locations is minimized.
- 2) *Phase 2:* Using the Lexicographic method, emission level and values (obtained in phase 1) are imposed to phase 2 as coordination constraints. Moreover, regarding the generation pattern in phase 1, the encouragement index is calculated and applied to the operation term of the economic target to obtain the most similar generation pattern to phase 1.
- 3) *Phase 3:* The reliability-driven GM scheduling without considering DSRs is solved in this phase while the calculated emission level and value, and system costs in phase 2, are imposed as coordination constraints.
- 4) *Phase 4:* In order to investigate the impacts of DSRs on system reliability, the ANRV over the scheduling horizon is maximized in the presence of DSRs. To prevent additional cost and emissions imposition to the system, the upper bound of coordination constraints are defined using the optimal solution of phase 3.

The encouragement and the proposed reserve margin value indexes in different periods are explained as follows.

2.1.1 Encouragement Index: As presented in Fig. 1, the encouragement index, obtained from the generation pattern of phase 1, is implemented to the economic target to ensure the most similar generation pattern as the prior phase. This index is proportional to the generation level of a unit in phase 1 and is applied to the operation term of the economic target in phase 2. In other words, to handle the generation pattern in phase 2, the higher the generation level in phase 1 is, the smaller the index in phase 2 will become. Therefore, the encouragement index is proposed as (1) [29].

$$\Gamma^i(t) = 1 + \left(\frac{P_{\max}^i - P_{ev}^i(t)}{P_{\max}^i} \right); \quad \forall i \in N_G, \forall t \in T \quad (1)$$

where P_{ev}^i is obtained from phase 1.

In order to clarify the encouragement index, a simple example is presented in Table 1. It is obvious that the encouragement index is lower in high generation level to encourage the unit producing more in phase 2.

Table 1 Encouragement index level for two sample generation pattern

Generation/Index	Time 1	Time 2	Time 3	Time 4
$P_{\max}^i = 400$	$\frac{P_{ev}^i(t)}{\Gamma^i(t)}$	400	280	100
	$\Gamma^i(t)$	1	1.3	1.75
$P_{\max}^i = 50$	$\frac{P_{ev}^i(t)}{\Gamma^i(t)}$	50	45	20
	$\Gamma^i(t)$	1	1.1	1.6

2.1.2 Reserve Margin Value: Corresponding to each period, the level of reserve margin is changed that affects the system operator to respond the unanticipated events in power systems. It is preferred that less capacity is taken under maintenance in peak periods, due to lower reliability margin. To reveal the reserve value in period t , index $\beta(t)$ is used at the reliability-driven target.

$$\beta(t) = \sum_{b \in N_B} D^b(t) / \left(\sum_{i \in N_G} P_{\max}^i - \sum_{b \in N_B} D^b(t) \right) \quad (2)$$

In previous works [22], $\beta(t)$ was defined as (3).

$$\beta(t) = 1 / \left(\sum_{i \in N_G} P_{\max}^i - \sum_{b \in N_B} D^b(t) \right) \quad (3)$$

To compare the old reserve value index (RVI) with the proposed RVI, a system with the total capacity of 5000 MW is considered. Table 2 provides the information of three periods with different loading levels (peak, off-peak, and valley).

From the RVI ratio of a period to the valley, it can be concluded that the proposed index is more efficient than the old one in reflecting the reserve value in most loading periods and to reveal the unused capacity of peak periods value.

Table 2 Reserve value index for a sample system

Period	Load (MW)	$\beta(t)$		$\left(\frac{\beta(t)^{\text{Period}}}{\beta(t)^{\text{Valley}}} \right)$	
		Old RVI	Proposed RVI	Old RVI	Proposed RVI
Valley	2000	0.00033	0.667	1	1
Off-peak	3500	0.00067	2.333	2.03	3.49
Peak	4500	0.002	9	6.06	13.49

