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A Robust Primary Frequency Response Constrained Unit Commitment Considering Uncertain Frequency Support of Units

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ABSTRACT

Power management in microgrids is a major challenge due to its low total inertia and capacity. The lower the microgrid generation capacity is, the higher the share of each generation unit in total power will be, and the higher the frequency deviation in less time will be when an outage occurs. So, preventive actions can be more reasonable and affordable than corrective actions for microgrid power and frequency control. In this regard, a new primary frequency response-constrained unit commitment model is presented here to prevent excessive frequency deviations by more commitment of higher inertia power plants and more contribution of renewable energy resources or energy storage systems' fast inertia response. To have a mixed-integer linear programming model, the primary frequency response constraints are linearized. The model is solved by the combination of two commercial solvers named MOSEK and YALMIP in the MATLAB 2018 environment. The proposed model is examined on a real isolated microgrid (an island). The results show that by activating the primary frequency support of distributed energy resources, the power can be managed with lower costs because there will be less need to start up fast (and expensive) gas turbine generation units. In addition, although comparing the model with others shows the more expensive management procedure, better frequency stability is obtained in contingencies.

NOMENCLATURE

Symbol	**Description**
c_j^{p}, c_j^{on}	Production/no-load cost of the generation unit j
c_j^{su}, c_j^{sd}	Startup/shutdown cost of generation unit j
c_j^{FCR}, c_j^{FRR}	Frequency conservation/recovery response cost of unit j
d_k	Total demand in time interval k
D_j	Droop coefficient of generation unit j
$e_{j,k}$	The state of charge of the unit j in time interval k
$\overline{e}_j, \underline{e}_j$	Max/Min storage capacity of unit j
$E^{FCR}(t)$	Total primary frequency response Energy in each time
E_j^{FCR}	The primary frequency response energy of unit j
$f, \dot{f}(t)$	Frequency and its derivative
$\underline{f}, f^{nom}, f^{tr}$	The minimum/nominal/nadir frequency
f^{st}	Steady-state frequency
$f_{lin}(t)$	Function of linear approximation of frequency
F	Laplace transform frequency
FCR, FRR	Frequency conservation/recovery response
H	Total inertia of the microgrid
H_j, I_j	Inertia/ Kinetic inertia coefficient of generating unit j
$I_{l,j}^{c}$	The contingency matrix
j, J	Generation unit index/ Set
$\overline{J}$	Set of outage units
k, K	time intervals index/Set
l, L	Collection index/Set

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$m\ ,M$	discretization points index/Set
N_j^P	pole pairs number of the generator j
P^{lost}	The lost power
$P^{FCR}(t)$	Total primary frequency response power in each time
P_j^{FCR}	The primary frequency response power of the unit j
$\tilde{P}_j^{FCR}$	Command sent to generator j to generate power in FCR
$\tilde{P}_j^{FCR_{st}}$	Command sent to generator j at steady-state start time
$\overline{P}_j^{FCR}$	Upper limit of the primary frequency response of the unit j
$p_{j,k}, r_{j,k}$	Power output/reserve of generation unit j in time interval k
$\overline{p}_{j,k}^f, \underline{p}_{j,k}^f$	Max/Min forecasted power of unit j in time interval k
$\overline{p}_j^t, \underline{p}_j^t$	Max/Min power capacity of unit j
$r_{j,k}^{FCR}, r_{j,k}^{FRR}$	Frequency conservation/recovery response reserve
$\overline{r}_j^{FCR}, \overline{r}_j^{FRR}$	Max frequency conservation/recovery response reserve
$r_{j,k,m}^{\delta p,FCR}$	Power of participation of generator j in time interval k and
$r_{j,k,m}^{\delta e,FCR}$	Generator j participation energy in time interval k and
$\delta\rho_j^{FCR}(t)$	Generator FCR operation activation function j
$\delta\rho_{j,m}^{FCR}$	Discrete function
$\delta\rho_{j,M}^{FCR}$	Maximum amount of power that can participate in the
R, R_j	Total online capacity/power capacity of unit j
t_s, T	Time step/ time horizon
t^c, t^{st}	Critical and steady-state time of frequency
t_m^{FCR}	Time m is the point of discretization of the FCR
$v_{j,k}^{on}, v_{j,k}^{su}, v_{j,k}^{sd}$	On/off, startup/shutdown status of unit j in time k
$\omega_j, \omega_j^{nom}, \omega_j^{\min}$	Generation unit angular velocity/its Nominal/Min value
$\omega_{j,k}$	Storage turbulence
ϕ	The objective function
λ	A fixed coefficient
$E_{k,l,m}^{res}, E_{k,l,m}^{con}$	Reserved/lost energy in time k, point m, and outage l
$E_{l,k}^{rot}$	Rotational energy in time k, outage l

INTRODUCTION

A. Background, Motivation, and Approach

By the expansion of low inertia renewable energy resources in microgrids, control of frequency deviation after occurring a contingency using provision of frequency response becomes a challenge [1]. In the traditional power systems, providing the secondary [2] or territory frequency control [3] was the aim of researchers. While, inertia and primary frequency response (PFR) has gained more importance than before [4]. If the primary frequency deviation cannot be limited in the first moments after an outage, under-frequency protections will be activated that would lead to a partial disconnection or blackout in the system [5]. Therefore, considering the primary frequency parameters such as rate of change of the frequency, frequency nadir and quasi steady state behavior is included in new power management models of microgrids [6]. For frequency response improvement either remedial actions [7] or preventative consideration [8]can be adopted which the latter is the focus of this paper.

