Energy Management for Zones-Based Isolated DC Multi-microgrids

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Abstract. In this paper, zones based distributed energy management for isolated multi-microgrids is proposed. Loads are categorized into different zones to form zonal multi-microgrids. Each microgrid has own energy management system which can locally manages the supply and demand of its zonal load and minimize the operational cost. Distributed Network Operator (DNO) act as central controller to facilitate the energy exchange between zonal microgrids and balancing the overall system-wide supply and demand in economic way. Demand Response Program (DRP) is also utilized for peak load shifting within the scheduling horizon. In addition to minimization of operation cost, the utilization of DR will also assure the reliability of supply. In the proposed distributed energy management, each microgrid balances its supply and demand locally and exchange surplus and deficit power with other microgrids through DNO. The performance of proposed scheme is demonstrated through case study simulation of radial multi-microgrid structure.

Keywords: Energy management · Isolated multi-microgrids · Load zones

1 Introduction

Microgrid (MG) is combination of loads, Energy Storage Systems (ESSs), DGs and interfacing converters with an energy management system (EMS) to regulate the power generation and its consumption. MGs have two modes of operation: a) Grid-Connected Mode, b) Islanded Mode. MG tends to maximize the benefit of microgrid in grid-connected mode while in islanded mode of operation, its objective is to improve the reliability and security in emergency events [1,20,24]. The uncertainties in renewable power generation, market prices of electricity, and penetration of electrical vehicles (EVs) and time varying load demand pose challenges for optimal operation of MG [13,16,21,23]. Several MGs can be combined together to form a multi-microgrids (MMG) in order to substantially handle

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the uncertainties [25]. In the recent past, a lot of research has been carried out relating to architecture and configuration of MMG system. The primary goals of MMG system are to minimize the operation cost, system wide supply reliability, balance of supply/demand for each individual microgrid [8].

The EMS architecture for MMG could be centralized, decentralized or hybrid depending on the objective under consideration. In centralized EMSs, the energy balance of entire network is managed by central EMS. However, with expansion of network size, the computational stress on central EMS also increases promptly [11,12,17]. Furthermore, centralized control is vulnerable to single point of failure and lacks plug & play capabilities [6]. The centralized controller requires reconfiguration with addition of new load or generator to the system. Additionally, the central EMS requires scheme of energy generation and utilization of each microgrid, therefore creating privacy concerns and also require an intensive communication infrastructure [2,7,19].

The decentralized EMS, in contrast to centralized EMS, has local EMS for individual microgrid. Local EMS of microgrid can communicate with other local EMS in network through communication infrastructure. The amount of information transfer is less compared to centralized scheme and therefore consequently there is less computational burden [9,14,18].

In an MMG system, each MG and the distribution network operator (DNO) can participate as independent units. However, with a coordinated EMS, both the DNO and MG owners could decrease their operational costs and the costumers could profit from a more reliable and secure electrical power [3]. Demand response programs (DRPs) are also utilized in MMG structures for more reliable supply in recent past [3,15]. Load curve of MG can be reshaped and peak loads can be reduced and transferred in time to other off-peak time slot through utilization of DRP schemes. In [10] a distributed energy management with price elasticity based DR scheme is proposed for interconnected operations of MGs. The time of use (ToU) based DR program is utilized in energy management for distribution system and multi-microgrids cooperative network in [5]. The energy management is formulated as multi follower bi-level game problem and is solved from DNO prospective to maximize profit. A bi-level model is proposed in [22] for economic operation of distributed network and microgrids. The control variable considered for upper level are the grid power and electricity price of MGs and the lower level variables are power of DG and the DN. In order to investigate the effect of demand response on residential load in the proposed work, real time pricing DRP is considered.

The majority of existing work is focused on the energy management of multi-microgrids in grid connected mode. The energy management of multi-microgrids operating in isolated mode still need further research and attention. The supply is always less then demand in grid isolated mode of multi-microgrid operation and therefore the objective of individual microgrid in isolated mode is different from the case of grid-connected mode of operation. This paper proposes distributed energy management of zonal load based multi-microgrid in isolated mode with consideration of demand response program. The similar set of loads are divided into zones are prioritized on bases of load type. Demand response program is utilized to reduced cost and increase the reliability of individual MG.