2.2. Mathematical Approach: Lexicographic Technique

In this paper, among the existing approaches to treating the Multi-Target (MT) problems, the Lexicographic technique is used to handle the MTGM problem [27]. In this technique, the targets are ordered due to importance, either by the decision maker or by an algorithm, and each objective is optimized at a stage. First, the optimal solution of the most important target is obtained, e.g. $\min F_1(x) = F_1^*$. Then, the second target is optimized, e.g. $\min F_2(x) = F_2^*$ while the optimal solution of the previous target is imposed as a constraint of the second target, $F_1(x) \leq F_1^*$, to retain the optimal solution of the first objective. Afterward, the third target is minimized while constrained to $F_1(x) \leq F_1^*$ and $F_2(x) \leq F_2^*$ to hold the previous optimal solutions. Therefore, the MT problem with n targets is presented as follows subject to (4); in some works, for this constraint, a larger search space is provided, as (5).

$$\min F_k(x)$$

s.t.

$$F_j(x) \leq F_j(x_j^*); \forall j = 1, 2, \dots, k-1; \forall k > 1; k = 1, 2, \dots, n(4)$$

$$F_j(x) \leq (1 + \delta_j)F_j(x_j^*); \forall j = 1, 2, \dots, k-1; \forall k > 1(5)$$

where $\delta_j \in [0, 1]$ is used to adjust the search space, [27, 30]; k represents the preferred ranking of objectives, and $F_j(x_j^*)$ denotes the optimum value of $F_j(x)$.

3. Demand Response Programs

The DR can be considered in resource adequacy studies, either as a load modifier or as a resource. In this concept, the DR can be defined as changes in demand by taking the advantages of DSRs, adjusting the regular consumption patterns as a response to changes in the price of electricity, or providing incentives that have been designed to induce lower electricity use at high wholesale market price periods, or when required to maintain system reliability. The DRPs are classified into two main clusters: *i*) time-based programs (TBPs) and, *ii*) incentive-based programs (IBPs). In TBPs, no penalty or incentive is used, while IBPs are categorized into three main clusters such as voluntary, mandatory, and market-based programs [31].

In a smart environment, the load profile can be regulated intelligently by the resultant benefit for electricity usage, the fluctuating price of energy, and incentive (which is offered for load reduction and shifting). In order to evaluate the impact of DRPs on load profile, responsive load economic models must be considered. The level of demand in the presence of responsive load depends on the percentage of nonresponsive load, the nominal potential of responsive load, the price elasticity of demand, and customers' benefit considered in (6) [32].

$$D_{DR}^b(t) = (1 - \xi)D^b(t) + \xi D^b(t) \times (1 + \sum_{j \in T} E(t, j) \frac{Pr_{DR}^b(j) - Pr_0^b(j) + \tau^a(j) inc_{opt}^b + \tau^e(j) pen_{opt}^b}{Pr_0^b(j)}) \quad (6)$$

In this work, we focus on the voluntary IBPs, so $pen^b(t)$ is neglected in (6). If the system operator pays \$“ inc_{opt}^b ” as an incentive to consumers for 1 MWh reduction of the maximum level of load, the total incentive for voluntary IBPs can be presented as (7). Demand ratio $\tau(t)$ is applied to inc_{opt}^b organizing the level of incentive in different time intervals. The award adjustment index a is defined to handle the effect of demand ratio parameter in IBPs [32].

$$\rho(\Delta D^b(t)) = \tau^a(t) inc_{opt}^b (D^b(t) - D_{DR}^b(t)); \quad (7)$$

where $\tau(t) = D^b(t) / D_{max}^b$

By substituting (6) in (7), the quadratic incentive function (8) is obtained that is recast into the piecewise linear function (9) [19].

$$\rho(\Delta D^b(t)) = h_1^b(t) inc_{opt}^{b^2} + h_2^b(t) inc_{opt}^b + h_3^b(t) \quad (8)$$

$$\rho(\Delta D^b(t)) = \sigma_{inc}^b \varphi^b(t) + \sum_{k \in N_{SI}^b} \sigma_k^b(t) \pi_k^b \quad (9)$$

4. Formulation of Proposed MTGM Considering DRPs

The aim of the proposed MTGM scheduling model is to obtain the optimal maintenance scheme satisfying the demand while minimizing the total expenditures and emission, and maximizing the system reliability. An economic responsive load model is used to evaluate the impacts of DSRs on system reliability while the tradeoff between the targets above is handled by the Lexicographic method. It is worth mentioning that the resulted model is recast into a MILP problem and the GAMS modeling language is used to formulate it. The formulations are presented in detail as follows.