Most of frequency control preventative actions is based on unit-commitment or power management of generation units or loads during the day. So, frequency constrained unit commitments models have been developed [9]. Contribution of load shedding [10] or integration of renewable energy resources [11] or energy storage systems [12] are also included in these models. The review of frequency constrained unit commitment models are presented in [13].

Primary frequency response is a concept that analyze the frequency dynamics immediately after an event that leads to a power imbalance followed by frequency oscillations in the network [14]. After a generation unit outage, the frequency decreases by a fast rate called rate of change of frequency (RoCoF). The absolute value of this ramp must not exceed from 1Hz/s (for less than 500 ms) [15]. According to the single-machine equivalent model of system and swing equation, RoCoF can be limited merely by inertia of the system[16]. Frequency decreases until the sum of inertia responses of other online units overcomes the lost power[17]. Then the frequency reach to its minimum value called nadir which is vital not to exceed its limits (about 500 mHz)[18]. According to [11, 19] the frequency nadir has a non-linear relation with inertia, governor droop and power fraction of high pressure turbine. In this regard, an analytical model for minimum frequency prediction is obtained in [20] using the polynomial fitting of governor PFR characteristic. Furthermore, in [21] a model predictive approach is introduced that calculate the time and frequency of nadir by solving a set of non-linear equation in isolated low inertia networks.

Frequency stability in isolated grids or small microgrids is somehow more complex than large scale power system. A small outage in an microgrid can lead to a large frequency deviation [10]. So, due to this sensitivity, more attention must be paid prevent measures. Utilizing any apparatus that improves the frequency stability is of great importance in microgrids [22]. Accordingly, the use of any virtual inertia of renewable energy resources or energy storage systems for frequency support is on the agenda of system operators [23]. Hence, in this paper a new microgrid power management model is presented that contribute the inertia response of renewable energy resources and energy storage systems for primary frequency support. The more details about the main distinction of this work with other models are mentioned below.

B. Literature review and contributions

In [24], several models of frequency-constrained unit commitment problem are compared from frequency improvement. In [25] using the general order frequency support model and swing equation, time domain dynamics of frequency obtained considering the same governor time constant. After calculation of frequency nadir, a nonlinear function representing the nadir constrain is piecewise linearized using multi variable regression method. The same approach is also stated in [11] while the primary frequency response of renewable energy resources such as photovoltaic and wind turbine are added to its model. A more complete frequency dynamics model is introduced in [26] that consider the details of converter control and generators dynamics. The piecewise linearization with curve fitting is done in it and a new bound extraction method is applied to reduce the computational burden.

A different nadir calculation approach is investigated in [27] which consider a predefined function for response of generation units and calculates the nadir point using time domain analysis in the presence of battery energy storage systems. The [28] assumes a predefined primary frequency response of each unit without any direct reference to nadir point. Instead, the provision of total lost power or energy is assumed as a linear constraint for frequency support. In [22] considering the droop behavior, headroom of generation units, and linear approximation of frequency changes from an outage to nadir time, several linear boundary conditions are obtained to support the lost power and energy of the network in the first moments. In [29-32] a logarithmic equation is formulated for nadir frequency constraints using a predefined function for generation unit primary frequency response. Their nonlinear nadir related terms are linearized using big-M method. Some forms of nonlinear nadir constraints are extracted in [33, 34]. Extraction of nadir constraints in multi-area networks is performed in [12, 35] an linearized using Pseudo-Boolean functions.

The contribution of this paper can be stated as follows:

a) The uncertainty of units contribution in PFR is included in the model as a distinctive novelty in comparison with all related works.
b) A new robust optimization is presented.
c) A new piecewise nadir frequency linearization is presented.
d) Several case studies are investigated to represent the distribution energy resources penetration level on the optimum results.

The rest of the paper is organized as follows. In section II the description of the proposed model is presented. Then, the solution method of the model is introduced in III as a flowchart. The simulation and analysis are expressed in IV. Finally, conclusions and future works is included in the part V.

MODEL DESCRIPTION

A. The basic unit commitment model

In the basic unit commitment problem, the operation of generation units is determined to meet the load and security power flow constraints with minimum costs. So, the basic unit commitment can be modeled as follows:

$$\min \ \phi^{UC} = \sum_{j\in J}\sum_{k\in K}\left(t_s c_j^{p} p_{j,k} + t_s c_j^{on} v_{j,k}^{on} + c_j^{su} v_{j,k}^{su} + c_j^{sd} v_{j,k}^{sd}\right) \quad (1)$$

$$\sum_{j\in J} p_{j,k} \ge d_k ;\forall k\in K \quad (2)$$

$$\underline{p}_j^{t} v_{j,k}^{on} \le p_{j,k} \le \overline{p}_j^{t} v_{j,k}^{on} ;\forall k\in K, j\in J \quad (3)$$

$$p^{f}{}_{j,k} \le p_{j,k} \le p^{f}{}_{j,k} ;\forall k\in K, j\in J \quad (4)$$

