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A novel frequency aware energy management system for a droop controlled microgrid

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***Abstract*— The present paper proposes a novel energy management system in islanded microgrids which considers static frequency. Microgrid frequency continuously deviates from the nominal value, subject to the unpredictable renewable and/or load variations. The small capacity and low inertia stack of the utilized inverter-based distributed energy resources intensify the importance of incorporating the frequency into the microgrid energy management system. Motivated by this need and owing to the direct coupling between the frequency and reserve scheduling, energy and reserve resources of an islanded microgrid are aimed to be scheduled such a way the frequency be managed securely. In this regard, first, the frequency dependent behavior of droop controlled distributed generations should be modeled in detail. Next, microgrid central controller can schedule the reserve resources in order to satisfy both economical and security issues by modification the reference power settings. Simulation results in a typical microgrid and over a daily period verify the effectiveness of the proposed frequency aware energy management system.**

Keywords-microgrid; energy management system; droop control; frequency control.

I. INTRODUCTION

Recently, owing to the environmental concerns and shortage of fossil fuels, utilization of renewable energy sources (RES) such Wind Turbines (WTs) and photovoltaics (PVs) is raising. To provide a reliable integration of RES, the concept of microgrids (MGs) has been introduced [1]. Indeed, MGs are low-voltage distribution power systems can work autonomously (islanded) or in coordination to the main-grid [1]. MGs cause power systems to be operated in a more reliable, economical and emission-less manner by facilitating the integration of distributed energy resources (DERs) in a small scale power system. Despite the obvious benefits, MGs are faced with a significant challenge stem from the intermittency of the RES and/or load demand fluctuations in their small capacity. On the other hand, due to characteristic of produced energy, the most DERs are connected to the MGs using static Voltage Source Inverters (VSIs) which have lower inertia. This makes the unpredictable power variations impact the MG security more critically. The control variable which directly reveals the MG security and level of power quality is the frequency [2-5]. Principally, the frequency is directly couples with energy and reserves scheduling problem of the MGs which should be considered into the energy management system. Although in the literature, many researches focused on energy managing of the MGs, however, to the best of our knowledge, there is no work which schedules MG energy and reserve resources considering to the frequency-dependent security issue. In [6], under a smart energy management system, optimal operation of DER units has been investigated. Authors in [7, 8], manages the energy sources to maximize the utilization of an islanded MG under a cheap operational policy. Energy management of a grid-connected MG has been studied in [9, 10]. In above mentioned researches, reserve requirements have not been scheduled and also the frequency related aspects of the MG were not modeled. In [11, 12], a proper load sharing approach was presented in an islanded MG. The authors modeled the dynamic behavior of the MG frequency to minimize the real time cost function of the DERs. However, the role of RES units was ignored and also reserve scheduling aspects have been disregarded. Besides, the cost function was minimized over minutes and not during a day-ahead time horizon. Hence, the control and management of the MG frequency, particularly in the islanded mode, is a great task which should be followed by the energy management system.

Similar to the conventional power systems, the frequency control function in the MGs can also be performed under a hierarchical structure [13]. In the primary control level, DERs automatically respond to the MG frequency deviations and release the scheduled primary reserves in proportion to their droop characteristics. In the secondary control level, MG-Central Controller (MGCC) is responsible for restoration the MG frequency and meanwhile assuring the economical operation of the MG. Finally, proper operation of the connected MGs in the power system or electricity markets are implemented by means of Distribution System Operator (DSO) over the tertiary control level [14-16]. Worth mentioning, in the islanding operation, due to unavailability of the main-grid, highest control level is the MGCC which procures the secondary control functions by readjustment the reference power settings [4].

In this paper, day-ahead energy, primary and secondary reserves of an islanded MG are managed simultaneously. The frequency droop control function of the VSI-based DERs are modeled and incorporated into the proposed hierarchical energy management system. Finally, the MG total operation

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costs are minimized such that the frequency lies in a secure range. The performance of the MGCC in adjusting the frequency deviations is also investigated. The proposed energy management system is formulated using an efficient mixed-integer linear programming approach. Numerical results in a typical MG verify impressiveness of the proposed frequency aware energy management system in precise scheduling reserve requirements of the MG and ensuring the MG security in a cost-effective manner.

