Spinning reserve contribution using unit responsibility criterion incorporating preventive maintenance scheduling

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ABSTRACT
Generators maintenance scheduling is addressed as a crucial issue that may affect both economy and reliability of power systems. System reserve procurement may facilitate preventive maintenance scheduling in such way to guarantee system reliability as well as security. In this paper, a new deterministic criterion for determining operating reserve capacity is introduced. In the proposed model, the unit reserve provision is handled based upon unit responsibility criterion (URC) that depends on unit capacities as well as number of committed units. Therefore, a new formulation for reserve assessment based upon URC incorporating preventive maintenance scheduling (PMSURC) is developed. The proposed model is structured as a mixed integer programming (MIP) and is solved using CPLEX solver. Several analyses are conducted to investigate the impact of unit responsibility criterion on the reserve assessment expenditure. An IEEE Reliability Test System (RTS) is employed to demonstrate the effectiveness of the proposed methodology and simulation results are promising.

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Introduction
Preventive maintenance can be defined as an undertaken activity at preselected intervals to operate satisfactorily and reduce the deterioration of the equipment [1]. In power system research studies, optimal outage scheduling of generating units is introduced as a preventive maintenance scheduling (PMS). Maintenance schedule of generating units is extremely crucial due to affecting short-term generation scheduling. Furthermore, regular preventive maintenance of generating units can defer capital expenditures for new power plants since increasing the generator’s lifetime [2]. The aim of PMS problem can be both economic-driven as well as reliability-driven. Economic driven minimizes total operation expenditures over a scheduling time horizon [3–7]; while reliability driven utilizes several reliability indices such as: expected lack of peak net reserve, expected energy not supplied (EENS), and loss of load probability (LOLP) [8–11].

This paper emphasizes on minimizing the total operation and maintenance expenditures in order to investigate the economic benefits of PMS. Indeed, PMS problem is contemplated as a large scale, non-convex, and mixed integer combinatorial optimization problem which can be solved via different deterministic [3,12], heuristic [2,4,13–16], and hybrid methods [17–20], in previous decades. Currently, in most cases, the commercial solvers are also utilized to solve such complicated problem [5,7,21,22]. In Ref. [5], general algebraic modeling system (GAMS) is employed to solve PMS to minimize the operation expenditure by utilizing cost reduction index. The impact of demand response program on PMS problem is investigated in [7]. Maintenance problem is solved by considering the network constraints besides the conventional constraints [21], whereas in [22] GAMS software is also employed to solve security constrained PMS to minimize the operation cost while fuel constraint and energy purchased from outside are also contemplated.

System reserve procurement is addressed as an essential constraint in PMS problem, which improves system reliability against sudden increase in demand and generating units’ unexpected outage. Although, system reserve ensures security but it increases operation cost due to calling more costly units which generates at a non-optimal point [23,24]. Multifarious deterministic and probabilistic techniques are utilized to determine spinning reserve requirements in power systems. Deterministic methods are more comprehensible and easier than probabilistic methods. Indeed, stochastic nature of the power system behavior is not contemplated in deterministic methods which cause to prefer by most utilities in comparison with stochastic ones [25,26]. In previous studies of PMS, spinning reserve requirement is usually considered as a pre-specified amount that is either equal to the largest unit...
Nomenclature

