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SECURITY PREVENTIVE MAINTENANCE SCHEDULING INCORPORATING OPTIMAL RESERVE PROCUREMENT

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Abstract- Effective preventive maintenance scheduling (PMS) of generating units ensures a reliable supply of demand and economical operation of power systems. Reserve acquisition as an imperative constraint of PMS promotes the system reliability as well as security. Hence, system reserve allocation may effect on economy of power markets especially in a restructured environment. In this paper, a new linearized formulation for cost-based preventive maintenance scheduling associated with the reserve procurement is developed as a mixed integer linear programming (MILP). Here, system reserve procurement and required energy scheduling are performed simultaneously to examine the economic benefit of proper reserve allocation. Several analyzes incorporating network constraints are conducted to investigate the impact of system reserve assessment on maintenance scheme as well as system expenditures. The well-known IEEE RTS is employed to demonstrate the effectiveness of the proposed methodology while simulation results are promising.

Keywords: Preventive Maintenance Scheduling (PMS), Spinning Reserve Assessment, Mixed Integer linear Programming, Network Constraint.

I. INTRODUCTION

Generally, maintenance scheduling is categorized into three stages of long-term, short term and real time in power system researches [1]. Long term maintenance scheduling of generating units is introduced as a preventive maintenance scheduling (PMS) which is performed at preselected intervals [2]. Basically, equipment failure, testing, unanticipated events, refueling, operator errors and regulatory restriction, may cause generating unit unavailability. Although refueling is compulsory, but planned periodic outage of the generating units may control and reduce the unanticipated event ratio that improves reliability as well as system performance [3].

Moreover, an effective schedule may increase the generator life time that causes to defer capital expenditure for new power plants. PMS is addressed as a significant issue due to affecting on fuel scheduling, unit commitment as well as optimal power flow problems of power systems [4-5]. Preventive maintenance scheduling problem can be investigated both economic and reliability considerations. In fact, system operator derived maintenance scheduling of generating units with target of enhancing power system reliability as well a decreasing whole system costs [6]. Economic driven minimizes the overall operating and maintenance costs over a specified time horizon [7-9]; while reliability driven utilizes several reliability indices such as: expected energy not supplied (EENS), loss of load probability (LOLP), and expected lack of peak net reserve [10-13].

In order to investigate the economic benefits of optimum system reserve allocation, a cost based model is proposed in this paper. Here, several constraints such as demand-supply equilibrium, spinning reserve capacity, generating rated capacity and maintenance duration are contemplated to reflect the actual operating conditions. Furthermore, despite the increasing complexity, the security network constraints are also considered to obtain more realistic results. System reserve requirement as an imperative constraint guarantees the service delivery continuation while decreases the load shedding probability against a sudden increase in demand or generating unit unexpected outages.

Although, system reserve ensures system security but it may cause an increase in the operating costs due to calling more expensive units while generated at a non-optimal point [14-16]. Therefore optimum allocating system reserve capacity among committed units is extremely crucial in a power system due to economic viability. In recent years, multifarious deterministic and probabilistic techniques have been expressed to determine spinning reserve necessity. Although, the stochastic nature of power system behavior is not contemplated in deterministic studies, but since they are much easier and more tangible than probabilistic methods preferable by most utilities [17-19].

In some researches, spinning reserve requirement is usually considered as the largest unit capacity or a given percentage of the forecasted peak load to ensure system security when an anticipated outage occurs. Several conventional, heuristic and hybrid optimization techniques are addressed in last decades for solving the

PMS problem as large scale, non-convex, and mixed-integer combinatorial optimization problem.

In [7], Benders decomposition is utilized for PMS to minimize the operation cost while a portion of demand is considered as the system reserve. Reference [20], has been expressed a method based on evolutionary programming to determine the power generation and transmission maintenance scheduling while a fuzzy model based on evolutionary programming technique is suggested in [21] for the security constrained maintenance scheduling problem of generation systems considering uncertainties in the load and fuel as well as maintenance costs.

In [22], ant colony (AC) optimization technique has been utilized to seek the optimum schedule of the unit maintenance which aims to improve the system economy as well as increasing the system reliability. Reference [23] has proposed a simulated annealing (SA) technique to solve preventive maintenance scheduling whereas in [24] a hybrid fuzzy genetic algorithm is presented to tackle the PMS of generating units.

In recent preventive maintenance studies, system reserve expenditure has not been contemplated during the scheduling time horizon. System security margin, i.e. system reserve, was procured with the most expensive committed units to merely decline the operation costs. Although, the operating costs in recent researches have been minimized, but the total system costs including operation, maintenance and reserve capacity has been increased due to the inappropriate reserve allotment.