4.1. Environmental Target: Emission Value Minimization

In a power system, the emission is usually modeled as a quadratic function that can be linearized by a set of piecewise blocks [14]. In this paper, to reflect the regional per unit emission value, depending on unit's location the v^i is applied to the emission function (10). This way, the specified level of emissions in the countryside is differentiated from urban sector.

$$\min f_1 : \sum_{t \in T} \sum_{i \in N_G} v^i (Em^i u^i(t) + \sum_{k \in N_{SE}^i} Em_k^i(t) Y_k^i) \quad (10)$$

This target is subjected to the following constraints.

4.1.1 Generation Constraints

$$\sum_{i \in N_G} G^i(t) = loss(t) + \sum_{b \in N_B} D^b(t); \quad (11)$$

where: $G^i(t) = \{P_{min}^i(t) \times u^i(t)\} + \sum_{k \in N_{SF}^i} G_k^i(t),$

$$0 \leq G_k^i(t) \leq \bar{G}_k^i(t).$$

$$\sum_{i \in N_G} u^i(t) P_{max}^i(t) \geq \left\{ SR(t) + loss(t) + \sum_{b \in N_B} D^b(t) \right\}; \quad (12)$$

where: $\sum_{i \in N_G} r^i(t) \geq SR(t),$

$$0 \leq r^i(t) \leq \{P_{max}^i(t) - P_{min}^i(t)\} \times u^i(t).$$

$$P_{min}^i(t) \leq G^i(t) \leq \{P_{max}^i(t) \times u^i(t)\} - r^i(t). \quad (13)$$

where the power balance in each period is satisfied by (11); the specified reservation level for unanticipated events in power system such as units' unexpected outage or sudden increase in demand should be procured by the committed units as is considered in (12); and (13) stands for units' generations limits.

4.1.2 Maintenance Constraints

$$\sum_{t \in T} m^i(t) = MD^i; \quad \forall i \in N_G \quad (14)$$

$$\sum_{t \in T} \varpi^i(t) = 1; \quad \forall i \in N_G \quad (15)$$

$$m^i(t) - m^i(t-1) \leq \varpi^i(t); \quad \forall i \in N_G, \forall t \in T \quad (16)$$

$$m^i(t) + u^i(t) \leq 1; \quad \forall i \in N_G, \forall t \in T \quad (17)$$

$$m^i(t) + m^j(t) + m^k(t) \leq 1; \quad \forall t \in T \quad (18)$$

$$\varpi^i(t) + \varpi^j(t) \leq 1; \quad \text{where: } \sum_{\tau \in T} \varpi^i(\tau) \geq \varpi^j(t); \quad \forall t \in T \quad (19)$$

$$\sum_{i \in N_G} m^i(t) \leq \nu(t); \quad \forall t \in T \quad (20)$$

$$\varpi^i(t) = \varpi^j(t + MD^i + k); \quad 1 \leq t \leq T - MD^i - k, \quad \sum_{t=1}^{T-MD^i-k} [\varpi^i(t) + \varpi^j(t + MD^i + k)] = 2. \quad (21)$$

$$\varpi^i(t) = \varpi^j(t + MD^i - h); \quad 1 \leq t \leq T - MD^i + h \quad (22)$$

$$\sum_{i \in T} \sum_{j \in N_G^h} m^j(t) \leq \bar{N}^{UM} \quad (23)$$

where (14) stands for maintenance of unit i for a pre-specified time, i.e., MD^i ; (15) shows that each unit can be maintained just once over the horizon; successive periods of maintenance is guaranteed via (16); (17) is used to satisfy the relationship between the maintenance and commitment statuses, i.e., the units can be connected or not, even though they are not under inspection; impossibility of units' simultaneous maintenance is stated by (18); the precedence constraint (19) states the maintenance order of units in which the maintenance of unit i is prior to the maintenance of unit j ; (20) stands for the number of simultaneous units' maintenance, due to technical limitation; (21) stands for interval constraints that means a number of periods k are introduced between maintenance of units i and j ; (22) states that the maintenance of units i and j includes a specified overlap times h ; and (23) stand for the maximum number of maintained units in a region, which avoid the reduction of electric capacity. It is worth mentioning that constraints (14)-(17) are mandatory restrictions of a maintenance scheduling problem, while constraints (18)-(23) are arbitrary limitations and depends on the conditions of the system.