The rest of the paper is organized as follows. Section 2 presents the system description and modeling. Section 3 explains the proposed strategy for energy management of multi-microgrid arrangement operating in grid isolated mode and objective functions are presented. In Sect. 4 case study simulation are provided to show effectiveness of proposed model. Finally, conclusion is document in Sect. 5.

2 System Description and Modeling

2.1 Zonal Multi-microgrids

In this section, a new concept of zonal microgrid is explained. In previous conducted research work, the microgrid is composed of composite community loads (hospital, school and residential). The load curve, due to composite loads, is very fluctuating and it is challenging task to maintain the supply and demand balanced. By separately categorizing identical loads into specific sets of load and forming a specific category load zones can achieve defined load curve and the supply and demand could be easily achieved.

In this proposed work, the various type of community loads (hospital, school and residential) are categorized into zones of identical load type to form zonal microgrid. Each microgrid represent one zone. The zone formations with identical load sets help in obtaining defined load curve for day-ahead scheduling of energy resources in particular microgrid. The small scale energy zones or zonal MGs operates in grid-isolated mode. These zonal microgrids can exchange surplus/deficit energy with each other through Distributed Network Operator (DNO). There is no direct exchange of power between microgrids. Each zonal microgrid has its own local Energy management for managing its energy resources in order to keep supply and demand balance locally.

The propose zonal microgrids general structure is illustrated in Fig. 1. Each zone has one type of load (Residential, Hospital or School). The considered distributed generation resources in each zone are photo-voltaic (PV) panel, wind turbine (WT) and diesel generator (DG). The detail mathematical models of sources, energy storage system and load are discussed in proceeding sections.

2.2 Load Model

The load of each zone is categorized in three type, I) Critical loads, II) deferrable loads and III) Interruptible loads. The user demand of i_{th} zone is represented by $P^t_{L_m}$ and is mathematically given as:

$$P^t_{L_m} = P^t_{CL_m} + \Delta P^t_{L_m} + P^t_{in_m} \tag{1}$$

here the subscript m represent the zonal microgrid and is defined as $m \in Z_i$, where $Z_i = \{Z_1, Z_2, ..Z_n\}$. Whereas $P^t_{L_m}$, $P^t_{CL_m}$, $\Delta P^t_{L_m}$ and $P^t_{in_m}$ are the forecasted load Demand, Critical Load, Defferable Load and Interruptable Load of

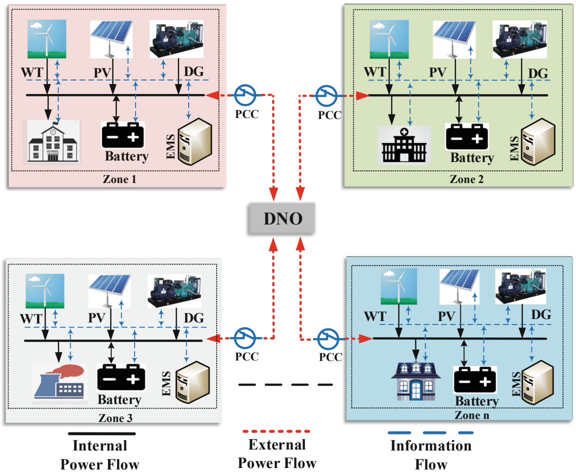


Fig. 1. General representation of Zonal Multi-microgrids structure

the zoned microgrid at time t and are subject to following constraints.

$$P_{L_m}^{min} \leq P_{L_m}^{t} \leq P_{L_m}^{max} \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{2}$$

$$\Delta P_{L_m}^{min} \leq \Delta P_{L_m}^{t} \leq \Delta P_{L_m}^{max} \qquad \forall t \in \mathcal{T}, \forall m \in Z_i, \tag{3}$$

$$P_{in_m}^{min} \leq P_{in_m}^{t} \leq P_{in_m}^{max} \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{4}$$

The constraints (2)–(4) shows the maximum and minimum limits of total zone load, deferrable and interruptible loads.

