Energy management for isolated microgrid to mitigate “demand & abandon” phenomenon with two types of subsidy policies

Li Liming¹, Chen Weidong¹ and Shi Xueqi²

¹ College of Management and Economics, Tianjin University, Tianjin, China
² School of Electrical and Information Engineering, Tianjin University, Tianjin, China
E-mail: shixueqi@tju.edu.cn

Abstract. This paper presents a game model about the microgrids energy management problem and its implementation in the centralized energy management system for isolated microgrids. The model mainly provides power management strategies based on the problem that power is imbalance, and analyses the impact of two types of subsidy policies on “Demand & Abandon” in the operation of microgrid. By analysing the experiment results, we conclude that: 1) energy storage device improves the flexibility of power usage strategy; 2) the implement of infrastructure subsidy policies can solve “Demand & Abandon” in a better way while the electricity subsidy policies are invalid.

1. Introduction

The excessive emissions of CO2 have incurred worldwide environment and energy problems such as globe warming. To reduce the emissions of CO2 and conserve energy, many major countries are trying to develop new technologies to utilize environment friendly energies (e.g. solar energy) without emitting much pollution [1]. Microgrid (MG) is such a promising approach. In MG, new power generation techniques, such as wind turbines (WTs), photovoltaics (PVs), fuel cells (FCs) and microturbines (MTs), utilize renewable and clean energies to produce power; new energy storage systems (EES) and energy conversion devices can improve the comprehensive efficiency of energy utilization [2, 3]. Therefore, the study of MG has obtained attentions from some major countries and they have put forward a series of encouragement policies [4]. For example, in USA, 30% initial investment subsidies were designed for renewable energy projects; in China, the government mandated utility companies to purchase electricity generated by renewable energy [5].

Generally speaking, the subsidy policies on MG can be divided into two categories: electricity subsidy policy and infrastructure subsidy policy, in which electricity subsidy policies include feed-in-tariff, investment tax credits, renewable energy portfolio, financing facilitation, net metering and government mandates and regulatory provisions, and infrastructure subsidy policies includes investment tax credits, public investment and government mandates and regulatory provisions [6, 7]. These policies have attracted a lot of attentions from researchers and they made a lot of contributions in analysis of policy utility, analysis and optimization of policy model, comparison of different policies, and policy market review [8-10].

Most of previous works have studied the influences of policies for development of MG, however, the study about impact of different polices for the operation of MG has been largely ignored [11, 12]. This motivated us to study how to choose polices to solve operation problems of MG. Specifically, one of the most serious operation problems is “Demand & Abandon”, which refers to the phenomenon that...
distributed energy resources (DERs) will still abandon some of power when the power demands of users are unsatisfied [13]. “Demand & Abandon” is mainly resulted from the peak period discordance between DERs’ power generation and agents’ power usage. Besides, the distribution of power produced from environment-friendly energies within a day is uneven, which further aggravates the “Demand & Abandon”. These characteristics lead to the unbalance of power supply and usage, and thus MG is not efficiently utilized [14]. To this end, we discuss the impact of existing policies on reducing the peak periods discordance between DERs and users to mitigate the “Demand & Abandon” of MG by using an energy management system (EMS) with an energy storage device.

Generally, according to a series of literatures, EMS methods can be divided into centralized optimization (CEMS) and distributed optimization (DEMS) [15,16]. For the DEMS, it mainly focuses on methods which include game theory-based distributed optimization, distributed convex optimization, alternating direction method of multipliers. For the CEMS, based on one operator, the framework for the development of CEMS is studied, such as a CEMS for a MG composed of hydrogen storage and wind power with a dynamic linear programming (LP) formulation, and a CEMS for a PV-storage in MG with an LP solution technique together with heuristics. Meanwhile, different algorithms and models are designed to make the centralized approach the most suitable for application of optimization techniques, such as a three-phase unbalanced system with presence of both dispatchable and non-dispatchable distributed generation for testing EMS in an isolated MG [17,18].

2. Model

In this paper, the trading problem within the MG can be modelled as a Stackelberg game, where the EMS is the leader, and buyers and sellers (defined as follows) are the followers, to capture the interaction.

2.1. Model of MG

Generally, in MG, agents are composed of different loads, PVs and WTs, named users and DERs respectively. Before participating in an energy sharing zone, define daily power generation of agent $i$ as:

$$E_i = [E_i^1, E_i^2, \ldots, E_i^{24}], i \in [1,2,\ldots,n]$$  \hspace{1cm} (1)

where $n$ is the total number of agents in MG, and the operation time is grouped into 24 hours.

