A Study on Power Distribution with Minimized Losses in the Smart Micro-Grids

最小損失に基づくスマートマイクログリッドの電力配分に関する研究

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To My Family

Abstract

With augment of global economics development in recent years, the demand of electricity is also increasing. However, when traditional centralized power plants use more fossil sources to generate electricity so as to increase production, more carbon dioxide and sulphur dioxide will be emitted into the atmosphere. These gases will aggravate global warming. Therefore, energy production and greenhouse gas put people into a dilemma. The smart micro-grids could avoid this dilemma, because it use renewable energy sources that cannot emit greenhouse gas to the atmosphere.

Smart micro-grid is a new kind of power grid. Compared with traditional centralized power plants, its scale is smaller. Therefore, it could be deployed close to the users. Moreover, power loss due to power transmission is less than that caused by traditional centralized power plants. Besides of scale, by using advanced communication and measure technologies, smart micro-grids could receive demand information from the users. Based on the information, the smart micro-grids can automatically adjust their production. However, because power production and the demand of users cannot be predicted, power will be transmitted among the smart micro-grids or between the micro-grids and the macro-station. Therefore, the power distribution control algorithms are proposed to help the micro-grids to meet the demands of users and minimize power loss.

In this thesis, we focus on the issue of designing algorithms to help smart micro-grids to find neighbours and exchange power with them so as to meet demands of users. Because power transmission accompanies power loss, the micro-grids want to minimize power loss. Towards such a target, we develop theoretical frameworks to analytically study smart micro-grids power distribution and power loss minimization in this thesis.

At first, we consider a centralized algorithm in a 3-layer smart micro-grid without power storage device. The micro-grids will supply power to the users that linked to the micro-grids. When power load of the users is more than the supply power of micro-grid, this micro-grid will buy power from its neighbors or the macro-station. To minimize power loss, the micro-grids send their demands to the data center which is in the macro-station. Based on the demands of micro-grids and our algorithm, data center calculates the coalitions of micro-grids. In other words, the result will decide that which coalitions are the micro-grids belong to. In the same coalition, the micro-grids can exchange power with others. Then the result will be sent to the micro-grids. The micro-grids will choose partner and exchange power depending on the result. The mathematical proofs guarantee that algorithm is optimal, stable and convergent. Moreover, simulations demonstrate that our proposed algorithm makes significant performance comparing with existed method.

Then, we extended the first centralized algorithm into the micro-grids with power storage devices case. A greedy coalition formulation algorithm is proposed. When the macro-station receives the demands of micro-grids, the macro-station coordinated mutual power

exchange among the micro-grids and between each micro-grid and the macro-station. To minimize total power losses across the entire power grid, including the cost of charging and discharging power storage devices and power losses due to power transmission, exchange pairs among the micro-grids are created. Additionally, priority is given to pairs with higher power loss reduction per exchanged power unit. The numerical results show that our proposed approach significantly reduces the average power loss compared with the conventional non-cooperative method, although the communications overhead of our proposal does not significantly affect the available communication resource.

Finally, we changed our focus from the centralized algorithm to the decentralized algorithm. Different from the centralized algorithm cases, there is no data center in the model. Therefore, by using the algorithm, the micro-grids are able to exchange power with their neighbors so as to minimize the total power losses of the smart grid. Moreover, communication overhead (bandwidth) is reduced, compared with centralized algorithm. The superior performances of our proposed algorithm are verified by the simulations.

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I would like to give my sincere thanks to Prof. Omachi and Prof. Tanaka. They give me lots of constructive comments for my thesis.

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This thesis is dedicate to my wife, my dear daughter Siyu, my parents, my father-in-law, Na Wei, my aunt Tianhua Wei and uncle Prof. Mingzhen Ma, and all my relatives, whose love and unconditional support provide a constant inspiration in my life. In particular, I would like to thank my wife, Xuesong, for her support during my studies, and love with me. I love you forever, my wife.

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Chapter 1

Introduction

1.1 Background

With the rapid development of economics, the electricity demand of users is sharply increasing. Traditional power plants generate power to meet the demands of users. However, the traditional power plants have shortcomings as follows:

- The traditional power plants use fossil fuels (e.g., oil, coal and so forth) to generate electricity. However, when fossil fuels combination, a mass of gas will be emitted to the atmosphere. It will aggravate global warming. Therefore, energy production and greenhouse gas put people into a dilemma.

- The traditional power plant is centralized power plant. In other words, traditional power plant cannot real-time adjust power generation based on the demands of users. Hence, traditional power plant cannot improve the efficiency of power.

To surmount the shortcomings of the traditional power plant, some new power grids are designed. These new type power grids use renewable energy sources instead of fossil fuels so as to alleviate the greenhouse gas emission. Additionally, the new type power grids could real-time adjust power generation depending on the demands of users. Smart grid is a typical new power grid that uses advanced technologies (e.g., analogue, digital information and communications) to gather information of the users so as to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity. By using smart meter installed in buildings or houses of the users, the smart grid can adjust power generation or electricity consumption of the users so as to enhance energy efficiency and power system reliability. Smart micro-grid is an important component of the smart grid. Due to high power efficiency, the smart micro-grid is of special interests to researchers from both academia and industry.

A smart micro-grid is a small-scale power grid that use renewable energy sources to generate power. It can operate independently or in conjunction with the area's main electrical grid. Due to small scale, it can be deployed close to the users. Therefore, power loss between the users and the smart micro-grid is less than that between the users and the power wholesaler (i.e., macro-station). Furthermore, the smart micro-grid easily adjust power generation. It can generate power depending on the users demand. Additionally, because of small-scale, the smart micro-grids are easier deployed or removed, according to the demand of users.

Motivated by the above advantages of the smart micro-grid, extensive researches from all over the world have been conducted. Although it will alleviate the greenhouse gas emission, these sources cannot guarantee the stability of production. For instance, solar farm cannot work in night. Furthermore, power consumption of users in different time of a whole day are different. The time of a day can be divided into two parts: peak period and off-peak period. During a day, the peak demand consists in the busiest (i.e., the heaviest electricity consumption) time while the remaining time is referred to as the off-peak period. Furthermore, the peak period differs in various seasons. For example, in the summer, the peak period is usually observed in the noon/afternoon due to the heavy usage of air conditioners. On the other hand, in the spring and autumn, the afternoon represents off-peak time. Therefore, when the demand of users is more than supply power of micro-grid, this micro-grid needs to buy power from its neighbours so as to meet the demand. Hence, power distribution algorithm will be proposed so as to help micro-grids to find neighbours. Furthermore, power loss accompanies with power distribution. Hence, power distributed algorithms will be proposed so as to minimize power loss.

1.2 Challenging Issues with Smart Micro-Grids

As introduced in last section, we find that there are a great number of significant advantages in smart micro-grids. However, smart micro-grids use renewable energy sources (i.e., solar power, wind power, plug-in hybrid electricity vehicle (PHEV) and so forth) to generate power. Although these sources could alleviate emission of carbon dioxide, the electricity productions of renewable energy sources is not stable. Moreover, the demands of users can be predicted. Therefore, proposing algorithm to help the micro-grids to meet the demands of users is an open problem in smart micro-grid. It should be noted that smart micro-grids have challenging issues, which have not been solved. These issues should be addressed to guarantee meeting demand of users.

Firstly, if we want to propose an algorithm for the smart micro-grids, optimality is the most important characteristic that we need to consider. In other words, for each micro-grid, the algorithm will help it to find the best partner to exchange power so as to minimize power loss.

Secondly, stability and convergence are also considered in our algorithms. Stability can guarantee that all the micro-grids will accept the optimal result. Convergence can guarantee that the optimal result does not depend on the initial values.

Thirdly, if the micro-grids have power storage devices such as battery, power can be charged or discharged. However, power charge or discharge operations will cause power loss. Therefore, algorithm can help the micro-grids to control the power storage devices.

Last but not least, when the demands of users are changed, the micro-grids need to find new neighbours so as to minimize power loss. Therefore, for the algorithms, they can change the micro-grids partners autonomously, when the demands have been changed. Additionally, is it safe that communicating with neighbours or data center? How to reduce the communication overhead? Which is the optimal number of micro-grid in a given zone?

1.3 Research Objectives

Power distribution is one important requirement for the smart micro-grids. Because the users are linked with responding micro-grid, the micro-grids need to supply power to the users. When the demands of users are more than the generation power of the micro-grid, this micro-grid wants to exchange power with their neighbours or the macro-station so as to meet the demand. In addition, when power is transmitted from the macro-station to micro-grid, the accompanied power loss is more than that between two micro-grids. For each micro-grid, the most important problem to be faced is how to choose appropriate neighbours exchange power so as to meet the demand of users and maximize utility (minimize power loss).

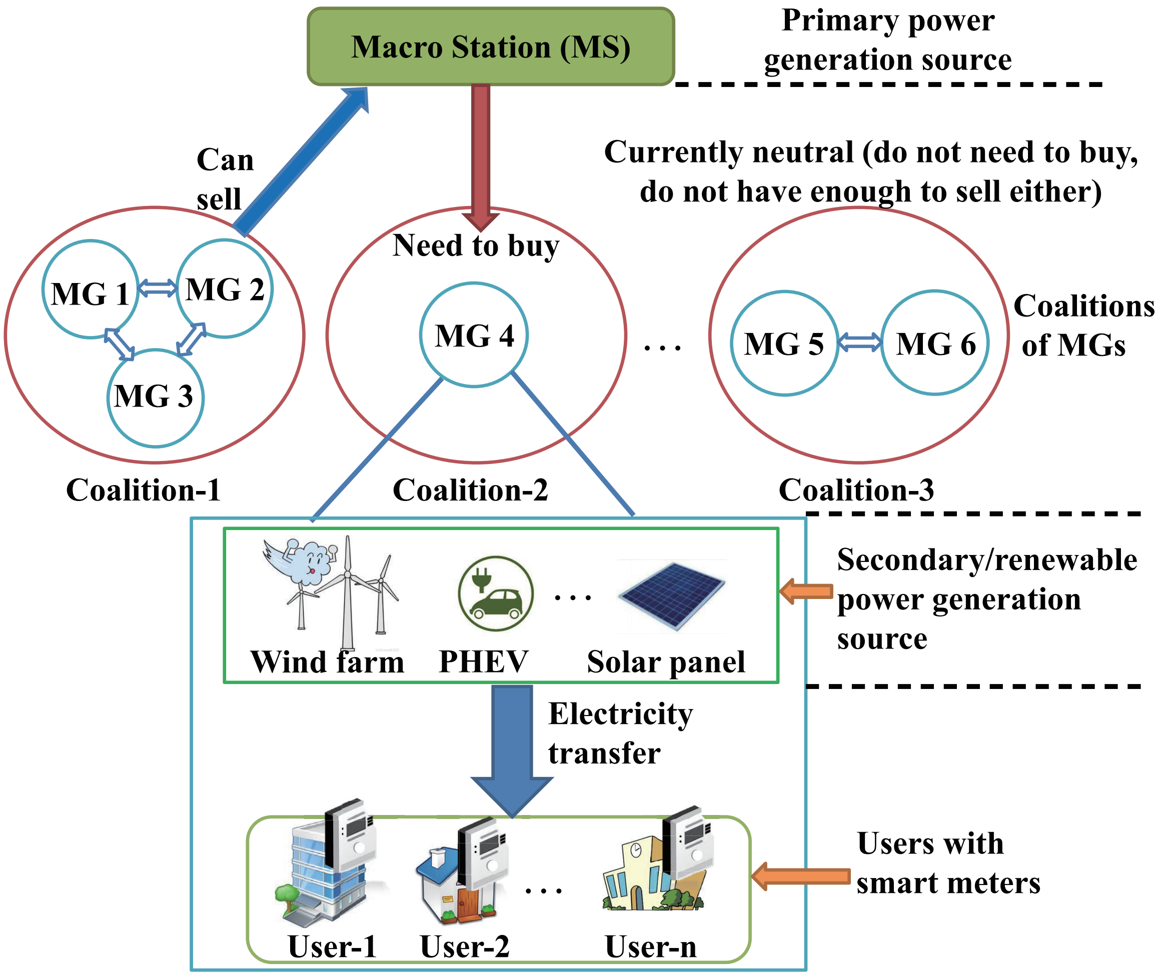

Figure 1.1: The construction of 3-layer smart micro-grids without buffer

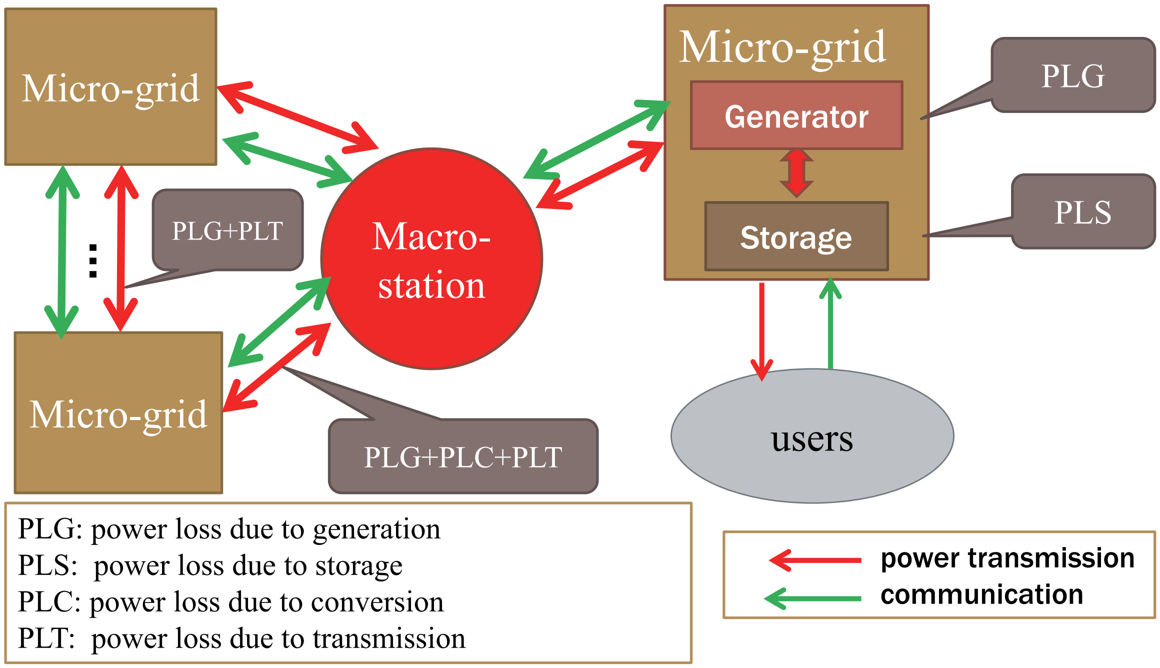

Figure 1.2: Micro-grids based power delivery system and different types of power losses that affect it.

