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***Abstract*—This paper proposes a novel model for optimal operation of microgrids (MGs) in grid-connected and islanded mode. The hierarchical control levels of MGs are considered in the proposed model and primary and secondary reserves are scheduled to mitigate the frequency deviations during islanded mode. Benders decomposition method is applied to decompose the grid-connected and islanded operation problem. A typical MG with hierarchal control level is used as case study. The obtained results show the importance of modeling frequency control levels in energy and reserve management of MGs.**

***Keywords*—Microgrid, islanded microgrid, frequency; optimization; benders decomposition method.**

NOMENCLATURE

Indices and Sets

g/DG	Index/set of distributed generators(DG)
e/ESS	Index/set of energy storages
i/INT	Index/set of control intervals
n/N	Index/set of network busses
p/PV	Index/set of photovoltaic (PV) generation
t/T	Index/set for time
pri/sec	Index of primary/secondary control interval

Variables

bsc/bsd	Charge/ discharge status of battery
η^c/η^d	Charge/discharge efficiency of battery
Δf	Frequency deviations of MG in each interval
I	Binary variable indicating islanding status of MG
LSH	Amount of load shed at each interval
$P^{Cha/Dis}$	Charged/discharged power of battery
P^{EX}	Exchanged power of MG with the upstream-network in grid-connected mode
$P^{DG,ref}$	Reference set points of DGs in secondary control of islanded mode.
P^{DG}	Scheduled power of DG
P^{PV}	Scheduled power of PV unit
P^{WT}	Scheduled power of wind turbine
R^{DG}	Scheduled reserve of DG
SOC	State of charge of energy storage
$u/u^{SU}/u^{SD}$	Binary variable indicating commitment/ start-up/ shut down status of DG
u^{on}/u^{off}	Binary variable indicating on/off status of DG

Parameters

a,b	Cost function coefficients of DG
C^{EX}	Price of exchanged power with main grid
C^{R}	Reserve price
C^{SU}/C^{SD}	Start-up/shut-down cost of DG
C^{ESS}	Cost of energy storage
C^{PV}/C^{WT}	Operation cost of PV/WT
C^{shed}	Penalty cost of load shedding
D	frequency elasticity of MG loads
f_0	Nominal frequency
k_{SOC}	Parameter related to minimum state of charge of battery
P^D	Load demand of MG
UR/UD	Ramp up/down of DG
UT/DT	Minimum up/down time of DG
r	Frequency droop parameter of DG

Symbols

$\overline{(\bullet)}/\underline{(\bullet)}$	Maximum/minimum bounds of variable $(\bullet)$

I. INTRODUCTION

A. *Aim*

With the increasing penetration of distributed generation (DG) into distribution networks Micro-grid (MG) concept has attracted growing attention [1]. MGs are defined as a cluster of DG units, loads and storage which can operate in grid-connected and islanded modes to improve service reliability by supplying loads locally and reducing load shedding [2]. However, after the MG is islanded from the upstream network due to the power mismatch between load and supply, frequency can be exposed to severe excursions [3]. Note that frequency excursions can put the MG security to risk and lead to considerable load shedding.

Within a daily framework, this paper aims to develop an optimal energy and reserve scheduling model for optimal operation of MGs in grid-connected and islanded modes. In the islanded mode hierarchal frequency control structure of MG is considered and primary and secondary reserves are scheduled to mitigate frequency deviations.

B. *Literature Review*

The MG optimal scheduling is extensively investigated in literature. Ref. [4] proposes a model for optimal generation and reserve schedule and dispatch of a grid-connected MG to reduce the impact of uncertainties of renewable sources, loads, and random component failures on power balance, operating costs, and system reliability. In [5], a resilience-oriented proactive methodology is proposed which aims at enhancing the resiliency of multiple energy carrier MGs against an approaching hurricane. In [6], an energy management system for a MG having a resiliency

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function, allowing to operate under the islanded mode after an accident, is proposed. In [7], a model for optimal management of MG is proposed in which multi-period islanding is considered. Authors of [8] deal with management of MGs in case of unscheduled islanding and suggest a stochastic framework. In [9], a model for scheduling MGs with dynamic network reconfiguration in grid-connected and islanded mode is proposed. Reference [10] conducts an optimal management model of energy resources and loads in islanded MGs. A decentralized model for optimal operation of a multi-MG distribution network is presented in [11]. However, only grid-connected mode is considered. In [12] the operation of a community based multi-party MG in grid-connected and islanded mode is optimized by an iterative bi-level model. Authors of [13] have evaluated the impact of uncertainties on resilience operation of MGs.