In this paper the impacts of appropriate system reserve allocation among committed units from economic view is scrutinized. In order to investigate such crucial issue, a cost-based model for preventive maintenance associated with reserve provision scheduling; the so-called PMSRAS; is provided. In PMSRAS, system reserve acquisition and energy scheduling are performed simultaneously. Here, both costly and inexpensive committed units can be contributed in reserve provision. Moreover, each unit reservation capacity as well as each unit participation level in demand satisfaction is determined so that the system total cost is minimized. PMSRAS is proffered as a combinatorial optimization problem to determine the unit maintenance status incorporating committed units' output power and unit reservation level as well.

Since the efficient mixed-integer linear programming (MILP) solvers are well developed, the proposed model is linearized and structured as an MILP problem to be appropriately solved. The main features of MILP method include a direct measure of optimality having more flexibility and accuracy. Here, CPLEX [25] as a sophisticated and computationally efficient MILP solver is employed for solving the proposed PMSRAS problem.

The rest of the paper is organized as follows: The proposed PMSRAS formulation based upon MILP is discussed in details in section II. Section III conducts the numerical simulations and finally concluding remarks are derived in section IV.

II. PROBLEM FORMULATION

The classical preventive maintenance scheduling (CPMS) is formulated as a basic model for such an optimization problem, where the objective function includes the sum of operation costs as well as maintenance costs. In CPMS, maintenance and operational constraints are considered, while reserve procurement costs is not included [7, 20-24]. Therefore, maintenance scheme is determined so that the operation cost is minimized without regarding the reserve expenditure of the system. In fact, 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 costs.

In this section, a cost based modeling is presented to handle the preventive maintenance scheduling incorporating system reserve allocation namely PMSRAS. Mathematically, PMSRAS is a decision making problem with an objective to be minimized with respect to a series of equality and inequality constraints. Moreover, in order to have realistic study, network constraints are also added to prevailing constraints. PMSRAS determines maintenance scheme while operating, maintenance and reserve costs over a time horizon is minimized.

Here, an alternative mixed integer linear programming (MILP) formulation of PMSRAS, suitable for available MILP software is presented. A common way for solving MILP problem is to relax some coupling constraints and decompose it into several sub-problems. In this paper, the employed optimization software is General Algebraic Modeling System (GAMS) [26] and CPLEX [25] as a commercial and computationally efficient MILP solver is used for solving the PMSURC problem. The cost based linearized objective function can be presented by Equation (1).

$$\min: \sum_{t=1}^{T}\sum_{i=1}^{N_g}\left[\begin{array}{l}\left(\underline{F}(i)u(i,t)+\sum_{m=1}^{N_{sf}(i)}P_m(i,t)b_m(i)\right)\\ +z(i,t)MC(i)+url(i,t)\Gamma(i)\end{array}\right] \tag{1}$$

In Equation (1), the first term is linearized fuel cost curve. Fuel cost function typically utilized in scheduling problems can be formulated as quadratic [27] form that is shown by Equation (2).

$$F(i,t)=a(i)+b(i)P(i,t)+c(i)P^2(i,t) \tag{2}$$

Equation (2) can be precisely approximated by a set of piecewise blocks [28]. The piecewise linear function can't be distinguished from the nonlinear model if enough segments are used. The analytic representation of such linear approximation is:

$$\underline{F}(i)u(i,t)+\sum_{m=1}^{N_{sf}(i)}P_m(i,t)b_m(i) \tag{3}$$

The second term of the objective function corresponds to maintenance costs, which is constant for each generating unit and is modeled by using maintenance indicator in such a way to minimize the system total expenditure. The third term of the objective function is reserve capacity costs.

$\Gamma(i)$ is assumed to be constant for each generating unit. The participation level of each unit in reserve provision is determined such that the system total cost is minimized. The objective function is subjected to the following constraints. Generated power from committed units must satisfy the required demand and system losses.

$$\sum_{i=1}^{N_g} P(i,t) = D(t) + loss(t) \qquad \forall t \qquad (4)$$

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 is determined by using a rule of thumb to satisfy as the largest unit capacity or somehow a portion of maximum demand. Hence maximum power of committed units in each time period should be greater than the summation of the system demand as well as reserve.

$$\sum_{i=1}^{N_g} u(i,t)\bar{P}(i,t) \ge D(t) + SRR(t) \qquad \forall t \qquad (5)$$

In Equation (5), the *i*th unit on/off status is symbolized by $u(i, t)$ which is one when the generator is on and otherwise it is zero.