\(a(\cdot), b(\cdot), c(\cdot)\) fuel cost coefficients

\(AUC(\cdot)\) maximum capacity of committed units in a cluster at a period

\(b_m\) slope of mth segment in linearized fuel cost curve

\(COUR(\cdot)\) class of unit responsibility of a cluster in a period

\(D(\cdot)\) power demand of a period

\(F(\cdot)\) unit fuel cost function

\(E(\cdot)\) lower limit on the fuel cost of a unit

\(I(AUC)\) unit index

\(IUR(\cdot)\) incremental unit responsibility of a cluster in a period

\(loss(\cdot)\) system losses in a period

\(m\) index segment for linearized fuel cost curve

\(M(\cdot)\) maintenance cost of a unit

\(N_C\) number of generating units

\(N_{sh}\) number of clusters

\(N_{sp}\) number of segments for the piece-wise linearized fuel cost curve

\(P(\cdot)\) output power of a unit in a period

\(P_m(\cdot)\) generated power in mth segment of linearized fuel cost curve

\(P_{m}(\cdot)\) maximum generated power in mth segment

\(P(\cdot)/P(\cdot)\) maximum/minimum generating capacity of a unit

\(R(\cdot)\) required maintenance crew of a unit in a period

\(s(\cdot)\) maintenance starting time

\(SRR(\cdot)\) system reserve requirement in a period based upon URC

\(SRN(\cdot)\) system reserve necessity in a period based on rule of thumb

\(t\) period index

\(T\) scheduling time horizon

\(TUR(\cdot)\) total unit responsibility of a cluster in a period

\(u(\cdot)\) commitment state of a unit in a period

\(up(\cdot)\) unit participation level in reserve procurement in a period

\(z(\cdot)\) maintenance status of a unit

\(Y_k\) number of units in kth cluster

\(\delta(\cdot)\) maintenance duration of a unit

\(\zeta(\cdot)\) total available maintenance crew in a period

\(\xi(\cdot)\) cluster index

In this section, the impact of unit responsibility criterion (URC) on reserve assessment is discussed. Furthermore, a mixed integer programming (MIP) formulation for the PMS is presented. In the following subsections, more explanations are also elaborated.

Unit responsibility criterion in reserve assessment

In this section, a procedure is nominated to assess the system reserve necessity among both inexpensive and costly committed units. In the proposed method, the reserve necessity is apportioned by introducing unit responsibility criterion (URC) that depends on both unit capacities as well as number of committed units. The hierarchy for achieving the unit contribution level in system reserve acquisition based upon URC incorporating PMS is depicted in Fig. 1. As presented in Fig. 1, PMS is firstly performed to determine the maintenance scheme as well as most economical committed units in each period. Then, committed units have to be classified in the descending order in terms of their capacities and the number of available units with similar capacities must be also specified in each cluster.

In the presented framework, the class of unit responsibility (COUR) is defined as the difference between the capacities of two successive units which can be presented as:

\[
COUR(\xi_t, t) = \begin{cases} 
AUC(\xi_t, t) - AUC(\xi_{t+1}, t) & \forall t \in \{1, 2, \ldots, N_{sh} - 1\}, \ 
AUC(\xi_t, t) & \forall t \in \{1, 2, \ldots, T\} 
\end{cases} 
\]  

(1)

In Eq. (1), \(N_{th}\), \(\xi_t\), and \(AUC\) represents number of clusters in terms of capacities, rth cluster and maximum capacity of committed unit in a cluster, respectively.

Incremental unit responsibility (IUR) of a committed unit can be acquired as Eq. (2), where \(Y_t\) represents the number of units in rth class.

\[
IUR(\xi_t, t) = \sum_{r=1}^{N_{sh}} \frac{\xi_t}{Y_t} \quad \forall t \in \{1, 2, \ldots, N_{sh}\}, \ t \in \{1, 2, \ldots, T\} 
\]  

(2)

In this step, each unit reservation level; the so-called total unit responsibility (TUR); is obtained as:

\[
TUR(\xi_t, t) = \sum_{r=1}^{N_{sh}} IUR(\xi_t, t) \quad \forall t \in \{1, 2, \ldots, N_{sh}\}, \ t \in \{1, 2, \ldots, T\} 
\]  

(3)

PMSURC formulation based on MIP

In this section, the impact of unit responsibility criterion (URC) on reserve assessment is discussed. Furthermore, a mixed integer
According to Eq. (3), the unit participation level \( (upl) \) in terms of its capacity to procure system reserve can be achieved by Eq. (4). Moreover, the available power of each unit for satisfying the load is commensurate with \( [1 - upl] \).

\[
\% upl(\xi, t) = \frac{TUR(\xi, t)}{AUC(\xi, t)} \times 100 \quad \forall t \in \{1, 2, \ldots, N_{\text{ alc}}\}, t \in \{1, 2, \ldots, T\}
\]  \hspace{1cm} (4)