$$v_{j,k}^{on} - v_{j,k-1}^{on} \le v_{j,k}^{su} ; \qquad \forall j\in J, k\in K \quad (5)$$

$$v_{j,k-1}^{su} - v_{j,k}^{sd} \le v_{j,k}^{sd} ; \qquad \forall j\in J, k\in K \quad (6)$$

$$v_{j,k}^{on}, v_{j,k}^{su}, v_{j,k}^{sd} \in \{0,1\}, \qquad \forall j\in J, k\in K \quad (7)$$

$$v_{j,k'}^{on} \ge v_{j,k}^{st},\ k'=[k, k+MUT-1], \quad \forall k\in K, j\in J \quad (8)$$

$$v_{j,k'}^{on} \le \left(1-v_{j,k}^{sd}\right),\ k'=[k, k+MDT-1], \quad \forall k\in K, j\in J \quad (9)$$

$$\underline{p}_j^{t} v_{j,k}^{on} \le p_{j,k} + r_{j,k}^{res} \le \overline{p}_j^{t} v_{j,k}^{on} ;\forall k\in K, j\in J \quad (10)$$

$$p_{j,k} - p_{j,k-1} \le \overline{\Delta p_j^{RU}} ;\forall k\in K, j\in J \quad (11)$$

$$p_{j,k-1} - p_{j,k} \le \overline{\Delta p_j^{RD}} ;\forall k\in K, j\in J \quad (12)$$

Eq. (1) shows the objective function of the basic unit commitment which is composed of power generation, no-load, startup and shutdown cost of generation units. This function must be minimized under certain circumstances. The most important factors that guarantees the supplementation of the load is defined as the Eq. (2) which forces the generation units to inject power more than or equal to the total demand of the network. Moreover, Eq. (3) and Eq. (4), prevents thermal generation unit and distributed energy resources to produce power more than their nominal capacity and less than their minimum range. Some binary variable such as unit on/off, startup, and shutdown statuses are linked together via equations (5)-(7). Furthermore, considering the minimum up and down time (MUT/MDT) constraints are included in model using equations (8) and (9), respectively. According to Eq. (10) each generation unit must be operated in the allowed range to have a capability for contribution in the spinning reserve support. Finally, the up/down ramp limits of power generation are included in the model using equation (11), and (12), respectively. The basic model is the lowest cost model because it merely considers the minimum cost without any flexibility to contingency or uncertainty in the network. So, the frequency stability may be lost in an unexpected outage. In some microgrids or island power systems, the frequency drop slope cannot be violated from 1Hz/s. So, if the frequency in not conserved in less than 2s, the frequency may experience more than 2Hz deviation from its nominal value that is not preferred. So, at this short period just preventative actions can be applied to the network. Keeping online the units with higher inertia and regulation of their droop coefficient to contribute in primary frequency response is the most effective solution for frequency conservation and restoration. So, a primary frequency constrained unit commitment is introduced as follows.

B. The primary frequency response constrained UC model

Modelling of primary frequency response constrained unit commitment problem is the integration of basic unit commitment model and some frequency limitations such as rate of change of frequency and nadir frequency limits. The rate of change of frequency is only depends on the total inertia of the network and the lost power. But the nadir time and frequency depend nonlinearly upon several parameters such as generation unit characteristics, power imbalance, and system inertia. So, linearization approach must be adopted. The model of primary frequency constraints problem is as follows:

$$\min\ \phi^{PFRUC} = \phi^{UC} + \sum_{j \in J}\sum_{k \in K}\left(t_s c_j^{FCR} r_{j,k}^{FCR}\right) \tag{13}$$

$$s.t: \quad \text{Equations (2)-(12)} \tag{14}$$

$$H_k^T \geq \left|\frac{\Delta P_k^{lost}}{2RoCoF}\right|; \forall k \in K \tag{15}$$

$$H_k^T = \sum_{j \in J} H_{j,k} R_j \Big/ \sum_{j \in J} R_j; \forall k \in K, \tag{16}$$

$$H_{j,k} = \frac{1}{2} I_j \left(\omega_j^{nom}\right)^2; \forall k \in K, \tag{17}$$

$$\sum_j r_{j,k}^{FCR} \geq P^{lost}; \qquad \forall k \in K \tag{18}$$

$$r_{j,k}^{FCR} \leq \delta\tilde{P}_{j,M}^{FCR}; \qquad \forall j \in J, k \in K \tag{19}$$

$$\delta\tilde{P}_{j,M}^{FCR} = -\left(\underline{f} - f^{nom}\right)\left(1/D_j\right) \tag{20}$$

$$\delta\tilde{P}_{j,m}^{FCR} = \frac{m}{M}\delta\tilde{P}_{j,M}^{FCR} \tag{21}$$

$$r_{j,k,m}^{FCR} = \frac{\delta\tilde{P}_{j,m}^{FCR}}{\delta\tilde{P}_{j,M}^{FCR}} r_{j,k}^{FCR} = \frac{m}{M} r_{j,k}^{FCR} \tag{22}$$

$$Er_{j,k,m}^{FCR} = Er_{j,k,m}^{FCR} + 0.5\left(t_m - t_{m-1}\right)\left(r_{j,k,m}^{FCR} - r_{j,k,m-1}^{FCR}\right) \tag{23}$$

$$\sum_j Er_{j,k,m}^{FCR} + \sum_j \frac{1}{2} I_j \left(\omega_j^{nom} - \underline{\omega}_j\right)^2 v_{j,k}^{on} \geq P^{lost} t_m \tag{24}$$

$$\Delta f^{Linear} = \frac{t}{t_c}\left(\underline{f} - f^{nom}\right) \tag{25}$$