2.3 Energy Storage Modeling

The energy storage play important role in balancing supply and demand of islanded microgrids. The energy could be stored during off peak hours or in case of availability of surplus energy in microgrid. Likewise, the stored energy can e provided to balance the demand in case of peak hours or shortage of energy. Battery is considered as energy storage source in this paper and its operating constraints are given as:

$$U_{ch}^{t} P_{B,ch_m}^{min} \leq P_{B,ch_m}^{t} \leq U_{ch}^{t} P_{B,ch_m}^{max}, \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{5}$$

$$U_{dis}^{t} P_{B,dis_m}^{min} \leq P_{B,dis_m}^{t} \leq U_{dis}^{t} P_{B,dis_m}^{max}, \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{6}$$

$$U_{ch,dis}^{t} \in \{0, 1\} \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{7}$$

$$U_{ch}^{t} + U_{dis}^{t} \leq 1 \tag{8}$$

$$SoC_{B_m}^{t} = SoC_{B_m}^{t-1} + (\eta_B^{ch} P_{B,ch_m}^{t} - P_{B,dis_m}^{t} / \eta_B^{dis}) \Delta t \tag{9}$$

$$SoC_{B_m}^{min} \leq SoC_{B_m}^{t} \leq SoC_{B_m}^{max} \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{10}$$

here P_{B,ch_m}^{t}, P_{B,dis_m}^{t}, $SoC_{B_m}^{t}$ represent charging, discharging and state of charge of the battery respectively.

2.4 Distributed Generation Models

We have considered both conventional and renewable sources for power generation in microgrid. Renewable sources like wind and PV are not being dispatchable and where as conventional sources like diesel generators are dispatchable.

Wind Turbine Model. Power harnessed from wind can be mathematically modeled with piece-wise equation for different scenarios of wind speed. It can be written in mathematical form as [4]:

$$P^t_{WT_m} = \begin{cases} 0 & 0 \leq v^t \leq v_{ci} \\ P_r \times \dfrac{v^t - v_{ci}}{v_r - v_{ci}} & v_{ci} \leq v^t \leq v_r \\ P_r & v_r \leq v^t \leq v_{co} \\ 0 & v_{co} \leq v^t \end{cases} \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{11}$$

where $P^t_{WT_m}$ is power generated by wind turbine of Zone$_i$ at time t, v^t is expected wind speed, v_{ci} is cut in speed, v_r is rated speed and v_{co} is cut off speed.

PV Model. The output power os PV is greatly depended on the solar irradiance (W/m^2) and ambient temperature (°C). The power generated by solar PV can be expressed as:

$$P^t_{PV_m} = P_s \frac{G_{Irr}}{G_s} \left[1 + k\left(T_c - T_r\right)\right] \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{12}$$

Where G_{Irr}, G_s and k are the solar incident irradiance, maximum irradiance at standard test ($1000\,\mathrm{W/m^2}$) and temperature coefficient respectively. coefficient of PV power generation. The T_c, T_r and P_s represents PV cell temperature, reference temperature and maximum power at standard test respectively.

Generator Model. A conventional DG unit such as diesel is a dispatch-able source, its output power is a variable with the following constraints:

$$\begin{aligned} & P^{min}_{G_m} \times U^t_m \leq P_{G_m}(t) \leq P^{max}_{G_m} \times U^t_m, && \forall t \in \mathcal{T}, \forall m \in Z_i \\ & U^t_m \in \{0, 1\} && \forall t \in \mathcal{T}, \forall m \in Z_i \end{aligned} \tag{13}$$

$$ramp^{down}_{G_m} \Delta t \leq \left[P_{G_m}(t) - P_{G_m}(t-1)\right] \leq ramp^{up}_{G_m} \Delta t, \quad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{14}$$