Referring to Eq. (3) and number of available units in per cluster, system reserve requirement \( (SRR) \) based upon URC can be presented as:

\[
SRR(t) = \sum_{i=1}^{N_{\text{ alc}}} TUR(\xi, t)Y_{i} \quad \forall t \in \{1, 2, \ldots, T\}
\]  \hspace{1cm} (5)

According to Eq. (3), Eq. (5) can be rewritten as:

\[
SRR(t) = \sum_{i=1}^{N_{\text{ alc}}} \left\{ IUR(\xi, t) \sum_{v=1}^{V} Y_{i} \right\} \quad \forall t \in \{1, 2, \ldots, T\}
\]  \hspace{1cm} (6)

Eq. (6) can be simplified according to Eq. (2) and the system reserve is derived by Eq. (7):

\[
SRR(t) = \sum_{i=1}^{N_{\text{ alc}}} COUR(\xi, t) \quad \forall t \in \{1, 2, \ldots, T\}
\]  \hspace{1cm} (7)

Now, referring to Eq. (1), Eq. (7) can be expressed as:

\[
SRR(t) = \sum_{i=1}^{N_{\text{ alc}}} \left\{ AUC(\xi, t) - AUC(\xi_{n_{\text{ alc}}}, t) \right\} + AUC(\xi_{n_{\text{ alc}}}, t) \quad \forall t \in \{1, 2, \ldots, T\}
\]  \hspace{1cm} (8)

According to Eq. (8), the system reserve requirement based upon URC is obtained equal to the largest unit's capacity. Indeed, one of the major contributions of the proposed URC technique is that the total spinning reserve is equivalent to the largest unit capacity.

**Preventive maintenance scheduling incorporating URC**

PMS is addressed as one of the crucial issues in power system studies, whereas the system reserve acquisition is considered as a challenging concern. In this paper, a cost-based model for the preventive maintenance problem is presented. The objective of the proposed model is to minimize the system total expenditures, including operating and maintenance over the scheduling time horizon. The suggested framework determines the maintenance scheme, the commitment status of generating units and energy scheduling simultaneously. Here, an alternative MIP formulation, which is suitable for available MIP software, is presented for the suggested structure. One of the main features of the MIP method includes direct measure of the optimality of a solution and more flexible and accurate modeling capabilities. The employed optimization software is general algebraic modeling system (GAMS) [28], and CPLEX [27] as a commercial and computationally efficient MIP solver is used for solving the problem.

The linearized objective function for PMS problem is presented as

\[
\text{Min} \sum_{t=1}^{T} \sum_{i=1}^{N_{\text{ alc}}} \left\{ E(i)u(i, t) + \sum_{m=1}^{N_{\text{ alc}}} P_{m}(i, t)b_{m}(i) \right\} + z(i, t)MC_{c}(i) \]  \hspace{1cm} (9)

The first term of the objective function is operation cost and the second one is maintenance expenditures. More explanations about each parameter of the objective function are outlined in the following.

The quadratic fuel cost function typically utilized in scheduling problems is formulated as:

\[
F(i, t) = a(i) + b(i)P(i, t) + c(i)P^{2}(i, t)
\]  \hspace{1cm} (10)

Eq. (10) can be accurately approximated by a set of piecewise linear blocks, which cannot be recognizable from the nonlinear model if enough segments are utilized. An analytic representation of the piecewise linear function is provided by

\[
F(i)u(i, t) + \sum_{m=1}^{N_{\text{ alc}}} P_{m}(i, t)b_{m}(i)
\]  \hspace{1cm} (11)

In Eq. (11), the ith unit on/off status is symbolized by \( u(i, t) \) which is one when the generator is on, and otherwise, it takes zero. Furthermore, \( z(i, t) \) in Eq. (9) shows the unit maintenance status which is one when the generator is under maintenance, and otherwise, it takes zero.