In the above reviewed literatures, frequency security of the MGs is ignored, especially, in the islanding operation mode. However, frequency excursions may endanger the MG security constraint [14] and therefore, considerable load shedding is unavoidable.

C. *Contributions*

In the above studies frequency constraints in islanded operation of MGs are not considered. To fulfill this gap, in this paper a model for optimal operation of MGs in grid-connected and islanded mode is presented. In the islanded mode hierarchal frequency control structure of MG is considered and reserves are scheduled to mitigate frequency deviations. The objective function consists of the operation cost of the system in grid-connected mode and the load shedding cost in the islanded mode. Benders decomposition method is used to decompose the grid-connected and islanded mode operation problem. The main contributions of this paper is summarized as follows:

- Proposing an optimal operation model for MGs in grid-connected and islanded mode in which hierarchal frequency control structure is considered.
- Scheduling primary and secondary reserves to mitigate frequency deviations of MG during islanding operation.
- Utilizing Benders decomposition method to solve the proposed model.

D. *Paper organization*

In the following sections first the frequency control structure in MGs is discussed and then an overview of frequency control in MGs is presented. In section III the problem is formulated grid-connected mode and islanded mode. The results are presented in section IV and finally the paper is concluded in section V.

II. FREQUENCY CONTROL STRUCTURE IN MICROGRIDS

In MGs the frequency control is conducted by a hierarchical structure. At the first level, the primary control mitigates the frequency deviations by activating the primary reserves according to the droop characteristic. However, the frequency may still deviate from its nominal value; therefore, the secondary control level compensates the steady state error by changing the DGs reference points. The frequency-droop equation for both primary and secondary intervals can be written by (1) [15]:

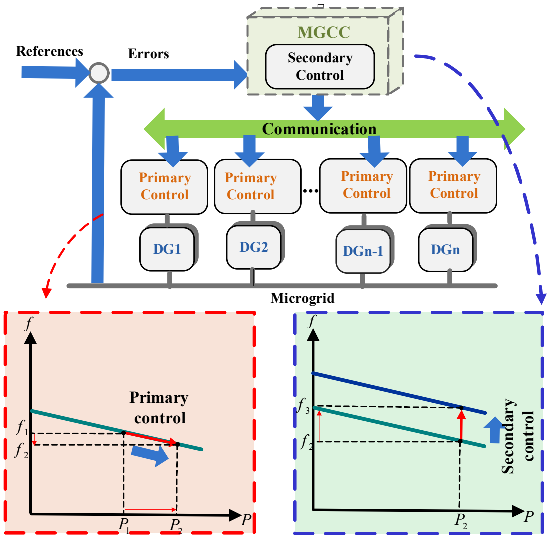

Fig. 1. MG hierarchical frequency structure

$$\sum_{g\in DG} P_{t,g,i}^{DG} = \sum_{g\in DG} P_{t,g,i}^{DG,ref} - \Delta f_{t,i}\left(D_t + \sum_{g\in DG}\frac{u_{t,i}}{r_g}\right) \tag{1}$$

Since the primary interval duration is short (e.g., 30 seconds) DG reference set-points and commitments states cannot be changed. Therefore, equation (1) for the primary interval can be re-written as:

$$ {}_{g\in DG}\left(P_{g,t}^{DG,pri} - P_{g,t}^{DG,pre}\right) = 0 - \Delta f_t^{pri}\ D_t + {}_{g\in DG}\frac{u_{g,t}^{pri}}{r_g} \tag{2}$$

According to (2), the frequency deviations in the primary interval are calculated as:

$$\Delta f_t^{pri} = \frac{-\sum_{g\in DG} P_g^{DG,pri} - P_{g,t}^{DG,pre}}{D_t + \sum_{j\in DG}\frac{u_{prim}}{r_g}} \tag{3}$$