In this thesis, we mainly focus on smart micro-grid. We will propose power distribution algorithms for different smart micro-grid models so as to minimize power loss. To guarantee the optimality, stability, and convergence, we will analyse our methodologies and make mathematical proofs. We will also evaluate and compare the performance of our proposed algorithms with other various existing methodologies.

First of all, we will propose power distribution centralized algorithm for a 3-layer smart micro-grid model (Fig. 1.1 IEEE copyright © 2014IEEE). By using this centralized algorithm, the micro-grids can choose their neighbours to form coalition and exchange power with other micro-grid within the same coalition towards minimizing power loss. Furthermore, the micro-grid could exchange their coalitions when the demands of users changed.

Then, we will extend previous model. In the new model, we consider smart micro-grid with power storage devices (Fig. 1.2 IEEE copyright © 2014IEEE). By using these devices, power surplus can be charged in off-peak period and discharged in peak time so as to alleviate power loss. However, power charge, discharge, and generation will cause power loss. Therefore, we need to consider more kinds of power loss than that in the previous model. The new centralized greed algorithm can help the micro-grids to decide whether the micro-grids charge or discharge power. Additionally, the algorithm will help the micro-grids to form coalitions and exchange power so as to meet the demands of users.

The previous two algorithms are centralized algorithms. In these models, data centres that are in the macro-station will decide the coalitions of the micro-grids. However, when smart micro-grids have not data center, those two algorithms do not work. Therefore, we will propose distributed algorithm for the smart micro-grids. By using this algorithm, each micro-grid just exchange information with its one-hop neighbours and decide how to exchange power with the neighbours. Compared with centralized algorithm, although the result of distributed algorithm is little worse than that of centralized algorithm, the distributed algorithm will occupy less bandwidth. Therefore compared with centralized algorithm, the distributed algorithm can guarantee more micro-grids communicate with their neighbours in the same time.

1.4 Thesis Outline

The remainder of this thesis is outlined as follows:

Chapter 2 Overview of Micro-Grid and Power Losses Formulation. In this chapter, the smart micro-grid is introduced. Some important and representative literatures in recent years are presented. Then, we point out that the demands of users cannot be predicted and renewable sources cannot guarantee the stability of power generation are the reasons that power is transmitted among the micro-grids. However, power loss accompanies with the power distribution. In this thesis, power distribution control algorithms will be proposed to help the micro-grids to find appropriate neighbors so as to improve the utilization of resources. In addition, we propose power loss formulations so as to help we to propose the algorithms in the next chapters.

Chapter 3 Power Loss Minimization Method for Smart Micro-Grids: A Centralized Approach (without buffer). In this chapter (Copyright ©2014IEEE. Reprinted, with permission, from C. Wei, Zubair Md. Fadlullah, Nei Kato and Akira Takeuchi, GT-CFS: A Game Theoretic Coalition Formulation Strategy for Reducing Power Loss in Micro Grids, IEEE transactions on parallel and distributed systems, September 2014 [1]), we introduce a centralized algorithm to reduce the power loss in smart micro-grid. Firstly, we introduce the smart micro-grids model that has 3 layers and concept of cooperative game theory. Secondly, we make a review of smart micro-grid and point out the problems that we will consider in this thesis. Thirdly, power loss functions are given. Based on these functions, we propose objective function. Fourthly, by analysing the properties of our model, we develop cooperative game algorithm so as to distribute power among smart micro-grids. This centralized algorithm is proposed to minimize the power loss during power distribution in our model. To prove the stability,convergence and optimal, the mathematical proofs are given. Additionally, we propose the optimal number of micro-grid in a given zone. At the end of this chapter, we make simulations whose significant better than existed method.

Chapter 4 Extended Power Loss Minimization Method with Storage (Copyright ©2014IEEE. Reprinted, with permission, from C. Wei, Zubair Md. Fadlullah, Nei

Kato and Ivan Stojmenovic, On Optimally Reducing Power Loss in Micro-grids With Power Storage Devices, IEEE journal on selected areas in communications, July 2014 [2]). We focus on the power distribution problem in the smart micro-grids with power storage devices. At first, we introduce the advantage of power storage devices. We then introduce the smart micro-grids with power storage model, four kinds of power losses and functions. Furthermore, we analyse the power distribution problem in our model and find that power transmission, generation and storage cause power loss. After that we propose a greedy algorithm which can help data center to make decision so as to minimize the total power loss in the model. This centralized algorithm is regarded as the extend research of the algorithm in the previous chapter. In this chapter, we will consider more kinds of power loss and power storage device. When the micro-grids receive the demands of users linked to the responding micro-grids, the algorithm can help the micro-grids to charge or discharge power so as to meet the demands. If supply power of the micro-grid is less than the demands, micro-grids will send information to the data center that is in the macro-station. By using the algorithm, the data center can help the micro-grids to exchange power so as to minimize the power loss. Though mathematical proof we can find that our algorithm is optimal. To verify the optimality of the algorithm, we make numerical simulations in this chapter.

Chapter 5 Power Loss Minimization Method: A Decentralized Approach (Copyright ©2014IEEE. Reprinted, with permission, from C. Wei, Zubair Md. Fadlullah, Nei Kato and Ivan Stojmenovic, A Novel Distributed Algorithm for Power Loss Minimizing in Smart Grid, IEEE international conference on smart grid communications, November 2014 [3]). In this chapter we focus on a kind of smart micro-grids, which has not data center. It means that each micro-grid only exchange information with one-hop neighbours. It is a distributed algorithm which can improve the communication security of the total power grid. We extend centralized algorithm to distributed algorithm. Additionally, by using this algorithm, communication overhead (bandwidth) can be reduced. From the numerical results we demonstrate that the distributed algorithm can lead to near-optimal result for alleviating the average power loss and the communication overhead significantly in contrast with the centralized approach.

In the last chapter, we summarize the overall thesis and discuss the future works.

1.5 Contributions

In this thesis, we studied power distribution with power loss minimization in the smart micro-grids. The main contribution of this thesis are summarized as follows:

1. We first propose a cooperative game theoretical algorithm to help micro-grid exchange power with their neighbours so as to minimize power loss. By using this algorithm, power can be transmitted among the micro-grids or the macro-station. Then, we proved that this algorithm was stable, convergent and optimal. After that, we discussed the optimal number of micro-grids in a zone. Finally, the simulation results indicate the superior performance of the algorithm.

2. We further develop a centralized greedy algorithm based on the first algorithm. We focus on four kinds of power loss and power storage device of the smart micro-grids. Hence, the algorithm will control the power storage devices and power transmission so as to minimize the total power losses. The algorithm has wider application scope in contrast with the first algorithm. Moreover, we make comparisons between existed algorithm and

our proposed algorithm to show the algorithm makes significant progresses.

3. After two centralized algorithms, we propose a distributed algorithm. By using this algorithm, the micro-grids only exchange information with their one-hop neighbours instead of the macro-station. We prove the distributed algorithm is near-optimal and make simulations. From the simulations, we find that although our average power loss of the distributed algorithm is little more than that of the centralized algorithm, the distributed algorithm cost less bandwidth than that cost by the centralized algorithm.

Chapter 2

Overview of Micro-Grids and Power Losses Formulation

2.1 Introduction to Smart Micro-Grids

The smart micro-grid ([4]) that takes on heavy responsibility to provide electricity to the users, is an important component of smart grid. It is regarded as the next-generation power grid([5]). For now anyway, the micro-grid has not a strict definition yet. However, because own situations and research objectives of countries are different, the definitions of micro-grid from the researchers ([6], [7], [8], [9], [10], [11], [12], [13]) are not same. For instance, Consortium for Electric Reliability Technology Solutions (CERTS) micro-grid concept assumed an aggregation of loads and microsources operating as a single system providing both power and heat [6]. Although the micro-grid has different definition, . A smart micro-grid is a small-scale power grid that use renewable energy sources to generate power. It can operate independently or in conjunction with the area's main electrical grid.

Generally speaking, the micro-grid is consisted of microsource (i.e., wind farm, solar panel and so forth), controller, power storage device and so forth (see Fig. 2.1). Compared with traditional power grid, the smart micro-grid has many advantages as follows.

- Efficiency: the micro-grid consists of local load and microsource. As a small-scale power grid, the main difference between micro-grid and the traditional power grid is flexible scheduling. In other words, micro-grid can real-time adjust power generation according to the demands of users so as to minimize power loss.

- Controllability: Based on demands, the micro-grid can choose different operating mode. Excellent control strategy can improve the reliability and guarantee the security of micro-grid.

- Interactivity: As an independent power generation equipment, micro-grid can provide powerful support for the main power grid when necessary. Additionally, micro-grid can obtain power from the main power grid.

- Independence: micro-grid can run independently under certain conditions and guarantee the electricity demand of local users.

- Reliability: Because micro-grids use renewable source that will not exhausted to generate power, the micro-grids do not consider the quantity of power source. Therefore, renewable source can guarantee the reliability of micro-grid.

- Economic savings: when smart meters are installed in user side, users can bi-direction communicate with the micro-grid. Hence, the micro-grids can manage the supply power with the demand response from the users.

- Sustainability: carbon footprint will be reduced, because the micro-grids use cleaner fuel resources.

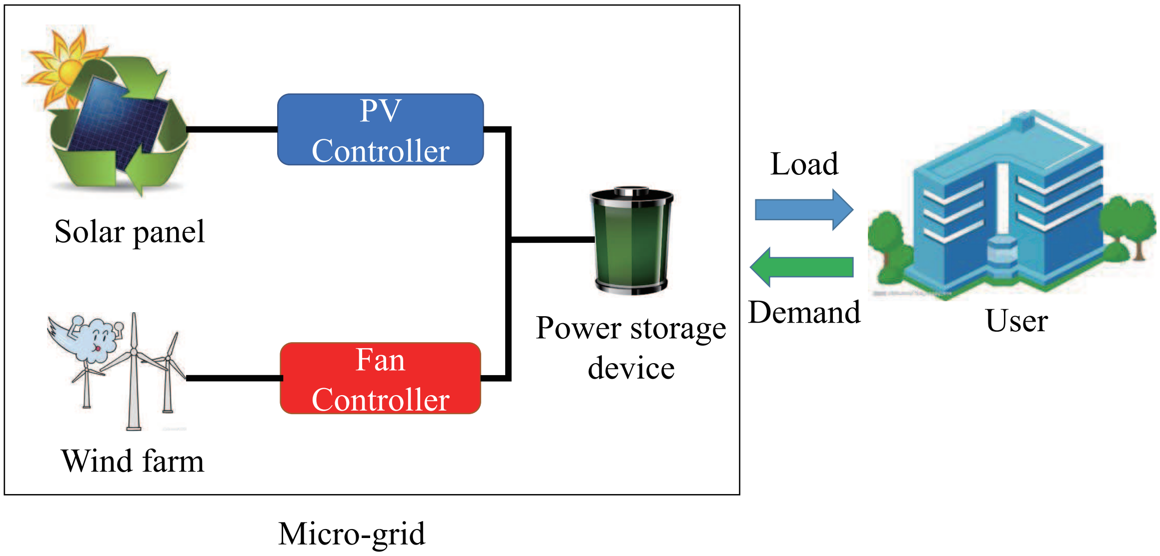

Figure 2.1: The schematic diagram of micro-grid

2.2 Related Work

With the development of the smart micro-grid technology, researchers increasingly pay attention to the smart micro-grid. The research of micro-grid mainly concentrate in two aspects. The first one is energy management. The other one is communication of micro-grid.

