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ECONOMIC OPERATION OF TYPICAL MICROGRIDS

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ECONOMIC OPERATION OF TYPICAL MICROGRIDS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Electrical Engineering
in the College of Engineering
at the University of Kentucky

By

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Lexington, Kentucky

Director: Dr. Yuan Liao, Professor of Electrical and Computer Engineering

Lexington, Kentucky

2018

ABSTRACT OF THESIS

ECONOMIC OPERATION OF TYPICAL MICROGRIDS

A microgrid is a subnetwork of power system that consists of a group of distributed energy sources and loads. It is designed to integrate distributed generation, loads, energy storage devices, converters, and monitoring and protection devices. Generally, a successful microgrid could run both in island mode (off-grid) and in grid-connected mode (on-grid), being able to convert between two modes at any time. With continuous development of the power system, distributed renewable generation unit accounts for an increasing proportion, since microgrid could effectively connect these generation units to the main grid, thereby improving the energy efficiency and the energy structure. Microgrid is increasingly playing an important role in the power system.

This thesis focuses on reducing the cost of microgrids through economic operation, including both static and dynamic economic operations. Three cases are tested based on these two methods. Also, each case will include four situations including one without ESS and three situations with 2MWh ESS, 3MWh ESS, 4MWh ESS, respectively.

KEYWORDS: Microgrid (MG), Static Economic Operation, Dynamic Economic Operation, Energy Storage System(ESS), Photovoltaic(PV) Generation.

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ECONOMIC OPERATION OF TYPICAL MICROGRIDS

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Chapter 1 Introduction

1.1 Background

A microgrid is a subnetwork of power system that consists of a group of distributed energy sources and loads. It is designed to integrate distributed generation, loads, energy storage devices, converters, and monitoring and protection devices. A micro grid could be considered as a controllable load or generator for the power grid, depending on whether the micro grid sells power to the power grid or buys power from the main power grid. At the same time, a micro grid is a small, complete power grid for itself consisting of every main part of a regular power grid. Generally, a successful microgrid could run both in an island mode (off-grid) and in grid-connected mode(on-grid), which could also convert between two modes at any time.

Microgrids become increasingly important and benefit from the development of renewable sources, with the solar power station as the core. Traditional power grids based on centralized generation and long distance transmission have the disadvantages of high pollution and huge losses. Also, an unpredictable fault is one of the factors that endangered its stability. Especially for the development of renewable sources, generation unit using renewable energy sources are distributed, unreliable, and result in huge capital costs [1], for example, the Photovoltaic (PV) system has different outputs in different seasons, weather, location, and time. It cannot provide stable voltage and frequency as a conventional energy sources generator. Contrarily, the combination of microgrids and renewable source generations overcome these limitations, thus, the prospect of micro grids is pretty broad with the development of renewable sources.

At the same time, there is an increase of complex demand among many customers across many regions. For example, islands and mountainous areas, separate industrial districts and business districts, even schools and hospitals. They are impossible and very costly to connect with power grids. They all rely on distributed generations like PV, wind power, or fossil fuel generation units. Automatically, a grid will form inside them known as the micro grid.

Last but not least, with the gradual improvement of microgrid research, more and more advantages regarding microgrids are that they are gradually emerging, safe, efficient, clear, and it can control itself. The microgrid is seen as an alternative to some places which have high demand for power stability, such as hospitals, schools, and some companies.

1.2 Literature Review

The following included details about different methods that are usually used in decreasing operation cost problems are proposed in other literatures. These methods may solve these problems in different aspects. In summary, there are two aspects: Reduce operating costs by adding or improving equipment and reduce operating costs by economic dispatch.

1.2.1 Adding or Improving Equipment

Reference [2] designs a transformation scheme for a low-voltage grid called the green energy demonstration project implemented to reduce electricity bill. Equipment of this microgrid includes a wind turbine, PV, two batteries, main transformer capacity, and power factor. Transformation scheme goes into two stages. First stage aims to transform the wind power system, PV system, battery system, and install the energy management system. During this stage, the author adds a bidirectional energy storage inverter between the wind power system and load bus. The second stage aims to transform the load control unit and the backup unit, especially EMS on the basis of controllable load. This scheme decreases 22% of electricity, and in general, it could save 35% of the electricity bill in total.

Reference [3] provides a novel idea to increase the utilization of an off-grid microgrid thus increase lifetime of its batteries. In order to keep battery performs in better condition, the author uses buck-boost converter with supercapacitors(SC) to control batteries' charging and discharging. After test model in laboratory, the result proves that SCs help batteries to charge in lower frequency current furthermore increase its lifetime.

Reference [4] designs an economic operation monitoring system for traction transformer. This system includes four data displays, they are load factor real-time displays, TT losses and losses rate real-time curve, alternative critical load losses curve. Because this system is designed for traction transformer used in electric railway, the operation result is more focus on power losses. By operating alternative, active, reactive and synthesis losses of all traction transformers, cost of the system do reduce as expect.

1.2.2 Economic Dispatch

Reference [5] presents a multi-agent based distribution control strategy to minimize the operation cost for a DC microgrid. Most of the applications optimize microgrid in centralized way with a single centralized controller, this method has many limitations. The author makes every distributed generations as an agent, then share its information with only communicating with its direct neighbors through each unit, every unit can get global information, making its decision locally to minimize the operation cost for the whole system. According to simulation, this method successfully reduces total operation cost in this DC microgrid without changing bus voltage.

Reference [6] provides an improved Differential evolution (DE) method, called the hybrid differential evolution (HDE). Its cost function contains valve point effect, system load demand, power losses, ramp rate limits, and prohibits operation zones, also, constraints for each known parameter which is needed. HDE method is a combination of two operations, migrating operation and acceleration operation. Then, through seven steps test on a 40-unit practical ED system of Taiwan Power Company and a 140-unit thermal generating units of Korean power system, result shows this method is more suitable for large-scale power system.

Reference [7] proposes a new approach to dynamic dispatch. This approach is based on Constructive Dynamic Programming (CDP), and test in a single bus system with 3 generating units for 24 hours' periods. The author sets constraints for each operating unit and set power balanced constraint, then uses the principle of dynamic programming by avoiding discretization. The result provides this improved CDP approach offers improved computational performance.

Reference [8] uses extended security constrained economic dispatch (ESCED) algorithm to solve the problem of multi-stage dynamic economic dispatch (MDED), at the same time, this problem consists of network security, regulating margin and ramp rate constraints. The author uses one-stage Lagrangian equivalence by define three matrixes, then uses standard Gaussian elimination techniques to get the result. The model tested here is a 1200 buses, 1700 lines, and 85 generating units largerscale power system, the result demonstrates MDED problem could be solved by ESCED algorithm, and 2-stages results is better than 1-stage results.

Reference [9] proposed possible methods for optimizing operation of distribution systems with distributed generations considering various components and constraints.

1.3 Thesis Objectives and Outline

This thesis focuses on an economic operation strategy to reduce the cost of the microgrid with energy storage system based on the method proposed in [9]. The thesis tests the methods with three cases. In order to make the results more meaningful, these three cases correspond to three realistic microgrid situations, as described below.

Case I is the microgrid in downtown areas, especially hospitals and schools. These places usually do not only require a large amount of stable electricity to maintain operation, but also to provide sufficient funding to build photovoltaic generators and a microgrid. A microgrid in these places always have enough energy provided by utilities grid. Backup generators, such as a diesel generator, are required to ensure a stable supply of energy. However, due to the limited construction area downtown, these areas usually are unable to establish large-scale photovoltaic power generation equipment. The power of photovoltaic power generation equipment is not high.

Case II is a microgrid in mountainous and islands areas. It is very difficult to build a long-distance grid in these areas, thus, utilities grid usually can only provide low-power energy. Especially for cities or villages in these areas, they need to build a microgrid that uses local resources to generate energy to supply local electricity needs. At the same time, due to loss of long-distance transmission, energy prices are always higher than downtown areas.

Case III is a microgrid in power stations. The generation of these microgrids are always much larger than load so that it can provide a large amount of energy to the utilities grid. Due to the instability of photovoltaic power generation, these power station need to establish a microgrid to provide stable power output. Also, since photovoltaics requires light to generate energy, no energy can be produced at night. For this reason, a backup generation is needed to meet to demand for basic operation requirements of the power stations.

This thesis is organized as follows: Chapter II introduces components and constraints of microgrid systems, including constraints for generators, load, energy storage system, utilities grid, and system power balance constraints; the parameters of each component in 3 cases. Chapter III presents a static economic operation method for this microgrid without an energy storage system and static economic operation was used for the 3 cases. Chapter IV presents a dynamic economic operation method and later uses this method to operate the microgrid with 2MWh, 3MWh, and 4MWh energy storage systems, respectively. Chapter V summarizes all results in both static and dynamic economic operation, concluding an economic operation effect.

Chapter 2 Components and Constraints of Microgrid System

A microgrid is always considered as a solution to overcome the problem of greenhouse gas and power suppled in remote areas [10] [11]. In this chapter, the author represents the components, parameters, and constraints of operating the microgrid. This microgrid mainly consists of generators, battery system, and load, and is expected to run both in an island mode (off-grid) and in parallel with power grid mode(on-grid), which could also convert between the two modes at any time. This can be organized in three types: Purchase energy from AEP, Sale energy to AEP, and Power balanced in itself. Also, there are transformers, inverters, protective system and other devices needed for microgrids because these are not main contents of this paper, the author will not introduce them later. Figure 3.1 presents systematic structure of this microgrid. The arrows in the figure represent the possible direction of the current.

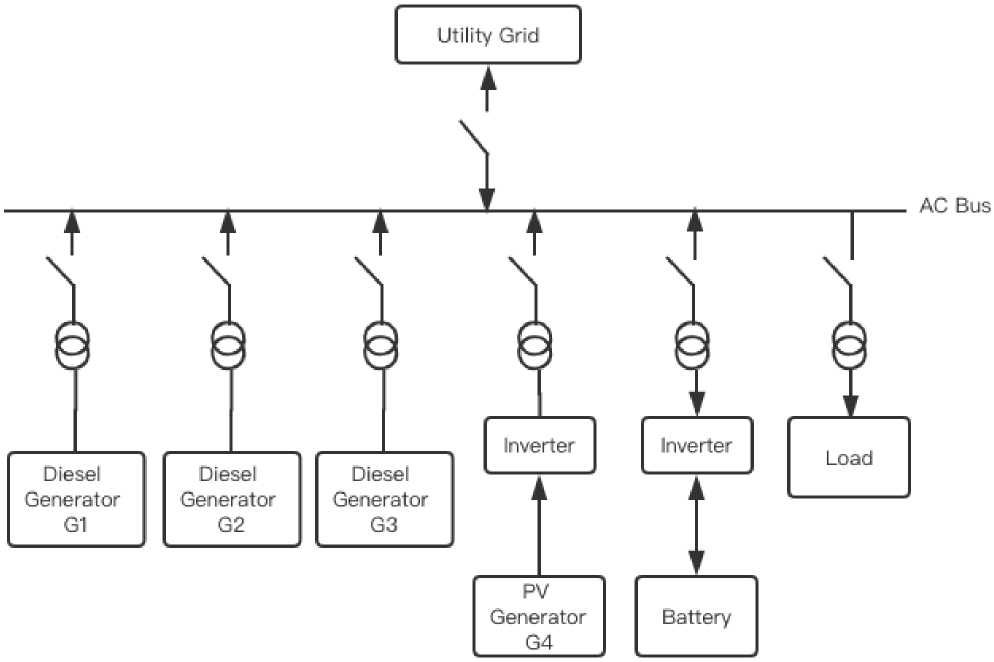


Figure 2.1 Systematic structure of the microgrid

In order to meet the requirement of economic operation, the known data include [9]:

- Generation characteristics: Generator types, maximum and minimum power rated, generator cost;
- Energy purchase price profile from AEP;
- Energy purchase upper capacity from AEP;
- Energy sale price for energy sold to AEP;
- Load profile in the microgrid;
- Storage system characteristics: maximum charging power rate, drawing power rate, maximum energy capacity, charging efficiency, drawing efficiency;
- Load characteristics: total amount, curtailable;

2.1 Microgrid Generators

2.1.1 Generator Parameter

There are 3 diesel generators and 1 Photovoltaic(PV) generator to provide energy in this microgrid. The main parameters of these generators are listed in Table 2.1. Some of the generating units are supplied with multiplied fuel resources such as coal, natural gas, oil etc. Here, all four generating units are a single-fuel resource [12]. G1, G2, G3 are diesel generators that could maintain running at a constant power at any time. G4 is a PV generator and its generation depends on the intensity of the light or time of the day. From the perspective of environmental protection, photovoltaic generators will always maintain their current maximum power operation, making full use of the energy generated by photovoltaics.