Define daily power consumption of agent $i$ as

$$D_i = [D_i^1, D_i^2, \ldots, D_i^{24}], i \in [1,2,\ldots,n]$$  \hspace{1cm} (2)

Therefore, daily net power of agent $i$ is shown as:

$$Q_i = \sum_{h=1}^{24}(E_i^h - D_i^h), i \in [1,2,\ldots,n]$$  \hspace{1cm} (3)

when $Q_i > 0$, the power of agent $i$ is surplus; when $Q_i < 0$, the power of agent $i$ is insufficient.

In a trade, we define agents as: $B = \{i|Q_i < 0\}$ and $S = \{i|Q_i > 0\}$. Obviously, $B$ is the set of buyers, $S$ is the set of sellers, and the role of agents is variable but confirmed at time.

The total demand in MG is

$$Q_D = \sum_{i \in B} Q_i$$ \hspace{1cm} (4)

The total supply in MG is

$$Q_T = \sum_{i \in S} Q_i$$ \hspace{1cm} (5)
where \( Q_d \leq Q_t \). Generally, \( Q_t \) is 8% higher than \( Q_d \) with high quality of power, but the characteristics, including fluctuation and intermittent, of DERs could increase the margin between \( Q_t \) and \( Q_d \).

The fixed load set of user \( i \) in the special period is defined as:

\[
FL_i \triangleq \{FL_i^1, FL_i^2, \ldots, FL_i^{24}\}, \quad i \in \{1, 2, \ldots, n\}
\]  

(6)

For the shiftable load, it means that users can choose the time to use the electrical appliances or equipment according to their preference. In this paper, each user is assumed to have dozens or hundreds of appliances or equipment with shiftable loads. Such appliances or equipment may include PHEVs, washers, dryers, dishwashers, etc. The shiftable load set of user \( i \) is defined as:

\[
SL_i \triangleq \{SL_i^1, SL_i^2, \ldots, SL_i^{24}\}, \quad i \in \{1, 2, \ldots, n\}
\]  

(7)

where \( k \) is the number of appliances or equipment with shiftable loads for user \( i \), and \( SL_i^h \), shiftable loads for user \( i \) in the specified period \( h \) is transferable power caused by \( k \) appliances or equipment. For example, user \( i \) often wash cloth at night and the washer consumes 0.225\( kW \) for working in 1h generally. In order to avoid the peak hours of power consumption, it would regulate the time to use washer. Therefore, 0.225\( kW \) is the shiftable load of washer for user \( i \).

For EMS, we assume that there is only one storage devise in EES, and its charging (CE) and discharging (DCE) strategies are

\[
CE = \{CE^1, CE^2, \ldots, CE^{24}\},
\]

\[
DCE = \{DCE^1, DCE^2, \ldots, DCE^{24}\},
\]

(8)

Meanwhile, exist

\[
E(t + 1) = E(t) + CE^h - DCE^h - \delta E
\]

(9)

where \( E(t) \) is remaining capacity of energy storage devise at time \( t \), \( CE^h \) is charging strategy in period \( h \), \( DCE^h \) is discharging strategy in period \( h \), \( E \) is the capacity of energy storage devise, and \( \delta E \) is self-discharging of EES.

Then we consider discharging strategy at time \( t \) as:

\[
DCE' = E(t) - \eta E
\]

(10)

where \( \eta E \) is the security capacity of energy storage devise with \( \eta E \).

2.2. Regulation strategy

\( Q^h < 0 \) means that the power generation could not satisfy the demand of agents in period \( h \). In this case, agents are required to transfer shiftable loads which are approximately equal to the margin between power generation and the demand of agents, \( Q^h \), from this period \( h \).

\[
\min \left| \sum SL_i^h + Q^h \right|
\]

(11)

When all shiftable loads are transferred from this period \( h \), the power generation is still far less \((\left| \sum SL_i^h + Q^h \right| \leq 0.5Q^h)\) than the demand of agents in period \( h \). There exists supplement from the energy storage device, hence, eq. (11) can be rewritten as:

\[
\min \left| \sum SL_i^h + DCE^h + Q^h \right|
\]

(12)

where \( SL_i^h \in SL_i^h \).
$Q^h > 0$ means that the power generation is more than the demand of users in period $h$ so that, after satisfying the self-power consumption first, agents would supply EES with surplus power. In this case, agents could transfer shiftable loads which are transferred from other periods into this period $h$. When there exists the surplus power, agents could supply to EES. The transfer-in loads is set of all transfer-out loads. However, the real transfer-in loads ($TL^h_{ik}$) are selected by (12) and form into

$$TL = \begin{bmatrix} TL_{i1} & TL_{i2} & \cdots & TL_{i1} \\ TL_{i2} & TL_{i2} & \cdots & TL_{i2} \\ \vdots & \vdots & \ddots & \vdots \\ TL_{im} & TL_{im} & \cdots & TL_{im} \end{bmatrix}$$

(13)

where if $SL_{ik}$ is selected in the period $h$, $TL^h_{ik} = SL^h_{ik}$; if $SL^h_{ik}$ is not selected in the period $h$ $TL^h_{ik} = 0$.