Energy management in the smart micro-grid received a lot of attention recently. Based on the energy management, the micro-grid can reduce power loss, e.g., in sensor network controlled lighting systems [14]. Arefifar *et al.* presented systematic and optimized approaches, with optimized self-adequacy, for the power distribution system containing a set of micro-grids [15]. Niyato *et al.* [16] proposed an algorithm, which optimizes the transmission strategy to minimize the total cost. The problem of minimizing power losses in distribution networks has been traditionally investigated by using a single, deterministic demand level. Meliopoulos *et al.* [17] whereby a real-time and coordinated control scheme was proposed with the participation of distributed generation resources that can be coordinated with the existing infrastructure. The objective of the work was to operate the distribution system with minimized power losses. S. Deilami *et al.* [18] proposed a novel load management solution for coordinating the charging of multiple plug-in electric vehicles (PHEVs) in a smart grid system. A. Vargas *et al.* presented an efficient optimal reconfiguration algorithm for power loss minimization [19]. A. Costabeber [20] *et al.* showed that the power loss reduction is possible without central controllers, by taking advantage of the local measurement, communication and control capability in the micro-grids. The work in [21] allowed the micro-grids to form coalitions and exchange power with other micro-grids and/or the macro-station. However, in that model, the considered micro-grids were not assumed to use power storage devices. Also, energy management issues were addressed in [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34] and [35].

Besides energy management algorithms, power storage might lead to improved power efficiency in micro-grids. When supply power of micro-grid is more than the demand of users, power storage device will charge power. The charged power will be discharged when the demand of users is more than the supply power. Therefore, researchers proposed the algorithms to help micro-grids to control the power storage device ([36], [18], [37], [38]). Recently, micro-grid developers and operators reported that lithium-ion batteries and flow batteries are quite capable of providing exceptional renewable energy integration services in micro-grids based power systems [39]. Ahn *et al.* [40] focused on an optimal control of the micro-grids power storage devices. Whereby stored energy was controlled to balance power generation of renewable sources to optimize the overall power consumption at the micro-grid. In [41], the authors presented novel photovoltaic power generation and load power consumption prediction algorithms for power storage device system in home. C. A. Hill *et al.* [42] presented an overview of the challenges of integrating solar power to the electricity distribution system, a technical overview of battery energy storage systems, and illustrated a variety of modes of operation for battery energy storage systems in grid-tied solar applications.

Many micro-grid papers are about communication. In smart grid networks, the micro-grids communicate with their one-hop neighbors or the macro-station. Therefore, the micro-grids need to consider some things. For instance, how to improve the security of communication, how to reduce the communication overhead (bandwidth), and so forth. In [43], M. Erol-Kantarci *et al.* proposed the Cost-Aware Smart Micro-grid Network design scheme and communication technology that enables economic power transactions within the smart micro-grid network. In [44], G. N. Ericsson introduced the security domains and access points of micro-grid. J. Brodsy *et al.* pointed out an attack on IEEE 802.15 wireless sensor networks in smart micro-grid [45]. A. Timbus *et al.* discussed the modeling of distributed generators in the utility control and communication technology infrastructures of power system operators [46]. S. Minnihan [39] discussed the security situation on micro-grids. Moreover, related communication work were introduced in [47], [48], [49], [50], [51], [52], [53] and [54].

Although there are lots of micro-grids researches, these existing power loss minimization and power loss technologies do not encompass the total power loss caused by the macro-station, numerous micro-grids and power storage devices. Usually they only discuss how to reduce the power loss within an individual micro-grid, or how to control power within individual power storage devices, or how to exchange power with the nearest neighbor so as to reduce power loss. On the other hand, in this thesis, we focus firstly on an envisioning total power loss minimization approach across the entire smart grid (without power storage device) that is managed centrally by the macro-station. After that, we extend the previous centralized algorithm to micro-grid with power storage device case. In this case, we will consider more kinds of power loss than that in without buffer case. Then, we consider the case that macro-station has not data center. Because the micro-grids cannot obtain optimal result from the macro-station, they only exchange information with their one-hop neighbours. Hence, we extend centralized algorithms to decentralized algorithm.

Existing power loss minimization and power storage techniques do not encompass all the power losses affecting the power system comprising the macro-station, numerous micro-grids and power storage devices. Usually they only discuss how to reduce the power loss within an individual micro-grid, or how to charge or discharge power within individual power storage devices. On the other hand, in this thesis, we focus firstly on an envisioning total power loss minimization approach across the entire smart grid that is managed centrally by the macro-station. Then, we extend our centralized algorithm to distributed algorithm.

2.3 Power distribution and Power Loss Formulation

2.3.1 Power distribution

In last subsection, we have introduced the micro-grid and its advantages. However, the most important problem that we need to solve is power distribution among the micro-grids or between the micro-grids and the macro-station. There are two reasons of power distribution.

The first one is the demand of users. The demands of users are different in different time of a day. The time can be divided into two parts based on the demands. The electricity consumption is high in peak period. In off-peak time, the electricity consumption is low. In additional, peak period in different season are different. Therefore, the demands of user cannot be predicted.

The other reason is the power generation stability of micro-grids. As we know, the micro-grids always use renewable power source to generate power. Although the renewable power source do not emit the "greenhouse" gas to the atmosphere, the source cannot guarantee the stability of power generation. For instance, wind farm cannot work , if the wind is too small.

In summary, the demand of the user and the generation power of micro-grids are not regarded as constant. Therefore, when the demand is more than the supply power of the micro-grid, the micro-grid needs to "buy" power from its neighbor or the power wholesaler (e.g., the macro-station). In other words, power will be transmitted from one micro-grid to other micro-grids. In real circumstance, power loss always accompanies with power distribution. Therefore, when the micro-grids want to buy the power so as to meet the demands of user, they will buy more power that they requirement. For instance, assume that the power loss is 1 watt when 100 watt power is transmitted from micro-grid B to micro-grid A. If micro-grid A only buys 100 watt from B, A only obtains 99 watt. Because of power loss, the micro-grids will need to consider which neighbor is the best one. To solve this problem, we propose power distribution algorithm for the micro-grids. Based on the power distribution algorithm, the micro-grids can choose proper neighbors and exchange power with them so as to meet the demands of user and minimize power loss.

2.3.2 Power Loss Formulation

Table 2.1: Parameters Declaration

Parameter	**Definition**
$G_i(t)$	Generation power of i^{th} micro-grid of slot t
$U_i(t)$	Actual supply power of i^{th} micro-grid of slot t
β_i	Storage power loss ratio of i^{th} micro-grid
$S_i(t)$	Currently stored power of i^{th} micro-grid within slot t
$S0_i(t)$	Stored power of i^{th} micro-grid at the beginning of slot t
$D_i(t)$	Demand of users linked to i^{th} micro-grid of slot t
$W_i(t)$	Currently remaining power of i^{th} micro-grid within slot t
$B_{0i}(t)$	Actual exchange power between i^{th} micro-grid and the macro-station of slot t
$\delta_i(t)$	Power that i^{th} micro-grid wants to sell or buy from the macro-station of slot t
$B_{ij}(t)$	Actual exchange power between i^{th} micro-grid and j^{th} micro-grid of slot t
α	Conversion power loss ratio
θ_i	Generation power loss ratio of i^{th} micro-grid
θ_0	Generation power loss ratio of macro-station
R_{ij}	Resistance between i^{th} micro-grid and j^{th} micro-grid
R_{0i}	Resistance between i^{th} micro-grid and macro-station
U_1	Voltage between i^{th} micro-grid and j^{th} micro-grid
U_0	Voltage between i^{th} micro-grid and macro-station
$PL_{ij}(t)$	Power loss when i^{th} micro-grid exchanges power with j^{th} micro-grid of slot t
$PL_{0i}(t)$	Power loss when i^{th} micro-grid exchanges power with macro-station of slot t
$PLG_i(t)$	Power loss due to power generation of slot t
$PLC_i(t)$	Power loss when power is converted from U_0 to U_1 of slot t
$PLT_i(t)$	Power loss due to power transmission of slot t
$PLS_i(t)$	Power loss due to power storage of slot t
$PLA_i(t)$	Total power loss of i^{th} micro-grid of slot t
S_{max}	Maximum of power storage devices

Before we introduce the power distributed algorithm, power loss formulations are given. In this thesis, four kinds of power loss will be considered (Table 2.1 IEEE copyright

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- Power Loss due to Generation (PLG [55]). This power loss is caused by power generator.

- Power Loss due to Storage (PLS [55]). When power is charged or discharged in power storage device, some power will lose. This loss is PLS.

- Power Loss due to Transmission (PLT [21]). The power distribution line will be heated, when power is transmitted. In other words, electricity power is converted into heat. It cause power loss.

- Power Loss due to Conversion (PLC [21]). Because voltage in the macro-station is 50 KV and that in micro-grid is 22 KV ([21]), when power is transmitted between the macro-station and the micro-grid, the voltage will be converted. Therefore, the conversion operation will cause power loss. This power loss is named as PLC.

Assume that the smart grid has a macro-station, N micro-grids and the users. The set of micro-grid is $\mathcal{N}$. The ith micro-grid $micro\text{-}grid_i \in \mathcal{N}$ $(1 \leq i \leq N)$. Assume that $B_{ij}(t)$ is real transmitted power from $micro\text{-}grid_i$ to $micro\text{-}grid_j$, $W_i(t)$ and $W_j(t)$ are the current remaining power, respectively. Similarly, $B_{0i}(t)$ is defined as real transmitted power form the micro-station to $micro\text{-}grid_i$ (0 represents the macro-station). $G_i(t)$ is generated power. $S0_i(t)$ represents the stored power of $micro\text{-}grid_i$ at the beginning of slot t.

At first, PLG of $micro\text{-}grid_i$ will be expressed as follows,

$$PLG_i(t) = \theta_i G_i(t), \tag{2.1}$$

where θ_i is generation power loss ratio of i^{th} micro-grid. The corresponding power loss $PLS_i(t)$ is expressed as

$$PLS_i(t) = \begin{cases} 0: \quad U_i(t) > D_i(t) \\ \beta_i S0_i(t) : (1-\beta_i)S0_i(t) + U_i(t) \leq D_i(i) \\ \frac{\beta_i}{1-\beta_i}(D_i(t) - U_i(t)) : otherwise. \end{cases} \tag{2.2}$$

where $U_i(t)$ is supply power and $D_i(t)$ is the demand of users. Because voltage and resistance are different, PLT among the micro-grids and that between the macro-station and the micro-grid are not same. We have two PLT formulations. If *micro-grid*$_i$ sells power to *micro-grid*$_j$, the power loss function $PL_{ij}(t)$ can be expressed as

$$PLT_{ij}(t) = \frac{R_{ij}B_{ij}^2(t)}{U_1^2}, \tag{2.3}$$

where $R_{ij}(t)$ is the resistance and $U_1(t)$ is the voltage between *micro-grid*$_i$ and *micro-grid*$_j$, respectively. If *micro-grid*$_i$ wants to buy power from the macro-station, the power loss due to transmission is follow:

$$PLT_{0i}(t) = \frac{R_{0i}B_{0i}^2(t)}{U_0^2}, \tag{2.4}$$

where $R_{0i}(t)$ is the resistance and $U_{10}(t)$ is the voltage between *micro-grid*$_i$ and the macro-staion, respectively. The power loss due to conversion can be expressed as follow:

$$PLS_i(t) = \alpha B_{0i}(t) \tag{2.5}$$

where α is conversion power loss ratio.

Based on the power loss formulations, we can propose the power distribution algorithms. From next section, we will propose power distribution algorithms in different circumstances of micro-grids.

2.4 Summary

In this chapter, we provide an overview of smart micro-grids and power loss formulation. At first, we introduce the smart micro-grid and its advantages. After that the most important problem of micro-grid is introduced. To minimize power loss, power distribution algorithm can help the micro-grids to find and exchange power with the proper neighbours. Then, power loss formulations are given.

Chapter 3

Power Loss Minimization Method for Smart Micro-Grids: A Centralized Approach (without buffer)

3.1 Introduction

In this chapter, we mainly focus on the power distribution algorithm for the smart micro-grids. To minimize the total power loss of smart grid, we propose a centralized algorithm for the micro-grids. The algorithm will help the micro-grids to form coalitions and exchange power with the neighbours instead of the macro-station. In additional, when the demands of users have changed, the algorithm can help the micro-grids to automatically find the new neighbour so as to meet the demands and minimize the power loss. The micro-grids calculate and send the current remaining power (demand of the micro-grids) to the macro-station. When the macro-station obtains the optimal result, the result will be sent to the micro-grids, and the micro-grids will choose and exchange power according to the result. Furthermore, we pay attention to calculate the optimal number of micro-grids in a given zone. We mathematically analyze the stability, convergency, and optimality of our algorithm. At the end of this section, we make the numerical simulation. Compared with non-cooperative case and conventional cooperative case, our algorithm can palpably reduce average power loss per micro-grid.

3.2 System Model

In this section, system model of the smart grid is presented. As shown in Fig. 1.1, we consider that the users are supplied electricity by the macro-station and/or a number of the micro-grids , each of which is linked to the macro-station. Because a user is only linked to one micro-grid at a time, for convenience, we assume the micro-grid and the users are linked to this micro-grid are considered as a whole. Smart meters are assumed to be installed at the user-end. The smart-meters measure the power consumption of the users, and they also have the capability to notify the micro-grid about the users' demands. Because the power loss between the macro-station and a micro-grid is more than that between two micro-grids, the micro-grids can alleviate the power loss through forming coalitions. If a sufficient number of micro-grids to form the coalition does not exist, the coalition will only have a micro-grid (e.g., the coalition 2 in Fig. 1.1). All micro-grids are connected by power lines (this is why micro-grids can change their partners (micro-grids) to form coalitions). Therefore, if the sum of demands of the users is more than the production of a micro-grid, this micro-grid will obtain power from other micro-grid(s) or the macro-station to meet demands of users.