II. MODEL DESCRIPTION

A. *Frequency droop control of VSI-based DERs*

In the MGs, the frequency is heavily dependent on the variations arise from the intermittency of WTs and PVs and load demand inherent fluctuations. Whenever a power deviation occurs in the MG, the committed DERs have to change their generated active power to compensate the imposed power imbalance. The static frequency control performance of the DERs in response to the power variations can be defined in both the primary and secondary levels as followed in (1):

$$\sum_{i=1}^{Ng}\Delta P_g(i,l,h)=\Delta P_d(l,h)+D(h).\Delta f(l,h) \\ -\sum_{w=1}^{Nw}\Delta P_w(l,h)-\sum_{v=1}^{Nv}\Delta P_v(l,h) \tag{1}$$

where, $\Delta P_g(i,l,h)$, $\Delta P_w(l,h)$ and $\Delta P_v(l,h)$ are *i*th DER, *w*th WT and *v*th PV active power change in *l*th control level (*primary and secondary*) and hour *h*, respectively. $\Delta P_d(l,h)$ and $\Delta f(l,h)$ are load demand fluctuation and frequency excursion in the control level *l* at hour *h*, respectively. *D(h)* stands for natural dependency of electrical loads to the frequency at hour *h*. The frequency is assumed to be constant over the whole MG. To model the static frequency of the MG, the frequency-droop control of the VSIs should be analyzed in detail. In the proposed modeling, it is assumed that the MG frequency is in the steady-state and all the oscillating modes are damped. Thus, the static power-frequency relation of the droop controlled VSI-based DERs can be represented by (2).

$$\Delta P_g(i,l,h)=\Delta P_{ref}(i,l,h)-(\frac{1}{m_p(i)}).\Delta f(l,h) \tag{2}$$

where, $\Delta P_{ref}(i,l,h)$ represents the change in reference power setting of *i*th DER, in *l*th control level and hour *h*. m_p is the droop coefficient of each DER. Any change in the DERs generated power can be resulted from a change in reference power setting or a change in the frequency. The reference power setting of the DERs can only be readjusted by means of the MGCC in the secondary level, therefore, in the primary frequency control level, due to inadequate time, the pre-specified active power set-point cannot be changed, hence, $\Delta P_{ref}(i,primary,h)=0$.

In the primary level, DERs instantaneously react to the frequency excursions using their droop control and change their active power generation proportionally. After the primary level, the MG frequency stabilizes at a newly steady-state value which is different from the rated one. The primary control reserves should be managed such that the primary frequency excursions lie in an allowable secure range as described by (3).

$$|\Delta f(l,h)|\le \Delta f_l^{\max},\ l=primary \tag{3}$$

In the secondary control level, the MGCC deploys the scheduled secondary control reserves to restore the MG steady-state frequency to its rated value. This control function can be performed by adjusting the reference power setting of the DERs. Notably, the DERs should provide enough primary and secondary control reserves to maintain the MG power balance under all disturbances. The up/down primary and secondary reserves requirements can precisely be depicted by (4) and (5), respectively.

$$R_g(i,l,ud,h)\ge P_{ref}(i,l,h)-P_g(i,h),\ \ ud=up \tag{4}$$

$$R_g(i,l,ud,h)\ge P_g(i,h)-P_{ref}(i,l,h),\ \ ud=dn \tag{5}$$

where, $R_g(i,l,ud,h)$, $P_g(i,h)$ and $P_{ref}(i,l,h)$ are the scheduled up/down primary and secondary control reserve, generated active power output and the reference power setting of *i*th DER at hour *h*. *ud* expresses the direction of the scheduled control reserves which can be *up* or *dn* (down). Notably, in the primary level, the generated active power and the reference power setting of the DERs are equal. Moreover, in this paper, it is assumed that the RES units are not participated into the frequency control procedure and they are generating their forecasted power.

B. *Objective function*

Day-ahead total operating cost of the MG is considered as the objective function of the paper as described by (6).

$$F=\sum_{h=1}^{24}\sum_{i=1}^{Ng}C_g^E(i,h)+\sum_{h=1}^{24}C_{RES}(h) \\ +\sum_{h=1}^{24}\sum_{i=1}^{Ng}\sum_{l}\sum_{ud}C_g^R(i,l,ud,h) \tag{6}$$

C_g^E and C_g^R are the hourly costs relating the provided energy and scheduled up/down primary and secondary control reserves, and represented by (7) and (8), respectively.