Table 2.1 List of generators in the system

Generator	Type	Minimum Generation(MW)	Maximum Generation(MW)	Cost($/MWh)
G1	Diesel	0	0.5	60
G2	Diesel	0	0.65	50
G3	Diesel	0	0.55	45
G4	PV	0	0.5 or 5	0

Assuming all diesel generators running without ramp up and ramp down, they could start up and shut down at any time. The power generation of photovoltaic generator is unstable, depending on many factors including illumination intensity, temperature, and so on. Figure 2.2 represents the PV generation in 24 hours and its power generation varies between maximum power rated and zero. Obviously, PV generation is at its highest level at noon and almost zero after sunset time.

For each case, diesel generators are utilized as backup generators. Therefore, the parameters for the 3 diesel generator are the same in all 3 cases. The maximum rated power of a PV generator is 0.5MW for Case I and in Case II, the microgrid in Case III is built for power station and its PV generator rated power is 5MW.

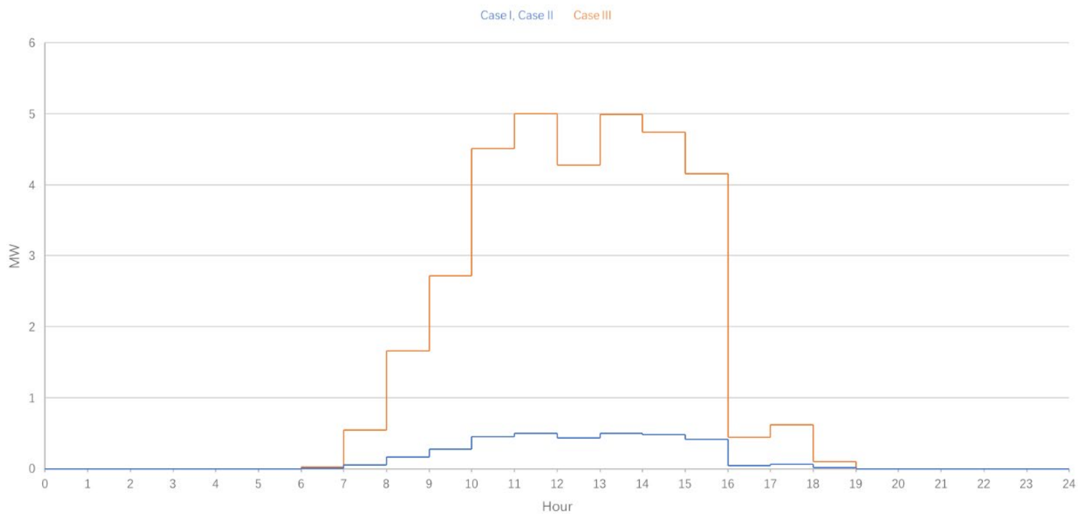


Figure 2.2 Power Generation of PV Generator in 24 Hours

2.1.2 Constraints for Generation Units:

$$P_{g\min i}u_{gik} - p_{gik} \leq 0, \forall\, k \in S_h, \forall\, i \in S_g$$

$$p_{gik} - P_{g\max i}u_{gik} \leq 0, \forall\, k \in S_h, \forall\, i \in S_g \qquad (2.1)$$

Equation (2.1) represents generation unit capacity constraints [9]. Where p_{gik} is power dispatch of generation unit i in hour k, P_{gi} is the power capacity of generation unit i in hour k, u_{gik} is the status of generation unit i in hour k. The power dispatch of generation i in hour k should not be smaller than the minimum capacity of this generation unit and no larger than the maximum capacity of this generation unit.

2.2 Load

2.2.1 Load Parameter

Load is the demand of the microgrid. This microgrid must meet the requirement of the demand in this system. Figure 2.3 shows the change in load of this system over 24 hours when demand at its highest level around 18:00, then gradually decreases.

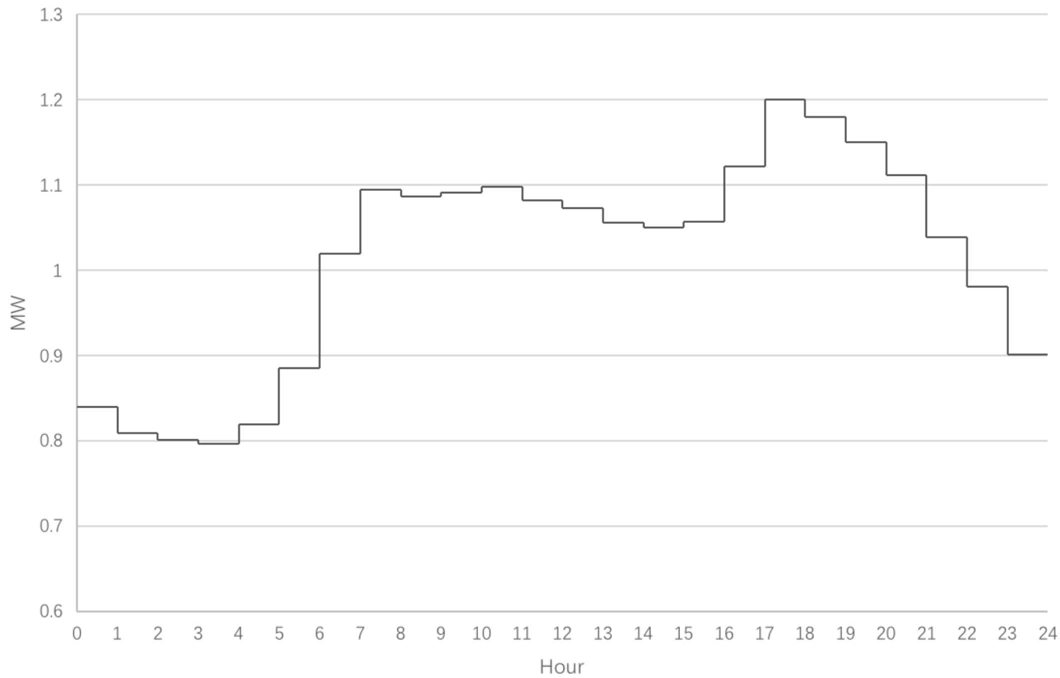


Figure 2.3 Load Demand in 24 Hours

In real life, the load is constantly changing and unpredictable based on different types of equipment. In general, it can be summarized into three groups: firm load, adjustable load, and interruptible load. In this system, the load is assumed to be a constant value within an hour interval. A microgrid system is needed to operate and meet the requirement of load. Also, in order to compare economic operation result, the author set load in each case as the same value.

2.3 Storage System

2.3.1 Energy Storage System Parameter

Storage system is a necessary part of the microgrid. It usually has four effects in the whole system [10] [13] [14] [15]:

- Backup power supply when system fault;
- Frequency regulation between the generation and demand side;
- Storing renewable generation peaks for use during demand peaks;
- Smoothens the output to eliminate rapid voltage and power swings of renewable generator on the microgrid.

In this microgrid system, we assume there is no time during the mode conversion between off-grid and on-grid of the microgrid. The storage system does not need to be considered as a backup power to compensate for the power shortage in the mode conversion. More importantly, storing energy for use during demand peaks or a utilities grid price peak, thereby reducing operation cost of whole system.

Table 2.2 Energy Container Parameters

Model	NaNiCl2
Power Rated	500kW
Nominal Capacity	2/3/4MWh
Charging Efficiency	85%
Depth of Discharge (DOD)	90%
System Voltage	480V

Table 2.2 represents parameters of energy storage system in the microgrid. Power rated is a charging and discharging rate in this ESS. Combined with charging

efficiency, the actual amount of charge should be the charging rate multiplied by charging efficiency. The discharging rate is equal to the charging rate and the actual amount of discharge should be the discharging rate divided by the discharging efficiency. Nominal capacity is the maximum capacity. There are three types of nominal capacities used in this thesis to test economic operation results. In order to protect ESS lifetime, an energy system should not be discharged exceeding DOD. Thus, the actual maximum capacity needs to be considered as DOD multiplied by Nominal Capacity.

2.3.2 Constraints for Energy Storage System

$$0 \leq q_{sik} \leq Q_{s\max i}, \forall\, k \in S_h, \forall\, i \in S_s \tag{2.2}$$

Equation (2.2) represents storage capacity constraints, where q_{sik} is energy of storage system i at end of hour k [9], $Q_{s\max i}$ is maximum capacity of storage system i. Energy of storage system i at end of hour k is between 0 and maximum energy capacity of this storage system.

$$s_{scik} + d_{scik} \leq 1, \forall\, k \in S_h, \forall\, i \in S_s \tag{2.3}$$

Equation (2.3) represents storage charging and drawing relationship constraint [9], where s_{scik} is charging status of storage system i at hour k and d_{scik} is discharging status, status is 1 when system performs this status otherwise is 0. Storage i can only performs charging or drawing action or neither in hour k.

$$q_{sik} - q_{si(k-1)} = s_{scik} p_{scrik} \varepsilon_{sdi} - d_{scik} p_{scrik} / \varepsilon_{sdi},\ \forall\, k \in S_h, \forall\, i \in S_s \tag{2.4}$$

Equation (2.4) represents storage charging and drawing power and energy constraints [9], where ε_{sdi} is charging efficiency of energy storage system i. Energy change of storage system i during hour k is equal to energy charging into this storage minus energy drawing from this storage.

$$q_{si0} = Q_{si0}, \forall\, i \in S_s \tag{2.5}$$

Equation (2.5) represents storage initial output constraints [9], where q_{si0} is energy of storage system i at beginning of time 0, Q_{si0} is initial energy of storage i. Energy of storage i in time 0 should be equal to initial energy of this storage system.

2.4 AEP Utilities Price

2.4.1 APE Utilities Parameter

Utilities grid is a commercial electric power distribution system, a microgrid usually need to connect utilities grid to purchase energy or sell energy. Here the author uses price data on 09/01/2018, ISO is PJM and zone is AEP [16]. AEP utilities price consist of two elements, price of sale energy to AEP Utilities and price of purchase energy from AEP Utilities. Each of them has the different price in different hour, in general, price is lower in night and higher in daytime. Thus, data in Figure 2.4 and Figure 2.5 is determining factors when to connect this microgrid with the main grid.