The commitment states and power set points of DGs can be changed in the secondary interval. Thus, the frequency-droop equation of (1) can be written as follows for the secondary interval:

$$\begin{aligned} &{}_{g\in DG}(P_{g,t}^{DG,\sec} - P_{g,t}^{DG,pri}) = {}_{g\in DG}(P_{g,t}^{DG,ref,\sec} - P_{g,t}^{DG,ref,pri}) \\ &-(D_t + {}_{g\in DG}\frac{u_{j,t}^{\sec}}{r_g})(f_t^{\sec} - f_t^{pri}) \end{aligned} \tag{4}$$

By substitution of $P_{j,t}^{DG,pri}$ from (2) into (4) the frequency excursions of the secondary interval can be obtained as follows:

$$\Delta f_t^{\sec} = \frac{-\sum_{g\in DG}(P_{i,g,t}^{DG,\sec} - P_{i,g,t}^{DG,ref,\sec})}{D_{n,t} + \sum_{j\in DG}\frac{u_{t,\sec}}{r_g}} \tag{5}$$

The elasticity frequency-dependent loads are modeled as follows [16]:

$$D_t = \sum_{n\in N} P_{n,t}^{D} \Big/ f_0 \tag{6}$$

It should be mentioned the focus in this study is given to the frequency droop control of inverter interfaced DG units assuming that the frequency control structure is reliable and always available.

III. OPERATION PROBLEM FORMULATION

The operation problem includes normal and islanded operation modes which benders decomposition method is applied to decompose it. The normal operation is considered as the master and the islanded operation is regarded as the sub-problem. In the islanded operation mode, the power of committed DGs are rescheduled in the primary and secondary intervals. Moreover, the reference power set-points of DGs can be changed in the secondary interval.

A. *Objective function*

The main objective of the problem is to minimize the operation cost of the MG. The operation cost of the MG consists of the cost of the grid-connected mode and islanded mode cost. In the grid-connected mode, the cost consists of cost of purchased power from the upstream grid, reserve provision cost of DGs, operation cost of DGs, and battery degradation cost. The cost of islanded operation consists of the load shedding cost in the primary and secondary control intervals during the islanding periods. The objective function can be formulated as follows:

$$
Min \begin{array}{l}
\sum_{t\in T}\left(C_t^{Ex}P_{n,t}^{Ex}\Big|_{n=1}\right)+\sum_{t\in T}\sum_{g\in DG}\sum_{i\in INT}\left(C_{i,g}^{R}R_{i,g,t}^{DG}\right)\\
+\sum_{t\in T}\sum_{g\in DG}\left(C_g^{SU}u_{g,t}^{SU}+a_g u_{g,t}+b_g P_{g,t}^{DG}+C_g^{SD}u_{g,t}^{SD}\right)\\
+\sum_{t\in T}\sum_{p\in PV}\left(C_p^{PV}P_{p,t}^{PV}\right)\\
+\sum_{t\in T}\sum_{e\in ESS}\left(\left\{C_e^{ESS}k_{\underline{SOC}}\left(1-\underline{SOC}_e\right)\right\}\times SOC_{e,t}\right)\\
+MaxMin\left\{\sum_{t\in T}\sum_{n\in N}\sum_{i\in INT}\left(C_t^{Shed}LSH_{i,n,t}\right)\right\}
\end{array} \tag{7}
$$

B. *Constraints of grid-connected operation mode*

In the normal operation mode, the load balance equation is taken into account by (8). DGs operation constraints such as minimum and maximum power limit, ramp up/down rate limit and minimum up/down time are taken into account by (9)-(14). Conflicted situations in DG start-up and shutting-down are avoided by (15)-(17). The scheduled power of PVs are restricted to their available generations by (18) and energy storage are modeled by (19)-(23).

$$P_t^{EX}+\sum_{g\in DG}P_{g,t}^{DG}+\sum_{p\in PV}P_{pv,t}^{PV}+\sum_{e\in ESS}\left(P_{e,t}^{Dis}-P_{e,t}^{Cha}\right)=\sum_{n\in N}P_{n,t}^{D} \tag{8}$$

$$0\le P_t^{EX}\le\overline{P^{EX}} \tag{9}$$

$$\underline{P_g^{DG}}u_{g,t}\le P_{g,t}^{DG}+R_{g,t}^{DG,pri}+R_{g,t}^{DG,\sec}\le\overline{P_g^{DG}}u_{g,t} \tag{10}$$

$$P_{g,t}^{DG}-P_{g,t-1}^{DG}\le UR_g\left(1-u_{g,t}^{ON}\right)+\underline{P_g^{DG}}u_{g,t}^{ON} \tag{11}$$