Constraint (13) illustrates the maximum and minimum permissible limit for the generated power of the particular DG. Constraint (14) emphasize on the ramp up and ramp down limitation of each DG. The cost function of a diesel generator follows a quadratic function of its generated power and can be expressed as follows:

$$CostP^t_{G_m} = \alpha(P^t_{G_m})^2 + \beta(P^t_{G_m}) + \gamma \tag{15}$$

Furthermore, a start up cost has been taken into account for the avoidance of frequent starting up or shutting down of diesel generator as below:

$$Cost_{up} = U_m^t \times st_{cost}^{Up} \tag{16}$$

here U_m^t shows the commitment status of the generator, its value can either be 1 for commitment state and 0 for non-commitment state. Consequently, the integrated cost of the diesel generator can be written as:

$$Cost_{G_m}^t = CostP_{G_m}^t + Cost_{up} \tag{17}$$

2.5 Demand Response Program

Demand Response Program (DRP) objective is to change user load demand according to variation in system power. The microgrid has the capability to shift its load from peak hours to off-peak hours with utilization of DRP and reduce cost of energy supply. DRP has various possible ways of employing such as load shifting, load curtailment and so on. We have utilized load shifting scheme and suppose that specific amount of load (20% of total load) can participate in DRP. The system load after applying DRP can be written in mathematical from as follow [5].

$$P_{LDR_m}^t = (1 - DR^t).P_{L_m}^t + ldr^t \qquad \forall t \in \mathcal{T}, \forall m \in Z_i, \tag{18}$$

$$DR^t \leq DR^{max} \qquad \forall t \in \mathcal{T}, \forall m \in Z_i, \tag{19}$$

$$\sum_{t-1:\mathcal{T}} ldr^t = \sum_{t-1:\mathcal{T}} (DR^t) \times (P_{L_m}^t) \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{20}$$

here $P_{LDR_m}^t$, ldr^t, and $P_{L_m}^t$ represents the percentage of load shifting from hour t, Shifted load from other hours t to hour t', and forecasted power demand at time t of MG, respectively.

The constraint in Eq. 19 limits the load portion that is to be shifted to off-peak time. Equation 20 shows the total assignable load and assure that daily consumption of energy will remain the same after utilization of DRP.

3 Proposed Scheme

The EMS for zonal MGs is explained and objective functions of MGs and DNO have been formulated in this section. In the proposed zonal multi-microgrid structure, MGs and DNO have their own objective functions. The problem of energy management has been solved in two steps in order to complete one round of optimization. At the first step, EMS of each MG receives the hourly information of its load profile and generation capacities as input and local optimization is performed with consideration of demand response program. EMS schedules its DERs locally to balance the supply/demand and computes deficit and surplus power as shown in Algorithm 1. The DNO is informed about surplus/deficit power status with request to sale/buy power to/with other zone's microgrid. DNO receives the information of surplus/deficit power from each zone and prioritize zones according to load priority. Global optimization is performed to balance system-wide supply and demand in second step using Algorithm 2.

The DNO has to deals with two cases. Case 1) supply/demand deficit, Case 2) Supply/demand surplus. In case of deficit power, DNO sales power to the zone with high priority first. The sensitive load zone microgrid supply and demand is balanced first and then other zones are served accordingly. Likewise, in case of surplus power, extra power is traded with other zonal microgrid while considering the priority of zones. This concludes first round of optimization.

In order to facilitate exchange of power among microgrids and achieve over all supply-demand balance, the following policy is considered by the DNO.

1. The load demand of high priority zone microgrid will be supplied at high priority all of the time.
2. In case of power deficiency in high priority zone microgrid, DNO will sale it power first.
3. The load demand of other zones will be meet next and DNO will consider sale of power to other zones after serving high priority zone first.

Algorithm 1. Local EMS

Get values of load and generation forecast;
Run local optimization for each microgrid
for $t < T$ **do**
    if $P_m^t = P_{LDR_m}^t$ **then**
        No deficit and surplus power
    else if $P_m^t < P_{LDR_m}^t$ **then**
        Calculate deficit power
        Check battery charge status
        if $SoC \geq 80\%$ **then**
            Discharge battery
        else if $SoC \leq 20\%$ **then**
            Send request to DNO for buying power
        end if
    else if $P_m^t > P_{LDR_m}^t$ **then**
        Calculate surplus power
        Send request to DNO for selling power
    end if
    t++
end for

