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Fast Response Units Scheduling to Provide Power System Required Flexibility under High Penetration of Wind Power Generation

Alireza Mansoori[1], Alireza Sheikhi Fini[2*], Mohsen Parsa Moghaddam[1]

[1]Department of Electrical Engineering, Tarbiat Modares University, Tehran, Iran

*[2] * **Niroo Research Institute (NRI),** Email: asheikhi@nri.ac.ir*

Abstract

In recent years, increasing of non-dispatchable resources has posed serious challenges to day-ahead generation scheduling of the power system. Since these resources are random in nature, the issue of flexibility to cover the uncertainty and variability of those has become an important research topic. Therefore, having flexible resources to cover changes in the generation of this resources during operation can play an important role in eliminating node imbalances, system reliability, providing the required flexible ramping reserve and reducing system operating costs. Among these flexible sources, we can mention fast-response dispatchable generation units such as gas units and combined cycle units. Therefore, in this paper, a mixed-integer two-stage and tri-level adaptive robust optimization has been used, which is solved by column-and-constraint generation decomposition-based algorithm in order to jointly clearing the energy and ramping reserve with the presence of fast response and flexible resources.

Keywords: Adaptive robust optimization, column-and-constraint generation, fast response resources, flexibility, non-dispatchable resources

Sets and Indices

B	Set of bus indices
B^u	Set of buses indices in which the wind generation unit is located
b	indices of bus
I	Set of generation units indices
I^{FR}	Set of fast response generation units indices
I^{SR}	Set of slow response generation units indices
I_b	Set of indices of generation units located at bus b
i	indice of generation units
L	Set of indices of power transmission lines
l	indice of power transmission lines
T	Set of indices of time periods
t	indices of time periods

Parameters

Δp_{bt}^{dn}, Δp_{bt}^{up}	Maximum down/up fluctuation of wind generation in bus b and time t (MW)
C_{it}^{FRU}, C_{it}^{FRD}	Downward/ upward spinning flexible ramping reserve cost of unit i at time t ($/MW/h)
C_{it}^{FRN}	Non-spinning flexible ramping reserve cost of unit i at time t ($/MW/h)
C_{it}^{sd}, C_{it}^{su}	Start-up and shut-down cost of unit i at time t ($)
c_i^f, c_i^v	Fixed cost ($) and variable cost ($/MWh) of unit i
d_{bt}	Forecasted demand bus b at time t (MW)
$\overline{F_l}$	Maximum capacity of line l (MW)
$fr(l)$	Primary bus of line l
M	Parameter related uncertainty budget.
$\underline{P_{it}}$, $\overline{P_{it}}$	Max/min generation capacity of unit i at time t (MW)

P_{bt}^{w}	Predicted output level of wind generation unit at bus *b* and time *t* (MW)
RU_i , RD_i	Ramp down/up unit *i*
SD_i , SU_i	Start-up and shut-down ramp rate unit *i*
$to(l)$	End bus of line *l*
x_l	Reactance of line *l*

Variables

a_{bt}^{up} , a_{bt}^{dn}	Binary variables represent the worst case of wind generation level
θ_{bt}^{u} , θ_{bt}	Voltage angle bus *b* at time *t* under uncertainty/ base-case
Φ	The value of power imbalance in the third level problem
Φ^{w}	Worst-case of system imbalance
Φ_{bt}^{-u} , Φ_{bt}^{+u}	Continuous variables indicate the value of power imbalance at bus *b* and time *t* under uncertainty condition
c_{it}^{sd} , c_{it}^{su}	Cost of start-up and shut-down of unit *i* at time *t*
, FRD_{it} FRU_{it}	Upward/downward spinning flexible ramping reserve provided by unit *i* at time *t*
FRN_{it}	Non-spinning flexible ramping reserve provided by unit I at time *t*
f_{lt}^{u} , f_{lt}	Power flow rate of line *l* at time *t* under uncertainty/ base-case
of	The value of the objective function related the minimum operating cost
P_{it}^{u} , P_{it}	Generation level of unit *i* at time *t* under uncertainty/ base-case
P_{it}^{wu}	Level of wind power generation under uncertainty
v_{it}	Binary variable indicates the scheduling status of generation units in base-case
v_{it}^{su} , v_{it}^{sd}	Binary variables indicate on/ off status of fast response units under uncertainty condition