The objective function is subjected to the following constraints:

(a) **Economic unit commitment constraints:**

(a.1) Generated power from committed units must satisfy the required demand and system losses.

\[
\sum_{i=1}^{N_{\text{ alc}}} P(i, t) = D(t) + \text{loss}(t) \quad \forall t \in \{1, 2, \ldots, T\}
\]  \hspace{1cm} (12)
(a.2) To encounter any unanticipated operating conditions such as unexpected outage of generating units or sudden increase in demand, the specified reservation amount must be considered. System reserve can be determined by a rule of thumb method or based upon URC method. According to the rule of thumb method, system reserve necessity (SRN(t)) is usually a pre-specified amount that is either equal to the largest unit or a given percentage of the forecasted load. Mathematically, system reserve is the total amount of maximum capacity of all synchronized units minus the total generating output which can be given by

\[
\sum_{i=1}^{N} s(i,t)P(i,t) > D(t) + loss(t) + \left\{ \begin{array}{ll}
SRN(t) & \text{Based upon URC} \\
0 & \text{Based upon rule of thumb}
\end{array} \right. \quad \forall t \in \{1, 2, \ldots, T\}. \tag{13}
\]

(a.3) Power generation constraint is expressed as

\[
P(i,t)u(i,t) + \sum_{m=1}^{N_{B}} P_m(i,t) \leq P(i,t)u(i,t) \quad \forall i \in \{1, 2, \ldots, N_C\}, t \in \{1, 2, \ldots, T\}
\]

\[
0 \leq P_m(i,t) \leq P_m(i,t) \quad \forall i \in \{1, 2, \ldots, N_C\}, t \in \{1, 2, \ldots, T\}, m \in \{1, 2, \ldots, N_{GB}\} \tag{14}
\]

(b) Maintenance constraints:

(b.1) Each unit must be maintained for specified time as follows.

\[
\sum_{t=1}^{T} s(i,t) = \delta_i \quad \forall i \in \{1, 2, \ldots, N_C\} \tag{15}
\]

(b.2) Each unit is taken under maintenance only once during the time horizon. \(s(i,t)\) is a maintenance starting variable that is considered equal to one if \(i\) th generating unit starts at the beginning of period \(t\), and otherwise it takes zero, i.e.

\[
\sum_{t=1}^{T} s(i,t) = 1 \quad \forall i \in \{1, 2, \ldots, N_C\} \tag{16}
\]

(b.3) The maintenance of each unit must be performed in successive periods.

\[
z(i,t) - z(i,t-1) \leq s(i,t) \quad \forall i \in \{1, 2, \ldots, N_C\}, t \in \{1, 2, \ldots, T\} \tag{17}
\]

(b.4) Connection constraint represents the relation between the maintenance status and the commitment status of the generating unit. Since nuclear units are low cost with higher startup time as well as shut down time; nuclear units are always committed except during the maintenance time.

\[
z(i_1,t) + u(i_1,t) \leq 1 \quad \forall i \in \text{Thermal and Hydro units}, t \in \{1, 2, \ldots, T\}
\]

\[
z(i_2,t) + u(i_2,t) = 1 \quad \forall i \in \text{Nuclear units}. t \in \{1, 2, \ldots, T\} \tag{18}
\]

(b.5) Exclusive constraint represents that \(i\) th and \(j\) th generating units cannot be taken under maintenance at the same time, i.e.

\[
z(i,t) + z(j,t) \leq 1 \quad \forall t \in \{1, 2, \ldots, T\}. \tag{19}
\]

(b.6) The total available technical staffs, i.e. \(\zeta(t)\), as well as the required crews for the specified unit maintenance the so called \(RC(i)\), in each period is definite. Therefore, number of the units which can be inspected simultaneously is limited.

\[
\sum_{i=1}^{N_c} RC(i)z(i,t) \leq \zeta(t) \quad \forall t \in \{1, 2, \ldots, T\} \tag{20}
\]

**Simulation results and discussions**

In this paper, the IEEE Reliability Test System has been utilized for simulation studies with a scheduling time horizon of 52 weeks as shown in Fig. 2. This system includes 26 generating units; 15 oil with 1031 MW namely OF1–OF15, 9 coal with 1274 MW so-called CF16–CF24 and 2 nuclear with 800 MW as N25–N26. The peak load is 2100 MW and the weekly load profile of the IEEE-RTS is used to obtain the annual load curve [5]. The fuel cost curves for generating units given as a quadratic function [29] are approximated by 20 linear segments between the minimum and maximum generating units’ capacity. Moreover, generating units offer capacity cost of reserve at the rate of 100% of their highest incremental cost of energy. More required data including operating and maintenance insights of the generating units are provided in [30]. In this study, the total available technical staffs in each period are considered equal to 30. The required maintenance crew for each unit is given in Table 1. Moreover, the network losses is disregarded during the scheduling period.