$$P_{g,t-1}^{DG}-P_{g,t}^{DG}\le DR_g\left(1-u_{g,t}^{OFF}\right)+\underline{P_g^{DG}}u_{g,t}^{OFF} \tag{12}$$

$$\sum_{h=t}^{t+UT_j-1}u_{g,h}\ge UT_g u_{g,t}^{ON} \tag{13}$$

$$\sum_{h=t}^{t+DT_g-1}(1-u_{g,h})\ge DT_g u_{g,t}^{OFF} \tag{14}$$

$$u_{g,t+1}-u_{g,t}\le u_{g,t+1}^{ON} \tag{15}$$

$$u_{g,t}-u_{g,t+1}\le u_{g,t+1}^{OFF} \tag{16}$$

$$u_{g,t+1}-u_{g,t}=u_{g,t+1}^{ON}-u_{g,t+1}^{OFF} \tag{17}$$

$$P_{p,t}^{PV}\le\overline{P_{p,t}^{PV}} \tag{18}$$

$$0\le P_{e,t}^{Cha}\le bsc_{e,t}\overline{P_e^{Cha}} \tag{19}$$

$$0\le P_{e,t}^{Dis}\le bsd_{e,t}\overline{P_e^{Dis}} \tag{20}$$

$$bsc_{e,t}+bsd_{e,t}\le 1 \tag{21}$$

$$SOC_{e,t}=SOC_{e,t-1}-P_{e,t}^{Dis}/\eta^d+P_{e,t}^{Cha}\eta^c \tag{22}$$

$$\underline{SOC_e}\le SOC_{e,t}\le\overline{SOC_e} \tag{23}$$

C. *Constraints of islanded operation mode*

In the islanded mode, the power balance equations in the primary and secondary intervals are taken into account by (24)-(25). The frequency excursions in the primary and secondary intervals are limited by (26)-(27). The amount of load shedding in each interval is limited by the load of the MG by (28)-(29).

The constraints of (30)-(33) limit the DGs' scheduled power in primary and secondary interval and reference power set-point within their lower and upper limits. Primary reserve limit is set to be the difference between its primary and previous generation level and secondary reserve is limited by the difference between reference and previous generation levels in constraints (34)-(35). Ramp-up and down limitations of DGs are modeled in (36)-(43) to cover primary and secondary intervals and their interactions.

$$
\begin{array}{l}
P_t^{EX}I_t+\sum_{g\in DG}P_{g,t}^{DG,pri}+\sum_{p\in PV}P_{p,t}^{PV}+\sum_{e\in ESS}\left(P_{e,t}^{Dis}-P_{e,t}^{Cha}\right)\\
+\sum_{n\in N}LSH_{n,t}^{pri}=\sum_{n\in N}P_{n,t}^{D}+D_t\Delta f_t^{pri}
\end{array} \tag{24}
$$

$$
\begin{array}{l}
P_t^{EX}I_t+\sum_{g\in DG}P_{j,t}^{DG,\sec}+\sum_{p\in PV}P_{p,t}^{PV}+\sum_{e\in ESS}\left(P_{e,t}^{Dis}-P_{e,t}^{Cha}\right)\\
+\sum_{n\in N}LSH_{n,t}^{\sec}=\sum_{n\in N}P_{n,t}^{D}+D_t\Delta f_t^{\sec}
\end{array} \tag{25}
$$

$$-\Delta f_t^{pri}\le\overline{\Delta f^{pri}} \tag{26}$$

$$-\Delta f_t^{\sec}\le\overline{\Delta f^{\sec}} \tag{27}$$

$$LSH_{n,t}^{pri}\le P_{n,t}^{D} \tag{28}$$

$$LSH_{n,t}^{\sec}\le P_{n,t}^{D} \tag{29}$$

$$\underline{P_{g,t}^{DG}}u_{g,t}^{pri}\le P_{g,t}^{DG,pri}\le\overline{P_{g,t}^{DG}}u_{g,t}^{pri} \tag{30}$$

$$\underline{P_{g,t}^{DG}}u_{g,t}^{\sec}\le P_{g,t}^{DG,\sec}\le\overline{P_{g,t}^{DG}}u_{g,t}^{\sec} \tag{31}$$