1. INTRODUCTION

In recent years, renewable energy resources, especially wind power generation, has been increasing, such a way that the vision of many governments, such as India and Japan, is to supply more than 50 percent of their electricity needs from renewable sources by the target year 2030 [1-3]. Use of these resources in the power system has many benefits, including reduction in greenhouse gases and fuel costs. However, the presence of these resources, which are also referred as non-dispatchable resources, due to the random nature of their generation, has created technical and economic challenges in the short-term operation that requires increased flexibility in the power system. Flexibility in the power system must respond to two important factors arising from the presence of renewable resources, namely uncertainty and variability. Uncertainty as a result of forecasting error and variability as a result of changes in production varies with the time of these resources. Therefore, the random nature of non-dispatchable resources has led to formation a kind of reserve that called the Flexible ramping Product (FRP) [4]. Among the resources of this type of reserve are conventional generation units that due to their ramping capacity, participate in the ancillary services market to provide flexible ramping reserve in order to cover changes in renewable power generation [5]. Therefore in efficient day-ahead operation planning, technical and economic characteristics of generation units including generation limits, inter-temporal operating constraints such as ramp rate, minimum up/ down time, generation costs, start-up and shut-down costs, network constraints and co-optimize energy and reserve to maximize social welfare, play an important role [6]. In many electricity markets, such as CAISO [4], the independent system operator schedules the system by solving a unit commitment (UC) problem that leads to optimal generation scheduling. On the other hand, increasing the penetration of non-dispatchable generation resources has created an opportunity for flexible and fast response resources in wholesale electricity markets so that in addition to slow response units, the potential of such resources in day-ahead operation planning can provide the required flexibility power system. This can complicate the new UC problem compared to its traditional counterparts and create new challenges in the solution process.

In recent years, various optimization frameworks have been developed to address the uncertainty of non-dispatchable generation resources in unit commitment problem. The most used frameworks are deterministic methods [7-9], two-stage stochastic programming [10] and multi-stage adaptive robust optimization [11], [12]. In deterministic methods, due to the consideration of uncertainty without the possibility of its occurrence, only part of the realized uncertainty can be managed. On the other hand, in stochastic programming, the accuracy of probabilistic information and its characteristics play an important role in scheduling. Therefore, stochastic programming requires a tradeoff between tractability and accuracy, which is difficult in practical applications. Therefore, due to the complexity and lack of transparency of this method, in practice, operators of the power system are reluctant to use it; Because they believe that the computational ability and efficiency of models based on stochastic optimization need more consideration before operationalization [13-16]. Recently, robust optimization has been proposed as a practical and alternative framework for the stochastic approach in which sources of uncertainty are modeled as decision variables under a set of uncertainties with a confidence interval based on historical or predicted data. The robust optimization approach provides a solution that is feasible under any realization of uncertainties within such uncertainty set. In fact, this solution is robust against the worst case scenario associated with sources of uncertainty [17]. In view of the above, many researches in day-ahead operation planning have used robust approach. A worth point about some of these works is the lack of attention to simultaneous clearing the energy and reserve to provide the required ramping capacity reserve of the system, and sometimes only the energy market is cleared in the worst case of uncertainty, which contradicts the current approach of electricity markets [18], [19]. In order to modify this approach, research aimed simultaneous clearing energy and reserve in order to cover the net load changes in the power system such as [20], [21] have used adaptive robust optimization decomposition methods including benders decomposition (BD) and column production (CCG). A worth point about these works is disregard separation of generation units based on their response speed in order to participate in providing ramping reserve capacity required the system. On the other hand, in some researches, the constraints related to ramping reserve capacity that can be provided by generation units have been ignored, which is contrary to technical considerations in day-ahead operation planning [22],[23]. Among the works done in the field of separation generation resources based on their response speed during operation time, we can mention [24], [25], [26], [27] .In [24] and [25] the Information Gap Decision Theory (IGDT) has been used in order operation planning with the of separating generation resources in form fast-response resources with the ability to provide spinning and non-spinning ramping reserve capacity and slow-response resources with the ability to provide spinning ramping reserve capacity. References [26], [27] use the nested CCG and benders decomposition Respectively for separation generation units based on their response speed. In the works mentioned, addition of binary variables is related to the change status of fast response units in sub-problem and optimal cuts in master problem which can leads to non-convexity of third level problem, increasing computational complexity and decreasing convergence speed.