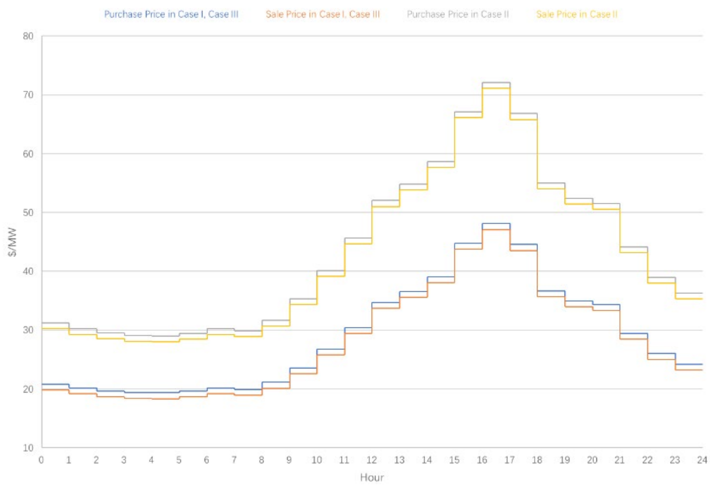


Figure 2.4 Price of AEP Utilities in 24 Hours

APE Utilities price is hourly price, the price depends on amount of load on this node in this hour, high demand leads to high price, low demand leads to low price.

2.4.2 Constraints for APE Utilities

$$P_{pur\min k} - p_{pur\,k} u_{pur\,k} \le 0, \forall\, k \in S_h$$
$$p_{pur\,k} u_{pur\,k} - P_{pur\max k} \le 0, \forall\, k \in S_h \tag{2.6}$$

Equation (2.6) represents constraints of purchase energy from utilities grid [9], where $p_{pur\,k}$ is energy purchased form utilities grid in hour k, $P_{pur\min}$ is minimum purchase energy in hour k, $P_{pur\max}$ is maximum purchase energy in hour k, $u_{pur\,k}$ is energy purchase status in hour k. A microgrid purchase energy from utilities grid in hour k should no less than minimum constraint and no more than maximum constraint in this hour.

$$P_{sale\min k} - p_{sale\,k} u_{sale\,k} \le 0, \forall\, k \in S_h$$
$$p_{sale\,k} u_{sale\,k} - P_{sale\max k} \le 0, \forall\, k \in S_h \tag{2.7}$$

Equation (2.7) represents constraints of sell energy to utilities grid [9], where $p_{sale\,k}$ is energy sold to utilities grid in hour k, $P_{sale\min}$ is minimum sale energy in hour k, $P_{sale\max}$ is maximum sale energy in hour k, $u_{sale\,k}$ is energy sale status in hour k. The microgrid sell energy to utilities grid in hour k should no less than minimum constraint and no more than maximum constraint in this hour.

2.5 System Power Balance Constraints

$$\textstyle\sum_{i1} p_{gi1k} + p_{purk} - p_{salek} = \sum_{i2} p_{si2k} + \sum_{i3} p_{li3k}, \forall\, k \in S_h \tag{2.8}$$

Equation (2.8) represents system power balance constraints, p_{gi1k} is power generation of generation unit i1 in hour k [9], p_{purk} is energy purchased from utilities grid in hour k, p_{salek} is energy sold to utilities grid in hour k, p_{si2k} is power consumed by energy storage system i2 in hour k, p_{li3k} is power consumed by load i3 in hour k. In a balanced power system, power supply is equal to power consumption. Power supply including generation, purchased power from AEP, and sale power to AEP. Power consumption including power for storage, and load.

Chapter 3 Static Economic Operation

3.1 Instruction of Static Economic Operation

Economic operation is a determine of each electricity generation facilities, to obtain optimal cost of output and meet the require of load. As a conventional economic dispatch problem, static economic operation is a method to solve short-term or particular time economic dispatch [17]. Static means this operation doesn't consider constraints in time domain, such as generator start-up and shutdown constraints, generator ramp up and ramp down constraints, and charging and discharging of energy storage system [9] [18]. Dispatching in each time period has no effect on other time period, operation result only depend generation, load demand and other condition in this time period.

$$Minimize\ \sum_k (C_{gek} + C_{purk} - C_{salek}) \tag{3.1}$$

Where,

C_{gek} generation energy cost, $C_{gek} = \sum_i (C_{gei} p_{gik})$

C_{purk} cost for purchasing energy from AEP, $C_{purk} = C_{epuri} p_{purk}$

C_{salek} revenue for energy sale to AEP, $C_{salek} = C_{esalek} p_{salek}$

Equation (3.1) is the objective function that minimizes the total operational cost for the microgrid, we can see that the way to optimize the microgrid and reduce operational cost is to reduce cost for energy production and sell more energy at the same time.

3.2 Studied Method

Based on characters of static economic operation and objective of each case, author decides to calculate economic operation using Liner Programming method.

Calculation Procedures is shown in Figure 3.1, because variables don't have effect and conflict in different time period, we optimize dispatch for each time period.

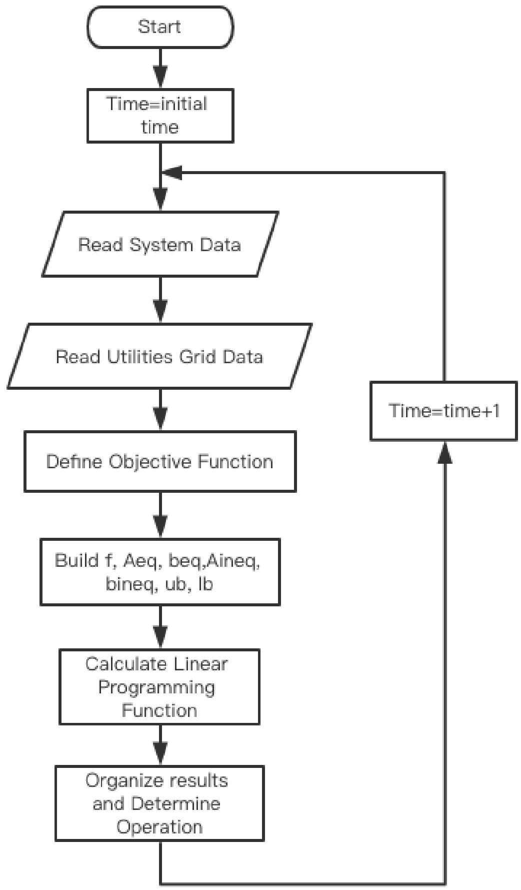


Figure 3.1 Main Calculation Procedures of Static Economic Operation

3.2.1 Objective Formulation

Based on Equation (3.1), the objective formulation of this microgrid is provided below. In this microgrid, there are three diesel generators and one PV generator, it can connect with main grid at any time. In each case, we calculate totally 24 hours' economic dispatch in one-hour period. On the other words, we minimize total cost of four generators, and purchase and sale energy with AEP grid.

$$Minimize \sum_k (C_{g1k} + C_{g2k} + C_{g3k} + C_{g4k} + C_{purk} - C_{salek}) \quad (3.2)$$

3.2.2 Unknown Variable

Set x_k is a list of unknown variable in time k, the way to minimize objective formulation is actually the way to dispatch the power of each variable, including power of each generator, purchase energy from AEP grid, sell energy to AEP grid.

$$x_k = [p_{g1k}, p_{g2k}, p_{g3k}, p_{g4k}, p_{pur\,k}, p_{sale\,k}] \tag{3.3}$$

3.2.3 Cost Coefficients

Set f_k is a list of cost coefficients for variables, it is the determination of liner programming to minimize total cost. Corresponding to each variable, they are operation cost of each generator, AEP energy purchase price and energy sale price.

$$f_k = [E_{price\ g1k};\ E_{price\ g2k}; E_{price\ g3k}; E_{price\ g4k};\ E_{price\ pur\ k}; -E_{price\ sale\ k}] \tag{3.4}$$

3.2.4 Constraints

In static economic operation for this microgrid, there are four constraints, based on Equation (2.1) (2.6) (2.7) (2.8), we obtain constraints equation (3.5) -(3.8) in this microgrid.

Equation (3.5) is power balance constraints, for each hour, power generation of four generators and energy exchange to AEP grid is equal to power demand of load. Equation (3.6) is capacity constraints of each diesel generator, in order to make full use of solar power, PV generator keep running at its current maximum power. Equation (3.7) and (3.8) is constraints for AEP Utilities, includes purchase constraints and sale constraints.

$$p_{g1k} + p_{g2k} + p_{g3k} + p_{g4k} + p_{pur\,k} - p_{sale\,k} = P_{load\,k} \tag{3.5}$$

$$P_{g\min i} \le p_{gik} \le P_{g\max i} \tag{3.6}$$

$$P_{pur\min k} \le p_{pur\,k} \le P_{pur\max k} \tag{3.7}$$

$$P_{sale\,\min k} \le p_{sale\,k} \le P_{sale\,\max k} \tag{3.8}$$

3.3 Test Result

Case I: Area of school, hospital

Areas like schools and hospitals, which located in the city, Utilities grid could provide enough energy with lower price, due to limited floor space, it couldn't provide large-scale solar power generation. In this case, known data is provided in Chapter 2, then doing linear programming with constraints in last section.

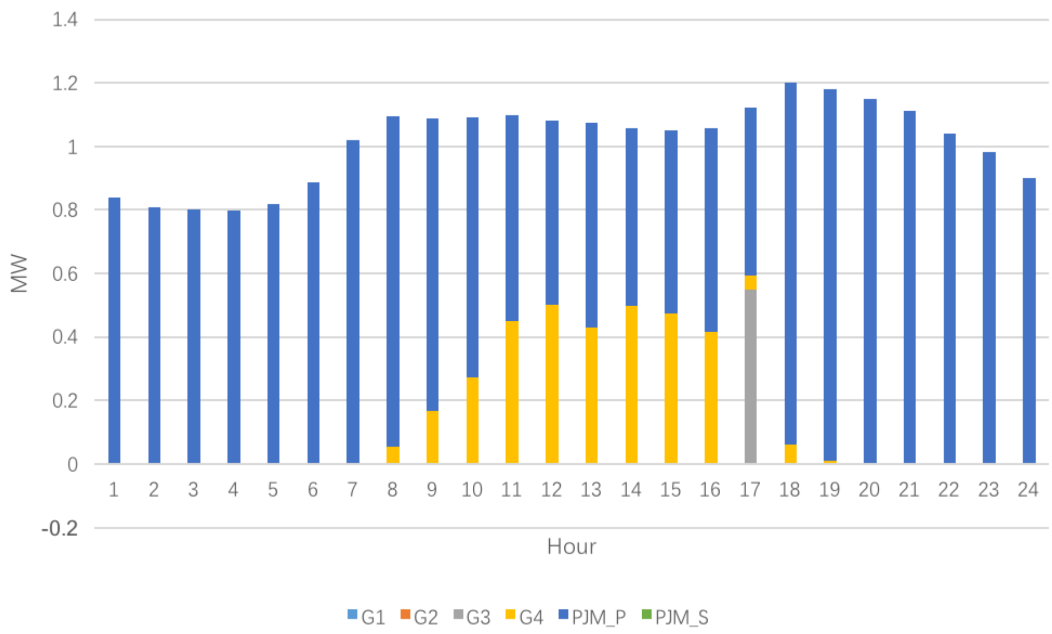


Figure 3.2 Result of economic operation in Case I without ESS

Calculation result of economic operation in Case I shown in Figure 3.2, energy purchased from AEP provided most of energy as shown blue column in figure; Yellow column is PV generation, it is fully utilized as except; Diesel generator 3 operated one hour during 17 o'clock. Total cost of the microgrid during 24 hours is \$606.9443.