$$\underline{P_{g,t}^{DG}}u_{g,t}^{pri}\le P_{g,t}^{DG,ref}\le\overline{P_{g,t}^{DG}}u_{g,t}^{pri} \tag{32}$$

$$\underline{P_{g,t}^{DG}}u_{g,t}^{\sec}\le P_{g,t}^{DG,ref}\le\overline{P_{g,t}^{DG}}u_{gt}^{\sec} \tag{33}$$

$$P_{g,t}^{DG,pri}-P_{g,t}^{DG,pre}\le R_{g,t}^{DG,pri}+\left(1-u_{g,t}^{pri}\right)\overline{P_g^{DG}} \tag{34}$$

$$P_{g,t}^{DG,ref}-P_{g,t}^{DG,pre}\le R_{g,t}^{DG,\sec}+\left(1-u_{g,t}^{\sec}\right)\overline{P_g^{DG}} \tag{35}$$

$$P_{g,t}^{DG,pri}-P_{g,t}^{DG,pre}\le UR_g u_{g,t}^{pri} \tag{36}$$

$$P_{g,t}^{DG,pre}-P_{g,t}^{DG,pri}\le DR_g u_{g,t}^{pri} \tag{37}$$

$$P_{g,t}^{DG,\sec}-P_{g,t}^{DG,pri}\le UR_g u_{g,t}^{pri}+\left(1-u_{g,t}^{\sec}\right)\overline{P_g^{DG}} \tag{38}$$

$$P_{g,t}^{DG,pri}-P_{g,t}^{DG,\sec}\le DR_g u_{g,t}^{\sec}+\left(1-u_{g,t}^{pri}\right)\overline{P_g^{DG}} \tag{39}$$

$$P_{g,t}^{DG,pri}-P_{g,t-1}^{DG,pri}\le UR_g u_{g,t-1}^{pri}+\left(1-u_{g,t}^{pri}\right)\overline{P_g^{DG}} \tag{40}$$

$$P_{g,t-1}^{DG,pri}-P_{g,t}^{DG,pri}\le DR_g u_{g,t}^{pri}+\left(1-u_{g,t-1}^{pri}\right)\overline{P_g^{DG}} \tag{41}$$

$$P_{g,t}^{DG,\sec}-P_{g,t-1}^{DG,\sec}\le UR_g u_{g,t-1}^{\sec}+\left(1-u_{g,t}^{\sec}\right)\overline{P_g^{DG}} \tag{42}$$

$$P_{g,t-1}^{DG,\sec}-P_{g,t}^{DG,\sec}\le DR_g u_{g,t}^{\sec}+\left(1-u_{g,t-1}^{\sec}\right)\overline{P_g^{DG}} \tag{43}$$

IV. MODEL OUTLINE

In this paper, benders decomposition method is applied to decompose and coordinate the normal and islanding operation of the MG. The flowchart of the proposed model is depicted in Fig. 2. The normal operation is considered as the master and the islanded operation is regarded as the sub-problem. The optimal solution of the master problem is fed to the sub-problem to check if it is feasible in islanded mode. If the solution is not feasible means there is not enough reserve to keep the frequency deviations of primary and secondary intervals in the permissible range, a benders cut is formed and the sub-problem solution is sent back to the master problem to be revised. This process continues iteratively until both master and sub-problem become feasible. However, in some cases the master problem cannot provide enough reserve to guarantee a feasible islanding, therefore, non-critical loads are shed to avoid power mismatch. Note that the proposed model is a mixed integer linear programming that the convergence of Benders decomposition method is guaranteed [17].