In this paper alongside presenting an efficient model with less computational complexity to separate generation resources in order to make optimal use of their ramping capacity, two-stage and tri-level adaptive robust optimization based on the CCG decomposition method that due to the existence of optimal cuts of the problem type has a higher convergence speed than other decomposition methods such as benders decomposition method, has been used.

Accordingly, the rest of this paper is organized as follows. Section 2 provides the tri-level robust operation planning model. In section 3, the problem solving approach is proposed. In section 4 is allocated to a comprehensive case study. In section 5, the numerical results and in section 6, conclusions will be presented.

2. PROBLEM FORMULATION

Problem formulation in this paper is a tri-level mixed integer programming that in the following, each level will be introduced.

A. First Level Problem

$$\sum_{i\in \mathrm{I}}\sum_{t\in \mathrm{T}}\begin{bmatrix} c_i^{f} v_{it} + c_i^{v} p_{it} + c_{it}^{su} \\ +c_{it}^{sd} + C_{it}^{FRU} FRU_{it} \\ +C_{it}^{FRD} FRD_{it} \end{bmatrix} + \sum_{i\in I^{FR}}\sum_{t\in \mathrm{T}} C_{it}^{FRN} FRN_{it} \tag{1}$$

$$\sum_{i\in I_b} p_{it} + \sum_{l\in L|to(l)=b} f_{lt} - \sum_{l\in L|fr(l)=b} f_{lt} = d_{bt} - p_{bt}^{w}$$

$$;\ \forall b \in \mathrm{B}, \forall t \in T \tag{2}$$

$$f_{lt} = \frac{1}{x_l}\left(\theta_{fr(l)t} - \theta_{to(l)t}\right);\ \ \forall l \in L, \forall t \in T \tag{3}$$

$$-\bar{F}_l \le f_{lt} \le \bar{F}_l;\ \forall l \in L, \forall t \in T \tag{4}$$

$$v_{it}^{su} \le 1 - v_{it};\ \forall i \in I^{FR}, \forall t \in T \tag{5}$$

$$v_{it}^{sd} \le v_{it};\ \forall i \in I^{FR}, \forall t \in T \tag{6}$$

$$\underline{p}_{it} v_{it} \le p_{it} \le \bar{p}_{it} v_{it};\ \forall i \in I, \forall t \in T \tag{7}$$

$$p_{it} + FRU_{it} \le \bar{p}_{it} v_{it};\ \forall i \in I, \forall t \in T \tag{8}$$

$$p_{it} - FRD_{it} \ge \underline{p}_{it} v_{it};\ \forall i \in I^{SR}, \forall t \in T \tag{9}$$

$$\underline{p}_{it}\left(v_{it} - v_{it}^{sd}\right) \le p_{it} - FRD_{it} \le \bar{p}_{it}(v_{it} - v_{it}^{sd})$$

$$;\ \forall i \in I^{FR}, \forall t \in T \tag{10}$$

$$0 \le FRN_{it} \le SU_i v_{it}^{su};\ \ \forall i \in I^{FR}, \forall t \in T \tag{11}$$

$$FRD_{it} \le SD_i + \bar{p}_{it}(1 - v_{it}^{sd});\ \ \forall i \in I^{FR}, \forall t \in T \tag{12}$$