- Maximum and minimum reservation levels of generating units:

$$0 \le url(i,t) \le \bar{P}(i,t) - \underline{P}(i,t) \qquad \forall i, \forall t \qquad (6)$$

$$\sum_{i=1}^{N_g} url(i,t) = SRR(t) \qquad \forall t \qquad (7)$$

- Unit output limit:

$$0 \le P_m(i,t) \le \bar{P}_m(i,t) \qquad \forall i, \forall t, \forall m \qquad (8)$$

$$\underline{P}(i,t)u(i,t) + \sum_{m=1}^{N_{sf}(i)} P_m(i,t) \le \bar{P}(i,t)u(i,t) - url(i,t) \quad \forall i, \forall t \qquad (9)$$

- Unit Maintenance duration:

$$\sum_{t=1}^{T} z(i,t) = \zeta_i \qquad \forall i \qquad (10)$$

Each unit is taken under maintenance just once during the time horizon. $\varpi(i,t)$ is maintenance starting variable that is considered equal to one if *i*th generator inspection starts at beginning of period *t*, and otherwise equal to zero.

$$\sum_{t=1}^{T} \varpi(i,t) = 1 \qquad \forall i \qquad (11)$$

- Each unit must be repaired in successive periods:

$$z(i,t) - z(i,t-1) \le \varpi(i,t) \qquad \forall i, \forall t \qquad (12)$$

Connection constraint represents the relation between the maintenance status and the commitment state of the unit. Since nuclear units are low cost with higher startup time as well as shut down time; nuclear units are always committed in their except maintenance durations.

$$\begin{aligned} z(i_1,t) + u(i_1,t) \le 1 \quad \forall i_1 \in \text{Thermal units}, \forall t \\ z(i_2,t) + u(i_2,t) = 1 \quad \forall i_2 \in \text{Nuclear units}, \forall t \end{aligned} \qquad (13)$$

The total available technical staffs as well as the required manpower for the specified unit inspection in each period are definite. Hence, number of the generating units which can be maintained simultaneously is limited.

$$\sum_{i=1}^{N_g} z(i,t) \le \upsilon(t) \qquad \forall t \qquad (14)$$

Transmission security constraint in preventive maintenance scheduling can be handled either by a Transportation Model (TM) or other power flow models. Since TM is a linear model, it is easier to be solved and may lead to feasible solutions but not necessarily an optimal one. In Equation (17), ε is the allowable unsupplied energy which is given by ISO. An increase in maximum unsupplied energy level results a reduction in operation costs as well as system total costs. Although, system total costs is reduced but system reliability level will be declined [5].

$$sf + g + r = d \qquad \forall t \qquad (15)$$

$$-\overline{PL}_L \le PL(l,t) \le \overline{PL}_L \qquad \forall t, \forall l \qquad (16)$$

$$\sum_{b=1}^{N_b} r(b,t) \le \varepsilon \qquad \forall t \qquad (17)$$

III. SIMULATION RESULTS

In this study, an IEEE Reliability Test System, as shown in Figure 1, has been utilized for our simulation studies with a scheduling time horizon of 52 weeks.

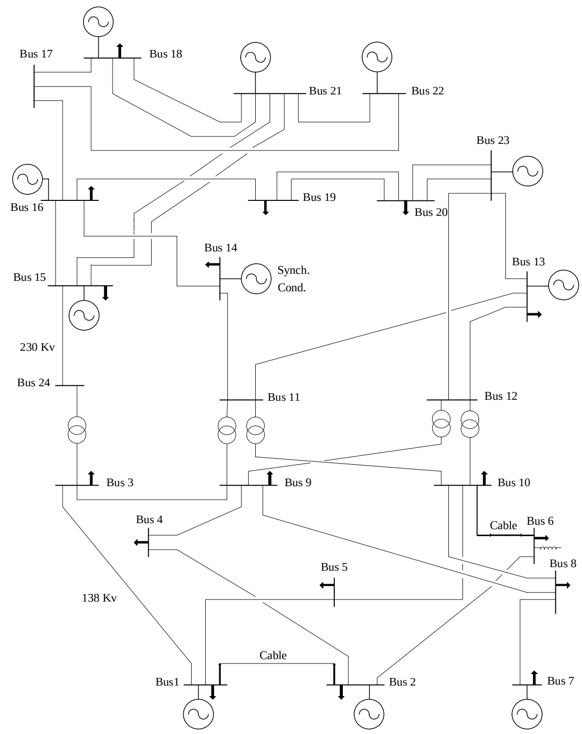

Figure 1. IEEE RTS system

The system is composed of 26 generating units ranging from 12 to 400 MW (15 oil: OF_1-OF_{15}, 9 coal: CF_{16}-CF_{24}, and 2 nuclear: N_{25}-N_{26}); 24 buses and 38 transmission lines. The peak load is 2100 MW and the weekly load profile of the IEEE-RTS is used to obtain the annual load curve [4]. The fuel cost curves for generating units given as a quadratic function in [29] are approximated by 20 linear segments between the minimum and maximum generating units' capacity.