Case II: Area of mountainous and island

Mountainous areas and islands always located far from cities, due to its remote location, it is difficult to connect to large-scale power grids. In this situation, it is different to provide enough energy by main grid, thus, in this case, utilities grid provide energy with 1.5 times higher price and 1 MW constraints for both purchase and sale.

Figure 3.3 Result of economic operation in Case II without ESS

Result is shown in Figure 3.3. Diesel generators operated when utilities grid with higher price between 12 o'clock and 21 o'clock. The microgrid buys energy from utilities grid at night when PV generator can't provide energy and utilities grid with lower price. Total cost in this case during 24 hour is $783.7414.

Case III: Area of PV power station

PV power stations have gradually developed in recent years, which provides clean energy to the grid. To meet local load requirements, PV power stations can often deliver large amounts of energy to the grid during the day. In this case, power rated of PV generation enhance to 5MW, also this microgrid has 3 backup diesel generator.

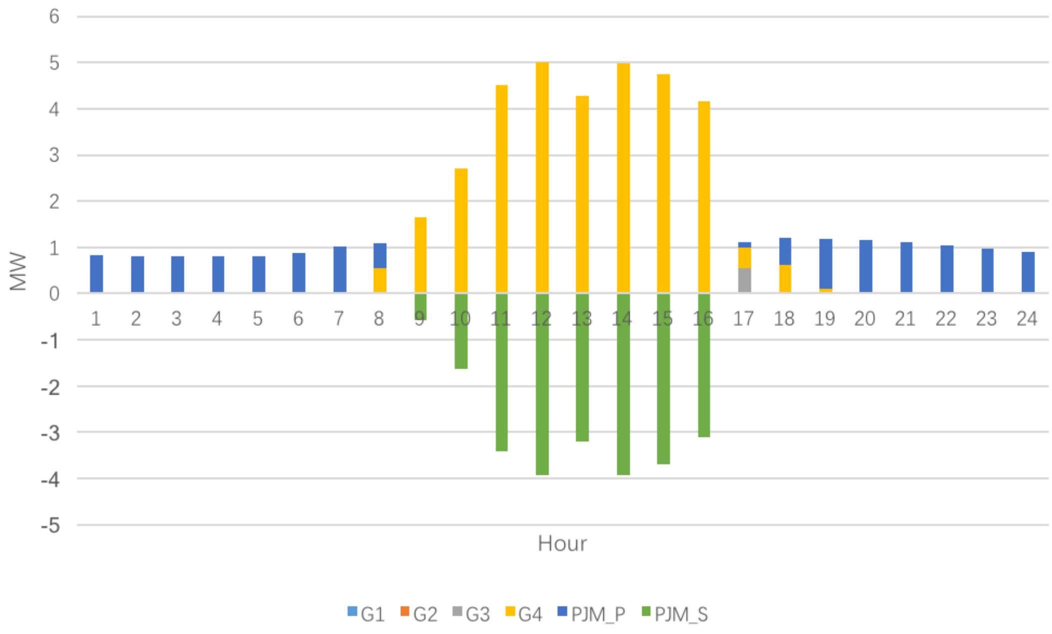


Figure 3.4 Result of economic operation in Case III without ESS

Result of economic operation is shown in Figure 3.4. This microgrid sell large amount of energy to grid during 9 o'clock to 16 o'clock when PV generator with higher generation. G3 is operated during 17 o'clock to make up for the lack of energy. Total cost after economic operation during 24 hours is $-393.5891, it means this microgrid earn $393.5891 thus provide energy to utilities grid per day.

Chapter 4 Dynamic Economic Operation

4.1 Introduction of Dynamic Economic Operation

In this chapter, the author adds an energy storage system(ESS) to the microgrid, ESS charging energy in one time and discharging energy in another time. In this situation, economic operation needs to be considered in time domain, the problem is becoming dynamic economic operation because it's need to consider economic operation in longer period such as 24 hours [17]. Dynamic economic operation is a strategy to decide output of each generating units and output or input of ESS and utilities grid, thereby reducing the total cost in the microgrid [19]. Earlier efforts of solving dynamic economic dispatch problem were using classical methods such as lambda iterative method, Gradient projection algorithm, Linear programming and Dynamic programming [20]. In this thesis, the author uses Integer programming to optimize ESS and Linear programming to optimize the rest.

$$Minimize\ \sum_k (C_{gek} + C_{purk} - C_{salek}) \tag{4.1}$$

Where,

C_{gek} generation energy cost, $C_{gek} = \sum_i (C_{gei} p_{gik})$

C_{purk} cost for purchasing energy from AEP, $C_{purk} = C_{epuri} p_{purk}$

C_{salek} revenue for energy sale to AEP, $C_{salek} = C_{esalek} p_{salek}$

Equation (4.1) is the function that minimize the total operational cost for the microgrid, ESS could be considered as generator or load at one time. But when we consider operation in long period, energy stored in ESS should be fully utilized at the end of period. Thus, the function doesn't include cost of ESS.

4.2 Studied Method

Calculation procedures of dynamic economic operation are shown in Figure 4.1, economic operation time need to be set at the beginning of calculation, then use Integer programming and Linear programming to optimize all variables in whole period.

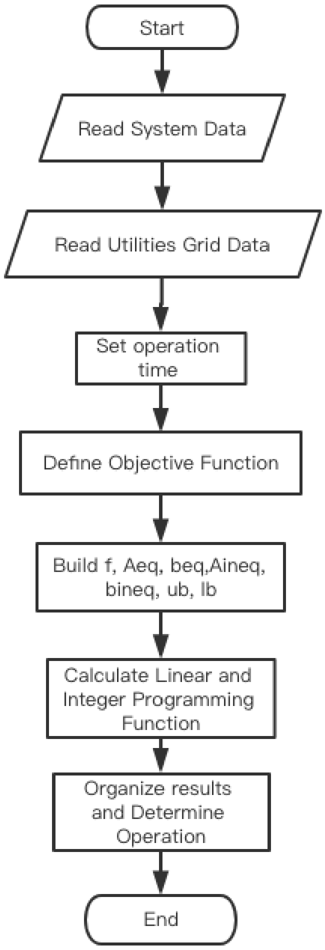


Figure 4.1 Main Calculation Procedures of Dynamic Economic Operation

4.2.1 Objective Formulation

Objective formulation of this microgrid is minimize cost of four generators and energy exchange with utilities grid in 24 hours, that means it is minimize the sum of 6*24 costs.

$$Minimize\ \sum_k (C_{g1k} + C_{g2k} + C_{g3k} + C_{g4k} + C_{purk} - C_{salek}) \tag{4.2}$$

4.2.2 Unknown Variables

Here, the author adds variables s_{sc1k} and d_{sd1k} to express charging action and discharging action of ESS in time k, also, set x includes 8*24 variables.

$$x = [p_{g1k}, p_{g2k}, p_{g3k}, p_{g4k}, p_{pur\ k}, p_{sale\ k}, s_{sc1k}, d_{sd1k}], k = 1,2,3 \ldots \tag{4.3}$$

4.2.3 Cost Coefficients:

Set f represents cost coefficients for each variables, because ESS doesn't have cost, cost coefficients of variables charging action and discharging action is 0. Similarly, set f also includes 8*24 variables.

$$f = [E_{price\ g1k};\ E_{price\ g2k}; E_{price\ g3k}; E_{price\ g4k};\ E_{price\ pur\ k}; -E_{price\ sale\ k};\ 0 * p_{scr1k};\ 0 * p_{sdr1k}], k = 1,2,3 \ldots \tag{4.4}$$

4.2.4 Constraints:

In dynamic economic operation, ESS is added into this microgrid. Comparing to constraints of static economic operation, constraints equation (4.6) (4.7) (4.8) (4.12) (4.13) is added as constraints for ESS, also, charging power and discharging power is added into power balance constraint equation (4.5).

Based on constraints in Chapter 2, in this microgrid, equation (4.6) is storage charging and discharging relationship constraint; Equation (4.7) is storage capacity constraint; Equation (4.8) is storage energy constraint; Equation (4.12) is storage charging and discharging action constraint; Equation (4.13) is storage initial output constraint.

$$p_{g1k} + p_{g2k} + p_{g3k} + p_{g4k} + p_{pur\,k} - p_{sale\,k} - p_{scr1k}s_{sc1k} + p_{sdr1k}d_{sd1k} = P_{load} \tag{4.5}$$

$$s_{sc1k} + d_{sd1k} \leq 1 \tag{4.6}$$

$$(1 - DOD)Q_{s\,max} \leq q_{s1k} \leq Q_{s\,max} \tag{4.7}$$

$$q_{s1k} - q_{s1(k-1)} = s_{sc1k}p_{scr1k}\varepsilon - d_{sc1k}p_{sdr1k}/\varepsilon \tag{4.8}$$