$$p_{it} + FRU_{it} - (p_{it-1} - FRD_{it-1}) \le RU_i v_{it-1}$$

$$+SU_i(v_{it} - v_{it-1}) + \bar{p}_{it}(1 - v_{it})$$

$$;\ \forall i \in I^{SR}, \forall t \in T \tag{13}$$

$$p_{it-1} + FRU_{it-1} - (p_{it} - FRD_{it}) \le RD_i v_{it}$$

$$+SD_i(v_{it-1} - v_{it}) + \bar{p}_{it}(1 - v_{it-1})$$

$$;\ \forall i \in I^{SR}, \forall t \in T \tag{14}$$

$$p_{it} + FRU_{it} + FRN_{it} - (p_{it-1} - FRD_{it-1} + FRN_{it-1})$$

$$\leq RU_i(v_{it-1} + v_{it-1}^{su}) + \bar{p}_{it}(1 - v_{it-1} - v_{it-1}^{su})$$

$$;\ \forall i \in I^{FR}, \forall t \in T \qquad (15)$$

$$p_{it-1} + FRU_{it-1} + FRN_{it-1} - (p_{it} - FRD_{it} + FRN_{it})$$

$$\leq RD_i(v_{it} + v_{it}^{su}) + \bar{p}_{it}(1 - v_{it} - v_{it}^{su})$$

$$;\ \forall i \in I^{FR}, \forall t \in T \qquad (16)$$

$$p_{it} + FRU_{it} + FRN_{it} \leq SU_i\left(1 - v_{it-1} + v_{it-1}^{sd}\right)$$

$$+\bar{p}_{it}(v_{it-1} - v_{it-1}^{sd});\ \forall i \in I^{FR}, \forall t \in T \qquad (17)$$

$$p_{it-1} + FRU_{it-1} + FRN_{it-1} \leq SD_i\left(1 - v_{it} + v_{it}^{sd}\right)$$

$$+\bar{p}_{it}(v_{it} - v_{it}^{sd});\ \forall i \in I^{FR}, \forall t \in T \qquad (18)$$

$$\{c_{it}^{su}\}_{t\in T}, \{c_{it}^{sd}\}_{t\in T}, \{v_{it}\}_{t\in T};\ \forall i \in I \qquad (19)$$

$$FRU_{it} \geq 0, FRD_{it} \geq 0, FRN_{it} \geq 0;\ \forall i \in I, \forall t \in T \qquad (20)$$

In the first level problem, objective function (1) and constraints (2) -(20) include the dispatch and scheduling of energy and flexible ramping capacity reserve with the minimum cost of reliable operation, under the uncertainty of wind generation units. In objective function (1), the costs related generation costs in base-case, start-up and shut-down of generation units and the costs related scheduling under uncertainty including upward and downward spinning ramping reserve capacity costs of the slow and fast response units and non-spinning ramping reserve capacity cost of fast response units, are minimized. Constraints (2) -(4) represent the limitations of transmission network in base-case, i.e. the amount of predicted net load. Constraint (2) related to nodal power balance. Constraints (3), (4) also represent the DC power flow and transmission lines capacity, respectively. Due to the ability of fast response units to provide ramping capacity around their power output in a short period of time, constraints (5) and (6), including start-up binary variables (v_{it}^{su}) and shut-down binary variables (v_{it}^{sd}), have been presented. Constraint (7) indicates the power generation limits in base-case. Constraints (8)-(10) are related to the spinning ramping reserve capacity that can be provided by fast and slow response generation units according to their allowed generation limits (FRU_{it}, FRD_{it}). Also constraint (10) indicates if fast response unit had been scheduled shut-down in uncertainty condition, it must be able to provide a downward ramping capacity within its power output limit. Constraint (11) states that if the fast response unit had been scheduled off in base-case, it is able to provide a ramping capacity equal to its start-up ramp rate (FRN_{it}). Constraint (12) represents that if due to the uncertainty realization need for shut-down fast response unit, it can provide ramping capacity to its shut-down ramp rate. Constraints (13) -(18) are related to the ability to change the power between two consecutive times by fast and slow response units in base-case and uncertainty condition due to their ramping constraints that can be provided by them. Constraint (19) indicates the minimum up/ down time and start-up and shut-down costs of generation units that details are provided in Appendix [28]. Constraint (20) indicates that the variables related to spinning and non-spinning ramping reserve capacity are non-negative.