4.1.3 Line Flow Constraints: Generating units are in different regions of the network. This may affect the maintenance scheme; hence, the transmission security is handled by a transportation model (TM) as (24), which merely stands the absolute power limits. The first equation in (24) shows the power balance, while the permissible level of load curtailment should be less than or equal to the load, as given in the second equation; the third equation stands for the lines' flow limit, and the fourth equation represents the total load curtailment which should be lower than the allowable unserved energy, i.e., ε .

$$\begin{aligned} s^T \bar{f}^L(t) + \bar{g}(t) + \bar{r}(t) &= \bar{D}^b(t); \quad \forall t \in T \\ 0 &\leq r^b(t) \leq D^b(t); \quad \forall t \in T \\ -f_{\max}^l &\leq f^l(t) \leq f_{\max}^l; \quad \forall t \in T, \forall l \in N_L \\ \sum_{b \in N_B} r^b(t) &\leq \varepsilon; \quad \forall t \in T \end{aligned} \quad (24)$$

4.2. Economic Target: System Expenditures Minimization

In this target, the total system expenditures including operating, maintenance, and reserve costs are minimized while the encouragement index Γ is applied to the operational term.

$$\min f_2: \sum_{t \in T} \sum_{i \in N_G} \{ \Gamma^i(t) (\underline{G}_c^i u^i(t) + \sum_{k \in N_{SF}^i} G_k^i(t) \Lambda_k^i) + m^i(t) \tilde{\lambda}_c^i + r^l(t) \mu_c^i \} \quad (25)$$

s.t.

$$\text{Constraints (11)-(24)} \quad (26)$$

$$\sum_{t \in T} \sum_{i \in N_G} (\underline{Em}^i u^i(t) + \sum_{k \in N_{SF}^i} Em_k^i(t) \Upsilon_k^i) \leq Em_i^* \quad (27)$$

$$\sum_{t \in T} \sum_{i \in N_G} v^i (\underline{Em}^i u^i(t) + \sum_{k \in N_{SF}^i} Em_k^i(t) \Upsilon_k^i) \leq Em_v^* \quad (28)$$

where (27) and (28) are coordination constraints reflecting the global warming and regional environmental aspects, respectively. The upper bounds are obtained from the first target using the Lexicographic concept and DM's opinion.

4.3. Reliability Target: Average Net Reserve Value Maximization

This target aims at maximizing the ANRV over the scheduling horizon, (29). To investigate the impacts of DSRs on system reliability improvement, the reliability target is solved with and without considering the DSRs. Note that this model considers the availability of DSRs; hence, the impacts of DRPs should be neglected in the absence of DSRs.

$$\max f_3: \frac{1}{T} \sum_{t \in T} \beta(t) \{ \sum_{i \in N_G} P_{\max}^i (1 - m^i(t)) - \sum_{b \in N_B} D_{DR}^b(t) \} \quad (29)$$

s.t.

$$\text{Constraints (11)-(24)} \quad (30)$$

$$\begin{aligned} \underline{inc}^b(t) &\leq inc_{opt}^b \leq \overline{inc}^b(t); \\ \text{where: } inc_{opt}^b &= \{ \underline{inc}^b(t) \times \varphi^b(t) \} + \sum_{k \in N_{SF}^b} \sigma_k^b(t), \quad (31) \\ 0 &\leq \sigma_k^b(t) \leq \bar{\sigma}_k^b(t) \end{aligned}$$

$$\sum_{b \in N_B} \varphi^b(t) \leq \bar{N}_{DRR}(t); \quad \forall t \in T \quad (32)$$

$$\begin{aligned} \sum_{i \in N_G} P_{\max}^i (1 - m^i(t)) - \sum_{b \in N_B} D_{DR}^b(t) &\geq R_{Th}(t); \\ R_{Th}(t) &= \alpha(t) \times \sum_{b \in N_B} D_{DR}^b(t) \times \left(\frac{\sum_{t \in T} (\sum_{i \in N_G} P_{\max}^i - \sum_{b \in N_B} D^b(t))}{\sum_{t \in T} \sum_{b \in N_B} D^b(t)} \right) \end{aligned} \quad (33)$$