$$P_{g\,\min i} \leq p_{gik} \leq P_{g\,\max i} \tag{4.9}$$

$$P_{pur\,\min k} \leq p_{pur\,k} \leq P_{pur\,\max k} \tag{4.10}$$

$$P_{sale\,\min k} \leq p_{sale\,k} \leq P_{sale\,\max k} \tag{4.11}$$

$$(s_{sc1k}, d_{sd1k}) \in 0, 1 \tag{4.12}$$

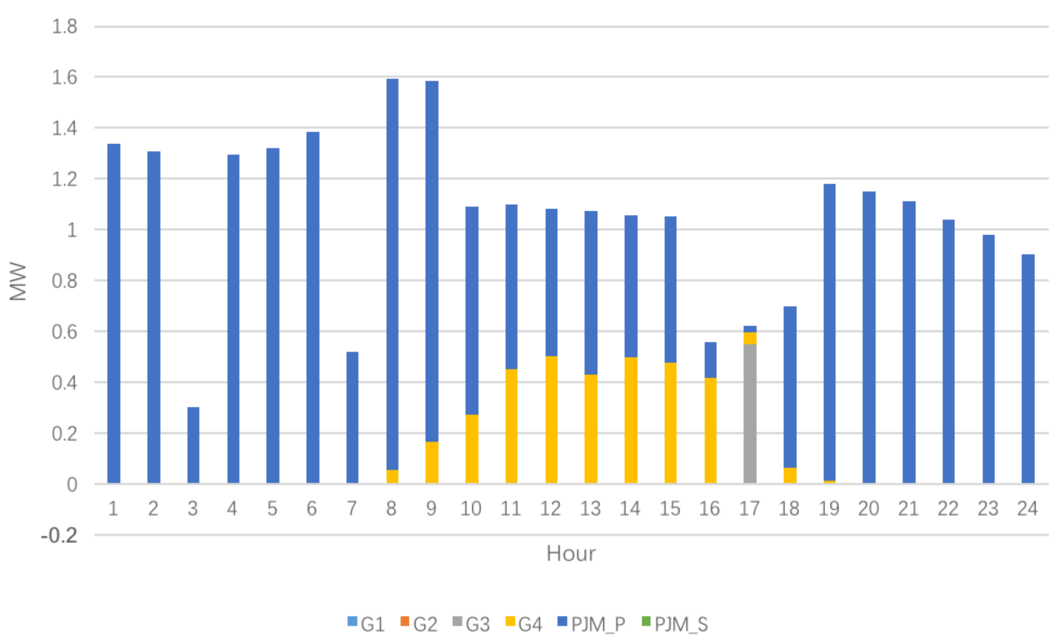
$$q_{si0} = Q_{si0} \tag{4.13}$$

4.3 Test Result

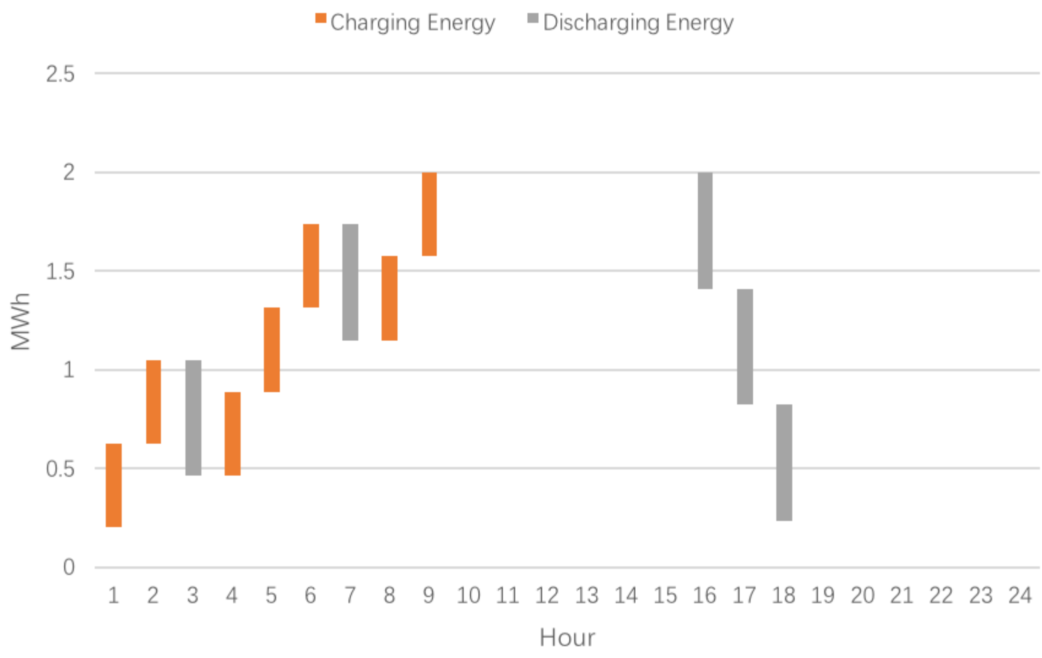
There are 3 types of ESS test in this chapter in each case, as said in chapter 2, they are 2MWh, 3MWh, and 4 MWh ESS with same other parameters. In this section, result of each ESS is presented one by one for each case.

Case I: Area of school, hospital

The microgrid with ESS is tested in this case, this microgrid includes 4 generators and one ESS, it can operate both on-grid mode and off-grid mode.



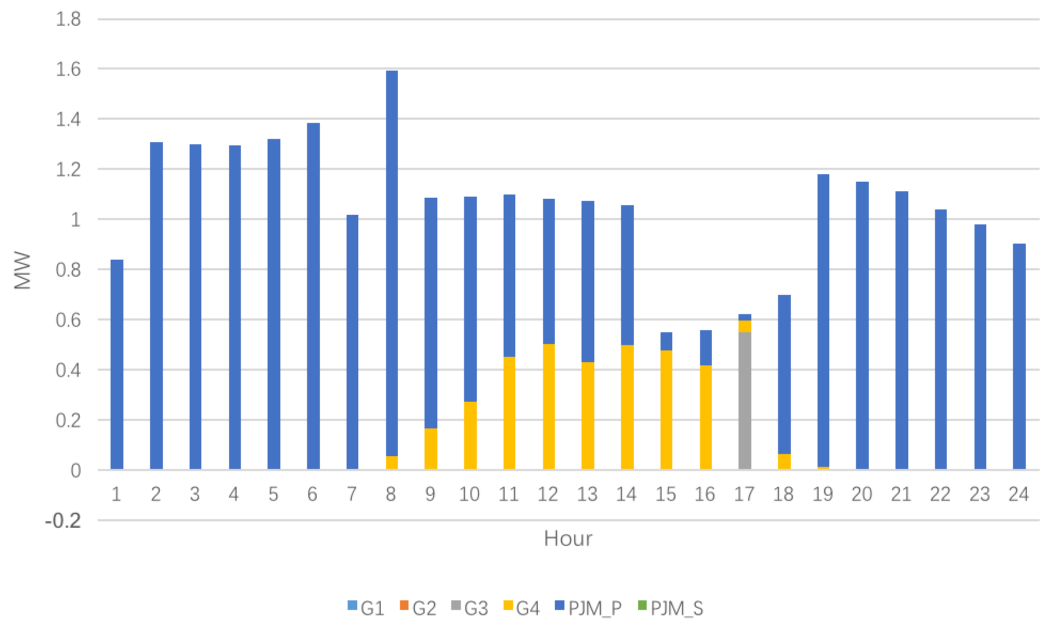
(a)



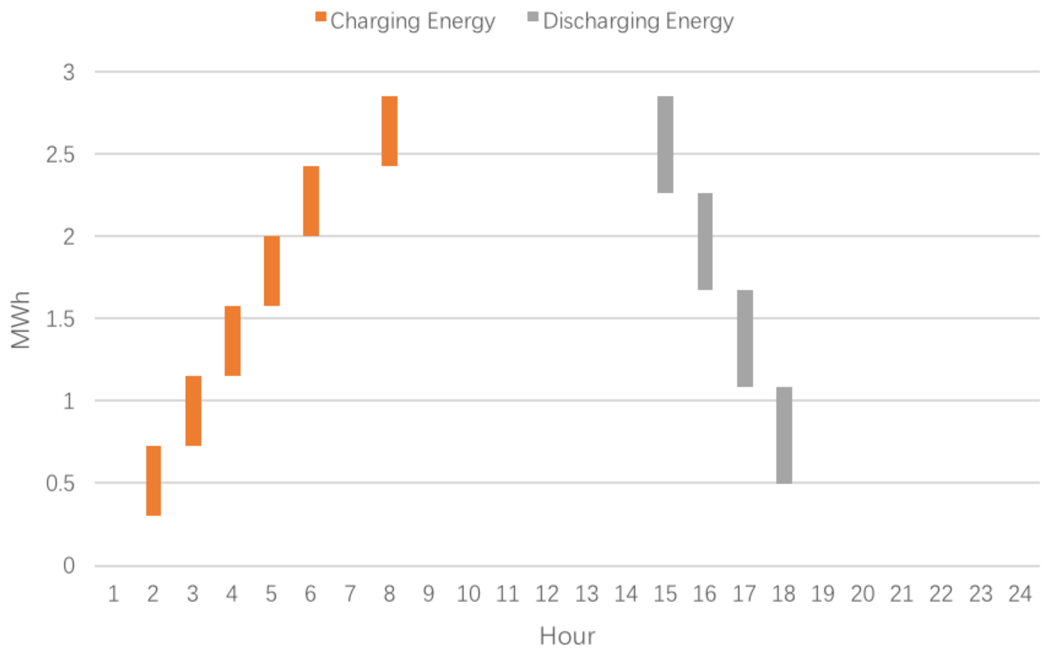
(b)

Figure 4.2 Result of economic operation in Case I with 2MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.2 is economic operation result of the microgrid with 2 MWh ESS. From figure 4.2(a), we can see PV generator is running at maximum power every hour, most of the energy is purchased from utilities grid to meet the demand, diesel generators only operated G3 at 17 o'clock. Figure 4.2(b) waterfall chart for energy in ESS, orange column is charging energy, the lowermost end of each column represents the energy of the ESS at the beginning of this hour, the uppermost end of each column represents the energy of the ESS at the end of the hour, the height of the column indicates the amount of charge for that hour. The gray column is exactly the opposite, the uppermost end of each column represents the energy of the ESS at the beginning of this hour, the lowermost end of each column represents the energy of the battery at the end of the hour, the height of the column indicates the amount of charge for the hour. Thus, ESS is charging at 1,2,4,5,6,8,9 o'clock as orange column in figure and discharging at 3,7,17,17 18 o'clock as gray column in figure. ESS is reach its maximum capacity at 9 o'clock, and its energy is more than the requirement of DOD at all time. The total economic operation cost is $588.5143.



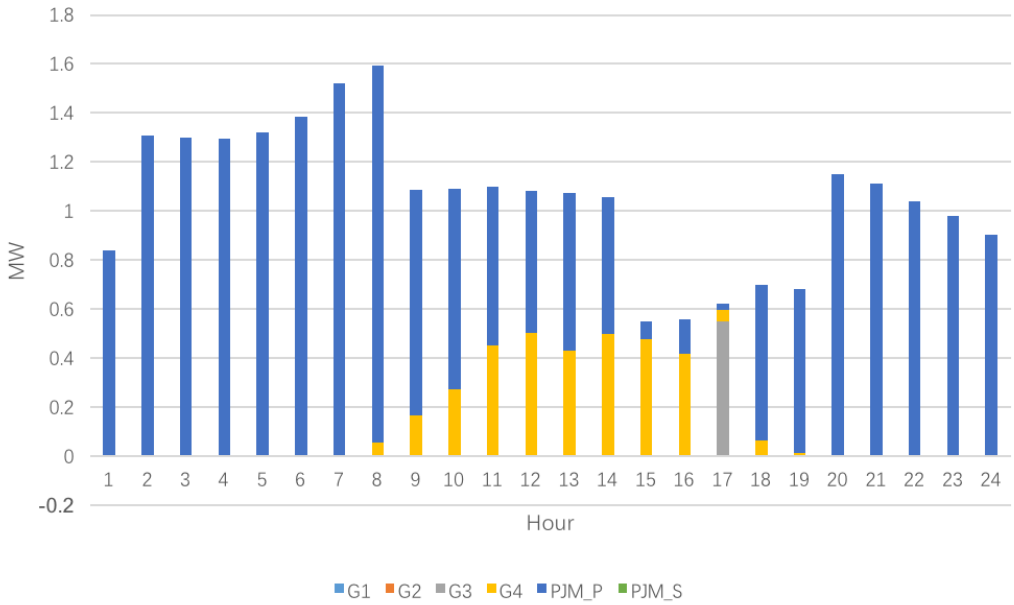
(a)



(b)

Figure 4.3 Result of economic operation in Case I with 3MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.3 is economic operation of the microgrid with 3MWh ESS. From figure 4.3(b), energy in ESS is at its maximum capacity in 8 o'clock, the energy is 2.85MWh, do not reach the maximum capacity. The total economic operation cost in this situation is $577.7493.