B. Second Level Problem

$$\Phi^w = Max \quad \Phi$$

Subject to: (21)

$$a_{bt}^{up} + a_{bt}^{dn} \leq 1;\ \forall b \in \mathrm{B}^u, \forall t \in T \qquad (22)$$

$$p_{bt}^w - \Delta p_{bt}^{dn} a_{bt}^{dn} \leq p_{bt}^{wu} \leq p_{bt}^w + \Delta p_{bt}^{up} a_{bt}^{up}$$

$$;\ \forall b \in \mathrm{B}^u, \forall t \in T \qquad (23)$$

$$\sum_{b\in \mathrm{B}^u}\left[\frac{\max\{0, p_{bt}^{wu} - p_{bt}^w\}}{\Delta p_{bt}^{up}} + \frac{\max\{0, p_{bt}^w - p_{bt}^{wu}\}}{\Delta p_{bt}^{dn}}\right] \leq M;\ \forall t \in T \quad (24)$$

The objective function (21) and constraints (22) -(24) represent the second level problem. Objective function (21) identifies the worst-case for nodal power imbalance with respect to the decisions made in first level problem. Constraints (21) -(23) represent use the Budget constrained polyhedral uncertainty set in which parameter M represents the uncertainty budget and indicates the number of buses that simultaneously experience fluctuations in wind power output and based on the predicted uncertainty is determined. Binary variables a_{bt}^{up} and a_{bt}^{dn} are presented in order to determine the worst-case scenario for up/ down fluctuations of wind generation units due to the uncertainty budget. Since a wind unit cannot experience both up and down fluctuations at the same time, constraint (22) has been represented.

C. The Third Level Problem

$$\Phi = Min \ \sum_{b\in \mathrm{B}} \sum_{t\in T} \Phi_{bt}^{-u} + \Phi_{bt}^{+u}$$

Subject to: (25)

$$\sum_{i\in I_b} p_{it}^u + \sum_{l\in L|to(l)=b} f_{lt}^u - \sum_{l\in L|fr(l)=b} f_{lt}^u = d_{bt} - p_{bt}^w$$

$$-\Delta p_{bt}^{up} a_{bt}^{up} + \Delta p_{bt}^{dn} a_{bt}^{dn} + \Phi_{bt}^{-u} - \Phi_{bt}^{+u}$$

$$;\forall b \in \mathrm{B}, \forall t \in T \qquad (26)$$

$$f_{lt}^u = \frac{1}{x_l}\left(\theta_{fr(l)t}^u - \theta_{to(l)t}^u\right);\ \forall l \in L, \forall t \in T \qquad (27)$$

$$-\bar{F}_l \leq f_{lt}^u \leq \bar{F}_l;\ \forall l \in L, \forall t \in T \qquad (28)$$

$$p_{it} - FRD_{it} \le p_{it}^{u} \le p_{it} + FRU_{it};\ \forall i \in I^{SR}, \forall t \in T \qquad (29)$$

$$p_{it} - FRD_{it} \le p_{it}^{u} \le p_{it} + FRU_{it} + FRN_{it}$$

$$;\ \forall i \in I^{FR}, \forall t \in T \qquad (30)$$

$$\Phi_{bt}^{-u} \ge 0, \Phi_{bt}^{+u} \ge 0;\ \forall b \in \mathrm{B}, \forall t \in T \qquad (31)$$

In objective function (25), the variables of nodal power imbalance under uncertainty realization condition, according to the decisions made in the first and second level problem, are minimized. Constraints (26) -(28) represent the nodal power balance, power flow and transmission lines capacity under uncertainty condition, respectively. Constraints (29) and (30) indicate the level of power generation of fast and slow response units under uncertainty condition and decision made in the first level problem. Constraint (31) also indicates the nodal power imbalance variables are non-negative.