Let $\mathcal{N}$ denote the set of micro-grids. In the given time period (e.g., one hour), every *micro-grid*$_i$ ($i \in \mathcal{N}$) is able to produce power G_i and supply power to satisfy $D_i(t)$, which is the sum of demands from all users linked to *micro-grid*$_i$. For *micro-grid*$_i$, we define the real function $W_i(t) = (G_i(t) - D_i(t))$ as the power demand or surplus of *micro-grid*$_i$ in time slot t. It means that *micro-grid*$_i$ wants to get power to meet its demand ($W_i(t) < 0$), *micro-grid*$_i$ has a power surplus to sell ($W_i(t) > 0$), or its demand equals its production ($W_i(t) = 0$). The micro-grids can be divided into two types, namely "sellers" and "buyers". The "sellers" have surplus to sell while the "buyers" need additional amount of power to meet the demands of users. If the request of *micro-grid*$_i$ is zero ($W_i(t) = 0$), *micro-grid*$_i$ is considered to be either a "seller" or a "buyer", and it cannot affect the result. In fact, demand $D_i(t)$ and production $G_i(t)$ are always considered as random numbers in the real Smart Grid networks [56]. As a consequence, the value of $W_i(t)$ is seen as a random number with a certain observed distribution. For convenience, we assume that a "seller" will sell all the power to the "buyer(s)" and/or the macro-station while a "buyer" has enough "money" to buy the power from the "seller(s)" and/or the macro-station for meeting its demand. Furthermore, the concept of "buyers" and "sellers" can also be extended to the group or coalitions formed by a number of micro-grids.

3.2.1 Existing Non-cooperative Coalition Model

Before we design the payoff function of coalition, let us see a non-cooperative case. In this case, each micro-grid only exchange power with the macro-station. In general, the medium voltage of power transfer between the micro-grid and macro-station is U_0. Any power transfer between micro-grid and macro-station is accompanied with the power loss. In this process of power transfer, we only consider two kinds of power loss, namely (i) the power loss over the distribution lines inside the network, and (ii) the power loss due to voltage conversion. If *micro-grid*$_i$ wants to sell $W_i(t)$ to the macro-station ($W_i(t) > 0$) or buy $W_i(t)$ from the macro-station ($W_i(t) < 0$), based on eqs. (2.4) and (2.5), we are able to express the power loss between the macro-station and $PL_{0i}(t)$ as follows.

$$PL_{0i}(t) = PLT_{0i} + PLC_i(t) = \frac{R_{0i}B_{0i}^2(t)}{U_0^2} + \alpha B_{0i}(t), \tag{3.1}$$

where R_{0i} is the distribution line resistance between the macro-station and *micro-grid*$_i$, and α is a fraction of power loss caused by voltage conversion. For simplicity, α is treated as a constant. $B_{0i}(t)$ is the power that *micro-grid*$_i$ wants to buy or sell. The value of $B_{0i}(t)$ is any of the following.

$$B_{0i}(t) = \begin{cases} W_i(t) & : \quad W_i(t) > 0 \\ L_i^*(t) & : \quad W_i(t) < 0 \\ 0 & : \quad W_i(t) = 0, \end{cases} \tag{3.2}$$

where $L_i^*(t)$ denotes the total amount of power that needs to be produced (or be made available to the system) to ensure that *micro-grid*$_i$ is able to obtain the power required to meet its demand, $W_i(t)$. In case of no power loss, $L_i^*(t) = |W_i(t)|$. Therefore, the power $L_i^*(t)$ is more than the demand $|W_i(t)|$ ($L_i^*(t) > |W_i(t)|$). $L_i^*(t)$ is the solution of following quadratic equation.

$$L_i(t) = B_{0i}(t) + |W_i(t)| = \frac{R_{0i}L_i^2(t)}{U_0^2} + \alpha L_i(t) - W_i(t). \tag{3.3}$$

For a given $W_i(t)$, three possible solutions of eq. (3.3) exist, namely none (zero), one, and two solutions. Because we want to minimize the value of $W_i(t)$, if eq. (3.3) has two roots, the smaller one is to be used. For the cases that eq. (3.3) has no solution, we assume that the root is the same as eq. (3.3) having a single root, which is $L_i^* = \frac{(1-\alpha)U_0^2}{2R_{0i}}$.

Because in the non-cooperative case each micro-grid can be regarded as a coalition, the payoff of micro-grid is equal to that of coalition. Thus, we are able to define the non-cooperative payoff (utility) of each $micro\text{-}grid_i$ as the total power loss due to the power transfer, as follows:

$$u(\{i\}) = -w_2 PL_{0i}, \tag{3.4}$$

where w_2 is the price of a unit power in macro-station. Because the objective is to minimize $u(\{i\})$, the negative sign is able to convert the problem into a problem of seeking the maximum.

3.2.2 Cooperative Coalition Model

In the remainder of this section, the cooperative coalition model is considered for managing the micro-grids acting as "buyers" and "sellers". Also, the functions of power loss and utility in the cooperative case along with how to form the coalitions are proposed. Toward the end of the section, the concept of "Shapley" function is presented.

Besides exchanging power with the macro-station, the micro-grids can exchange power with others. Because the power loss during transmission among the neighbouring micro-grids are always less than that between the macro-station and a micro-grid, the micro-grids can form cooperative groups, referred to as coalitions throughout this paper, to exchange power with others, so as to alleviate the power loss in the main smart grid and maximize their payoffs in eq. (3.4).

Before formally studying the cooperative behaviour of the micro-grids, the framework of coalition game theory is firstly introduced in the work in [56]. A coalition game is defined as a pair $(\mathcal{N}, v)$. The game comprises three parts, namely the set of players $\mathcal{N}$, the strategy of players, and the function v: $2^{\mathcal{N}} \rightarrow \mathbb{R}$. In this game, v is a function that assigns for every coalition $S \subseteq \mathcal{N}$ a real number representing the total profits achieved by S. We divide any coalition $S \subseteq \mathcal{N}$ into two parts: the set of "sellers" denoted by $S_s \subset S$ and the set of "buyers" represented by $S_b \subset S$. S_s and S_b satisfy that $S_s \cup S_b = S$. Therefore, for a *micro-grid*$_i \in S_s$, $W_i(t) > 0$ and it means that *micro-grid*$_i$ wants to sell power to others. On the other hand, an arbitrary $micro-grid_j \in S_b$ having $W_j < 0$ indicates that *micro-grid*$_j$ wants to buy power from others. It is obvious that any coalition $S \subseteq \mathcal{N}$ should have at least one seller and one buyer.

In order to calculate the payoffs of all the coalitions, players of which are micro-grids $\in \mathcal{N}$, we need to define the payoff function *v(S)* for each S $\subseteq \mathcal{N}$. Subsequently, for any coalition $S = S_s \cup S_b$, we study the local power transfer between the sellers S_s, the buyers S_b, and the macro-station.

In a formed coalition, there are many micro-grids, which are to exchange power with others or even with the macro-station. Let a "seller" and a "buyer" be denoted by $micro-grid_i \in S_s$ and $micro-grid_j \in S_b$, respectively. If *micro-grid*$_i$ and *micro-grid*$_j$ want to exchange power, based on eq. (2.3), the power loss function PL_{ij} can be expressed as follows.

$$PL_{ij}(t) = PLT_{ij}(t) = \frac{R_{ij}B_{ij}(t)^2}{U_1^2}, \tag{3.5}$$

where R_{ij} is the resistance of the distribution line between *micro-grid*$_i$ and *micro-grid*$_j$. U_1 denotes the transfer voltage between *micro-grid*$_i$ and *micro-grid*$_j$ and it is less than U_0. Because there is no voltage conversion between two micro-grids, when power is transmitting among micro-grids, we only calculate the transfer power loss among micro-grids.

In other words, eq. (3.5) is the special case of eq. (3.1), when $\alpha = 0$. Also, B_{ij} is as follow,

$$B_{ij}(t) = \begin{cases} W_i(t) & : \quad |W_i(t)| \leq |W_j(t)| \\ W_j(t) & : \quad otherwise, \end{cases} \tag{3.6}$$

It means that if $micro\text{-}grid_i$ (i.e, the "seller") cannot meet the demand of $micro\text{-}grid_j$ (i.e., "the buyer"), then the seller only sells Q_i to $micro\text{-}grid_j$. In addition, since there is power loss between the micro-grids, $micro\text{-}grid_j$ will buy power $\frac{U_1^2}{2R_{ij}}$ (due to the power loss between $micro\text{-}grid_i$ and $micro\text{-}grid_j$) from $micro\text{-}grid_i$ at least.

In any given coalition S, the total payoff function is consists of three terms, namely (i) the power loss between the micro-grids which can be obtained from eq. (3.5), (ii) the power loss caused by the micro-grid selling power to the macro-station, and (iii) the power loss caused by the micro-grid buying power from macro-station. (ii) and (iii) are given by eqs. (3.1) and (3.2). Therefore, the total payoff function of the coalition S is as follows.

$$u(S,\Omega) = -(w_1 \sum_{i \in S_s, j \in S_b} B_{ij}(t) + w_2 \sum_{i \in S_s} P_{i0}(t) + w_2 \sum_{j \in S_b} P_{j0}(t)), \tag{3.7}$$

where $\Omega \in \mathcal{S}_S$ is the join order of the micro-grids, which decide to join the coalition S, and $\mathcal{S}_S$ is the set of the micro-grids' order in S. w_1 and w_2 represent the price of a unit price of power in the coalition and that in the macro-station, respectively. P_{0i} and P_{0j} are given by eqs. (3.1) and (3.2). B_{ij} is given by eq. (3.5). By using eq. (3.7), which represents the total power loss incurred by the different power transfers for S, we can define the value function for the micro-grids ($\mathcal{N}$,v) coalition game:

$$v(S) = \max_{\Omega \in \mathcal{S}_S} u(S,\Omega) \tag{3.8}$$

3.3 Envisioned Game Theoretic Coalition Formulation Strategy (GT-CFS)

In a game, players can make different choices, e.g., which coalitions to join and which coalition/micro-grids/macro-station to buy the power from. Each player confronts the best possible choice for him. Note that this is the reason behind our motivation to propose an adequate algorithm to help the micro-grids to choose the best decision. Therefore, an effective strategy is essential to ensure that the sum of the power transfers between the coalitions and the macro-station is the minimum, so as to maximize the payoffs of the micro-grids. To achieve this objective, we want to increase the utilities of the coalitions. In eq. (3.7), $u(S, \Omega)$ is made up of three terms. Generally speaking, the power loss between the macro-station and micro-grids is much higher than that between the micro-grids. Hence, the first term is much lower than the second term and the third term in the same condition. In other words, we can minimize the power transfer between the coalition and the macro-station to alleviate the power loss out of the coalition. Therefore, in order to maximize eq. (3.8), a strategy will be designed that can find the coalition having the micro-grids so as to ascertain the minimum power loss between the coalition and the macro-station, or obtain the maximum profit from forming the coalition. To achieve this target, micro-grids can calculate the value of Difference of Power loss per unit Power (DPP) between within coalition and out of the coalition. It is obvious that the greater difference will bring greater payoff for the coalition. If $micro\text{-}grid_i$ wants to form coalition with $micro\text{-}grid_j$ and the quantity of transfer is Q_{ij}, the function of DPP between them is as follow.

$$DPP(i,j) = \frac{PL_{0i}(B_{ij}(t)) + P_{0j}(B_{ij}(t)) - PL_{ij}(B_{ij}(t))}{Q_{ij}(t)} \tag{3.9}$$

where PL_{0i}, PL_{0j}, and $PL_{ij}(t)$ are given by eqs. (3.1) and (3.5). In other words, the function of DPP is the marginal value of a micro-grid for the coalition. For maximizing the profit of coalition, micro-grids will find the partners which are able to maximize the eq. (3.9). In this vein, our envisioned strategy is as follows.

- Initialization: sort S_s and S_b in descending order, according to the requests of micro-grids (selling or buying), i.e., $S_b = \{b_1, ..., b_k\}$, and calculate the sum of sets respectively and find the less one of two sets. To facilitate the description of the algorithm, we may assume that S_b is the less one. Then, select $b_l \in S_b$ as the objective.

- Step 1: depending on the demand of objective, based on eq. (3.9), find the *appropriate* micro-grids in S_s or S_b to form coalition S with objective, which can ensure that the profit of coalition S is the maximum. Thus, this step indicates that the power loss of micro-grids in coalition S is less than that between the macro-station and the micro-grids belonging to the coalition S

- Step 2: If the remainder of S_s is less than that of S_b, select the biggest one in S_s as the objective. Go to step 1, until there is no availability in the sets or one of the sets is an empty set.

- Step 3: If the remainder of S_s is more than that of S_b, select the biggest one in S_b as the objective. Go to step 1, until no availability in the sets or one of sets is empty set.

Again refer back to eq. (3.8), which represents the maximum total utility produced by any $S \subseteq \mathcal{N}$. This represents that the minimum power loss over the distribution lines. Therefore, comparing with the non-cooperative case (described in Sec. 3.2.1), the sum of utilities of micro-grids in the considered coalitions increase. That is to say, the micro-grids produce the extra profits through forming the coalition. Upon completion of the coalition formation, the micro-grids belonging to the same coalition face the problem of how to distribute the extra profits appropriately in the coalition. If the allocation of profits is not appropriate, the coalition will be split into parts. Thus, we need an appropriate allocation for the profits.