$$C_g^E(i,h)=a_i+b_i.P_g(i,h) \tag{7}$$

$$C_g^R(i,l,ud,h)=\alpha_i(l,ud).R_g(i,l,ud,h) \tag{8}$$

where, a_i and b_i are the cost function coefficients of *i*th DER and α_i describes the price of up/down primary and secondary control reserves of *i*th DER. The costs of deployment the RES units into the MG can be illustrated by C_{RES} in (9).

$$C_{RES}(h)=\sum_{w=1}^{Nw}\eta_w.P_w(h)+\sum_{v=1}^{Nv}\eta_v.P_v(h) \tag{9}$$

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where, $P_w(h)$ and $P_v(h)$ are the forecasted value of power output of wth WT and vth PV at hour h, respectively. η_w and η_v are the costs of deployment of WTs and PVs, respectively.

The proposed objective function is minimized subject to several constraints which are follows. Additionally the energy management system should consider the frequency related constraints described in (1)-(5).

Both the generated active power and the reference power setting of the DERs have to satisfy the physical limitations of the generation power which are described by (10) and (11).

$$P_g^{\min}(i).u(i,h) \le P_g(i,h) \le P_g^{\max}(i).u(i,h) \tag{10}$$

$$P_g^{\min}(i).u(i,h) \le P_{ref}(i,l,h) \le P_g^{\max}(i).u(i,h) \tag{11}$$

The generated hourly active power in lth control level, can be easily explained by (12).

$$P_g(i,l,h) = P_g(i,h) + \Delta P_g(i,l,h) \tag{12}$$

The hourly power balance equality must be satisfied in both normal condition (when there is no disturbance) and primary and secondary control levels. The power balance equalities are expressed by (13) and (14).

$$\sum_{i=1}^{Ng} P_g(i,h) + \sum_{w=1}^{Nw} P_w(h) + \sum_{v=1}^{Nv} P_v(h) = P_d(h) \tag{13}$$

$$\begin{aligned}&\sum_{i=1}^{Ng} P_g(i,l,h) + \sum_{w=1}^{Nw} P_w(l,h) + \sum_{v=1}^{Nv} P_v(l,h)\\ &= P_d(l,h) + D(l,h).\Delta f(l,h)\end{aligned} \tag{14}$$

Finally, the described model also considers the other technical restrictions of the DERs such as ramp up/down and minimum up /down time constraints.

III. NUMERICAL RESULTS

The proposed energy management system has been performed on a typical low voltage MG as depicted in Fig. 1. The MG consists of five droop controlled distributed generation units which are including two micro turbines (MTs), two fuel cells (FCs) and a gas engine (GE) unit. Also, two 100 kW WTs, a 50 kW WT and two 70 kW PVs installed in the distribution feeders. The technical and economical data of the VSI-based DERs are illustrated in Table I. All data have been taken from [17]. The cost of WT and PV are selected as 10.63 and 54.84 cent/kW. The costs of the DERs' primary and secondary control reserves equal to 120% and 50% of *'b'* coefficient of the DERs. The droop coefficients of the VSIs are set at 0.25 per unit of their rated power capacity. The hourly forecasted values of MG load are depicted in Fig. 2. Beside, in Fig. 3. The forecasted power outputs of the WTs and PVs are shown. The MG primary frequency excursion allowable limit is ±300 mHz. It is assumed that the MGCC restores the secondary frequency to its nominal value, i.e. 60 Hz. The MG is operated in islanded mode and the energy and reserve resources are scheduled over a 24-h time horizon.

TABLE I.

TABLE II. TECHNICAL AND ECONOMICAL DATA OF VSI-BASED DERS

DER	*Min power (kW)*	*Max Power (kW)*	*a (cent/h)*	*b (cent/kWh)*
MT	25	150	85.06	4.37
FC	20	100	255.18	2.84
GE	35	200	212.00	3.12