The objective function of primary frequency response constrained unit commitment model is described in the Eq.(13) which is the summation of basic unit commitment objective function and the cost of primary frequency response provision. Furthermore, according to the Eq. (14) all the constraints of Eq.(2)-(12) must be applied in the model. The rate of change of frequency constraints is given in the Eq. (15). As stated before, this parameter just depends upon the total inertia of the network and the lost power. Calculation of the network total inertia is presented in Eq. (16). Also, the inertia of a thermal units can be calculated using the Eq. (17). The nadir frequency constraints are formulated in equations (18)-(25) as linear boundary conditions. The nadir frequency can be calculated using assumption of Eq. (25), that considers the frequency dynamics as a linear function of time, which its details are described in [22]. Therefore, the concepts of the Equations (18)-(25) is summarized here, for better understanding of frequency nadir conservation. In order to keep the nadir frequency in its allowed range, two enough constraints must be met in practice. First of all the total lost power in the nadir point must be equal to the total primary frequency response of the generation units, according to the Eq.(18). The second boundary condition, is related to primary frequency energy provision for the lost power that guarantees total energy generated by units and the kinetic energy (or Inertia response) of thermal units must be higher than total lost energy in each time, which its final form is given in the Eq. (24). In order to calculate this energy, it is required to use some assumption to simplify the calculations. At first it is assumed that before the nadir point, the frequency has a linear (or piecewise linear) behavior according to the Eq. (25). Furthermore, the primary frequency response of each generation unit is according to its governor droop setting. So, the primary frequency response of each unit can be obtained from the Eq. (20) at the nadir point. Before this point, because of the linear behavior of the frequency, several discretized points denoted by $m = 1, 2, .., M$ is considered to segment the frequency during the time interval from outage to nadir point. So, in these points the value of frequency conservation power and the energy generated by each unit is calculated using the Eq. (21) and Eq. (23), respectively. This is the deterministic model that don't consider any uncertainty. In the most of the literature review, the uncertainty of the load, wind energy, or other renewable energy resources power is considered. However, no discussion about the uncertainty of units in detecting the frequency deviation and providing the primary frequency response in the system is presented. But, it in the real-world problems, it is possible for a unit that was online and had a headroom but cannot deliver its power in a short time to the network in an outage, So, in this paper we present a robust model that consider this possibility. Considering this uncertainty can increase the flexibility of the network in preventive unit commitment.

C. The robust primary frequency response constrained UC

In the proposed model it is assumed that a unit participation in primary frequency support is not deterministic. It means that this unit cannot contribute in the primary frequency response or because it cannot track the frequency changes or delivery its response to the network in the first seconds after an outage. So, its behavior is uncertain and can be modelled as follows:

$$r_{j,k}^{FCR} \leq \left(1 - \tilde{u}_{j,k}\right)\overline{r}_j^{FCR}; \qquad \forall j \in J, k \in K \tag{26}$$

$$\frac{1}{J}\sum_j \tilde{u}_{j,k} \leq \tilde{\varepsilon}; \qquad \forall k \in K \tag{27}$$

According to the Eq. (26), in some intervals, each generation unit may be faced with a problem that cannot deliver its frequency response to the network. In this case we use an uncertain parameter $\tilde{u}_{j,k}$ that is zero in normal condition and is 1 whenever the generation unit j cannot contribute in the primary frequency response. Therefore, according to the Eq.(26), the reserve of this unit will be zero in this case. While in normal condition $\tilde{u}_{j,k} = 0$, and consequently, the Eq.(26) will be convert to the Eq.(19). Mathematical expectation of $\tilde{u}_{j,k}$ must not violated from the ambiguity radius $\tilde{\varepsilon}$. When the ambiguity set is zero, a PFR-constrained UC is obtained. When this value in increases the number of failure unit is increased. When this parameter is one, all the generation unit can faced with failure in each time interval.

OPTIMIZATION APPROACH

The flowchart of optimization implementation is shown in Fig. 1. At First, all the necessary data required for the simulation will be called and converted to the desired format of YALMIP software. These data are related to the power system topology, generation and load units, distribution energy resources, the predicted weather conditions, economic data and primary frequency support essential parameters.

After receiving the information, the basic unit commitment model is solved using the MOSEK solver to reach the cheapest operation of powers systems. Then the primary frequency response of this network is analyzed in the largest unit outage condition in each time interval. If there is no frequency instability, so, there is no need to primary frequency response constrained unit commitment and the program will be terminated. But if the nadir frequency violates its standard deviation value, the proposed unit commitment method is pplied to prevent the system from instability. After solving the model, the frequency response of the system is analyzed after contingency to validate the effectiveness of the model. After that, the contribution of some online distribution energy resources is deactivated to see the effect of this failure on the frequency dynamics. If there an instability is occurred the proposed robust model is simulated to achieve more reliable results of the problem. After plotting the results, the program will be terminated.