For this purpose, we choose the "Shapley" value concept from cooperative game theory [57]. In each the cooperative game, it assigns a unique distribution (among the players) of a total surplus produced by the coalition of all the players. When a micro-grid joins in a coalition, it will bring income for the coalition. However, different order that micro-grids join in the coalition means different income. Shapley value is average income, which is generated by a micro-grid joins in a coalition. In other words, the Shapley value of a micro-grid is the contribution of that micro-grid to its coalition. Profit distribution totally depends on the micro-grids' contribution for the coalition. Furthermore, the "Shapley" value of a micro-grid is the contribution of this micro-grid. Therefore, if all the "Shapley" values of micro-grids are given, the profit may be distributed. If there is a coalition game $(\mathcal{N}, v)$, the Shapley value of player i ($micro\text{-}grid_i$) can be calculated by following formula:

$$\phi_i(v) = \sum_{S \subseteq \mathcal{N} \setminus \{i\}} \frac{|S|!(n - |S| - 1)}{n!} (v(S \cup \{i\}) - v(S)), \tag{3.10}$$

where n is the total number of players and the sum extends over all the subsets S of $\mathcal{N}$ without the i^{th} player, and $v(S)$ is given by eq. (3.8). The formula can be interpreted as follows. Imagine that the coalition is formed one player at one time, each player demands their contribution $v(S \cup \{i\}) - v(S)$ as an appropriate compensation, and then averages over the possible different permutations in which the coalition can be formed. In Section 3.2, the function v of micro-grid is given. Hence, the "Shapley" value can be calculated.

Furthermore, since the payoffs depend upon the micro-grids' order in the coalition, the payoffs are likely to be different in different orders. In fact, the contribution of a player to the coalition is independent of the order. Therefore, the fraction in eq. (3.10) attempts to calculate the average of the payoffs in all conditions, and this average is the contribution of the player to the coalition. Additionally, the Shapley value has nothing to do with the costs of the players. For example, consider three players, costs of whom are 10, 20, 30, respectively. Then, the payoff function is as follows.

$$v(S) = \begin{cases} 1 & : \quad S = \{1,2,3\} \\ 0 & : \quad otherwise, \end{cases}$$

The number of orders is six. Different orders mean different payoffs. Now, let us calculate the Shapley value of the 1^{st} player. From Table 3.1 (Copyright ©2014IEEE), we can find the value of the 1^{st} player to be $\frac{1}{3}$. Similarly, note that the values of the 2^{nd} and 3^{rd} players are the same as the 1^{st} player. All the values are $\frac{1}{3}$. Thus, their contributions for the coalition are same, although their costs are different.

From eq. (3.10), we can see that if two micro-grids have equal contributions to the coalition, their corresponding Shapley values are the same, although their individual val-

Table 3.1: The shapley value of player 1

Order	$v(S \cup \{1\}) - v(S)$
Order 1,2,3	$v(\{1\}) - v(\emptyset)$=0-0=0
Order 1,3,2	$v(\{1\}) - v(\{\emptyset\})$=0-0=0
Order 2,1,3	$v(\{2,1\}) - v(\{1\})$=0-0=0
Order 3,1,2	$v(\{3,1\}) - v(\{1\})$=0-0=0
Order 2,3,1	$v(\{2,3,1\}) - v(\{2,3\})$=1-0=1
Order 3,2,1	$v(\{3,2,1\}) - v(\{3,2\})$=1-0=1

ues are different. Furthermore, the value is independent of the order of micro-grid in the coalition. At the first glance, the result may appear to be unfair; however, it indicates the practical contribution of the players to the coalition. Therefore, micro-grids in the same coalition may distribute the extra payoff, based on eq. (3.10).

Based on the envisioned strategy for objective selection and the concept of Shapley value for extra profit distribution in a coalition, we propose an algorithm to formulate distributed coalitions of micro-grids in the remainder of this section. First, we need to introduce an important definition from [56].

Definition Consider two collections of disjoint coalitions $\mathcal{A} = \{A_1, ..., A_i\}$ and $\mathcal{B} = \{B_1, ..., B_j\}$ which are formed out of the same players. For one collection $\mathcal{A} = \{A_1, ..., A_i\}$, the payoff of a player k in a coalition $A_k \in \mathcal{A}$ is $\phi_k(\mathcal{A}) = \phi_k(A_k)$ where $\phi_k(A_k)$ is given by (9) for coalition A_k. Collection $\mathcal{A}$ is preferred over $\mathcal{B}$ by *Pareto order*, i.e. $\mathcal{A} \triangleright \mathcal{B}$, if and only if

$$\mathcal{A} \triangleright \mathcal{B} \Leftrightarrow \{\phi_j(\mathcal{A}) \geq \phi_j(\mathcal{B}), \forall k \in \mathcal{A}, \mathcal{B}\} \tag{3.11}$$

with at least one strict inequality ($>$) for a player k.

The Pareto order means that a group of players prefer to join a collection $\mathcal{A}$ rather than $\mathcal{B}$, if at least one player is able to improve its payoff when the structure has been

Algorithm 1 GAME THEORETIC COALITION FORMULATION ALGORITHM OF MICRO-GRIDS

Initial State

Each coalition is one micro-grid, which means that all micro-grids cannot form coalition with others. Therefore the network is partitioned by $\mathcal{S} = S_1, S_2, ..., S_N$.

Stage 1 Preparing Work

Stage 2 Coalition Formation:

repeat

a)$\mathcal{M} = Merge(\mathcal{S})$: the micro-grids will form coalition or merge small coalitions to big one.

b)$\mathcal{S} = Split(\mathcal{M})$: the micro-grids will decide to leave from the coalitions to form new coalitions through the Pareto Order in eq. (3.11).

until no micro-grids can do merge-and-split operation to get more payoffs, and the network is partitioned by C'.

Stage 3 Power transfer:

repeat for every formed coalition

the micro-grids in same coalition will exchange power with others by the order of forming coalition.

until no local power transfer in coalition.

if every $C_i \in C'$, any seller or buyer, which has not meet its demand or has power surplus to sell, can exchange power with macro-station.

---

changed from $\mathcal{B}$ to $\mathcal{A}$ without cutting down the payoffs of any others.

In order to form the coalition, two distributed rules are needed: *merge* and *split* [**?**] defined as follows:

Definition Merge: Merge any set of coalitions $\{S_1, ..., S_l\}$ where $\{\cup_{i=1}^{l} S_i\} \triangleright \{S_1, ..., S_l\}$, hence,$\{S_1, ..., S_l\} \rightarrow \{\cup_{i=1}^{l} S_i\}$.

Definition Split: Split any coalition $\{\cup_{i=1}^{l} S_i\}$ where $\{\{S_1, ..., S_l\} \triangleright \cup_{i=1}^{l} S_i\}$, hence,$\{\cup_{i=1}^{l} S_i\} \rightarrow \{S_1, ..., S_l\}$.

From the definitions of merge and split, we find that some micro-grids and some micro-grids coalitions will join a new coalition or merge with a bigger coalition, respectively, if at least one of them can improve its payoff and do not cut down the payoffs of any other micro-grids and coalitions, respectively. On the other hand, a big coalition will be split into some small coalitions (or even disappear) if the micro-grids find that they can leave the coalition or merge with a smaller coalition, so as to get more payoffs than that in the current coalition. Hence, a merge or split decision by Pareto order will ensure that all the involved micro-grids agree on it (namely, merge-and-split proof).

Because the micro-grids act as players of a cooperative game, we propose a coalition formation algorithm called Game Theoretic Coalition Formulation Strategy (GT-CFS) by exploiting the merge and split operations as shown in Alg. 1. First, in our envisioned algorithm, each micro-grid could obtain information of others (e.g., position, neighbour micro-grids, and so on) by using the communication infrastructure or communication technology of smart grid (i.e., smart meters). Second, the micro-grids will produce the power, meet the demands of the users, and decide to buy or sell the power. Third, the forming coalition stage starts when the merge process occurs as follows. Given a partition $\mathcal{S} = \{S_1, ...S_k\}$, each coalition $S_i \in \mathcal{S}$ will communicate to its neighbours. Using these negotiations, the coalitions will exchange the information with others. micro-grids want to find the best partners micro-grids to form coalitions, so as to get more profits (payoff). The rules of merge and split will help them to deal with it. The coalitions or micro-grids calculate their payoffs by employing eqs. (3.7) and (3.8), find that the payoffs of all of them will increase, and this is the Pareto order in eq. (3.11), if they can form a coalition. They will do it with the rule of the merge operation. For example, consider that there is a micro-grid, which is able to sell power. Assume that the power loss between it and the macro-station is 0.2. If it can find a coalition, which needs power, and the power loss between them is 0.15, the micro-grid will join the coalition. But during the next time interval, the surrounding circumstances of the micro-grid may change, such as the coalition does not want to buy power from the micro-grid, or there exists another coalition for the buyer such that the power loss is lower than that in the current coalition. Therefore, the micro-grid will leave this coalition to find a new one so as to alleviate its power loss.

For any micro-grid, the decision of merge and split is a distributed operation, and it is not be affected by other micro-grids or the macro-station. Most importantly, a micro-grid is able to make it individually by following Alg. 1. After the merge and split iterations, the network will compose of disjoint coalitions, and no coalitions may have any incentive to perform further merge or split operation. Upon such convergence, the micro-grids within each formed coalition will start its power transfer stage.

In next section, a proof on the stability, convergence, and optimality of proposed GT-CFS algorithm is presented.

3.4 Proof of stability, convergence, and optimality of GT-CFS

It is important to show that our proposal is stable regardless of the environmental changes in the grid. Furthermore, it is also important to prove that it converges to an optimal solution. We begin our proof by providing a definition of stability followed by two theorems. The proof of each of the theorems is provided separately.

Definition A coalition C: $= \{C_1, ..., C_k\}$ is $\mathbb{D}_{hp}$-stable if the following two conditions are satisfied.

(a) for each $i \in \{1, ..., k\}$ and for each partition $\{P_1, ..., P_l\}$ of the coalition C_i: $v(C_i) \geq$

$\sum_{j=1}^{l} v(P_j)$.

(b) for each set T $\subseteq \{1, ..., k\}$: $\sum_{i \in T} v(C_i) \geq v(\cup_{i \in T} C_i)$.

Theorem 3.4.1 *The coalition formed by proposed algorithm is $\mathbb{D}_{hp}$-stable.*

Proof From the definition of $\mathbb{D}_{hp}$-stable, we know that if a coalition formed by our proposed GT-CFS is $\mathbb{D}_{hp}$-stable, it must satisfy two conditions. At first, let us see the first condition. Assume $\{P_1, ..., P_l\}$ is an arbitrary partition of any stable coalition C_i. Select partition P_k arbitrarily from coalition C_i where $k \in \{1, ..., l\}$. Because each coalition and partition must have a "seller" and a "buyer", there exists a *micro-grid*$_j$ belonging to both P_k and C_i at least. If the payoff of *micro-grid*$_j$ in P_k is more than that in C_i, *micro-grid*$_j$ will use the proposed algorithm to split the coalition C_i into smaller coalitions so that the coalition C_i will not exist. Therefore, for any stable coalition C_i, which is formed by the proposed algorithm, condition (a) must be satisfied.

Then, let us discuss the second condition. For each coalition C_i which is formed by the proposed algorithm, if there exists a bigger coalition C' which is satisfied $C_i \subseteq C'$ and $v(C_i) < v(C')$, the micro-grids in C_i make use of the proposed GT-CFS to *merge* other coalitions with a bigger coalition C' where the micro-grids are able to get more payoffs than that in the smaller coalition C_i. However, C_i is formed by GT-CFS, and it is the final result. Hence, C' cannot exist. It contradicts the assumption of stable coalition C'. Therefore, for each coalition C_i formed by the proposed algorithm, condition (b) must be satisfied.

Remark: The first condition in Theorem 3.4.1 means that if a coalition is formed by the proposed algorithm, one cannot find its subsets, which are satisfied as the sum of subsets' payoffs is more than that of the coalition. Similarly, in the second condition, it means that it is not possible to find a bigger coalition C', which satisfies $C_i \subseteq C'$ and $v(C_i) < v(C')$. In other words, coalition C_i cannot provide extra profits for others when C_i joins a bigger coalition. As a consequence, another coalition does not want to merge with C_i to formulate a bigger one. Therefore, by using the proposed GT-CFS repeatedly, the final result becomes stable (regardless of the initial value).

Theorem 3.4.2 *In the studied ($\mathcal{N}$,v) micro-grids coalition game, the proposed GT-CFS converges to the Pareto optimal $\mathbb{D}_{hp}$-stable partition, if such a partition exists. Otherwise the final partition is merge-and-split proof.*

Proof It is an immediate consequence of Theorem 3.4.1.

From theorems 3.4.1 and 3.4.2, we can see that the $\mathbb{D}_{hp}$-stable partition is an outcome of the algorithm of formation coalition based on merge-and-split iterations. In other words, the Pareto optimal one is only stable situation. Therefore, the micro-grids can exploit the operation of merge or split to change the coalitions until they get the $\mathbb{D}_{hp}$-stable.

Finally, by using GT-CFS, the micro-grids will make a decision regarding merge and split operations to finally determine whether the micro-grids will stay in the coalition or not, so as to increase their payoffs upon environmental changes (i.e., the variations in the surplus or the need of power due to the changes in the demand or production of one or more micro-grids). To deal with it, GT-CFS is repeated periodically so that it allows the micro-grids to make a new decision of merge or split to adapt to the environment which has been changed.