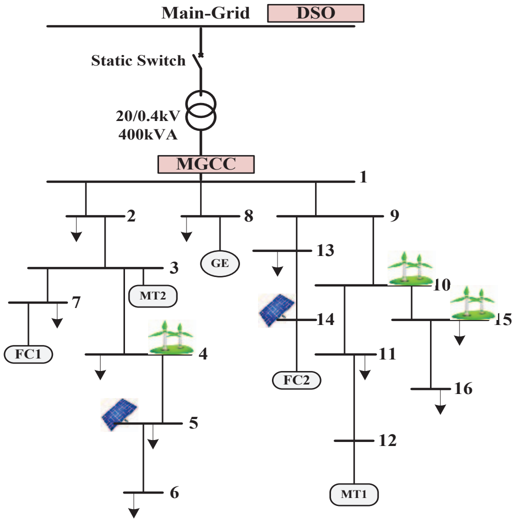

Figure 1. The MG test system

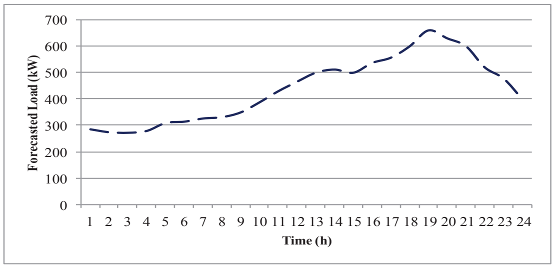

Figure 2. Hourly forecasted load demand

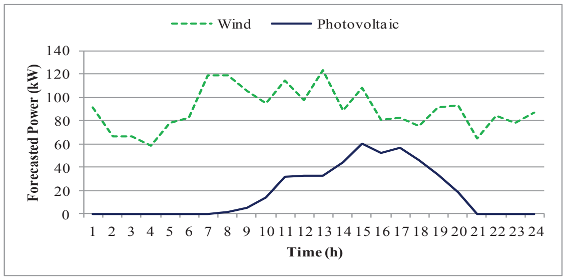

Figure 3. Hourly forecasted power outputs of WTs and PVs

The formulations are implemented in the GAMS environment and solved using mixed-integer linear programming solver CPLEX 9.0 [18]. The simulations have been performed under two case studies.

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Case I- 20% increase in the hourly forecasted load

The increase in hourly load causes the MG frequency to be dropped from its rated value. The daily frequency profile is depicted in Fig. 4. The MG frequency is managed within the allowable frequency range. The total operating cost in this case is 107875.110 cents. The optimal values of the scheduled energy and primary and secondary control reserves are represented in Figs. 5 to 7, respectively. As illustrated in Figs. 6 and 7, since the frequency excursions are negative in case I, therefore, the DERs have to increase their power output, hence only the upward reserves have been scheduled.

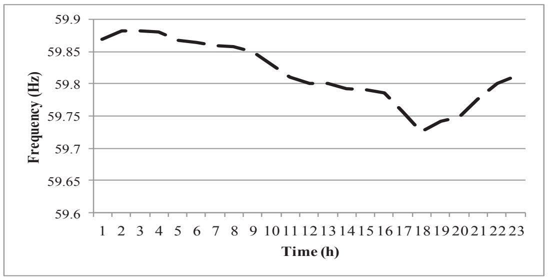

Figure 4. Hourly frequency profile of the MG in case I

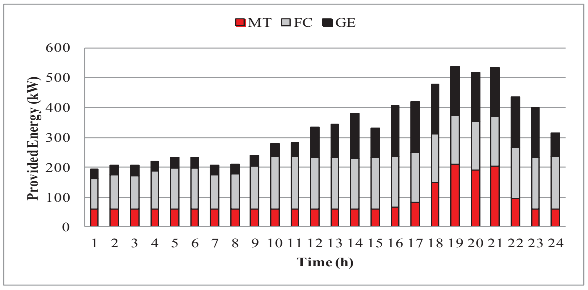

Figure 5. Hourly provided energy in case I

The amounts of the primary reserves are in propoetion to the MG frequency excursions and have the broad freedom exists in the scheduling of the secondary control reserves. Therefore, precise calculation of the primary frequency control reserves is a serious control function which should be considered by the energy management system. The role of primary reserves are significant in preservation the MG security once after an imbalance occurs in the MG. For example, in hour 19, which has the peak load demand, 132 kW increase in load consumptions, causes the MG frequency to be dropped within -0.028 mHz. The DERs should have enough scheduled primary reserves to alleviate the frequency excursion. In this hour the precise amount of primary control reserves are 56.571, 37.714 and 37.714 kW for MTs, FCs and GE, respectively. The amounts of secondary control reserves should be managed such that the MG frequency be set at its rated value.