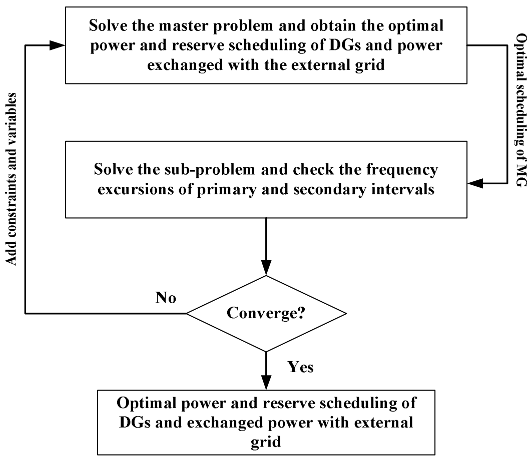

Fig. 2. Flowchart of the proposed model

V. RESULTS AND DISCUSSION

To analysis the performance of the proposed model, a typical MG test system with hierarchical control levels is used which is depicted in Fig. 3. The MG includes five droop controlled DGs which their economic and technical data are presented in Table 1. All the installed PVs are the same type and their forecasted power generation is retrieved from [18]. The forecasted power generation of PVs, demand of MG, and market price are depicted in Fig. 4 [18] .The data of battery energy storage systems are presented in Table 2. Furthermore, the penalty cost of load shedding (C^{shed}) is set to 1000 \$/MWh. The allowable frequency deviations limits in primary and secondary intervals are assumed to be ±300 mHz and ±100 mHz, respectively [19]. The proposed model is programmed in GAMS environment and solved using CPLEX 12.5.1 solver on a 2.30-GHz intel Core i7 CPU personal computer with 8 GB of RAM memory.

It is predicted that following an event in the upstream network the MG may be islanded at hour 7 for 5 consecutive hours. In Fig. 5 the MG day-ahead scheduling results of the proposed model are shown. In addition, the exchanged power of the MG with upstream network is depicted as a benchmark. As it can be seen since the MG may get

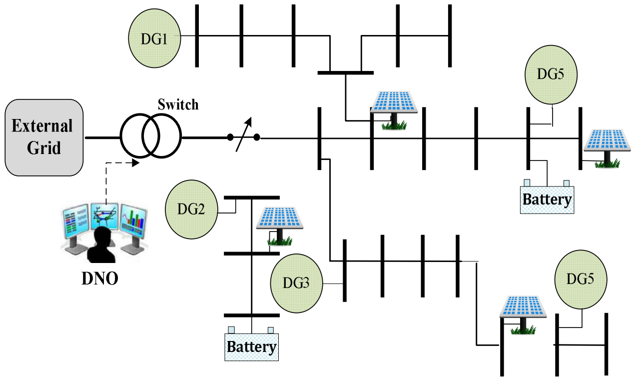

Fig. 3 MG test system

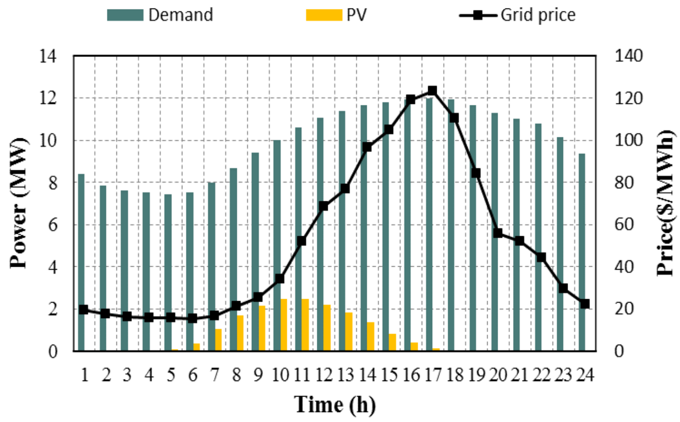

Fig. 3. Hourly forecasted values of demand, PV generation and market price

TABLE I. TECHNICAL AND ECONOMIC DATA OF DGS

Unit	Pmax/Pmin (MW)	MUT/MDT (hour)	RU/RD (MW/h)	SUC/SDC (\$)	Droop (mHz/kW)
DG1	4.5/1	2/2	1.5/1.5	15/10	0.1
DG2	4/0.75	2/2	1.5/1.5	10/10	0.1
DG3	4/0.75	2/2	1.5/1.5	10/10	0.1
DG4	4/0.75	2/2	1.5/1.5	10/10	0.15
DG5	4.1/1	2/2	1.5/1.5	15/15	0.075

TABLE II. TECHNICAL DATA OF ENERGY STORAGE

Parameter	Value
$P^{ess,nom}$	1 MWh
SOC^{max} / SOC^{min}	90% / 10%
SOC^{ini}	90%
$\overline{P^{cha}} / \overline{P^{dis}}$	0.2MWh
k_{SOC}	0.15
C^{ess}	106.5 \$/MWh

islanded at hour 7 the MG reduces its exchange power (blue line) with the upstream network and schedules its own DGs even though they have a higher price. This is due to the fact that the day-ahead scheduling is performed in a way that in the hours which the MG is predicted to get islanded it exchanges minimum power to the grid so if in real time it islanded is the lost power is least and load shedding is avoided. In case of islanding this strategy reduces load shedding significantly. At hours 15-17 which the grid price is high and no islanding is forecasted, DG1, DG3, and DG5 with lower operation cost are mainly dispatched and the exchanged power with upstream network is zero.