3.5 Optimal number of Micro-Grids in a region

In the previous section, our proposed algorithm of forming coalitions dubbed GT-CFS is presented. micro-grids will supply the users with the power to meet their demands. However, an excessive number of micro-grids will increase the maintenance cost, and this will raise the costs of users. Therefore, a key question arises in terms of the appropriate number of micro-grids in a given region to participate in the coalitions formation. This issue is addressed in this section.

Assume that the total demands of the users in a region are fixed to D_{total} and the maintenance cost of the micro-grid is a constant C_0. Additionally, assume that the maximum production of micro-grids are the same, denoted by G. From eq. (3.5), when m power is transmitted, the average power loss is:

$$PL_1(m) = \frac{R_{avg1} m^2}{U_1^2}, \tag{3.12}$$

where R_{avg1} refers to the average resistance among micro-grids and it is an area-related constant. When the electricity production m does not meet the demand D_{total}, the users need to buy power from the macro-station. Based on eq. (3.12), the request function $R_{MS}(m)$ is:

$$R_{MS}(m) = D_{total} - m + PL_1(m). \tag{3.13}$$

By using eqs. (3.1), (3.2), and (3.3), we can calculate the average power loss between the micro-grids and the macro-station, when power $R_{MS}(m)$ is transmitted between the micro-grids and the macro-station. The power loss function $PL_2(m)$ is given as follows.

$$PL_2(m) = \frac{R_{avg2}m^2}{U_0^2} + \alpha m, \tag{3.14}$$

where R_{avg2} is the average resistance between the micro-grid and the macro-station. It is also an area-related constant. When the production of electricity from the micro-grids is less than the demands of users, the users are able to buy the rest from the macro-station. The total cost C_1 can be expressed as:

$$C_1(n) = w_1(nG) + w_2(R_{MS}(nG) + PL_2(R_{MS}(nG))) + nC_0, \tag{3.15}$$

where $n \in \mathbb{N}$ denotes the number of micro-grids. Similarly, when the production is not less than the demands, the cost can be expressed as C_2 as below.

$$C_2(n) = w_1(D_{total}) + nC_0. \tag{3.16}$$

Therefore, when the number of deployed micro-grids is $n \in \mathbb{N}$, the COsting Money for Electricity ($COME$) is given by:

$$COME(n) = \begin{cases} C_1(n) & : \quad nG \leq D_{total} + PL_1(nG) \\ C_2(n) & : \quad otherwise \end{cases} \tag{3.17}$$

If N is the optimal number of micro-grids, *COME(N)* will satisfy

$$COME(N) = \min_{n \in \mathbb{N}} COME(n) \tag{3.18}$$

The next theorem will guarantee that the function *COME(n)* exists with a minimum.

Theorem 3.5.1 *The function* COME(n) *exists with a minimum.*

Proof If a minimum of COME(n) exists, it must satisfy ($\min COME(n) = \min(C_1(m), C_2(l))$, $\forall n, m, l \in \mathbb{N}$). If C_1 and C_2 exist with their minimum, the minimum of $COME$ exists. It is obvious that $C_2(n)$ is an increasing function of n. Therefore, a minimum of $C_2(n)$ exists. Let us consider the function $C_1(n)$. Note that $n \in [1, \lceil \frac{D+P_1(NG)}{G} \rceil]$, when $COME(n) = C_1(n)$. Hence, the minimum of $C_1(n)$ exists. As a consequence, the function *COME(n)* exists with a minimum.

Thus, if the afore-mentioned parameters are known, the optimal number of micro-grids can be calculated.

When we know the maximum of demand, based on our algorithm, the maximum number of micro-grids is given. When the demand below the maximum, micro-grids will decrease their productions, or may not even generate additional power for some period. Therefore, our algorithm is able to adjust the number in a real system.

In the following section, the effectiveness of our proposal is evaluated.

3.6 Performance Evaluation

In this section, simulation results are presented to evaluate the effectiveness of our proposed GT-CFS. Our considered simulation scenario comprises a power distribution grid topology, area of which is 10×10 km^2. The macro-station is placed at the center of the grid, and the micro-grids are deployed randomly in the topology. For convenience, the micro-grid and the users linked to this micro-grid are regarded as a whole. Therefore, the demands of user is equal to the demand of micro-grid. The power requirement parameter of $micro\text{-}grid_i$ denoted by $W_i(t)$ is assumed to be a random variable distributed from -200 MW to 200 MW (note that the negative and positive signs of Req_i imply that $micro\text{-}grid_i$ is a "buyer" or a "seller", respectively). The resistance between the micro-grids is the same as that between the macro-station and any micro-grid, and its value $R = 0.2\ \Omega$ per km. The fraction number of power transfer $\alpha = 0.02$ according to the assumption in [58]. The voltage values of U_0 and U_1 are set to 50 kV and 22 kV, respectively, which represent practical values in a variety of smart grid distribution networks [58]. The price of the each of the unit power loss parameters is set as $w_1 = 1$ and $w_2 = 3$. These values are set arbitrarily and do not affect the fundamental observations in the conducted simulation. The simulation results are presented in the remainder of this section.

Fig. 3.1 (Copyright ©2014IEEE) depicts the average power loss per micro-grid for varying number of micro-grids from two to 100 in case of the non-cooperative model, a conventional algorithm called NMS (the micro-grids will find the nearest neighbour micro-grid to form coalition), and our proposed GT-CFS. The results in the figure indicates that when the number of micro-grids increases, the average power loss changes just a little in the non-cooperative game case. However, in the cooperative coalition cases, i.e., in our GT-CFS and the conventional NMS, the power losses decrease (sharp initial drop followed by gradual descent) with the increasing number of micro-grids. For instance, when the number of micro-grids is 100, the power loss in GT-CFS reaches up to significant reduction in contrast with the non-cooperative game case, and exhibits better performance compared to the cooperative NMS approach. The good performance of GT-CFS can be attributed

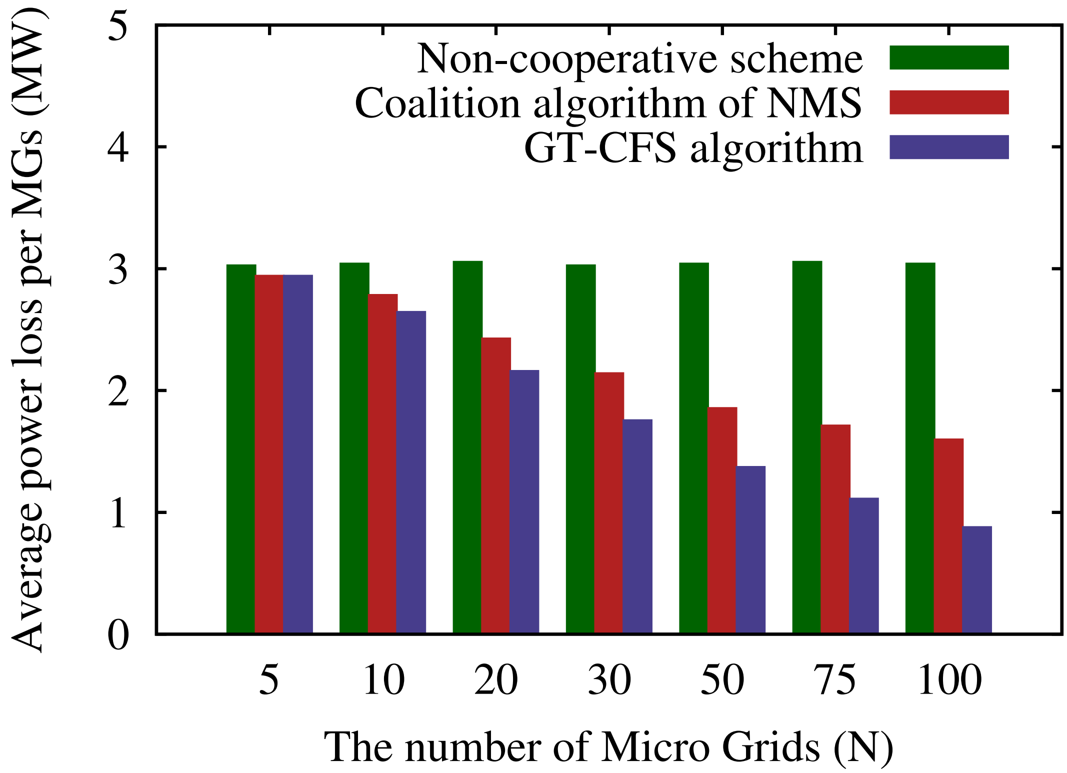


Figure 3.1: The comparison of Noncooperative case and coalition case

due to the fact that the power losses within its formed coalitions are much lower than those between the macro-station and micro-grid(s). Hence, when most of the micro-grids are in the coalitions, the whole costs of the users decrease. However, power losses exist in the coalition, when power has been transmitted. Therefore, the average power loss does not always fall, as verified by the shape of the curve demonstrated in Fig. 3.1.

Furthermore, in GT-CFS, the sum of power losses in the coalitions is less than that in the NMS. This is because GT-CFS helps coalitions to select micro-grids, marginal values of which for the coalition are the maximum. In other words, the value of DPP is the maximum. On the other hand, when the power loss between the micro-grids remain the same, the coalition selects the micro-grids which are further away from the macro-station, and thus, the coalition gets more profit from the selected micro-grids. However,

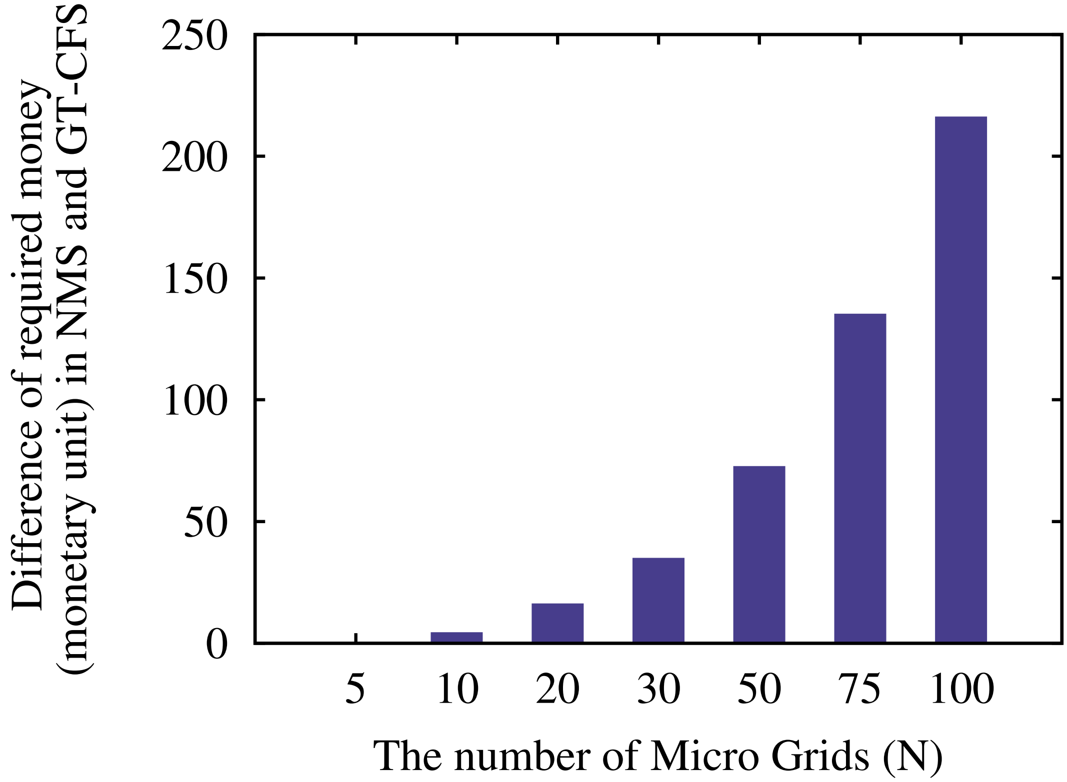


Figure 3.2: The comparison of NMS case and GT-CFS case

NMS only selects the nearest micro-grid to form coalition and it cannot guarantee the profit of coalition is maximum. As a consequence, GT-CFS outperforms NMS in terms of improvement of the average power loss.