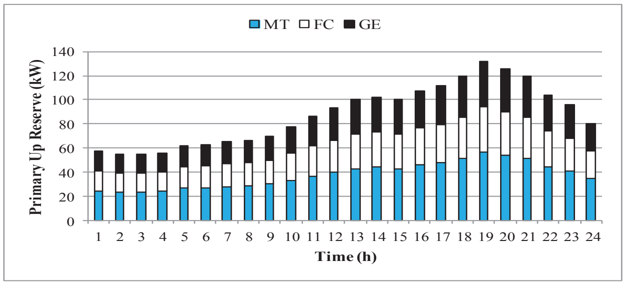

Figure 6. Hourly scheduled upward primary reserves in case I

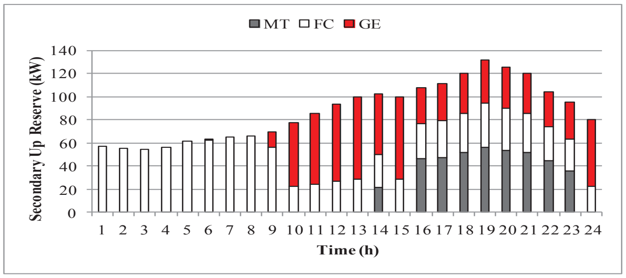

Figure 7. Hourly scheduled upward secondary reserves in case I

Case II- 10% decrease in hourly load and 20% increases in the WTs and PVs power outputs

In this case, the MG frequency incearses in all hours because the net power deviations are increased from the normal condition, therefore, the DERs have to decrease their output power. The scheduled primary and secondary control reserves are also downward. The optimization results in the case II are depicted in Figs. 8 to 10. Besides, the simulation has been ran without the consideration of the load-frequency dependency and the derived frequency values are compared. Obviously, when the load-frequency dependency is modeled, the frequency excursions are smaller. Furthermore, the operating cost of the MG is decreased from 104395.587 to 104318.059 cents, when the load-frequency dependency has been considered.

I. CONCLUSIONS

The paper dealt with the precise energy management of an islanded MG by consideration the static frequency. The steady-state frequency of the MG has been modeled using the droop control of the VSI-based DERs. Moreover, the elasticity of electrical loads to the frequency excursions was incorporated in the proposed formulation. The primary and secondary up/down control reserves have been scheduled such that the MG frequency lied in a secure range. Besides the simulation results in two case studies, verify the effectiveness of the frequency aware energy management system. In the cases when the power deviations are negative, the frequency excursion will be positive and the DERs have to decrease their output power, thus the downward control reserves are

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implemented, in contrast, the upward control reserves are served to mitigate the negative frequency excursion. Furthermore, consideration of the load-frequency dependency intensifies the MG operation in the terms of both security enhancement and reduction in scheduling costs. The paper gives an insight view to the MGCC, to provide a techno-economic operational policy for the MG that coincides to the eventual goals of the MG idea.

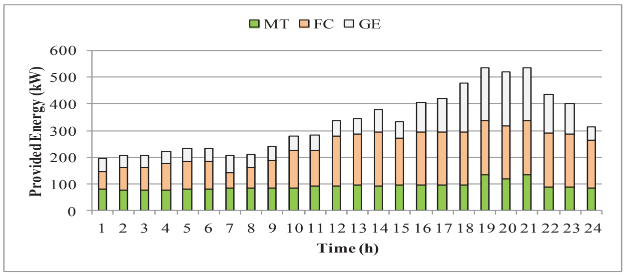

Figure 8. Hourly provide energy in case II

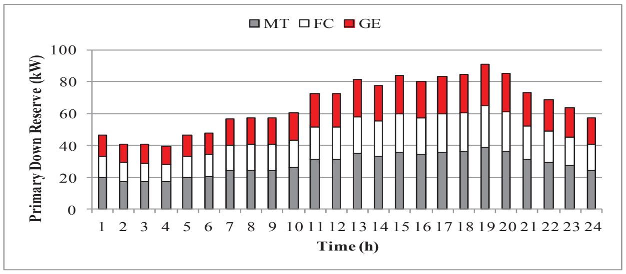

Figure 9. Hourly scheduled downward primary reserves in case II

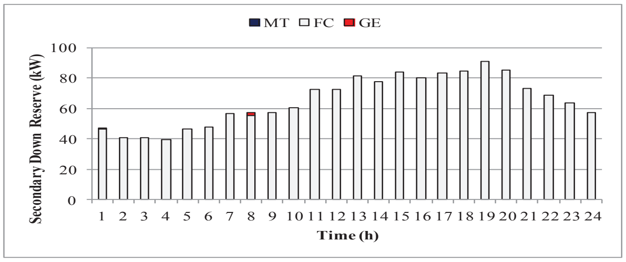

Figure 10. Hourly scheduled downward secondary reserves in case I

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