$$\sum_{t \in T} \sum_{i \in N_G} (\underline{Em}^i u^i(t) + \sum_{k \in N_{SF}^i} Em_k^i(t) \Upsilon_k^i) \leq Em_i^{**} \quad (34)$$

$$\sum_{t \in T} \sum_{i \in N_G} v^i (\underline{Em}^i u^i(t) + \sum_{k \in N_{SF}^i} Em_k^i(t) \Upsilon_k^i) \leq Em_v^{**} \quad (35)$$

$$\begin{aligned} \sum_{t \in T} \sum_{i \in N_G} (\underline{G}_c^i u^i(t) + \sum_{k \in N_{SF}^i} G_k^i(t) \Lambda_k^i + m^i(t) \tilde{\lambda}_c^i + r^l(t) \mu_c^i) \\ + \sum_{t \in T} \sum_{b \in N_B} (\underline{\sigma}_{inc}^b \varphi^b(t) + \sum_{k \in N_{SF}^b} \sigma_k^b(t) \pi_k^b) \leq TC_l^{**} \end{aligned} \quad (36)$$

where in (11), (12), and (24), in the presence of DSRs, $D^b(t)$ is replaced by $D_{DR}^b(t)$; Depending on system operator purpose in implementing the DRPs, amount of incentive is restricted by (31); (32) stands for the maximum number of locations with the capability of performing DRPs; the level of net reserve in GM scheduling is guaranteed in (33) where $R_{Th}(t)$ is contemplated as a specified threshold and is proportional to the demand's percentage and the average gross reserve over the scheduling horizon; and (34), (35), and (36) are coordination constraints of the emission level, emission values, and total cost, respectively. The upper

bounds are obtained by solving the prior target as provided in Fig. 1.

5. Numerical Evaluation

The performance of the proposed model is demonstrated using a modified 24-bus IEEE-RTS as portrayed in Fig. 2. This system has 26 generating units; 15 oil-based units (O_1 - O_{15}), 9 coal-fired units (C_{16} - C_{24}), and 2 nuclear units (N_{25} - N_{26}). The system data was obtained from [33]. The scheduling horizon is 52-week where the peak load is 2100 MW. Both the emission and cost functions are approximated by 20 linear segments [19]. The number of segments is selected so that the incremental rate in successive slopes is obtained lower than 0.05 in order to have a very good approximation for the quadratic functions. To reflect the regional value of per unit emission, three areas are considered where the v^i is set to 0.8, 1, and 1.2 1/lbs, respectively. To have a higher reserve in higher loading periods, unlike the previous work, [22], different values for $\alpha(t)$, are considered in (33); for loading higher than 88% of maximum demand, $\alpha(t)$ is set to 0.5 while for loading between 75-88% and loading lower than 75% of maximum demand, it is set to 0.45 and 0.4, respectively. Similar priority in units' maintenance is considered while three units can be maintained simultaneously. The network losses are neglected and, no unserved energy is allowed by the system operator. In the Lexicographic method, δ_j is set to 0.1. The proposed model is implemented in GAMS modeling language and the MILP problems are solved via the Cplex 12.5.1.0.

To determine the maintenance scheme and evaluate the system reliability via the proposed model, two different conditions such as without and with considering DSRs are taken into account.

using the obtained result, 109.568 million (M), the encouragement index Γ^i is calculated and applied to the economic target while emission level and value of phase 1, by a 10% increase, as constraints are imposed to the phase 2. Therefore, the right side of (27) and (28) are set to 137.675 Mlbs and 120.525 M, respectively. In phase 3, the ANRV is maximized while emission level and value, and total cost of phase 2, by 10% increase, are imposed to phase 3 as constraints. Therefore, the right sides of (34), (35), and (36) are set to 139.404 Mlbs, 121.518 M, and \$264.078M, respectively.

The emission value and level, and the total cost of all phases in Case 1 are depicted in Fig. 3. As can be seen, the emission value is placed at its minimum level in phase 1, while the system costs in phase 2 have been minimized. In phase 3, by regulating the upper bound of (34)-(36) up to 110% of optimal results of phase 2, compared to the previous phases, the ANRV is increased. The ANRVs, which depend on the $\beta(t)$ and net reserve level (NRL) over the scheduling horizon, in phases 1-3 are 1421.576, 1420.683, and 1460.865 MWs.