In order to investigate the impact of unit responsibility criterion on reserve assessment, the PMS is firstly performed to specify the maintenance scheme incorporating the most economical units in each period. The system reserve necessity, i.e. \(SRN(t)\), as a rule of thumb is considered equal to the largest unit capacity [5]. Here, the system demand is supplied by the most economical committed units merely to minimize the operating cost while the system reserve is provided with the most expensive committed units. Applying CPLEX 12.4.0 [27], system total expenditures including operating, maintenance and reserve, is obtained as 240.42 million $/year in PMS problem. Moreover, the maintenance scheme of generating units is presented in Table 2.

**Table 1**

<table>
<thead>
<tr>
<th>Unit</th>
<th>(RC(i)) Unit</th>
<th>(RC(i)) Unit</th>
<th>(RC(i)) Unit</th>
<th>(RC(i)) Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>OF1–OF9</td>
<td>15</td>
<td>OF10–OF15</td>
<td>10</td>
<td>CF16–CF24</td>
</tr>
<tr>
<td>CF25</td>
<td>9</td>
<td>N25–N26</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>
Now, by determining the most economical units in each period, unit responsibility criterion impacts on the system reserve assessment as well as system expenditures can be investigated. The participation level of committed units, i.e. upl, in system reserve provision can be achieved from Eqs. (1)–(5). The procedure for reserve allotment based upon URC is presented for the first period of scheduling as follows.

The system demand is equal to 1810.2 MW for the 1st period. In consequence of performing PMS, 16 units with total generation capacity of 2222 MW are committed to supply the demand as well as providing system reserve requirement, i.e. 400 MW, which categorized in 6 clusters (\( \xi_1 \)–\( \xi_6 \)). Referring to Eqs. (1)–(5), the system reserve assures among the aforementioned committed units which has been shown in Table 3. As reported in Table 3, the summation of unit reservation levels is commensurate to 400 MW which is equivalent to the largest unit capacity.

The proposed procedure is similarly repeated for the other time periods. Due to the cooperation of all committed units in reserve provision, the available power of committed units to satisfy the demand is lesser than the maximum capacity. Therefore, a generation re-dispatch is necessitated to meet the demand in each period. This point must be considered in generation re-dispatch that, available power of a unit in per period is the difference between the unit’s marginal capacity and the unit’s reservation level. By applying CPLEX 12.4.0 optimizer as a computationally efficient MIP solver [27], system total expenditure is computed equal to 230.8 million $/year in PMSURC. The optimization results of PMS and PMSURC has been provided in Table 4.

Referring to Table 4, operation and maintenance cost in PMSURC is increased 11.11%, while the reserve expenditure is decreased 47.08% due to the more proper reserve allocation in comparison with PMS. Moreover, the system total costs including operation, maintenance and reserve declines 240.4 – 230.8 = 9.6 million $/year, which is about 3.99%.

Generation pattern of committed units can be compared during the scheduling time in PMS and PMSURC. This issue is depicted for one of the lowest cost as well as the most expensive units in Figs. 3 and 4, respectively.

N26 as one of the lowest cost units in this system is committed with its maximum capacity in PMS except the maintenance time; while in PMSURC due to participating in system reserve procurement, the aforementioned unit does not cooperate in demand satisfaction with its maximum capacity. Indeed, this unit is committed 46 periods; hence, the available capacity over the time horizon is equal to 400 \( \times 46 = 18,400 \) MW. The generation power of 26th unit, i.e. N26, is 18,400 MW and 12970.65 MW in PMS and PMSURC, respectively; so the percentage of generation in terms of the available capacity is obtained equal to 100% and 70.49% in PMS and PMSURC, respectively. The generation pattern of 26th unit during the scheduling time is shown in Fig. 3.

