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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.

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

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Nomenclature

$a(.), b(.), c(.)$	fuel cost coefficients
$\overline{AUC}(.)$	maximum capacity of committed units in a cluster at a period
b_m	slope of mth segment in linearized fuel cost curve
$COUR(.)$	class of unit responsibility of a cluster in a period
$D(.)$	power demand of a period
$F(.)$	unit fuel cost function
$\underline{F}(.)$	lower limit on the fuel cost of a unit
i	unit index
$IUR(.)$	incremental unit responsibility of a cluster in a period
$loss(.)$	system losses in a period
m	segment index for linearized fuel cost curve
$M_C(.)$	maintenance cost of a unit
N_G	number of generating units
N_{cls}	number of clusters
N_{SF}	number of segments for the piece-wise linearized fuel cost curve
$P(.)$	output power of a unit in a period
$P_m(.)$	generated power in mth segment of linearized fuel cost curve
$\overline{P}_m(.)$	maximum generated power in mth segment
$\overline{P}(.)/\underline{P}(.)$	maximum/minimum generating capacity of a unit
$R_C(.)$	required maintenance crew of a unit in a period
$s(.)$	maintenance starting time
$SRR(.)$	system reserve requirement in a period based upon URC
$SRN(.)$	system reserve necessity in a period based on rule of thumb
t	period index
T	scheduling time horizon
$TUR(.)$	total unit responsibility of a cluster in a period
$u(.)$	commitment state of a unit in a period
$upl(.)$	unit participation level in reserve procurement in a period
$z(.)$	maintenance status of a unit
Υ_k	number of units in kth cluster
$\delta(.)$	maintenance duration of a unit
$\zeta(.)$	total available maintenance crew in a period
ξ_ℓ	cluster index

capacity or a given percentage of the forecasted load to ensure system security. The demand is supplied with the most economical units while the system reserve is provided with the most expensive generators to merely decrease the operating expenditure without considering the reserve expenditures. Although the operation cost has been minimized but the total cost including operation, maintenance, and reserve expenditures has been increased due to the improper reserve assessment.

In this paper, an effective deterministic method is proposed to assess system reserve among generating units by introducing unit responsibility criterion (URC), where this compels all committed units to cooperate in system reserve procurement. The unit contribution level in reserve provision depends on both the unit's capacity as well as other committed units' capacities. Since both costly and inexpensive committed units contribute in reserve procurement, the system reserve expenditure is declined. Here, in order to scrutinize the economic benefits of URC, a new formulation for reserve assessment incorporating PMS, the so-called, PMSURC, is developed. In the nominated structure, the system reserve is allocated among committed units based upon URC whereas economical units are determined by PMS; then a generation re-dispatch is accomplished to satisfy the demand. More detailed explanation about URC is provided in Section 'PMSURC formulation based on MIP'. The suggested framework is developed as a combinatorial optimization problem, which is linearized and structured as a mixed-integer programming (MIP) problem. The advantages of an MIP method include global optimality, direct measure of the optimality of a solution, and more flexible and accurate modeling capabilities. Here, CPLEX as a sophisticated and computationally efficient MIP solver [27] is applied for solving the proposed model.

The rest of the paper is organized as follows. The proposed formulation of reserve assessment based upon URC and the MIP-based formulation for PMS are elaborated in details in Section 'PMSURC formulation based on MIP'. Section 'Simulation results and discussions' conducts the numerical simulations and finally, the concluding remarks are given in Section 'Conclusions'.

PMSURC formulation based on MIP

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 proffered 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:

$$COUR(\xi_\ell,t)=\begin{cases}\overline{AUC}(\xi_\ell,t)-\overline{AUC}(\xi_{\ell+1},t) & \forall \ell\in\{1,2,\ldots,N_{cls}-1\},\\ & t\in\{1,2,\ldots,T\}\\ \overline{AUC}(\xi_\ell,t) & \text{otherswise}\end{cases} \quad (1)$$

In Eq. (1), N_{cls}, ξ_ℓ and $\overline{AUC}$ represents number of clusters in terms of capacities, ℓth 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 Υ_r represents the number of units in rth class.

$$IUR(\xi_\ell,t)=\frac{COUR(\xi_\ell,t)}{\sum_{r=1}^{\ell}\Upsilon_r}\quad \forall \ell\in\{1,2,\ldots,N_{cls}\},\ t\in\{1,2,\ldots,T\} \quad (2)$$

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

$$TUR(\xi_\ell,t)=\sum_{r=\ell}^{N_{cls}}IUR(\xi_r,t)\quad \forall \ell\in\{1,2,\ldots,N_{cls}\},\ t\in\{1,2,\ldots,T\} \quad (3)$$