The maintenance time of the units is presented in Table 3, while the NRL over scheduling time is portrayed in Fig. 4. Using Table 3 and Fig. 4, it can be seen that the NRLs in weeks 10-15 and weeks 34-41 in phase 3 are lower than those in phases 1-2. This occurs due to more generation outage capacity over the aforementioned periods in phase 3 (450-947 MW) compared with phases 1-2 (231-555 MW).

Fig. 3. Optimization results of case #A

Table 3 Maintenance scheme of units in multifarious phases of case 1

Unit	O ₁	O ₂	O ₃	O ₄	O ₅	O ₆	O ₇
Phase 1	47-48	3-4	24-25	20-21	51-52	1-2	32-33
Phase 2	17-18	32-33	40-41	13-14	35-36	20-21	1-2
Phase 3	21-22	21-22	7-8	7-8	21-22	8-9	42-43
Unit	O ₈	O ₉	O ₁₀	O ₁₁	O ₁₂	O ₁₃	O ₁₄
Phase 1	23-24	14-15	29-31	3-5	50-52	24-27	20-23
Phase 2	23-24	12-13	29-31	24-26	7-9	24-27	1-4
Phase 3	16-17	16-17	40-42	31-33	9-11	35-38	38-41
Unit	O ₁₅	C ₁₆	C ₁₇	C ₁₈	C ₁₉	C ₂₀	C ₂₁
Phase 1	17-20	6-8	17-19	36-38	26-28	36-39	39-42
Phase 2	46-49	21-23	17-19	36-38	26-28	36-39	39-42
Phase 3	12-15	31-33	27-29	27-29	27-29	39-42	14-17
Unit	C ₂₂	C ₂₃	C ₂₄	N ₂₅	N ₂₆		
Phase 1	9-12	40-43	31-35	6-11	12-17		
Phase 2	9-12	40-43	31-35	6-11	12-17		
Phase 3	34-37	31-34	9-13	34-39	10-15		

Fig. 2. One-line diagram for modified 24bus system

5.1. Case 1: MTGM Scheduling without DSRs

To handle the MTGM problem without considering DSRs, first, the value of generated emissions are minimized. Then,

Fig. 4. Available net reserve in multifarious phase of case 1

5.2. Case 2: MTGM Scheduling considering DSRs

In this case, the impacts of DSRs on the system reliability as well as the impacts of the number of available DSRs' on the system reliability and locational incentives are investigated. The nominal potential of DRPs is 10% of the total load in each bus, and the loads' weekly price elasticity is extracted from [32].

Since the emission level and value, and the total cost do not increase compared to Case 1, the right sides of (34)-(36) are set to optimal results of Case 1, 133.44 Mlbs, 120.17 M, and \$246.34 M, respectively. Considering (36), in Case 1, the total operating, maintenance, and reserve cost is \$246.34 M; therefore, in Case 2, these costs plus the total incentives should be lower than \$246.34 M.

5.2.1. Case 2.a: Evaluating impacts of DSRs on system reliability

Assuming that DRPs are performed in all load buses (17 locations in 24-bus system), the ANRV in Case 2 is 1498.45 MW, which is 2.57% higher than the ANRV of Case 1. A comparison between the obtained parameters of Case 2.a and Case 1 is provided in Table 4. It shows that, although an additional cost (incentive) has been imposed on the system in Case 2.a, total cost and emissions are quasi-similar to Case 1.

Table 4 Economic and environmental parameters of case 1 and case 2.a

Case	O&M (M\$)	Reserve (M\$)	Total incentive (M\$)	Total cost (M\$)
1	192.099	54.24	---	246.339
2.a	191.704	51.655	2.64	246
Case	SO ₂ (Mlbs)	NO _x (Mlbs)	Total emission (Mlbs)	Emission value (M)
1	38.122	95.311	133.443	120.17
2.a	38.046	95.116	133.16	120

The available NRL over the scheduling time in Case 1 and Case 2.a are compared in Fig. 5. As can be seen, the

consumers' demand is altered during the horizon due to demand elasticity in the presence of DSRs where in the peak periods the customers decline their consumption due to more tangible effects of self-elasticity. However, in the valley and off-peak periods, the demand is increased because of the more considerable impact on cross elasticity. Comparing with Case 1, NRLs of Case 2.a during periods 2, 23-25, and 44-52 has been increased, due to DSRs presence and high reserve threshold.