Fig. 3.2 (Copyright ©2014IEEE) demonstrates the difference of the money required for buying power in case of NMS and that in our proposed GT-CFS. As shown in the figure, when the number of micro-grids increases, the difference of the required money (i.e., saved money by using GT-CFS) becomes larger. It is because GT-CFS will help coalition to find the micro-grids which can bring maximum payoff with coalition while NMS only considers finding the nearest micro-grid to decrease the power loss. Coalitions are able to obtain more profit from GT-CFS than that from NMS. Hence, our algorithm may help the micro-grids to save a significant amount of money in contrast with the NMS

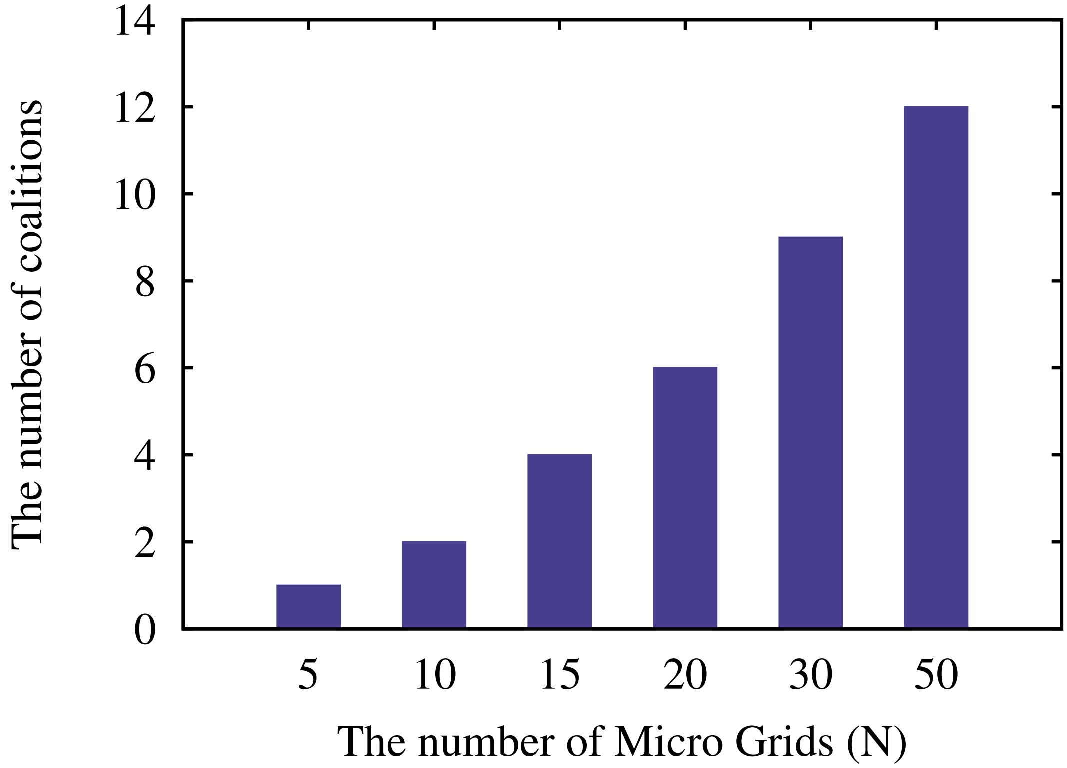


Figure 3.3: The number of coalitions

algorithm.

Next, from Fig. 3.3 (Copyright ©2014IEEE), we can see that the number of coalitions increases with the number of micro-grids increasing. This supports intuition. If we analyse numerically, the number of coalitions increases from 1 (for 5 micro-grids) to 12 (for 50 micro-grids). Note that the positions of micro-grids are fixed since their random deployment in the simulation grid topology. Hence, the power losses between the micro-grids and macro-station are fixed when they want to transmit the same power. However, with the increasing number of micro-grids, the distance between them becomes shorter and shorter and the power losses among the micro-grids decrease. Therefore, in order to decrease the power loss, the micro-grids can form the coalitions and exchange power with others.

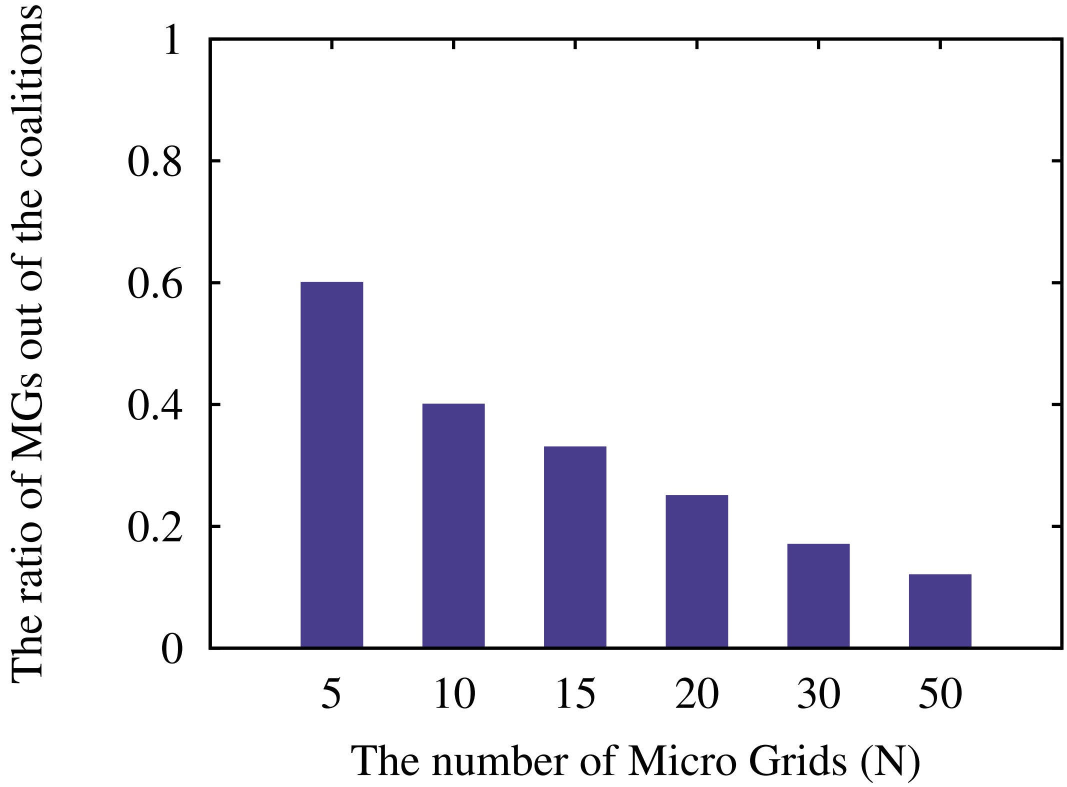


Figure 3.4: The ratio of micro-grids out of coalitions

In Fig. 3.4 (Copyright ©2014IEEE), the result demonstrates that with the increasing of number of micro-grids, less and less micro-grids are left without being inside coalitions. Also, it indicates that the micro-grids can form coalitions easily, because of the shortened distance among them. Furthermore, it also reflects the fact that the micro-grids can sell or buy power easily from other micro-grids than the macro-station. However, from this figure, we find that some micro-grids are out of the coalitions. There are two reasons that a micro-grid is not part of a coalition. The first reason is that the micro-grid is far away from other micro-grids. In this case, the power losses among this micro-grid and others are larger than that between this micro-grid and macro-station. Therefore, no coalition will allow this micro-grid to join any of the coalitions. The second reason is that the demands of micro-grids is zero (e.g., the coalition 3 in Fig. 1.1). It means that the

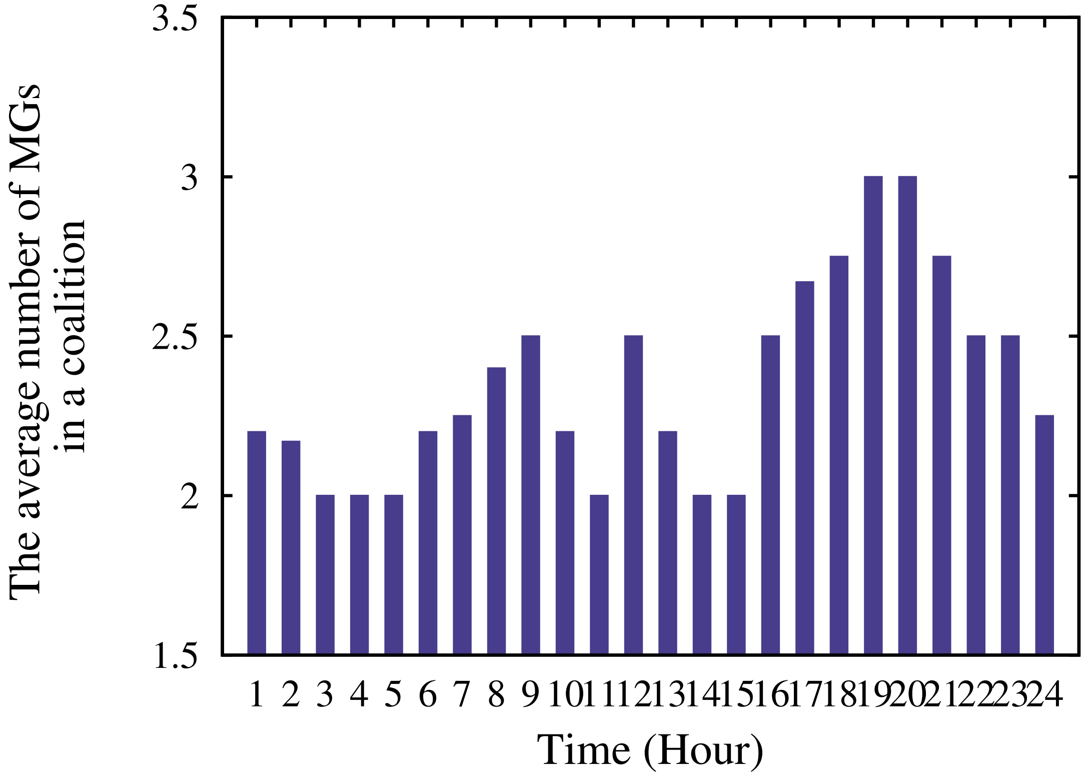


Figure 3.5: The average number of micro-grids in coalitions

micro-grid does not need to exchange power with others.

Assume, for example, that the peak period in the power grid is observed twice a day, namely in the morning (from 6 AM to 9 AM) and in the evening (from 4 PM to 9 PM). Furthermore, the number of micro-grids is 15 whose situations remain fixed since their initial random deployment in the simulated grid. Fig. 3.5 (Copyright ©2014IEEE) shows the variation of the average number of micro-grids in a coalition in a day. The average number of micro-grids per coalition during the peak period is 2.58 while during the off-peak period it has a lower value of 2.11. It is because that during peak time, the users need more electricity to meet their demands than that in off-peak time, and the micro-grids will not exchange power when they belong to different coalitions. Therefore, the micro-grids need to change coalitions to buy power from others. Thus, it also becomes

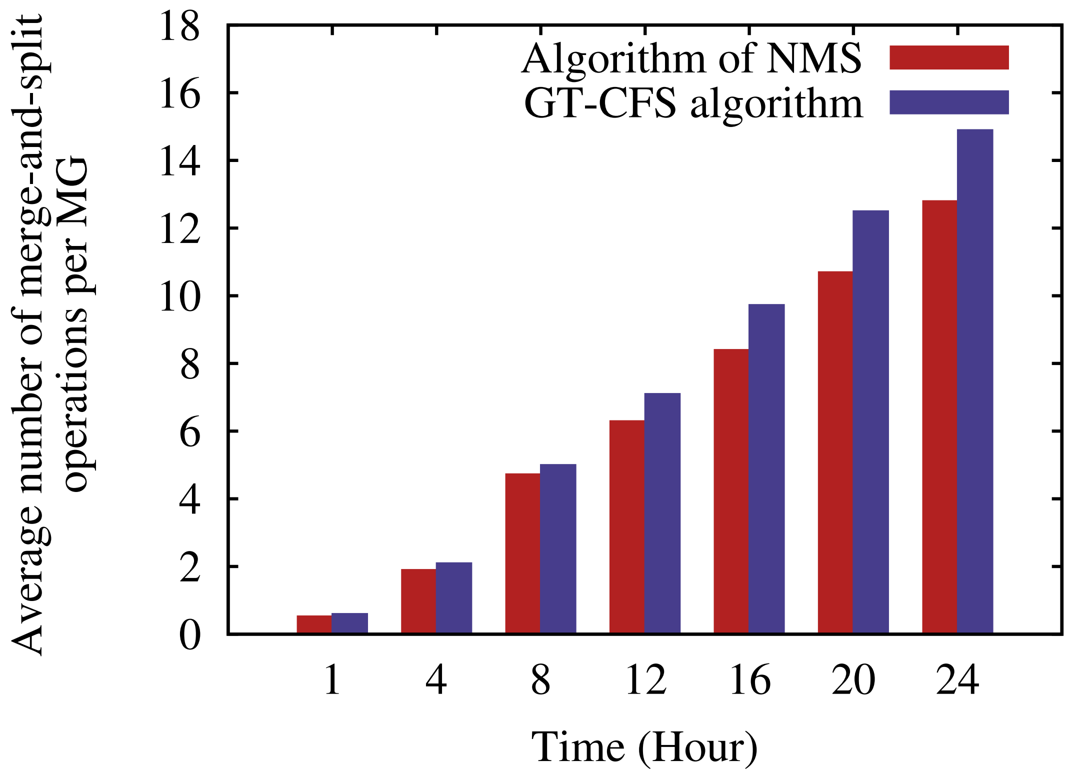


Figure 3.6: Average number of merge-and-split operations per micro-grids versus the frequency of changes in the power needs of the micro-grids over a period of 24 hours

obvious that forming coalition is a good choice for the micro-grids, regardless of whether they act as “buyers” or “sellers”.