3.1 Microgrids Objective Function

The objective of each microgrid in proposed model is to balance its supply and demand with minimal operational cost. The objective function of individual microgrid provided in Eq. (21) contains CDG generation cost, startup cost for CDG, power trading cost, and battery charging and discharging cost at time t interval of scheduling horizon. The scheduling horizon considered in this paper is 24 h with interval of one hour.

$$\min \sum_{t\in\mathcal{T}} Cost^t_{G_m} + \sum_{t\in\mathcal{T}} (\lambda_{buy} \times P^t_{def_m} - \lambda_{sale} \times P^t_{sur_m}) + \sum_{t\in\mathcal{T}} Cost^t_{B_m}(P^t_{B_m,dis} - P^t_{B_m,ch}) \tag{21}$$

$$s.t:$$

$$\sum_{t\in\mathcal{T}} (P^t_{PV} + P^t_{WT} + P^t_{DG} + P^t_{B_m,dis} + P^t_{def_m}) = \sum_{t\in\mathcal{T}} (P^t_{LDR_m} + P^t_{B_m,ch} + P^t_{sur_m}) \qquad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{22}$$

and constraint (2)–(10), (13)–(14) and (18)–(20).

Here λ_{buy}, λ_{sale}, $P^t_{def_m}$ and $P^t_{sur_m}$ represents the buying price, selling price, deficit power and surplus power respectively. Eqs. (2)–(4) provides the upper and lower bounds for individual MG load. The operating limits and start-up cost of generator is also considered and given by constraints (13)–(14). Power generated by microgrid DG should balance the load demand at each interval and is given by (22). The maximum amount of shift-able load is constrained by (19). The load after applying DR (load shifting) can be computed by using Eq. (18). Each MG computes its surplus and shortage power amount according to Algorithm 1 and after the execution of local optimization by each MG-EMS, theses values are conveyed to the DNO.

3.2 DNO Objective Function

The DNO receives the information of surplus and deficit powers from each microgrid and performs global optimization in second step. The objective of DNO is to guarantee over all system-wide balance of supply and demand in economic way. In order to formulate objective function for DNO, the cost of buying (selling) from (to) is required to be considered. The objective function for DNO is given

Algorithm 2. Energy exchange

```
1: Initial values;
2: Gets power status of each microgrid
3: Prioritize microgrid
4: for t < T do
5:    for all i < N do
6:       if Deficit powert > 0 then
7:          sale power to high priority MG first
8:       end if
9:       if Surplus power> 0 then
10:         Buy surplus power from MG
11:         if supply& demand balanced then
12:            Go to step 18
13:         else
14:            Charge battery
15:         end if
16:      end if
17:   end for
18:   t++
19: end for
```

by Eq. (23) and it contains cost of buying power from MG and cost of selling power to MG.

$$\min \sum_{m \in Z_i} \sum_{t \in \mathcal{T}} (\lambda^t_{buy} \times P^t_{buy_m} - \lambda^t_{sale} \times P^t_{sale_m}) \tag{23}$$

Subject to:

$$\sum_{t \in \mathcal{T}} \sum_{m \in MG} (P^t_{PV_m} + P^t_{WT_m} + P^t_{DG_m} + P^t_{B_m,dis} + P^t_{buy_m}) = \sum_{t \in \mathcal{T}} \sum_{m \in MG} (P^t_{LDR_m} + P^t_{B_m,ch} + P_{sale_m}) \quad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{24}$$

$$\sum_{t \in \mathcal{T}} \sum_{m \in MG} P^t_{def_m} = \sum_{t \in \mathcal{T}} \sum_{m \in MG} P^t_{sur_m} \quad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{25}$$

$$P^{min}_{sur_m} \leq P^t_{sur_m} \leq P^{max}_{sur_m}, \quad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{26}$$

$$P^{min}_{def_m} \leq P^t_{def_m} \leq P^{max}_{def_m}, \quad \forall t \in \mathcal{T}, \forall m \in Z_i \tag{27}$$

The energy exchange between microgrids and DNO is performed according to Algorithm 2. The constraint (24) guarantee the system wide balance of supply and demand, where is the balance of deficit and surplus power is constrained by (25).