Then agents are required to transfer shiftable loads which are approximately equal to the margin between power generation and the demand of agents, $Q^h$, in this period $h$.

$$\min \left| \sum_{TL_{ik} \in TL} TL^h_{ik} - Q^h \right|$$

(14)

when all shiftable loads are transferred in this period $h$, the power generation is still far more $\left| \sum TL^h_{ik} - Q^h \right| > 0.5Q^h$ than the demand of agents in period $h$. There exists supplement to the energy storage device, hence, (14) can be rewritten as:

$$\min \left| \sum_{TL_{ik} \in TL} TL^h_{ik} + CE^h - Q^h \right|$$

(15)

2.3. Cost structure

In a trade, for sellers, the generation cost is:

$$COS_i = aPV_i^2 + bPV_i$$

(16)

where $PV_i$ is the capacity of generation of DER$_i$. Therefore, the profit generic function is:

$$\pi_p = \max \left( P_i Q_i - (aQ_i^2 + bQ_i) \right)$$

(17)

where power generation of DERs is not only traded in MG, but could use by themselves. For the cost caused by the part of power generation used by DERs themselves, we do not consider. After considering electricity subsidy, the profit generic function is:

$$\pi_p = \max \left( P_i + \lambda_i Q_i - (aQ_i^2 + bQ_i) \right)$$

(18)

where $\lambda_i$ is unit electricity subsidy.

For EMS, its cost is divided into initial investment cost $\beta E^2$ and operation cost $\gamma CE$, where $\beta E^2$ means that, with increasing capacity of energy storage device, the investment increases and marginal cost decreases.

$$COE = \beta E^2 + \gamma CE.$$ 

(19)

Therefore, the profit generic function is:

$$\pi_p = \max \sum_{i=1}^{24} \left( (P_1 - P_i) Q_o - \beta E^2 - \gamma CE' \right)$$

(20)
where $P_1$ is the unit price to buy power, and $P_2$ is the unit price to sell power. After considering infrastructure subsidies, the profit generic function is:

$$\pi_p = \max \sum_{t=1}^{24} \left[ (P_1 - P_2)Q_D - \beta E^2 - \gamma CE' \right] + \lambda E$$

(21)

where $\lambda$ is the unit infrastructure subsidy.

3. Implementation

In this section, we will build an optimal model based on the discussion above and give an optimal solution of the model.

3.1. Optimal solution

Now consider the case that the government provides electricity subsidies. Suppose that the unit price to sell power is $P_2$ which is a constant, and the unit electricity subsidy from the government is $\lambda$. Then the total profit for sellers in a trade can be formulated as following (18).

Proposition 1. For sellers in a trade, the optimal trading strategy:

$$Q_s = \left( P_1 + \lambda - b \right) / 2\alpha$$

(22)

Then consider the case that the government provides infrastructure subsidies. Suppose that the unit price to buy power is $P_1$ which is a constant, and the unit infrastructure subsidy from the government is $\lambda$. Then the total profit for EMS in a trade can express as (21).

In the isolated MG, there exists the power balance equation, which can be formulated as:

$$Q_s = CE + Q_D$$

(23)

Then the optimal operation strategy problem of EMS can be formulated as following:

$$\begin{align*}
\max \sum_{t=1}^{24} \left[ (P_1 - P_2)Q_D - \beta E^2 - \gamma CE' \right] + \lambda E \\
\text{subject to:} \\
Q_s = CE + Q_D \\
DCE' = E(t) - \eta E \\
E(t + 1) = E(t) + CE^h - DCE^h - \delta E
\end{align*}$$

(24)

Proposition 2. Consider the optimal strategy model (12) for EES to keep stable operation of EMS: the optimal discharging strategy is:

$$DCE'' = E(h) - \eta \frac{24\gamma(\eta - \delta) + \lambda}{2\beta}$$

(25)

The optimal charging strategy is:

$$CE'' = E(h+1) - (\eta - \delta) \frac{24\gamma(\eta - \delta) + \lambda}{2\beta}$$

(26)

The optimal capacity of the energy storage device is:

$$E'' = \frac{24\gamma(\eta - \delta) + \lambda}{2\beta}$$

(27)

The implementation process of the Stackelberg game model is a problem of linear programming. It is difficult to directly obtain the optimal solution with conventional mathematical methods. Therefore, an
algorithm will be adapted to solve this problem. The general implementation process of the model executed by users is shown in Figure 1.