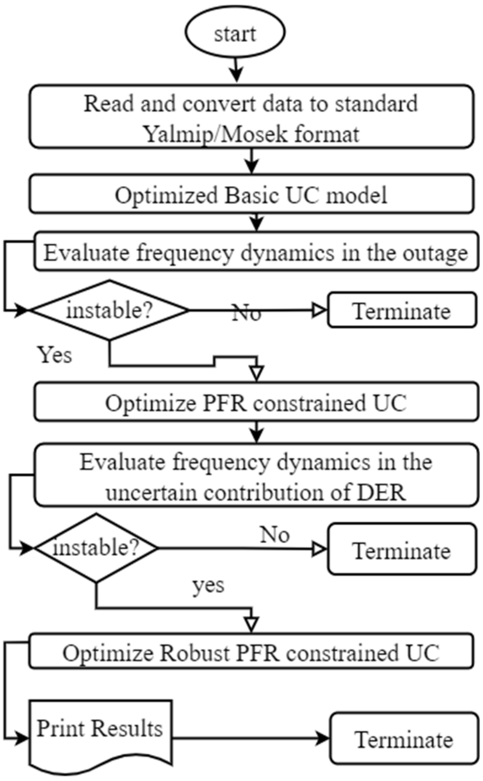


Fig. 1. Flowchart of the proposed algorithm

Simulation and analysis

Simulation of the proposed method is applied to a real island microgrid in the Finland which has 9 generation units. Technical and economic data of these units are given in the Table 1 in which hydro, diesel and wind power plant are denoted by H, D, and W symbols, respectively. Furthermore, the primary frequency related parameters are described in the Table 2. Three case studies are investigated, here, the basic model, the PFR-based model, and the robust PFR-based model. The largest unit outage is considered as a contingency in each time interval. A combination of YALMIP and MOSEK solvers is utilized in this paper. At first, using a semi-definite programming, constraints, variables, and the objective function are modeled in MATLAB (2021b) software [36]. Then, by setting the solver to MOSEK 9.2, a branch and bound algorithm based optimization is started [37]. We use the academic version. Implementation is done by a DELL latitude laptop with a 6th-generation corei5 CPU, 8 GB of RAM and a 256 GB SSD hard drive.

TABLE 1

Generation unit parameters

Technical Param	Value	Dimension
Type	[H, H, H, D, D, D, H, W]	-
Pole pair number	[8,8,8,14,10,12,40,8,0]	% of nominal
Capacity	[8.6,8.6,7.7,2.2,6.3,4,7.2,3.5,10]	Hz
Min power	[2.7,2.7,3,1.0,1.3,1.8,7,1.2,0]	Hz
Momentum	[5.9,5.9,8.05,2.1,4.4,23.3,22.5, 4.8,0]×1000	-
Time constant	[3,3,3,2,2,5,5,3,0.5]	h
Economic Param	Value	Dimension
Marginal cost	9	-
Startup cost	0.05	-
Shutdown cost		
No-load cost		
FCR cost		

TABLE 2

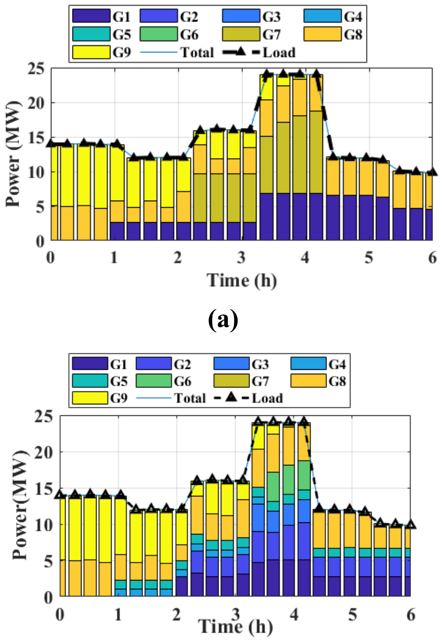
Technical parameters of the model

Quantity	Value	Dimension
Governor droop	0.05	-
Max allowed FCR	100	% of nominal
Nominal frequency	50	Hz
Min frequency	48	Hz
Discretized points	4 point in 2s	-
Time horizon	6	h
Time step	15	min
Num of generation unit	9	-
Optimization Gap	0.05	-

TABLE 3

Unit commitment results

Online time		Generation
PFR-based UC	Basic UC	
2:15-6:00	1:00-6:00	G1
2:30-6:00	Off	G2
3:30-4:15	Off	G3
1:15-3:30	Off	G4
1:15-6:00	Off	G5
3:45-4:15	Off	G6
Off	2:30-4:15	G7
All time	All time	G8
0:00-4:45	0-4:45	G9