4 Case Study Simulation

In this section a case study is considered to illustrate the effectiveness of proposed algorithm. The configuration is shown in Fig. 2. Three interconnected microgrids

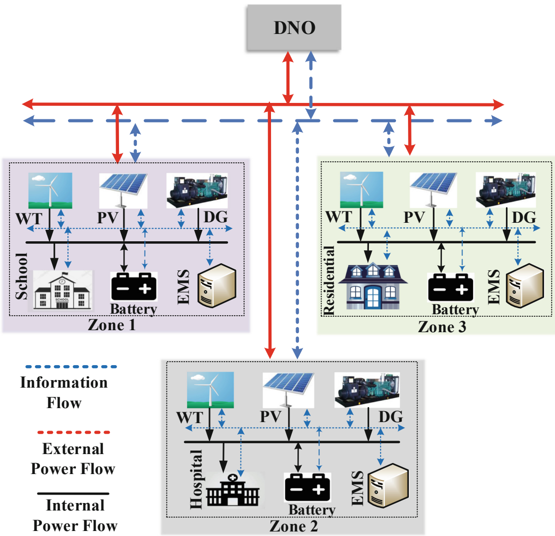
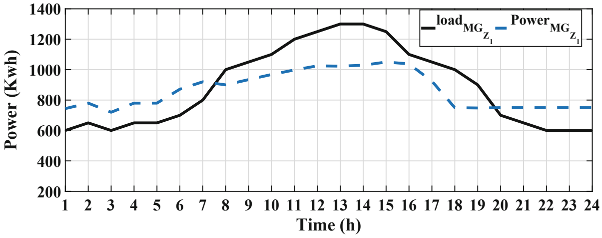


Fig. 2. Considered case study for multi-microgrids energy management

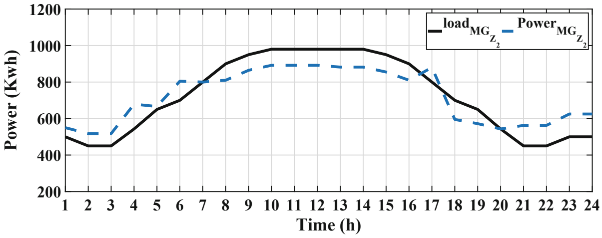
are operated in grid-isolated mode. Each microgrid represents a categorized load zone. The zones are prioritized according to load sensitivity. The hospital load zone has higher priority then school load. The least priority is given to residential load zone. The microgrids can exchange energy through DNO. The DNO does not contain any generating unit and load point. Each microgrid consists of conventional generator (diesel), Wind turbine and PV source. The parameters of diesel generators for each microgrid are listed in Table 1. The proposed energy management is performed in two steps and operation of each step explained in proceeding subsection for case study simulation.

Table 1. Cost coefficients of microgrids diesel generator

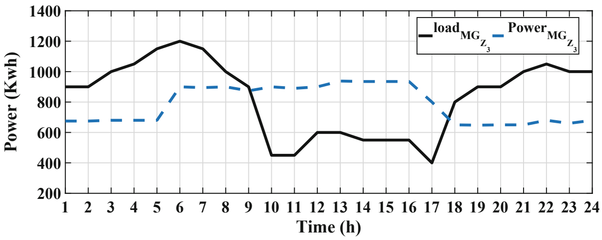
Parameter	MG_1	MG_2	MG_3
Capacity (kW)	300	200	200
α (¥/kWh^2)	0.0056	0.0061	0.0061
β (¥/kWh)	0.142	0.091	0.091
γ (¥)	0.221	0.184	0.184
Start-up cost (¥)	0.9	0.7	0.7