5.2.2. Case 2.b: Evaluating number of available DSRs on system reliability

This case investigates the impacts of a number of available DSRs' on locational incentives and net reserve allocation. Customers cooperate in DRPs in different locations (1, 5, 9, 13, and 17) that makes different scenarios while incurred costs, emissions value, and level are set lower than the optimal solution of Case 1. The obtained ANRVs of these scenarios are 1465.258, 1478.082, 1487.388, 1493.955, and 1498.456 MWs, respectively. It can be seen that the ANRV is improved as the number of available DSRs increases, due to more variations of the demand pattern. The awards in per location are presented in Table 5 where the received incentive per location is determined so that the operator can use the maximum potential of DSRs. From this table, it is clear that bus 18 is the most sensitive location for implementing voluntary DRPs.

Figure 6 demonstrates different parts of incurred costs (operating and maintenance cost (O&M-C), reserve cost (Re-C), and total incentives (Inc)), emission level (Em-L), and emission value (Em-V) of all scenarios in Case 2.b. As can be seen, by increasing the number of DSRs, the level of paid award to the consumers, is increased. Note that the variation of other parameters is due to demand variations in the presence of DSRs (reducing or shifting load). Considering Table 5 and Fig. 6 shows that, although incentive imposes an additional cost, the total cost and emissions are lower than or equal to the final solution of Case 1, while ANRV is increased considerably (4.3 MW-37.6 MW) depending on the number of available DSRs.

Fig. 5. Net reserve allocation over the horizon with and without DSRs

Table 5 Optimal value of the award (\$/MWh) and location of DRPs implementation in multifarious scenarios, case 2.b

Bus no	Allowable Location				
	1	5	9	13	17
#1	-	-	-	4.902	4.902
#2	-	-	-	-	4.888
#3	-	-	4.658	4.658	4.658
#4	-	-	-	-	4.866
#5	-	-	-	-	4.866
#6	-	-	-	4.866	4.866
#7	-	-	-	5.025	5.025
#8	-	-	5.003	5.003	5.003
#9	-	-	4.717	4.717	4.717
#10	-	4.762	4.762	4.762	4.762
#13	-	4.651	4.651	4.651	4.651
#14	-	4.63	4.63	4.63	4.63
#15	-	4.292	4.292	4.292	4.292
#16	-	-	-	-	4.505
#18	4.405	4.405	4.405	4.405	4.405
#19	-	-	4.525	4.525	4.525
#20	-	-	-	4.484	4.484

Fig. 6. Economic and environmental parameters of Case 2

Table 6 provides the maintenance scheme of units for all scenarios of Case 2.b in the presence of DSRs where the GM plan of units is nearly similar in all scenarios, as a consequence of obtaining the maximum reliability criteria.

Fig. 7 shows the system capacity in different periods regarding the maintenance capacity and load profile in the presence of DRPs. By increasing the number of available DSRs the system reserve capacity is increased in peak periods due to more demand reduction, and the reserve capacity in off-peak periods is decreased due to more shifting; e.g., in period 51, by increasing the DSRs, the percentage of the net reserves in different scenarios are 49.6%, 54.9%, 59.1%, 62.1% and, 64.3% of the demand, while during off-peak period 38, the net reserves are 58.1%, 57.3%, 56.7%, 56.3%, and 56% of the demand, respectively