Figure 1. The flow chart of Algorithm.

4. Case study

4.1. Basic data

Figure 2. Study case network of the insulated microgrid.

Figure 3. Load curves of the typical day.

Actual data of a demonstration project of China Midland Grid, Zhumadian Wenquan power station, is used for the case study. In the system, there are Residential Buildings (RB), Commercial Buildings (CB) and Office Building (OB), as shown in Figure 2. All of the buildings have installed PVs with capacity ranging from 100 to 300 kW, and WT with capacity ranging from 200 to 300 kW. The output curves of PV and microturbine of a typical day are shown in Figure 3. The daily consumption curves of these agents are shown in Figure 4.
Agents have different load characters and power outputs. These mainly lie in the following two aspects: (1) the numbers and the times of peaks of power generation and consumption are not same. For example, as shown in Figure 5, the peak of power consumption is at approximate 20:00, and there is a large quantity of power generated by agents around 13:00. (2) the numbers of power generation and consumption in the rest periods do not match. For example, in the period from 0:00 to 5:00, the power consumption exists while the power generation of this period is 0.

4.2. Power regulation strategy

In this section, we will show how to regulate shiftable loads between agents and EMS by using the model and algorithm. According to Figure 3 and Figure 4, total net power of each period \( Q_h \) could be formulated by EMS. Then EMS could judge the condition of each period to regulate power. When \( Q_h > 0 \), shiftable loads could be transferred in this period, and when \( Q_h < 0 \), shiftable loads should be transferred from this period. For example, the shiftable load should be transferred from the periods 0:00-7:00 and 18:00-24:00 respectively, and the shiftable load could be transferred in the period 8:00-17:00.

In the periods 0:00-7:00 and 18:00-24:00, EMS requires to transfer a certain shiftable loads out, and agents could fulfill this requirement as possible according to their actual situation. Previous studies show that shiftable loads account for 35%–55% of the total loads. In this section, we assume that shiftable loads account for 55% of the total loads and shiftable loads of each agent are allocated to 5 appliances or equipment randomly. Then, for all agents, their shiftable loads are allocated to 5 appliances reasonably. Then agents provide information about shiftable loads to EMS. By using the algorithm, the EMS could obtain the optimal power regulation strategy and the power charging and discharging strategy.

4.3. Results of power regulation strategy with different shiftable loads rates

Considering electricity subsidy policies, EMS adopts the optimal power regulation strategy to transfer power from the periods 0:00-7:00 and 18:00-24:00 respectively to the period 8:00-17:00. Then the power consumption can be changed as shown in Figure 6.
Figure 6. Regulated total power consumption and generation curves of a day (45% shiftable loads).

Figure 7. Regulated total power consumption and generation curves of a day (55% shiftable loads).

Figure 6 show that daily generation curve will better fit daily consumption curve after adopting the optimal regulation strategy than before (simply adopting electricity subsidy policies), which means that the discordance between the power consumption composed of shiftable loads and net power and power generated by WTs and PVs decreases, and the effect of fluctuation and intermittent of distributed generation on agents’ demand decreases as well. However, there still exists a gap between regulated total power generation and consumption. This means that power curtailment condition exists in the period 5:00-17:00 while the power demand could not be satisfied in the period 0:00-4:00 and 18:00-24:00. Therefore, there still exists “Demand & Abandon”.

5. Conclusion
In this paper, we study the problem of the operation in isolated MG. Our proposed methods address following major challenges: (1) the management strategy of EMS with energy storage device and without energy storage device respectively, (2) how to solve the operation problem (“Demand & Abandon”) in MG with different subsidy policies.

To cope with these challenges, we propose a game model about the MG’s energy management problem with a CEMS in isolated MGs. The model shows that, without energy storage device, agents could not effectively relieve power curtailment condition by regulating shiftable loads to reduce the discordance between their generation and consumption. However, after this regulation, “Demand & Abandon” cannot be solved. When the percentage of shiftable loads increases to 55%, the power demand can be satisfied but power curtailment still exists, as shown in Figure 7. This means that “Demand & Abandon” can be better improved. But, for general agents, the shiftable loads which account for 55% of total loads are difficult to achieve, because agents are forced to shift loads and freedom of power usage is limited, after which use of comfort would be affected or damaged.

With energy storage device, our model shows that, with 45% shiftable loads, “Demand & Abandon” can be solved, because the surplus power could be charged into energy storage device to solve power curtailment condition, and power in energy storage device could be discharged to satisfy agents’ demand when the generation is not enough. Meanwhile, the regulation strategy of power is more flexible for agents.

6. References
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