The presented model optimizes the primary and secondary reserves to minimize load shedding in the islanding interval and ensure frequency security. The primary and secondary scheduled reserves of DGs and frequency of MG are shown in Figs. 6. As mentioned before these reserves are utilized to remain the primary and secondary frequency deviations within pre-specified ranges and their value is not fixed. As can be seen at hour 9 the total reserve is less than other hours, this is due to the fact that at hour 9 the MG buys the least power from the upstream network therefore, less primary and secondary reserve needs to be scheduled to compensate the loss of grid power and frequency deviations.

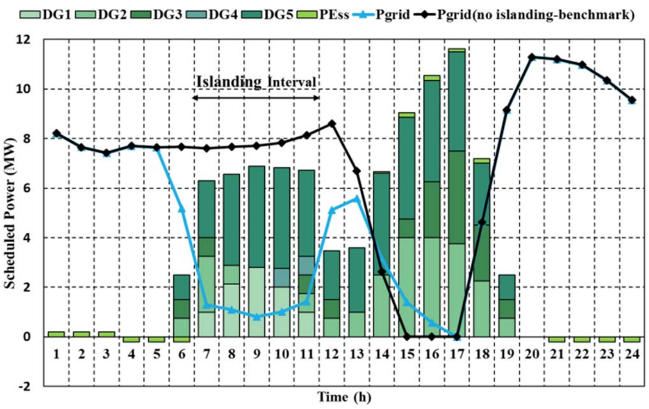

Fig. 4. Scheduled power of MG

The proposed model optimizes the scheduled primary and secondary power, reserve and reference set-points of DGs, consequently not only load shedding becomes zero in the primary and secondary interval, but the frequency security is assured. In Fig. 7 the frequency of MG in primary and secondary interval is depicted. As can be seen the frequency is in the permissible limits and frequency security is assured.

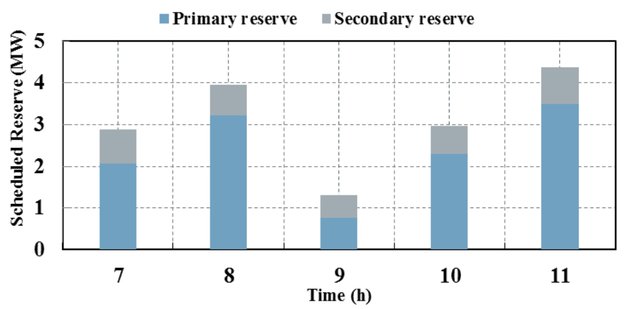

Fig. 5. Scheduled reserves of MG in islanding operation

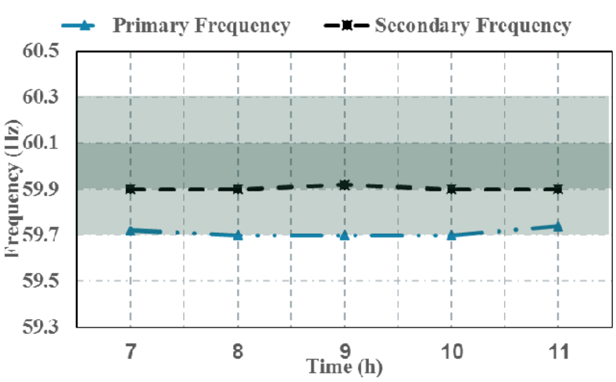

Fig. 6. Frequency of MG in primary and secondary interval of the islanding operation

VI. CONCLUSIONS

In this paper a novel model for optimal management of a MG in grid-connected and islanded modes was presented in which the hierarchical frequency control structure of MG was formulated and considered. Primary and secondary reserves are scheduled to mitigate primary and secondary frequency deviations. Benders decomposition method was used to decompose the grid-connected and islanded operation problem. The simulation results demonstrated that the proposed model not only minimizes total operation cost and load shedding but assures frequency security. The results also showed the significance of considering the frequency control structure in optimal management of energy and reserve.

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