(a) MG_{z_1}



(b) MG_{Z_2}



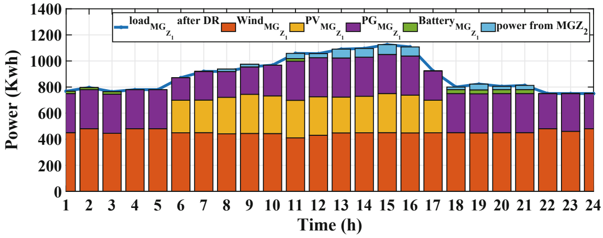
(c) MG_{Z_3}

Fig. 3. Power and Load demand forecast of (a) MG_{Z_1} (b) MG_{Z_2} (c) MG_{Z_3}

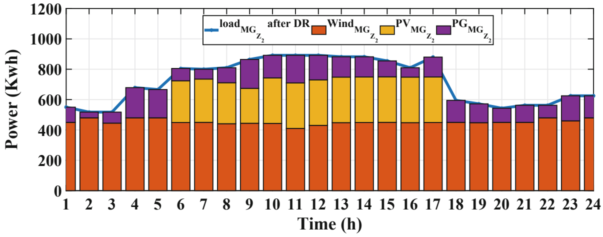
4.1 Step 1

The local EMS of individual microgrid gets the information of its load forecast and available generation for energy management in scheduling horizon. The scheduling horizon considered in this work is 24 h with interval of one hour each. The load and generation forecast for each microgrid is shown in Fig. 3. It can be clearly seen that in isolated mode, the generated power, in three MGs, is less then required load demand. It can be observed from Fig. 3(a) that, the peak load interval of MG_{Z_1} is from 8am to 18pm. Likewise, from Fig. 3(b), the peak load interval of MG_{Z_2} is from 8am to 16pm.

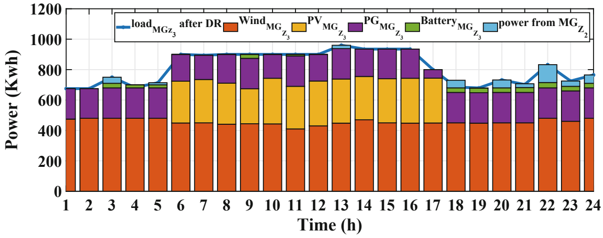
Whereas, peak load interval of MG_{Z_3} is between 1am to 8am and 18pm to 24pm as shown in Fig. 3(c). The load from these intervals will be shifted to the off-peak intervals after applying DR in step 1. The local EMS of each microgrid apply DRP to the initial forecasted load demand and solve the local optimization problem to schedules its generating units accordingly. The Surplus



(a) MG_{Z_1}



(b) MG_{Z_2}



(c) MG_{Z_3}

Fig. 4. Energy schedule of (a) MG_{Z_1} (b) MG_{Z_2} (c) MG_{Z_3}

and deficit power is calculated as a difference of supply and demand. The status of individual surplus and deficit power is communicated to DNO for possible sale and purchase of energy in either case.

4.2 Step 2

In second step, DNO receives the power status of each microgrid and prioritize each microgrid according to load. Hospital zone has high priority than school and school priority is higher than residential. The DNO perform as central controller in order to facilitate prioritize energy exchange between MGs and guarantee system wide supply and demand balance. The DNO make decision based upon the received energy status of corresponding MG. In this case study, MG_{Z_1} and MG_{Z_3} has deficit power. The DNO gives preference to MG_{Z_1} due to its high priority. The surplus power in MG_{Z_2} is first sold to MG_{Z_1} to balance its power deficiency. The remaining power is sold to MG_{Z_3}. This is shown in Fig. 4(a), surplus power from MG_{Z_2} is first soled to MG_{Z_1} and the remaining power is offered to MG_{Z_3} based on priority. After completion of energy exchange, if there is still surplus power available, it is utilized for charging batteries.

5 Conclusion

This paper proposes a zones based distributed energy management for multi-microgrids operating in isolated mode. The load are categorized into different zones to get specific load profile. Demand response program are considered for shifting loads from peak hour to off peak hour in order to make the energy supply more reliable and also facilitate the energy scheduling scheme. The focus of this paper is to achieve over all supply and demand balance and provide reliable power to prioritized critical load zones. The reliability of zonal multi-microgrids is enhanced through prioritized energy exchange. Simulation results are performed to illustrated the effectiveness of proposed energy management scheme. The results demonstrates that supply and demand can be balanced in isolated multi-microgrids through proposed energy management scheme effectively.

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