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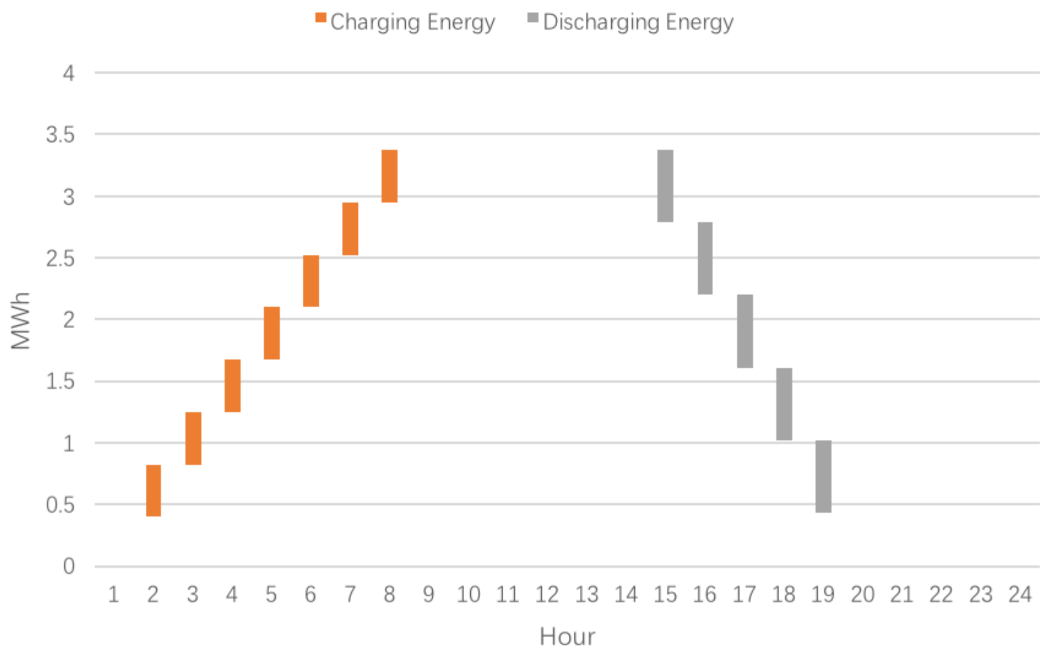


(b)

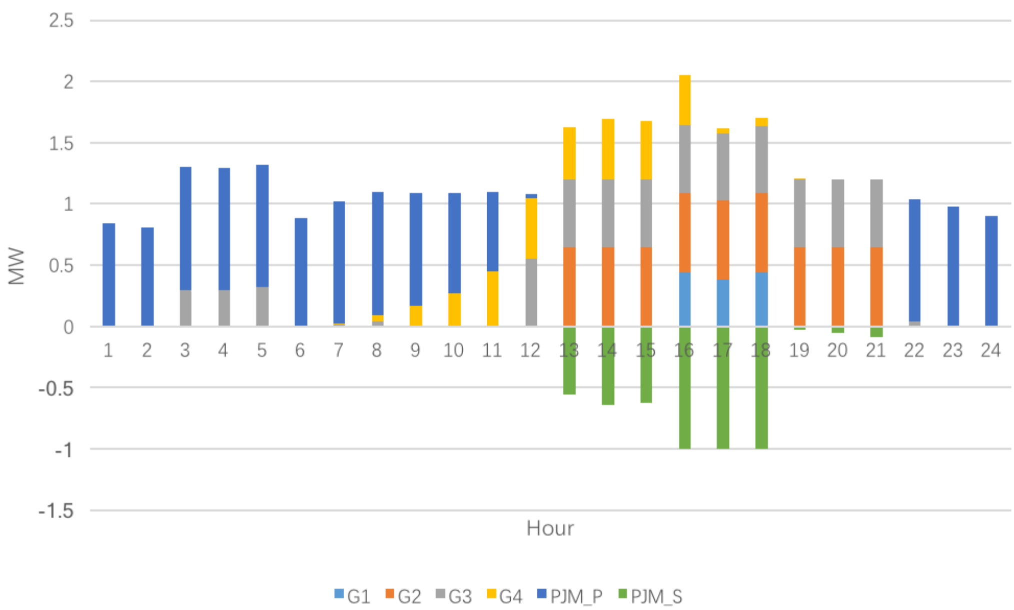
Figure 4.4 Result of economic operation in Case I with 4MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.4 represents the economic operation result of the microgrid with 4MWh ESS. Focus on figure 4.4(b), the maximum charging energy 3.375MWh is 0.625MWh less than maximum capacity of ESS. Total cost of economic operation is $569.4993.

In downtown areas, it is possible to provide enough energy by utilities grid, the cost of diesel generators is relatively higher than utilities grid. Thus, for these areas, ESS will be used to store energy in the utilities grid, diesel generators are more likely to be considered as a backup generation in some situation.

Case II: Area of mountainous and islands

Similarly, case II also provides economic operation for three different capacities of ESS, 2MWh, 3MWh, and 4MWh. This case has higher price for both energy purchase and energy sale, and 1MW rated power limitation for energy exchange with utilities grid.



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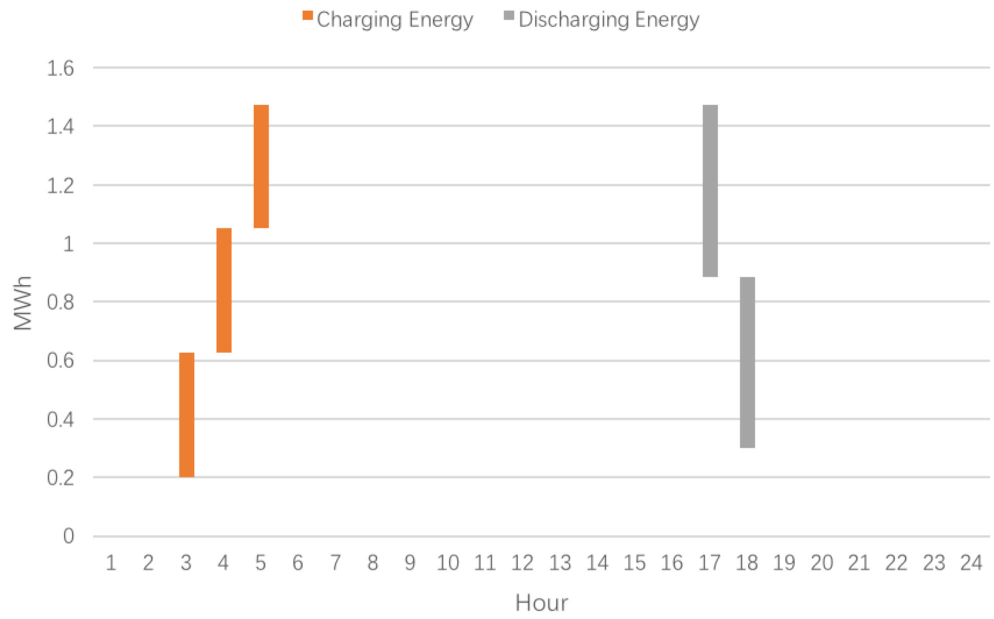
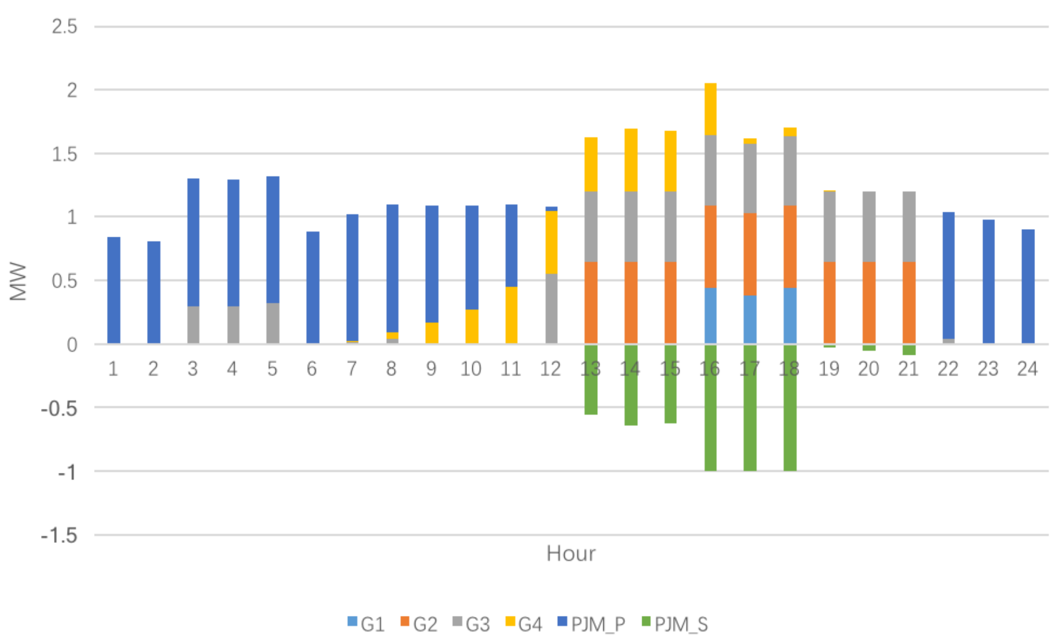


(b)

Figure 4.5 Result of economic operation in Case II with 2MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.5 shows economic operation result of the microgrid with 2MWh ESS. Figure 4.5(a) is economic operation for this microgrid, light blue column, orange column, and gray column is generation of G1, G2, and G3, yellow column is PV generation, blue column is energy purchased from utilities grid, green column is energy sold to utilities grid, energy sale is negative, indicating that energy has left the microgrid. Figure 4.5(b) shows charging and discharging energy in ESS, orange is charging and gray is discharging. Charging period is 3 hours and discharging period is 2 hours. Total cost after economic operation is $775.2579.