D. Master Problem

The master problem is the relaxed version of problem (1)-(31), to which, for iterations $j > 1$, a set of constraints related to operating conditions is added, which is equivalent to constraints (26)-(30). It should be noted that these constraints are parameterized by the sub-problem that solved in the previous iteration. Therefore, the master problem in iteration j is as follows:

$$\mathit{Objective\ Function}\ \ (1)$$

Subject to: (32)

$$\mathit{Constraints}\ (2)\text{-}(20) \qquad (33)$$

$$\sum_{i \in I_b} p_{it}^{m} + \sum_{l \in L|to(l)=b} f_{lt}^{m} - \sum_{l \in L|fr(l)=b} f_{lt}^{m} = d_{bt} - p_{bt}^{w}$$

$$-\Delta p_{bt}^{up} a_{bt}^{up(m)} + \Delta p_{bt}^{dn} a_{bt}^{dn(m)} + \Phi_{bt}^{-u} - \Phi_{bt}^{+u}$$

$$;\ \forall b \in \mathrm{B}, \forall t \in T, m = 1, \dots, j-1 \qquad (34)$$

$$f_{lt}^{m} = \frac{1}{x_l}\left(\theta_{fr(l)t}^{m} - \theta_{to(l)t}^{m}\right)$$

$$;\ \ \forall l \in L, \forall t \in T, m = 1, \dots, j-1 \qquad (35)$$

$$-\bar{F}_l \le f_{lt}^{m} \le \bar{F}_l;\ \forall l \in L, \forall t \in T, m = 1, \dots, j-1 \qquad (36)$$

$$p_{it} - FRD_{it} \le p_{it}^{m} \le p_{it} + FRU_{it}$$

$$;\ \forall i \in I^{SR}, \forall t \in T, m = 1, \dots, j-1 \qquad (37)$$

$$p_{it} - FRD_{it} \le p_{it}^{m} \le p_{it} + FRU_{it} + FRN_{it}$$

$$;\ \forall i \in I^{FR}, \forall t \in T, m = 1, \dots, j-1 \qquad (38)$$

E. Subproblem

The master problem includes the max-min model of the second and third level problems, which is covert to the single level maximization model using dual theory and represents the realized uncertainties that lead the maximum imbalance in the system according to the decision made in the master problem. It should be noted that in each iteration, the outputs of the master problem include $p_{it}^{(j)}$, $FRD_{it}^{(j)}$, $FRU_{it}^{(j)}$ and $FRN_{it}^{(j)}$, enter the sub-problem and in the sub-problem, the worst-case of nodal power imbalance are determined with binary variables a_{bt}^{up}, a_{bt}^{dn} that these binary variables return to master problem for next iteration.

3. SOLUTION METHODOLOGY

Figure 1 shows the problem solving procedure according to the iterative method based on column and constraint generation (CCG) algorithm. In this method, in each iteration, the master problem is solved based on the worst-case of nodal power imbalance, under uncertainty budget M that obtained by sub-problem in previous iteration ($j-1$) and co-optimization energy and ramping reserve capacity include fixed and variable costs, start-up and shut-down costs and ramping reserve capacity of fast and slow response generation units to cover changes in the net load of the system with the minimum operation cost are done.

A worth point in the problem solving process is the addition of optimal cuts for iteration $j > 1$, including constraints (34)-(38) to master problem. According to figure 1, the problem is repeated until the decision made in master problem, even in the worst-case scenario, lead to nodal power balance. Therefore, in this case, with the achievement of global optimality, the problem solving process will stop.