### Table 2
Preventive maintenance scheme.

<table>
<thead>
<tr>
<th>Unit no.</th>
<th>Maintenance period</th>
<th>Unit no.</th>
<th>Maintenance period</th>
<th>Unit no.</th>
<th>Maintenance period</th>
<th>Unit no.</th>
<th>Maintenance period</th>
<th>Unit no.</th>
<th>Maintenance period</th>
</tr>
</thead>
<tbody>
<tr>
<td>OF1</td>
<td>5–6</td>
<td>OF7</td>
<td>49–50</td>
<td>OF12</td>
<td>14–16</td>
<td>CF17</td>
<td>18–20</td>
<td>CF22</td>
<td>40–43</td>
</tr>
<tr>
<td>OF2</td>
<td>15–16</td>
<td>OF8</td>
<td>40–41</td>
<td>OF13</td>
<td>29–32</td>
<td>CF18</td>
<td>19–21</td>
<td>CF23</td>
<td>45–48</td>
</tr>
</tbody>
</table>

### Table 3
Unit reservation level based upon URC in a sample period.

<table>
<thead>
<tr>
<th>Unit cluster (( \xi_\ell ))</th>
<th>( AUC(\xi_\ell) )</th>
<th>( COUR(\xi_\ell) )</th>
<th>( Y_\ell )</th>
<th>( IUR(\xi_\ell) )</th>
<th>( TUR(\xi_\ell) )</th>
<th>upl(( \xi_\ell )) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \xi_1 )</td>
<td>400</td>
<td>Eq. 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \xi_2 )</td>
<td>350</td>
<td>195</td>
<td>1</td>
<td>65</td>
<td>81.978</td>
<td>23.42</td>
</tr>
<tr>
<td>( \xi_3 )</td>
<td>155</td>
<td>55</td>
<td>4</td>
<td>7.857</td>
<td>16.937</td>
<td>10.92</td>
</tr>
<tr>
<td>( \xi_4 )</td>
<td>100</td>
<td>24</td>
<td>1</td>
<td>3</td>
<td>9.08</td>
<td>9.08</td>
</tr>
<tr>
<td>( \xi_5 )</td>
<td>76</td>
<td>64</td>
<td>4</td>
<td>5.33</td>
<td>6.08</td>
<td>3.62</td>
</tr>
<tr>
<td>( \xi_6 )</td>
<td>12</td>
<td>12</td>
<td>4</td>
<td>0.75</td>
<td>0.75</td>
<td>6.25</td>
</tr>
</tbody>
</table>

\[ SRR = (2 \times 106,937) + 81.978 + (4 \times 16,937) + 9.08 + (4 \times 6.08) + (4 \times 0.75) = 400 \]

### Table 4
Comparison of the cost in PMS and PMSURC.

<table>
<thead>
<tr>
<th></th>
<th>PMS</th>
<th>PMSURC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation and maintenance cost (m$/year)</td>
<td>177.9887479</td>
<td>197.7795985</td>
</tr>
<tr>
<td>Reserve assessment cost (m$/year)</td>
<td>62.43588392</td>
<td>33.035</td>
</tr>
<tr>
<td>System cost (m$/year)</td>
<td>240.4246318</td>
<td>230.8145985</td>
</tr>
<tr>
<td>Variation of operation and maintenance cost (%)</td>
<td>–</td>
<td>11.11</td>
</tr>
<tr>
<td>Variation of reserve assessment cost (%)</td>
<td>–</td>
<td>–47.588</td>
</tr>
<tr>
<td>Variation of system cost (%)</td>
<td>–</td>
<td>–3.99</td>
</tr>
</tbody>
</table>
The presented procedure is also examined for OF1 as displayed in Fig. 4. In PMS, OF1 is merely committed with its minimum capacity to procure system reserve requirement. Considering unit responsibility criterion, OF1 reservation level is decreased while the produced power rate will be increased. This unit is committed 32 periods during the scheduling; so the unit’s available capacity is equal to 384 MW along the time horizon. The unit’s generated power is equal to 76.8 MW in PMS and 320.992 MW in PMSURC; hence, the generation’s percentage of OF1 is equivalent to 20% and 83.6% in PMS and PMSURC, respectively.