Table 6 Inspection time in different scenarios of case 2.b

Unit	Allowable Location				
	1	5	9	13	17
O ₁	21-22	21-22	7-8	21-22	7-8
O ₂	21-22	21-22	21-22	7-8	21-22
O ₃	7-8	7-8	7-8	21-22	21-22
O ₄	21-22	7-8	21-22	21-22	21-22
O ₅	7-8	21-22	21-22	7-8	7-8
O ₆	16-17	16-17	16-17	8-9	16-17
O ₇	8-9	16-17	16-17	16-17	8-9
O ₈	16-17	8-9	42-43	42-43	16-17
O ₉	42-43	42-43	8-9	16-17	42-43
O ₁₀	9-11	9-11	40-42	40-42	9-11
O ₁₁	40-42	31-33	9-11	9-11	31-33
O ₁₂	31-33	40-42	31-33	31-33	40-42
O ₁₃	38-41	38-41	38-41	12-15	38-41
O ₁₄	35-38	12-15	12-15	35-38	12-15
O ₁₅	12-15	35-38	35-38	38-41	35-38
C ₁₆	27-29	27-29	31-33	27-29	27-29
C ₁₇	27-29	27-29	27-29	31-33	27-29
C ₁₈	31-33	31-33	27-29	27-29	31-33
C ₁₉	27-29	27-29	27-29	27-29	27-29
C ₂₀	31-34	31-34	31-34	31-34	31-34
C ₂₁	14-17	39-42	34-37	34-37	14-17
C ₂₂	39-42	14-17	39-42	39-42	39-42
C ₂₃	34-37	34-37	14-17	14-17	34-37
C ₂₄	9-13	9-13	9-13	9-13	9-13
N ₂₅	34-39	34-39	34-39	34-39	10-15
N ₂₆	10-15	10-15	10-15	10-15	34-39

Fig. 7. Available gross reserve in Case 2.b

Fig. 8. Available net reserve in Case 2.c

5.2.3. Case 2.c: Evaluating arbitrary awards of DRPs on system parameters

In this case, the effects of arbitrary awards on reliability, costs, and emission level and value are studied. In this regard, it is supposed that DSRs are available in all load buses while different scenarios are studied for optional awards: *i)* S1 with $1 \times \text{inc}^b$, *ii)* S2 with $2 \times \text{inc}^b$, and *iii)* S3 with $3 \times \text{inc}^b$. Table 7 presents a comparison of the results under these scenarios for Case 2.c.

It can be concluded that although the system reliability is increased in the presence of DSRs, maximum reliability margin cannot be achieved by using arbitrary awards. However, the load profile is affected by DRPs. Note that the reliability margin depends on GM plan and demand pattern. Therefore, the more incentive is paid, the more peak shaving and the more reserve capacity is obtained. The NRL over the scheduling horizon in different scenarios of Case 2.c is compared in Fig. 8. It is obvious that due to dissimilar demand variations as a result of diverse received awards by customers, NRL over the scheduling horizon is not identical to Case 2.c that leads to diverse ANRV.

TABLE 7 Economic, environmental and, reliability factors of case 2.c

Scenario	S1	S2	S3
ANRV (MW)	1470.713	1480.555	1490.398
O&M-C (M\$)	190.687	189.938	190.194
Re-C (M\$)	55.208	54.965	53.626
Inc (M\$)	0.104	1.096	2.179
Em-L (Mlbs)	132.45	131.93	132.11
Em-V (M)	120	120	120

6. Conclusion

In this paper, a multi-target generation maintenance (MTGM) scheduling model under smart grid environment aiming at finding a compromise among different targets such as *i)* environmental, *ii)* economic, and *iii)* reliability using Lexicographic method has been proposed. The DSR as one of the smart grids' capability has been studied to improve the system reliability. First, in the environmental target, unlike the previous studies in which the global emission was minimized, regional impacts of pollutants value and level have been considered; both are considered as correlation constraints of next phases. Then, incurred costs (operating, maintenance, and reserve costs) are minimized and, finally, the reliability index is maximized with and without DSRs considerations. The proposed model has been tested on the 24-bus IEEE-RTS. The proposed model determines the optimum incentive in per location, nominal, and actual potential for participating consumers in DRPs, maintenance scheme, commitment status, reserve, and energy schedules. It has been concluded that the system reliability has been improved tangibly by considering DRPs while the produced contaminants and total costs over the horizon have not been increased. In addition, it is shown that the system reliability has been improved by increasing the number of available DSRs, although the required capital costs of DSRs infrastructure may increase. It has also been proven that arbitrary incentives cannot satisfy the customers to participate in DRPs in their maximum potentials which conduct to lessen ANRV.

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8. References

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