More required data including operating and maintenance insights of the generating units as well as transmission lines characteristics are provided in [30]. System reserve requirement, i.e. SRR, is considered equal to the largest unit capacity [31]. In this study, it is assumed that three generators can be repaired simultaneously due to the technical limitation. Here, the network loss is disregarded during the scheduling time horizon. Moreover, the load must be satisfied completely in each period which means that no unsupplied energy is allowed by ISO and ε is considered equal to zero in Equation (17).

In order to tackle the effect of optimum system reserve allocation on the maintenance schedule as well as system total cost, CPMS is first performed where the system demand is supplied by the most economical committed generators just to minimize the operating cost while system reserve requirement is provided with the most expensive committed units. By applying CPLEX 12.4.0 [25], the system total costs including operating, maintenance and reserve, is obtained as 241.11 $ M/year. Then, preventive maintenance scheduling associated with the reserve allocation scheduling, i.e. PMSRAS, is solved and the system total cost is computed 226.09 $ M/year. In Table 1, generating units maintenance schedule of two aforementioned analyzes are presented.

Table 1. Maintenance scheme

Unit	Maintenance start week		Unit	Maintenance start week	
	CPMS	PMSRS		CPMS	PMSRS
OF_1	28	16	OF_{14}	42	22
OF_2	21	19	OF_{15}	43	5
OF_3	21	8	CF_{16}	1	31
OF_4	46	21	CF_{17}	39	19
OF_5	24	20	CF_{18}	22	32
OF_6	15	9	CF_{19}	9	1
OF_7	41	29	CF_{20}	41	15
OF_8	2	30	CF_{21}	26	39
OF_9	30	18	CF_{22}	17	40
OF_{10}	15	6	CF_{23}	6	15
OF_{11}	34	43	CF_{24}	30	27
OF_{12}	3	4	N_{25}	35	9
OF_{13}	17	24	N_{26}	10	34

The optimization results, including operation and reserve costs are provided in Table 2. Referring to Table 2, total operation and maintenance costs is increased 25.99 million $/year in PMSRAS, while the reserve expenditure is decreased 41.01 million $/year due to more proper system reserve allocation. Furthermore, the system total costs including operation, maintenance and reserve declines $241.11-226.09=15.02$ million $/year, which is about 6.23 percent.

Table 2. Optimization results

	CPMS	PMSRAS	Variation (%)
O & M costs ($ M/year)	177.6135368	203.6075368	12.76
Reserve costs ($ M/year)	63.49832872	22.4868	-64.58
System total costs ($ M/year)	241.1118655	226.0943368	-6.23

The impacts of optimal reserve scheduling on generation pattern and system reserve provision of multifarious units are presented in Table 3, for a sample period. In CPMS, the most economical units are committed with their maximum capacity to supply the demand and expensive committed units just procure the system reserve capacity to merely minimize the operation costs. In PMSRAS, the expensive cost units are also cooperating in supplying demand. Therefore the operation cost in PMSRAS is increased in comparison with CPMS, but the total cost decreased considerably.

Table 3. System reserve assessment and generation pattern in peak load

Committed Unit	CPMS		PMSRS	
	Output Power (MW)	Reserve Capacity (MW)	Output Power (MW)	Reserve Capacity (MW)
OF_1	2.4	2.5	0	0
OF_2	2.4	9.6	0	0
OF_3	2.4	9.6	0	0
OF_{10}	25	75	100	0
OF_{11}	0	0	100	0
OF_{12}	25	75	100	0
OF_{13}	68.95	128.05	126	0
CF_{16}	42.56	33.44	76	0
CF_{17}	57.76	18.24	76	0
CF_{18}	54.72	21.28	76	0
CF_{19}	48.81	27.29	76	0
CF_{20}	155	0	155	0
CF_{21}	155	0	155	0
CF_{22}	155	0	155	0
CF_{23}	155	0	155	0
CF_{24}	350	0	350	0
N_{25}	400	0	205	195
N_{26}	400	0	195	205

Moreover, the generated power of committed units can be compared during the scheduling time in CPMS and PMSRAS. This issue is depicted for one of the lowest cost as well as the most expensive committed units in Figures 2 and 3, respectively. N_{26} as one of the lowest cost units in this system is committed with its maximum capacity in CPMS except the maintenance time; while in PMSRAS due to participating in system reserve procurement, the aforementioned unit doesn't cooperate in demand satisfaction with its marginal capacity.