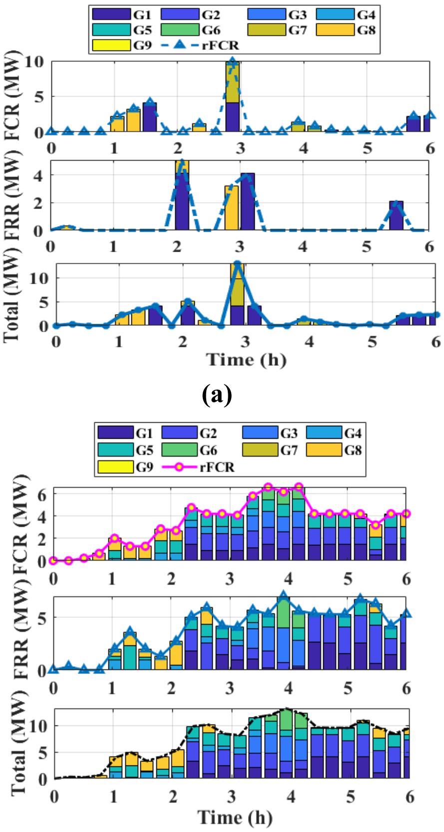


(a)

(b)

Fig. 2. Contribution of each unit in load supply (a) the basic UC model and (b) the PFR-constrained UC model

The on/off status (or the online time) of each generation unit in the basic and PFR-constrained unit commitments is compared in the Table 3. The lowest price units are operated under the basic unit commitment conditions which are wind power plants, power plants number 8 and 1. Furthermore, in some hours the G7 contributes in the load supplementation. In the PFR-constrained UC the number of online units in each time interval is more than basic UC to provide more reserve for any contingency, however, the total cost is increased about 31.52% compare to the basic model. The share of each power plants in meeting the load is depicted in the Fig.1 (a) and (b), for basic and PFR based model, respectively. The total load is supported by generation units, adequately. In the basic model, the more expensive units (G7) are only contributed during the peak load time. During the wind energy availability, total generation of conventional units are reduced. So, in the basic model, the number of online units in the off-peak is reached to two power plants. On the other hand, the minimum number of online units in the PFR-based model is more than basic model in at each time interval, according to Fig. 2(b). Keeping more units online, can bring several merits such as reserve conservation and frequency stabilization, although implemented with more operation cost. So, a trade-off must be considered between technical and economic benefits. The base load of the network in the PFR-based model is supplied by three units (G1, G8, and G9). But the contribution of these three units is lower than basic model to keep more reserve for frequency problems. The lower contribution in demand meeting, the lower imbalance power in an outage, the smaller frequency deviation, the more stable network with higher operating cost. From the primary frequency reserve aspect, the need for more energy reserve PFR-based mode is demonstrated in the Fig. 3. Considering the frequency nadir and RoCoF constraints, would force the power system operators to reserve energy more than before. The offline units have no contribution in the frequency response. The online units except wind power generation have ability to contribute in the primary frequency response.

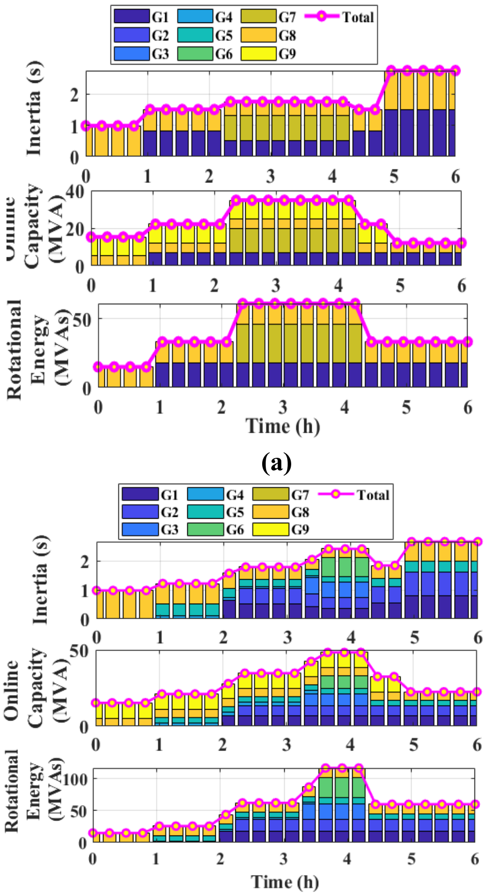


(a)

(b)

Fig. 3. Contribution of each unit in total reserve (a) the basic UC model and (b) the PFR constrained UC model

The value of the reserved is limited to 35% of each generation unit to prevent from the derate of efficiency in the power plant when it works far from its nominal point. Fig. 4 (a) and (b) shows the total inertia, total online capacity and total rotational energy of the network, for the basic and PFR-model, respectively. The effect of the primary frequency response limits in the optimum solution can be easily realized from this figure. The value of the total inertia in the basic model (Fig. 4(a)) is lower than two seconds, because of the more contribution of cheap wind energy which has no or low inertia response. But by increasing the share of conventional high inertia units in the system, the inertia of the power system is increased as depicted in this figure. So, the penetration level of wind power has negative effect on the frequency dynamics parameters of the network. Using the PFR-based mode the more online capacity or rotational energy can provide more flexibility and reliability in the network and frequency stability. When there is an uncertainty in the power plants primary frequency response, the network nadir frequency or RoCoF may faced with a threat of violation from their standard limits. By increasing the possibility of disability of generation units in injection of power in a contingency, the risk of frequency nadir violation is increased and the more generation units must be operated and the higher cost is obtained. By increasing the ambiguity radius from zero to 10%, the nadir point may violate more than 5% in if it is not considered in PFR-based model. By considering this uncertainty, the operating cost is increased about 1% compared to the PFR-based model.