4. CASE STUDY

In order to evaluate the effectiveness of slow and fast response generation separation approach in providing the required flexibility of the power system as well as the performance of the proposed solution method, modified 24-bus IEEE Reliability Test System in [21], including 26 thermal generation units, 24 buses, 38 power transmission lines, 6 wind power generation units and each unit with 160MW capacity in buses 3, 5, 7, 16, 21 and 23, the maximum 3498.66MW system load and uncertainty of wind power characterized by a ± 20% fluctuation around the forecast generation level, is used. Among the 26 thermal units in this test system, there are 6 fast response units including units 6, 7, 8, 9, 28 and 26, whose non-spinning ramping reserve capacity price, twice the upward spinning ramping reserve capacity price has been considered. Given the existence of 6 wind generation units, which are the sources of uncertainty, the budget of uncertainty M can have a range of change from 0 to 6; M=0 and M=6 indicate the base-case and the worst-case of uncertainty realization in the system, respectively. It should be noted that in performed simulations, the optimum accuracy of the master problem and the sub-problem are set to 10^{-4} and 0 respectively. In order to examine the proposed approach, the following scenarios are considered:

1) Non-separation generation units based on their speed of response.
2) Separation generation units based on their speed of response.

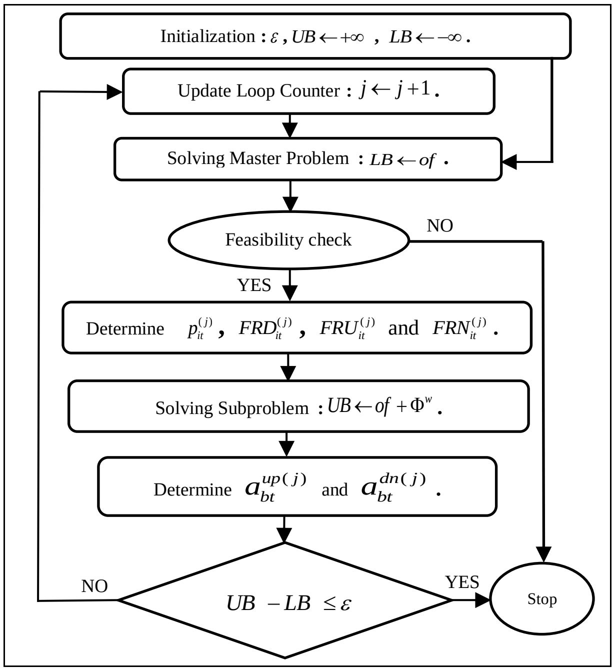

Fig. 1. CCG PROBLEM SOLVING FLOWCHART

5. NUMERAL RESULTS

In order to evaluate the effectiveness of the proposed model, the test system mentioned in section 4 has been evaluated that as an example, the results of this evaluation can be seen in Tables 1 and 2 for the worst-case of uncertainty realization in the power system, i.e. M=6. By comparing these two tables, it can be concluded that in case of separation of generation resources due to their response potential under uncertainty, the need for expensive units to be online (status 1) in order to use from their spinning ramping reserve capacity in case fluctuations in wind power output will decrease; because fast response units with the ability to change the status from off to on and vice versa in a short period of time and provide non-spinning ramping reserve capacity, significantly reduced operating costs. A significant part of these reduced costs is related to fixed and variable costs of generation units. As stated, Table 3 shows the reduction in operating costs for different amounts of uncertainty budget.

As shown in Table 3, as the uncertainty budget increases, so does the operating cost; because there is a need to deploy more ramping reserve capacity to cover changes in the power output of wind units. On the other hand, if we take full advantage of the potential of ramping capacity of fast response resources such as gas units, we see a reduction in operating costs for different amounts of uncertainty budget; for example in the worst-case scenario, operating costs were reduced by 6786.6$ or 0.85%. It is worth mention that under the worst-case scenario, the cost of robustness in the first scenario was (803546.9-784333.2)/784333.2$=2.45% which in the second scenario decreased to 1.58%. In figure 2, as an example, the allocation of spinning and non-spinning ramping reserve capacity per hour for M=6 have been shown. According to the figure, the important role of fast response units in providing the required ramping capacity of the system at different hours can be seen.