Generated power percentage of committed units in terms of their available capacities is presented in Table 5 during the scheduling time. It is concluded from Table 5 that, the most economical units are available with their maximum capacity in PMS; while due to decreasing the generation level of economical units in PMSURC, the costly units participate more in demand satisfaction.

Furthermore, the participation percentage of committed units to procure system reserve in terms of their available capacities is reported in Table 6.

It can be deduced from Tables 5 and 6 that without considering the unit responsibility criterion, the most expensive units are merely committed with their minimum capacities to provide system reserve necessity; while in PMSURC all committed units participate in reserve acquisition. Therefore, the reservation level of expensive units is lessened in PMSURC whereas the cooperation amount of economical unit in reserve provision is increased in comparison with PMS.

The impact of unit responsibility criterion on generation pattern of multifarious units for a sample period (period #51) is displayed in Fig. 5. As shown in Fig. 5, the most economical generators, i.e. CF24–N25–N26, are committed with their maximum capacities in PMS; while the generation level of the aforementioned units is decreased in PMSURC due to participating in reserve acquisition. Indeed, the unit responsibility criterion compels the most economical units to decrease their generated power and enforces the most expensive committed units to raise their produced power for satisfying the demand. Therefore the operation expenditure is increased in PMSURC in comparison with PMS.

Unit participation level in reserve acquisition is depicted in Fig. 6 for maximum loading period. Referring to Fig. 6, it can be concluded that both inexpensive and costly units participate in reserve provision in PMSURC, while without consideration of URC, expensive units just procure the system reserve. Here, the reserve assessment cost in PMS is more in comparison with PMSURC due to inappropriate system reserve allotment.

Furthermore, the generation and reservation pattern of units for the minimum loading period, 38th period, is also provided in

Table 5

<table>
<thead>
<tr>
<th>Unit no.</th>
<th>Available periods</th>
<th>Produced power (%)</th>
<th>Unit no.</th>
<th>Available periods</th>
<th>Produced power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PMS</td>
<td>PMSSURC</td>
<td></td>
<td>PMS</td>
<td>PMSSURC</td>
</tr>
<tr>
<td>OF1</td>
<td>32</td>
<td>20</td>
<td>83.6</td>
<td>OF11</td>
<td>38</td>
</tr>
<tr>
<td>OF2</td>
<td>25</td>
<td>20</td>
<td>85.43</td>
<td>OF12</td>
<td>19</td>
</tr>
<tr>
<td>OF3</td>
<td>22</td>
<td>20</td>
<td>80.5</td>
<td>OF13</td>
<td>5</td>
</tr>
<tr>
<td>OF4</td>
<td>15</td>
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Table 6

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Table 7. As shown in Table 7, the generation level of economical units, i.e. CF$_{24}$–N$_{25}$–N$_{26}$, is increased in PMS in comparison with PMSURC due to declining operation expenditures. Moreover, reservation level in expensive units, i.e. OF$_{10}$, is decreased in PMSURC in comparison with PMS because of economical units’ participation in system reserve provision.

Conclusions

Preventive maintenance scheduling is addressed as one of the most crucial issues in power system studies aiming to increase the energy efficiency. System reserve provision is considered as one of the imperative constraints in PMS which guarantees the system reliability and security against unanticipated events. In this paper, a deterministic method associated with the unit responsibility criterion (URC) is proposed for spinning reserve allocation. URC compels all synchronized units in order to support system reserve requirements. Therefore, a new methodology is proffered for reserve procurement based upon URC incorporating PMS the so-called PMSURC in which largest unit capacity will be allotted through all committed units by using URC inherently. The proposed technique is then applied to the IEEE-RTS system and the results are compared with conventional PMS. Although the operating cost is increased in PMSURC, while reserve procurement expenditure as well as system total cost are declined considerably that demonstrates the net benefits of such suitable spinning reserve allotment. Moreover, this method can be utilized for any desired reliability level by imposing a conversion factor. Future research is needed to develop the proposed framework incorporating the impacts of URC on maintenance scheme in the presence of security constraints.

References


Cplex 12.4.0 Manual ILOG corp.