(a)

(b)

Fig. 4. Contribution of each unit in total inertia (up), online capacity (center), and rotational energy (down), (a) the basic UC model and (b) the PFR constrained UC model

CONCLUSIONS

In this paper, a mixed-integer linear programming model of primary frequency response unit commitment model is presented that consider the uncertainty of the generation units contributions in primary frequency support. A robust model is introduced to investigate the impacts of distribution energy resource penetration level in the microgrid. Simulation results show that considering the nadir frequency constraints forces the more cost to the power system. In the other words, the more online unit must be operated and the more expensive units with faster response get more priority than before. So, frequency stability achievement has a cost. Moreover, increasing the penetration level of distribution energy resources, comes with more frequency instability and power imbalance that limits their more developments in the network. Therefore,

considering the primary frequency response constraints in the unit commitment model can provide more chance for the expansion of these green technologies. Preventing the system from blackout or under-frequency relays are other achievement of the proposed model.

Considering the uncertainty of the generation units shows that there is need to turned on more generation units in the network. By increasing the penetration level of distribution energy resources or increasing the probability of errors in detection primary frequency response support the number of online units must be increased. So, the more cost must be considered for provision of primary frequency response by unit commitment in the presence of uncertainty. For future work, including the proposed model in generation and transmission expansion planning is on the agenda of the authors of this paper.

REFERENCES

[1] A. Karimi, Y. Jafarian, H. Bevrani, and R. Mirzaei, "Frequency response improvement in microgrids: a fuzzy–based virtual synchronous generator approach," International Journal of Industrial Electronics Control and Optimization, vol. 3, no. 2, pp. 147-158, 2020.

[2] M. Alizadeh, H. Askarian Abyaneh, A. Bakhshai, and N. Khodabakhshi Javinani, "An Enhanced Distributed State Feedback for Secondary Control in an Islanded Microgrid," International Journal of Industrial Electronics Control and Optimization, 2022.

[3] P. Sheikhzadeh-Baboli and M. Assili, "Introducing a New Optimized Emergency Demand Side Management Method to Restore the Power System Frequency," International Journal of Industrial Electronics Control and Optimization, vol. 5, no. 1, pp. 1-9, 2022.

[4] A. Karimipouya, S. Karimi, and H. Abdi, "Microgrid frequency control using the virtual inertia and ANFIS-based Controller," International Journal of Industrial Electronics Control and Optimization, vol. 2, no. 2, pp. 145-154, 2019.

[5] Z. Wu et al., "State-of-the-art review on frequency response of wind power plants in power systems," Journal of Modern Power Systems and Clean Energy, vol. 6, no. 1, pp. 1-16, 2018.

[6] R. Sepehrzad, S. Nakhaeisharif, A. Al-Durra, M. Allahbakhshi, and A. Moridi, "Islanded micro-grid frequency control based on the optimal-intelligent lyapunov algorithm considering power dynamic and communication uncertainties," Electric Power Systems Research, vol. 208, p. 107917, 2022.

[7] A. Conde, G. Perez, G. Gutierrez-Alcaraz, and Z. Leonowiczc, "Frequency improvement in microgrids through Battery Management System control supported by a remedial action scheme," IEEE Access, 2022.

[8] R. Rajan, F. M. Fernandez, and Y. Yang, "Primary frequency control techniques for large-scale PV-integrated power systems: A review," Renewable and Sustainable Energy Reviews, vol. 144, p. 110998, 2021.

[9] A. Safari and H. Shahsavari, "Frequency-constrained unit commitment problem with considering dynamic ramp rate limits in the presence of wind power generation," Neural Computing and Applications, vol. 31, no. 9, pp. 5241-5254, 2019.

[10] D. Rebollal, M. Chinchilla, D. Santos-Martín, and J. M. Guerrero, "Endogenous Approach of a Frequency-Constrained Unit Commitment in Islanded Microgrid Systems," Energies, vol. 14, no. 19, p. 6290, 2021.

[11] Z. Zhang, E. Du, F. Teng, N. Zhang, and C. Kang, "Modeling frequency dynamics in unit commitment with a high share of renewable energy," IEEE Transactions on Power Systems, vol. 35, no. 6, pp. 4383-4395, 2020.

[12] S. S. Oskouee, S. Kamali, and T. Amraee, "Primary Frequency Support in Unit Commitment Using a Multi-Area Frequency Model With Flywheel Energy Storage," IEEE Transactions on Power Systems, vol. 36, no. 6, pp. 5105-5119, 2021.

[13] N. Yang et al., "A Comprehensive Review of Security-Constrained Unit Commitment," Journal of Modern Power Systems and Clean Energy, 2021.

[14] Z. A. Obaid, L. M. Cipcigan, L. Abrahim, and M. T. Muhssin, "Frequency control of future power systems: reviewing and evaluating challenges and new control methods," Journal of Modern Power Systems and Clean Energy, vol. 7, no. 1, pp. 9-25, 2019.