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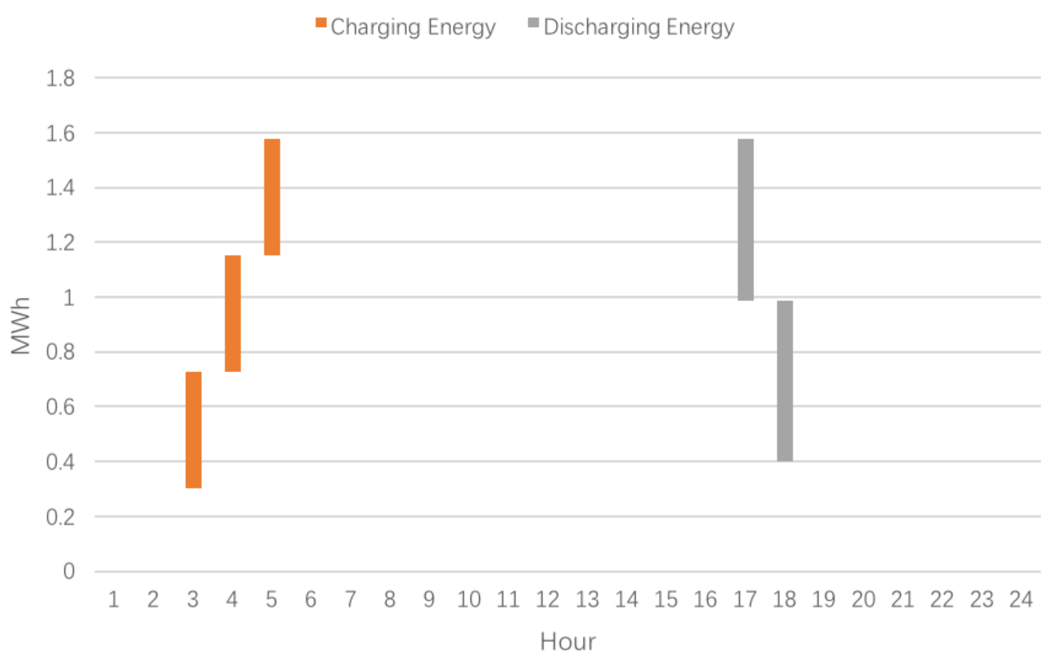
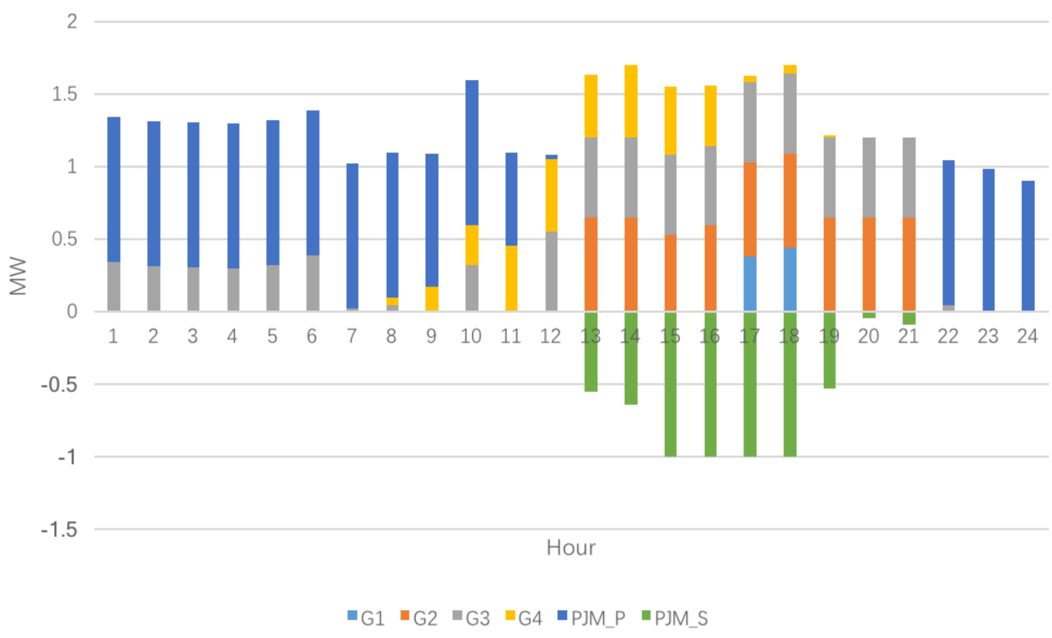


(b)

Figure 4.6 Result of economic operation in Case II with 3MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.6 represents result of economic operation with 3MWh ESS. In this situation, economic operation result is totally same with the result of 2MWh ESS except energy capacity. That is because 2MWh and 3MWh ESS have different initial energy, on the other side, it doesn’t mean this microgrid system is already optimized. Without changing any power input for any time, total cost of this microgrid is still $775.2579.



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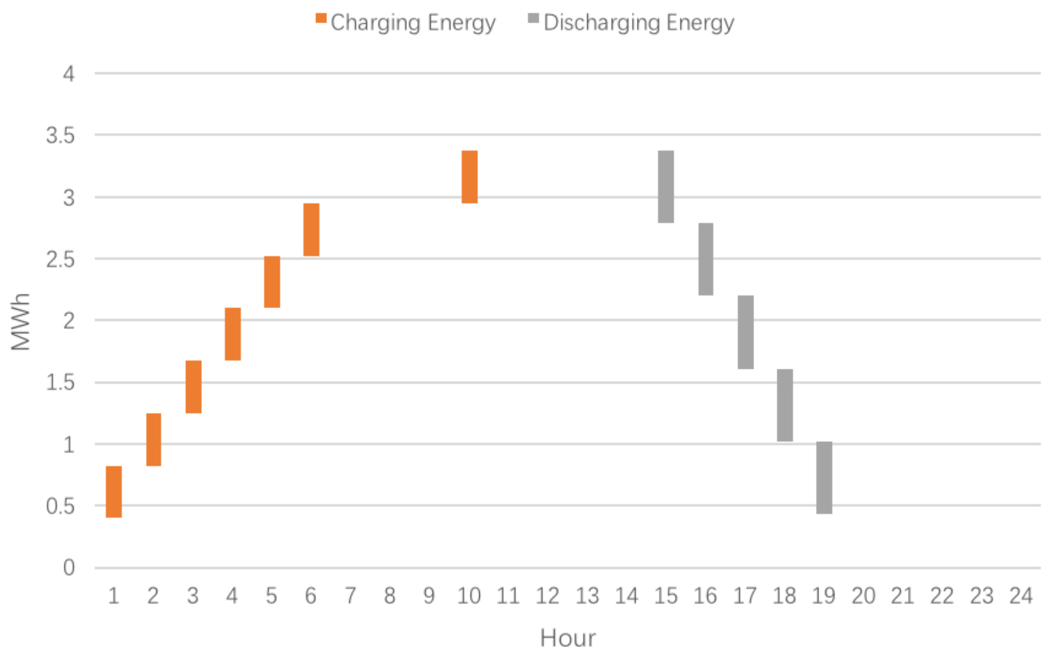


(b)

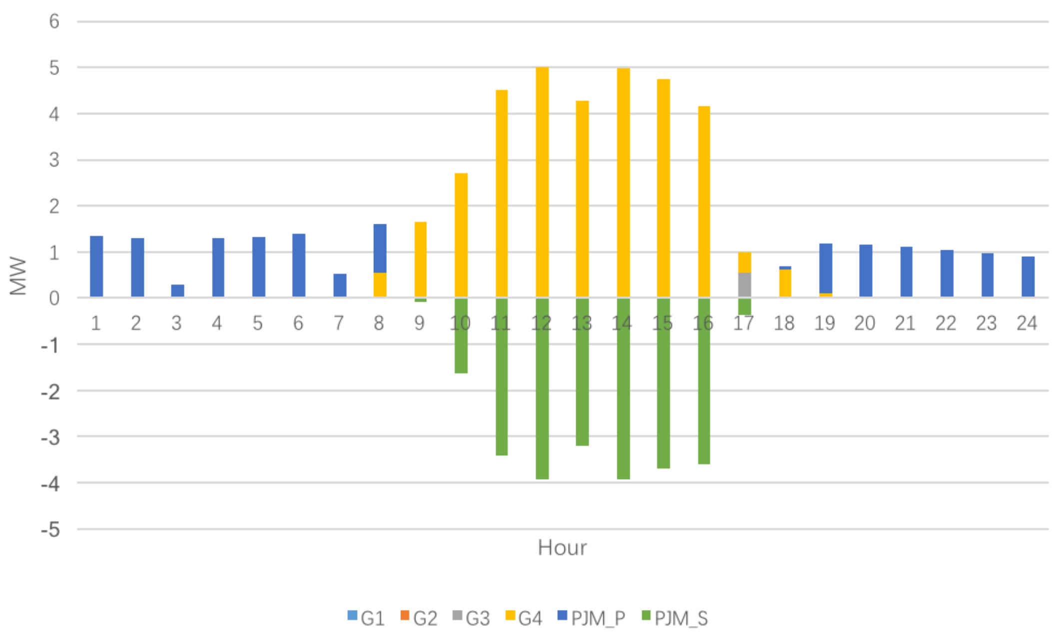
Figure 4.7 Result of economic operation in Case II with 4MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.7 shows economic operation result of the microgrid with 4MWh ESS. In this situation, ESS utilization is higher than before, charging period increase to 7 hours and discharging period increase to 5 hours. Total cost after economic operation decrease to \$772.4085.

Due to higher energy price and 1MW power purchase and sale limitation, the microgrid in case II fully uses all generators to lower total cost. In mountainous and islands areas, it is best to make full use of local energy, such as diesel generator and PV generator in this microgrid, also wind power generation and tidal power generation are good choices for these areas.

Case III: Area of PV power station

PV power station with local load is a great case to study economic operation, similarly with cases above, this microgrid still connects with 2MWh, 3MWh, and 4MWh ESS, respectively.



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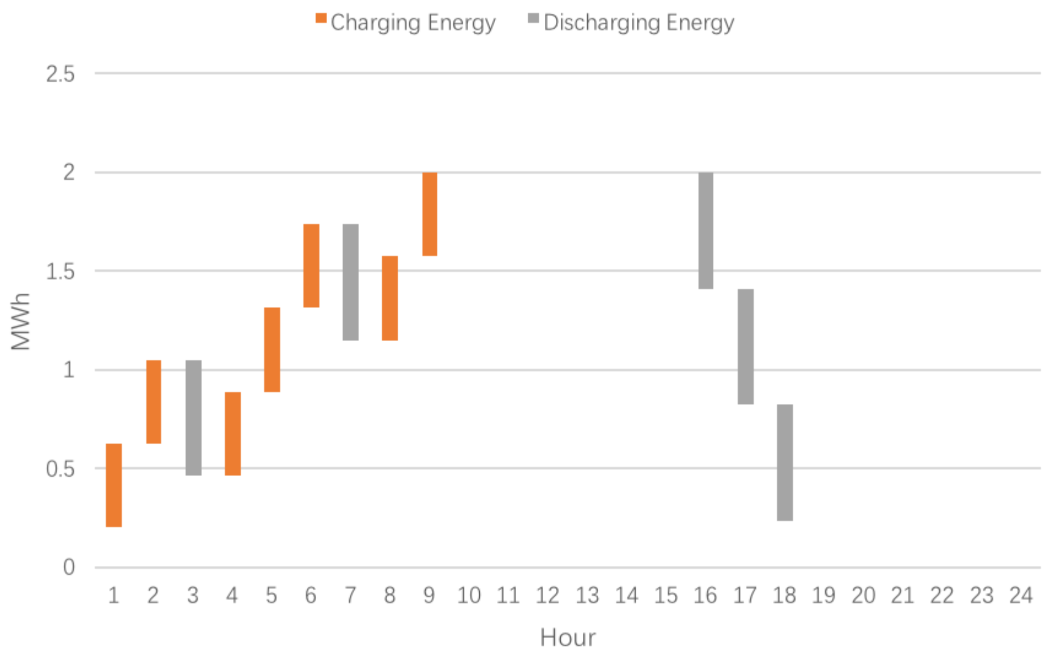
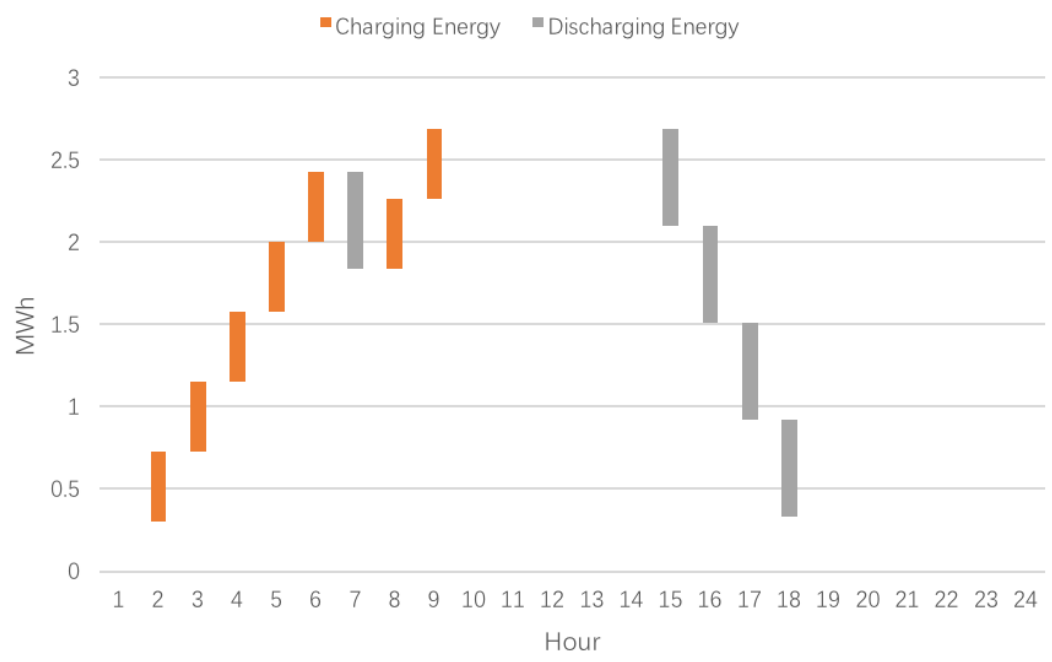


(b)

Figure 4.8 Result of economic operation in Case III with 2MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.8 shows economic operation result of the microgrid in Case III with 2MWh ESS. In figure 4.8(a), blue column is energy purchased from utilities grid, yellow column is PV generation for each hour, green column is energy sell to utilities grid, and gray column is generation of diesel generators G3. In figure 4.8(b), orange column is charging energy for each hour, gray column is discharging energy for each hour. value of the highest point of the orange column and the lowest point of the gray column is energy storage in ESS at end of this hour. Cost after economic operation for this microgrid is \$-411.6494, it means this microgrid earns \$411.6494 in this 24 hours.