TABLE. 1. UNIT COMMITMENT IN FIRST SCENARIO

	Number of units																								
hour	1	2	3	4	5	6	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
t0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	1	1
t1	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	1
t2	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	1
t3	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	0	0	0	1	0	1
t4	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	0	0	0	1	0	1
t5	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	0	0	0	1	0	1
t6	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	0	0	0	1	0	1
t7	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	1	1
t8	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	0	0	1	1	1
t9	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1
t10	0	0	0	1	0	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
t11	0	0	0	1	0	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
t12	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
t13	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
t14	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
t15	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t16	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t18	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t19	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t20	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
t21	0	0	0	1	0	0	0	0	1	1	1	1	0	0	1	1	1	1	1	0	1	1	1	1	1
t22	0	0	0	1	0	0	0	0	1	1	1	1	0	0	1	1	1	1	1	0	0	0	1	1	1
t23	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	1	1
t24	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	1	1	1	1	0	0	0	1	0	1

TABLE. 2. UNIT COMMITMEN IN SECOND SCENARIO

	Number of units																			
hour	3	4	5	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
t0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	1	1
t1	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	1
t2	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	1
t3	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	0
t4	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	0
t5	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	0
t6	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	0
t7	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	1	1
t8	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	0	0	1	1	1
t9	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1
t10	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
t11	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
t12	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
t13	0	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
t14	0	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
t15	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t16	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
t20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
t21	0	0	0	1	1	1	1	0	0	1	1	1	1	1	0	1	1	1	1	1
t22	0	0	0	1	1	1	1	0	0	1	1	1	1	1	0	0	0	1	1	1

t23	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	1	0
t24	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	0

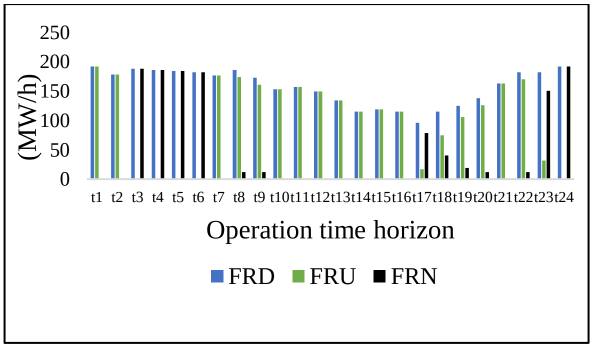

Fig. 2. ALLOCATION OF SPINNING AND NON-SPINNING RAMPING RESERVE CAPACITY PER HOUR FOR M=6

TABLE. 3. OPERATING COST OF EACH MENTIONED SCENARIOS

Uncertainty budget	Scenario 1 ($)	Scenario 2 ($)
M=0	784333.2	784333.2
M=1	786999.6	786015.6
M=2	790221.8	787839
M=3	793183.8	789544.7
M=4	797507.6	791670.5
M=5	799543.1	794270.3
M=6	803546.9	796760.3

It should be noted that the use of adaptive robust optimization based on column and constraint centration algorithm along with the proposed model to provide the required ramping capacity of the system, including separation generation resources approach based on response speed and change their status to caver fluctuations of wind power output, has a efficient convergence speed according to Table 4; so that the problem has converged in 3 iteration with an average computational time equal 64s for each amount of uncertainty budget.

TABLE. 4. SPEED OF SOLVING THE PROPOSED MODEL IN IEEE 24-BUS TEST SYSTEM

Uncertainty budget	computational time (s)	The number of iterations
M=1	62	3
M=2	62	3
M=3	82	3
M=4	55	3
M=5	65	3
M=6	59	3

6. CONCLUSION

Due to the increase of renewable energy resources in the power system, especially wind power generation units, the optimal day-ahead operation planning of generation resources in order to provide the required flexibility of the system has become an important issue. Therefore, in present article, the approach of separating generation units into fast and slow response resources was used which the results shows the high potential of this approach in the optimal operation of generation units; so that for different amounts of uncertainty budget, we see an average reduction in operating costs and robustness by 0.52%. On the other hand, using adaptive robust approach with column and constraint centration algorithm, has had a acceptable efficiency in problem solving speed; so that the problem is solved and converge in a maximum of 3 iterations with an average calculation time of 64s for deferent amounts of uncertainty budget.

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