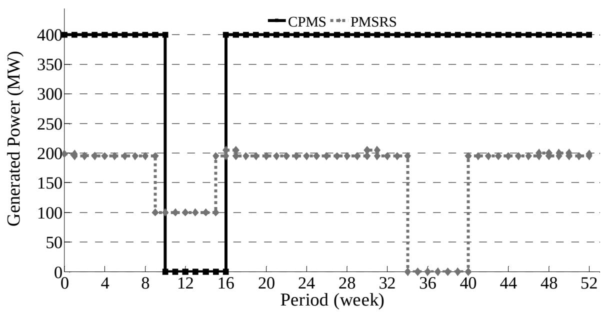

Figure 2. Generated power in N_{26}

Furthermore, OF_1 is merely committed with its minimum capacity to procure system reserve requirement in CPMS, while the aforementioned unit generation level is increased in PMSRAS due to the generation level reduction of committed units.

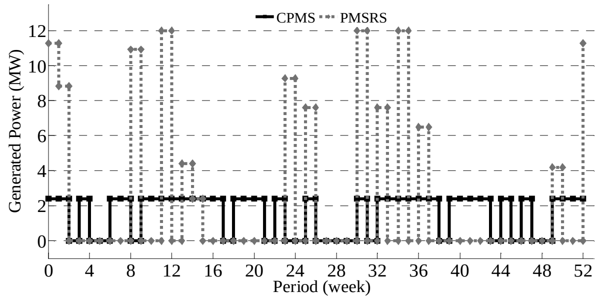

Figure 3. Generated power in OF_1

IV. CONCLUSION REMARKS

Preventive maintenance scheduling is addressed as a crucial issue due to its severe impacts on power systems asset management by reducing operating costs as well as enhancing reliability worth. System reserve procurement is considered as one of the imperative constraint in PMS which assures the system reliability and security against unforeseen breakdown. Today, in restructured electricity market, optimal system reserve procurement is extremely important due to economic consideration. In this paper, the impacts of simultaneous system reserve procurement and energy scheduling on system total expenditure are examined in maintenance problem.

Furthermore, an MILP cost based model is proffered for preventive maintenance scheduling considering reserve assessment scheduling; the so-called PMSRAS. PMSRAS has been then applied to the IEEE RTS system and several case studies are conducted. The PMSRAS outcomes are compared with the conventional formulation of PMS to reflect the effectiveness of the proposed model. Although the operation costs is increased in PMSRAS, but the reserve as well as system total costs are declined considerably that demonstrate the benefits of suitable reserve allotment.

NOMENCLATURES

$a(.), b(.), c(.)$: Fuel cost coefficients

b : Bus index.

$b_m(.)$: Slope of mth segment in linearized fuel cost curve

$D(.)$: Power demand of a period

d : Demand vector

$F(.)$: Unit fuel cost function

$\underline{F}(.)$: Lower limit on the fuel cost of a unit

f : Active power flow vector through transmission lines

g : Generated power vector

i : Unit index

$loss(.)$: System losses in a period

l : Line index

$MC(.)$: Maintenance cost of a unit

m : Segment index for linearized fuel cost curve

N_b : Number of buses

N_g : Number of generating units

N_L : Number of transmission lines

N_{sf} : Number of segments for the piecewise 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

$\bar{P}_m(.)$: Maximum generated power in mth segment

$\bar{P}(.) / \underline{P}(.)$: Maximum/minimum generating capacity of a unit

$PL(.)$: Power flow of a line in a period

$\overline{PL}_L$: Capacity of a line

r : Dummy units vector associated with the unsupplied energy in a period

$SRR(.)$: System reserve requirement in a period

s : Node-branch incidence matrix

t : Period index

T : Number of periods for scheduling time horizon

$u(.)$: Commitment state of a unit in a period

$url(.)$: Unit reservation level in a period

$z(.)$: Maintenance status of a unit

$\varpi(.)$: Maintenance starting time

$\Gamma(.)$: Offered capacity cost of a unit for providing system reserve

$\zeta(.)$: Maintenance Duration of a unit

$\upsilon(.)$: Maximum number of under inspection units in a period

ε : Accepted level of expected unsupplied energy

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