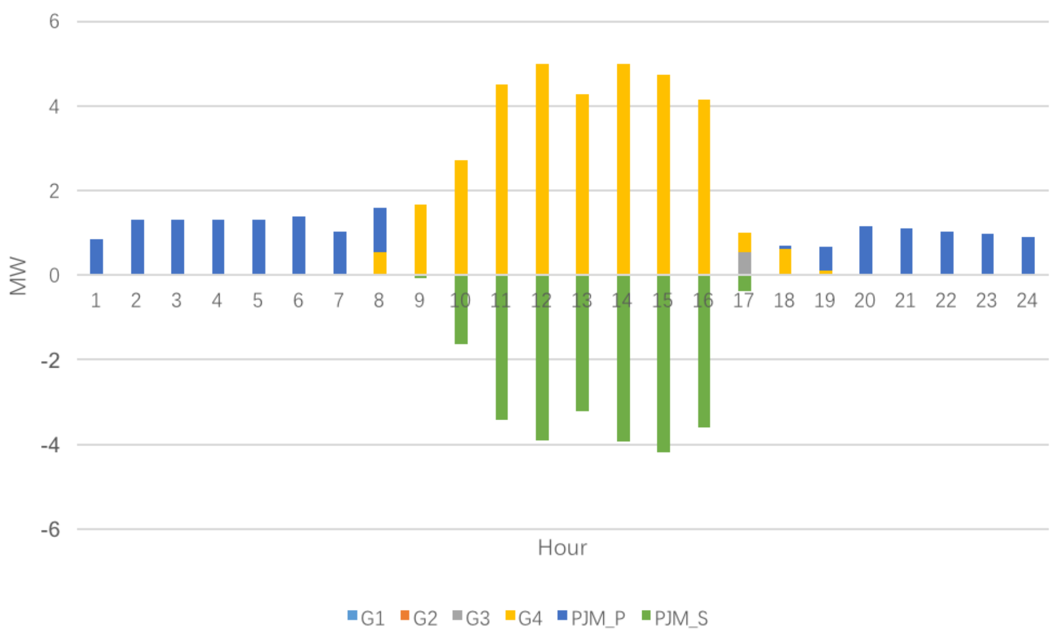
(a)



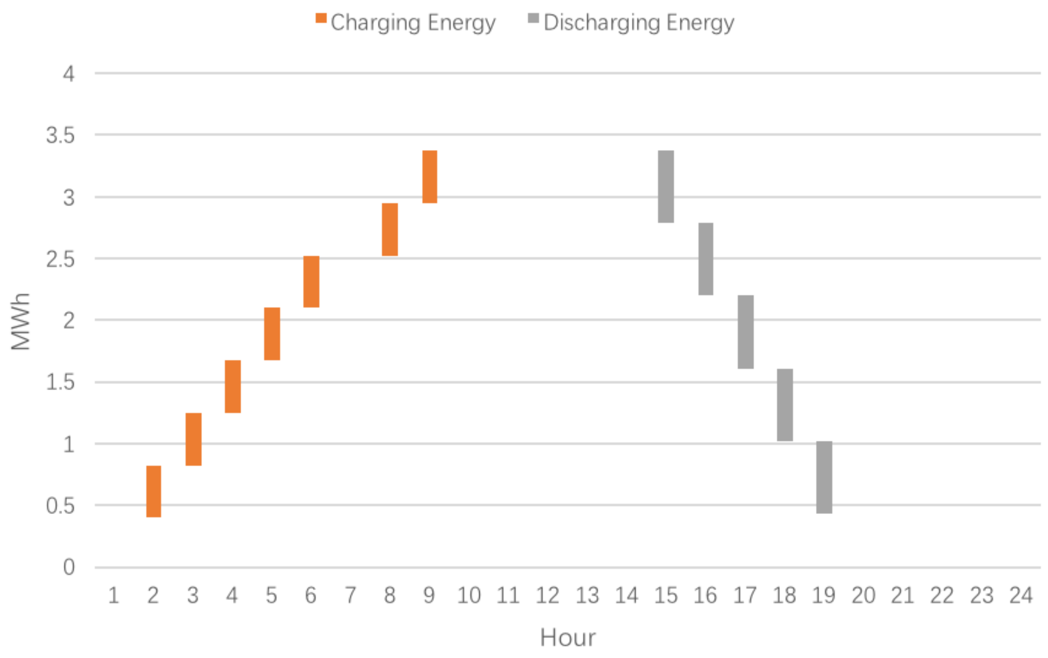
(b)

Figure 4.9 Result of economic operation in Case III with 3MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.9 is the result of economic operation for the microgrid with 3MWh ESS. Diesel generator G3 still operated at 17 o'clock, ESS charging time is 2, 3, 4, 5, 6, 8, and 9 o'clock, discharging time is 7, 15, 16, 17, and 18 o'clock. ESS reach its maximum charging capacity at 9 o'clock is 2.687MWh. Total cost of this microgrid after economic operation is $-421.4344, this microgrid earns $421.4344 in this 24 hours.



(a)



(b)

Figure 4.10 Result of economic operation in Case III with 4MWh ESS. (a) Economic operation. (b) Charging energy and discharging energy.

Figure 4.10 represents economic operation result for the microgrid with 4MWh ESS. G3 still generated at 17 o'clock, most of the energy generated by PV generation sell to utilities grid between 9 o'clock to 17 o'clock, 4MWh ESS storage maximum 3.375MWh energy at 9 o'clock and discharging between 15 o'clock and 19 o'clock. Total cost of this microgrid after economic operation is $-429.6844, thus, this microgrid earns $429.6844 during these 24 hours.

In this case, maximum PV generation is 5MW, greater than load. Without considering the cost of maintenance of PV generator equipment, PV generation's cost is 0 at all time. After providing enough energy to load, most of the energy sells to utilities grid when utilities provide higher price, at the same time, this microgrid also buys energy from utilities grid when price is lower. Because the peak time of PV generation and the peak time of utilities grid prices are very similar, energy could be sold to utilities grid immediately. Energy storage in ESS is more likely to meet the load demand when PV generator couldn't provide enough energy during night time.

Chapter 5 Conclusions

5.1 Summary of Results Obtained

In previous two chapter, the author presents static and dynamic economic operation for 3 cases and their results. The reason that we perform economic operation and add ESS to the microgrid is we want to reduce total operation cost for the microgrid, and thus, the author summarizes all economic operation results in this chapter, expect to see the effect of adding ESS by comparison.

Table 5.1 Total Cost of Economic Operation for Each Case

	No ESS	2MWh ESS	3MWh ESS	4MWh ESS
Case I	606.9443	588.5143	577.7493	569.4993
Case II	783.7414	775.2579	775.2579	772.4085
Case III	-393.5891	-411.6494	-421.4344	-429.6844

A simple observation can be found that adding ESS does reduce costs, and as the ESS capacity increasing, the cost is gradually reducing. Number in Case III is negative, the reason is that the microgrid in Case III is profitable, the smaller the value, the more profitable. But the numerical reduction does not allow us to intuitively feel the reduced effect, then using Equation (5.1) to calculate reduced cost ratio.

$$Reduced\ Cost\ Ratio = \frac{Cost\ with\ ESS - Cost\ without\ ESS}{Cost\ without\ ESS} \times 100\% \tag{5.1}$$

Table 5.2 Reduced Cost Ratio Compare to the Microgrid Without ESS

	2MWh ESS	3MWh ESS	4MWh ESS
Case I	-3.04%	-4.81%	-6.19%
Case II	-1.08%	-1.08%	-1.45%
Case III	4.59%	7.07%	9.17%

Based on Equation (5.1), the author gets reduced cost ratio for each case as shown in Table 5.2, negative values indicate the percentage reduction, positive values indicate the percentage increase. Compare with Case I, cost reduction in Case II is inconspicuous, it is only 1.45% reduction with 4MWh ESS compare with 6.19% reduction in Case I. The reason is that Case II has 1MW energy exchange limitation with utilities grid, and 1.5 times utilities grid energy price compared to Case I.

5.2 Conclusion

Nowadays, electricity prices are gradually increasing, the requirements for green energy are getting higher and higher, distributed power generation that can effectively utilize local resources is also gradually emerging, so the demand for this microgrids has also emerged. The microgrid can effectively reduce the impact of unstable energy sources such as photovoltaic and wind energy on the main power grid, at the same time, the internal energy balance can also be used to reduce the cost of electricity. Therefore, this paper aims to reduce the operating cost of the microgrid by economic operation and adding ESS.

The test cases of this thesis demonstrate that adding ESS to the microgrid can effectively reduce costs, or increase income in PV power station. The effect of reducing costs is directly proportional to the capacity of ESS, but as ESS capacity increases, the cost may remain at a fixed value and may not decrease all the time. Thus, if you want to get the best ESS capacity for the current microgrid, you only need to set the nominal capacity to a large value, the value of the maximum capacity of the ESS in the optimized result is the best ESS capacity for the microgrid. By comparing the three cases, it can be found that the limitation of energy exchange with the grid will reduce the cost reduction effect; Selling electricity at higher electricity prices, buying electricity at lower electricity prices is a good strategy; The longer the battery is continuously charged, the better the cost reduction effect.

5.3 Future Work

This thesis demonstrates the positive significance of adding ESS to the microgrid, and the capacity of the ESS can affect the cost. Future work may consider the following points.

First, other factors can also be analyzed. This thesis compares cost changes by changing nominal ESS capacity. Similarly, other factors could be changed. For example, you can change the power of the generators, compare the impact of power changes on the cost, and find the generator which is most suitable for the current microgrid. Or you can change the purchase and sale price of the utilities grid, and find the impact of electricity prices on the cost of the microgrid.

Second, the system studied in this thesis is a relatively simple microgrid. Bigger systems that require more constraints may be studied.

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