[15] F. Teng, V. Trovato, and G. Strbac, "Stochastic scheduling with inertia-dependent fast frequency response requirements," IEEE Transactions on Power Systems, vol. 31, no. 2, pp. 1557-1566, 2015.

[16] Q. Shi, F. Li, and H. Cui, "Analytical method to aggregate multi-machine SFR model with applications in power system dynamic studies," IEEE Transactions on Power Systems, vol. 33, no. 6, pp. 6355-6367, 2018.

[17] L. Badesa, F. Teng, and G. Strbac, "Optimal portfolio of distinct frequency response services in low-inertia systems," IEEE Transactions on Power Systems, vol. 35, no. 6, pp. 4459-4469, 2020.

[18] R. Doherty, G. Lalor, and M. O'Malley, "Frequency control in competitive electricity market dispatch," IEEE Transactions on Power Systems, vol. 20, no. 3, pp. 1588-1596, 2005.

[19] P. M. Anderson and M. Mirheydar, "A low-order system frequency response model," IEEE Transactions on Power Systems, vol. 5, no. 3, pp. 720-729, 1990.

[20] L. Liu, W. Li, Y. Ba, J. Shen, C. Jin, and K. Wen, "An analytical model for frequency nadir prediction following a major disturbance," IEEE Transactions on Power Systems, vol. 35, no. 4, pp. 2527-2536, 2020.

[21] Y. Teng, C. Fan, and Z. Zhang, "Minimum frequency predictive model for remote isolated power system of hydro generation," in 2020 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia), 2020: IEEE, pp. 875-880.

[22] L. E. Sokoler, P. Vinter, R. Bærentsen, K. Edlund, and J. B. Jørgensen, "Contingency-constrained unit commitment in

meshed isolated power systems," IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 3516-3526, 2015.
[23] T. Kerdphol, F. S. Rahman, Y. Mitani, M. Watanabe, and S. K. Küfeoğlu, "Robust virtual inertia control of an islanded microgrid considering high penetration of renewable energy," IEEE Access, vol. 6, pp. 625-636, 2017.
[24] C. Cardozo, L. Capely, and P. Dessante, "Frequency constrained unit commitment," Energy Systems, vol. 8, no. 1, pp. 31-56, 2017.
[25] H. Ahmadi and H. Ghasemi, "Security-constrained unit commitment with linearized system frequency limit constraints," IEEE Transactions on Power Systems, vol. 29, no. 4, pp. 1536-1545, 2014.
[26] M. Paturet, U. Markovic, S. Delikaraoglou, E. Vrettos, P. Aristidou, and G. Hug, "Stochastic unit commitment in low-inertia grids," IEEE Transactions on Power Systems, vol. 35, no. 5, pp. 3448-3458, 2020.
[27] Y. Wen, W. Li, G. Huang, and X. Liu, "Frequency dynamics constrained unit commitment with battery energy storage," IEEE Transactions on Power Systems, vol. 31, no. 6, pp. 5115-5125, 2016.
[28] J. F. Restrepo and F. D. Galiana, "Unit commitment with primary frequency regulation constraints," IEEE Transactions on Power Systems, vol. 20, no. 4, pp. 1836-1842, 2005.
[29] V. Trovato, A. Bialecki, and A. Dallagi, "Unit commitment with inertia-dependent and multispeed allocation of frequency response services," IEEE Transactions on Power Systems, vol. 34, no. 2, pp. 1537-1548, 2018.
[30] T. Ding, Z. Zeng, M. Qu, J. P. Catalão, and M. Shahidehpour, "Two-Stage Chance-Constrained Stochastic Thermal Unit Commitment for Optimal Provision of Virtual Inertia in Wind-Storage Systems," IEEE Transactions on Power Systems, vol. 36, no. 4, pp. 3520-3530, 2021.
[31] V. Prakash, P. Kushwaha, K. C. Sharma, and R. Bhakar, "Frequency response support assessment from uncertain wind generation," International Journal of Electrical Power & Energy Systems, vol. 134, p. 107465, 2022.
[32] F. Teng and G. Strbac, "Assessment of the role and value of frequency response support from wind plants," IEEE Transactions on Sustainable Energy, vol. 7, no. 2, pp. 586-595, 2016.
[33] L. Badesa, F. Teng, and G. Strbac, "Simultaneous scheduling of multiple frequency services in stochastic unit commitment," IEEE Transactions on Power Systems, vol. 34, no. 5, pp. 3858-3868, 2019.
[34] D. T. Lagos and N. D. Hatziargyriou, "Data-Driven Frequency Dynamic Unit Commitment for Island Systems With High RES Penetration," IEEE Transactions on Power Systems, vol. 36, no. 5, pp. 4699-4711, 2021.
[35] P. Rabbanifar and N. Amjady, "Frequency-constrained unit-commitment using analytical solutions for system frequency responses considering generator contingencies," IET Generation, Transmission & Distribution, vol. 14, no. 17, pp. 3548-3560, 2020.
[36] J. Lofberg, "YALMIP: A toolbox for modeling and optimization in MATLAB," in 2004 IEEE international conference on robotics and automation (IEEE Cat. No. 04CH37508), 2004: IEEE, pp. 284-289.
[37] M. ApS, "Mosek optimization toolbox for matlab," User's Guide and Reference Manual, Version, vol. 4, 2019.

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