In Fig. 3.6 (Copyright ©2014IEEE), we plot the average number of merge and split operations per micro-grid (i.e., overhead) versus the frequency of changes in the power needs of the micro-grids over a period of hours, for N = 15 micro-grids in the different algorithms. Here, an interval of one hour is considered. Comparing with the conventional NMS approach, the number of operations in our proposed GT-CFS is slightly higher per day. It is because that the micro-grids need to change coalitions during different time periods to get an optimal power loss improvement. Indeed, in our proposal, the micro-grids form the coalitions based on the minimization of the total power loss during power transfer within the coalitions. Therefore, the average number of merge and split operations is found

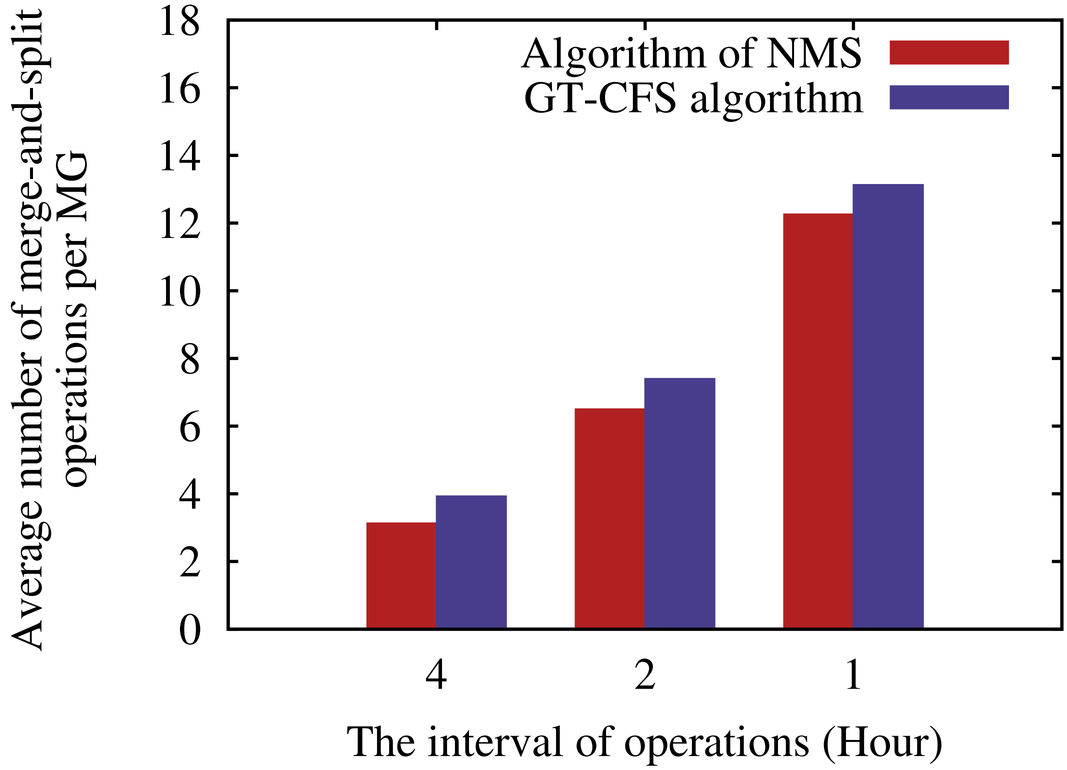


Figure 3.7: Average number of merge-and-split operations per micro-grid versus the different interval over a period of 24 hours in the different algorithms

to be slightly higher than that in the NMS algorithm. However, from earlier sections, we also know that there exists a minimum power transfer between the micro-grids and the first part of eq. (3.7) is significantly less than the others in the same condition. In other words, to choose the nearest micro-grid in a coalition does not mean the total power loss is minimum. The proposed GT-CFS is able to guarantee maximization of the total power in the coalitions and minimization of the power loss between the considered micro-grids or between the macro-station and micro-grid(s). Hence, GT-CFS exhibits better performance in contrast with NMS.

Next, Fig. 3.7 (Copyright ©2014IEEE) demonstrates that, as the dynamics of the environment change and become faster, i.e., the frequency of changes increases, the micro-grids require a higher number of merge and split operations to adapt to the updated

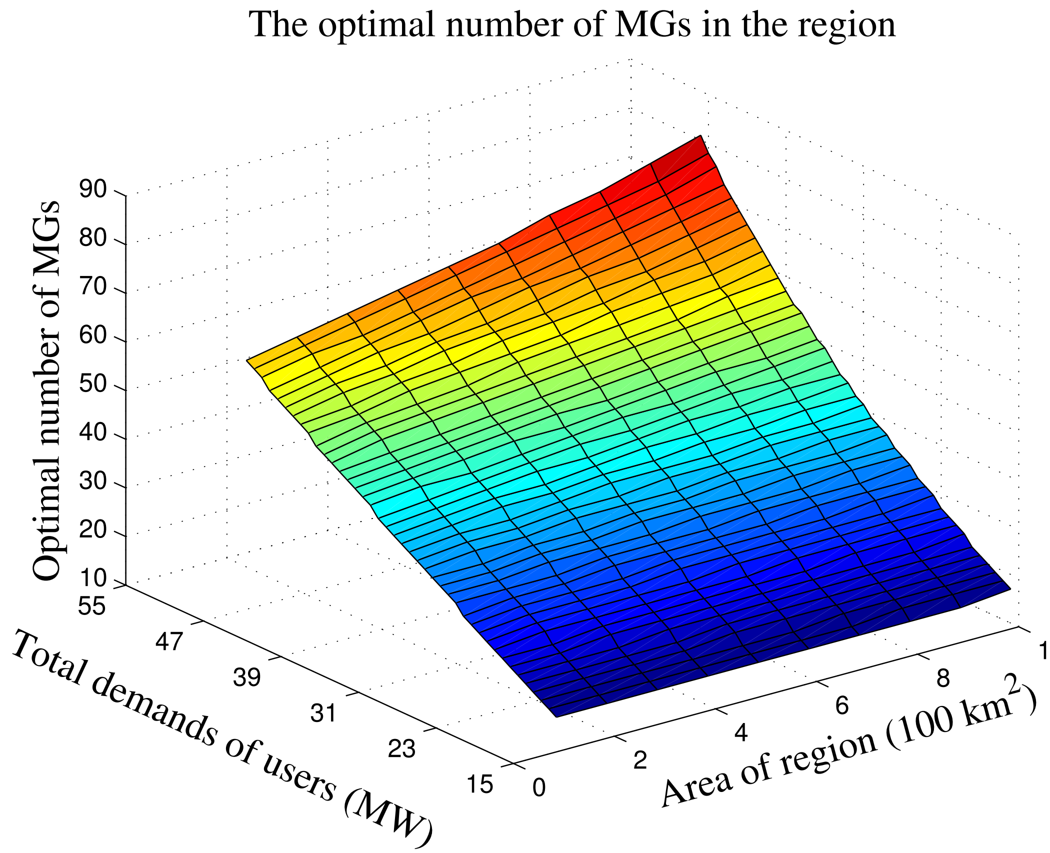


Figure 3.8: The optimal number of micro-grids in the region

network structure. For instance, while 3.13 and 3.93 merge-and-split operations are required when the power needs change 6 times every 24 hours (for N = 15 micro-grids) by using the different algorithms respectively, these numbers increase to 12.26 and 13.13 when the power needs change roughly every hour. Nevertheless, in smaller time intervals, the difference of merge and split operations in existing NMS algorithm and proposal is not high. In fact, our proposed GT-CFS saves a significant amount of power loss with a slight higher overhead.

In terms of saving money of the users, Fig. 3.8 (Copyright ©2014IEEE) depicts the optimal number of micro-grids in different cases. Remember that the optimal number of micro-grids depends on the area of the considered region and the demands of users in that area. For this reason, with their increasing demands, users need more electricity from the micro-grids to reduce their costs. For example, the optimal number becomes from 15 to 50, when the demands change from 15 MW to 55 MW in the the simulated grid area of $10 \times 10\ km^2$. Additionally, a higher resistance means a higher power loss. Hence, when the area is larger, more micro-grids are wanted to minimize this higher power loss. When the area changed from 100 km^2 to 1000 km^2 and the demands are 15 MW, the number of micro-grids becomes from 15 to 17. Thus, it is evident from Fig. **??** that the increasing speed of demands is more than that of the power loss.

3.7 Summary

In this chapter, a cooperative game theoretic coalition formulation strategy dubbed GT-CFS for micro-grids is proposed. To meet the demands of users and minimize power loss, by using the algorithm, the micro-grids can form coalitions and exchange power with other micro-grids in the same coalition. Moreover, the algorithm can help the micro-grids to whether to change their coalitions so as to minimize power loss. We make stability and optimality proof for the algorithm. After that, we discuss the optimal number of micro-grids in a given area. At the end of this chapter, the simulation results show the effectiveness of our superior performance, compared with the noncooperative case.

Chapter 4

Extended Power Loss Minimization Method with Storage

4.1 Introduction

In the previous chapter, we consider the algorithm for the micro-grids without power storage device. By using that algorithm, the micro-grids can form coalition and exchange power so as to meet the demands of users. In this chapter, we extend that algorithm into the micro-grid with power storage device case. In this case, micro-grid can control the power storage device charge or discharge power so as to reduce the power loss. Additionally, more kinds of power loss will be considered in this case. Our propose centralized greedy algorithm can collect the demand of micro-grids, calculate the power exchange pairs of micro-grids and sent the pairs to the corresponding micro-grids. According to the pairs, the micro-grids choose the appropriate neighbours and exchange power with them so as to minimize the total power loss. The comparison simulations show the significant performance of our algorithm.

4.2 System Model and Problem Statement

There are three layers in our considered system model, as depicted in Fig. 1.2. The first layer is the macro-station. It can sell power or buy the power surplus from the micro-grids, using power distribution lines between them. The second layer comprises the micro-grids, which are capable of generating power by using various renewable resources. The generated power can be transmitted from the micro-grids to the end-users according to their demands. Additionally, the micro-grids are assumed to have power storage devices (e.g., batteries, PHEVs, flywheels, and so forth). Although their initial deployment may be relatively expensive, power storage devices in the micro-grids can save the power in off-peak time and use it during the peak time, and minimize the total power loss while meeting the users' demands. Finally, the users, who obtain power from their respective micro-grids, form the last layer of our considered system.

Let $\mathcal{N}$ denote the set of micro-grids $\textit{micro-grid}_i$ $(1 \leq i \leq N)$, and $N = |\mathcal{N}|$. Power generation, storage, and transmission will cause power losses. Compared with the generated, saved and delivered power, the total power losses across the considered system are typically not negligible. We will consider four kinds of power losses, due to generation (PLG) , storage (PLS) transmission (PLT) and conversion (PLC). The other types of power losses are assumed to be negligible. This includes also power loss solely due to storage over time; that is, we only consider storage loss due to charging and discharging processes.

We assume that time is slotted and discretized, and normalized to $t = 0, 1, \ldots$ which conveniently may refer to the status at the beginning of the slot or during the slot before the next one starts. At the beginning of slot t, $\textit{micro-grid}_i$ stores power $S0_i(t) = S_i(t-1)$.

$S_i(t)$ denotes stored power during slot t and is a variable amount, affected by charging and discharging during the time slot; when slot t starts, the last value of $S_i(t-1)$ at the previous slot is the value for $S0_i(t)$ at the beginning of new slot.

At the beginning of time slot t, to minimize the total power loss, $micro\text{-}grid_i$ needs to know, as input, the total demand $D_i(t)$ from users who are linked to it, stored power $S0_i(t)$, and generated power $G_i(t)$.

$G_i(t)$ and $D_i(t)$ distributions were studied in [56]. Based on eq. (2.1), the power loss $PLG_i(t)$ associated with $G_i(t)$ is:

$$PLG_i(t) = \theta_i G_i(t), \tag{4.1}$$

where θ_i is generation power loss ratio of i^{th} micro-grid. Therefore, the actual supply power $U_i(t)$ is:

$$U_i(t) = (1-\theta_i)G_i(t). \tag{4.2}$$

$Micro\text{-}grid_i$ will first act on its own input and make some decisions to respond to the received demand directly. It will use newly generated power first, if possible, to fully meet the requested demand from users. In that case, $U_i(t) > D_i(t)$ and stored power will not be affected ($S_i(t) = S0_i(t)$). This power surplus could be exchanged to other micro-grids or the macro-station. The power $W_i(t)$ remaining for exchange is

$$W_i(t) = (1-\beta_i)S0_i(t) + U_i(t) - D_i(t). \tag{4.3}$$

Further, demand is changed to $D_i(t) = 0$, while the current remaining power is reduced $U_i(t) = U_i(t) - D_i(t)$.

If not, user demand could be met with the help of stored power. If $(1-\beta_i)S0_i(t)+U_i(t) \leq D_i(t)$ then all generated power and all power storage will be used, and afterwards $D_i(t) = D_i(t) - U_i(t) - (1-\beta_i)S0_i(t)$, $U_i(t) = 0$, and $S_i(t) = 0$. β_i is the storage power loss ratio of *micro-grid*$_i$. The remaining power demand $W_i(t)$ is given by the same equation above. $W_i(t) < 0$ in this case indicates that *micro-grid*$_i$ needs to buy power from other micro-grids or the macro-station.

In the remaining case, newly generated power $U_i(t)$ and stored power $S0_i(t)$ suffice to meet the demand. We decide that newly generated power is used in full and is helped with the portion of storage needed. The remaining stored power is then $S_i(t) = S0_i(t) - \frac{1}{1-\beta_i}(D_i(t) - U_i(t))$. Further, demand and generation are changed to $D_i(t) = 0$ and $U_i(t) = 0$, respectively. In this case, $W_i(t) \geq 0$. If $W_i(t) = 0$, the micro-grid does not participate in the power exchange.

The corresponding power loss $PLS_i(t)$ is expressed as

$$PLS_i(t) = \begin{cases} 0: \quad U_i(t) > D_i(t) \\ \beta_i S0_i(t) : (1-\beta_i)S0_i(t) + U_i(t) \leq D_i(i) \\ \frac{\beta_i}{1-\beta_i}(D_i(t) - U_i(t)) : otherwise. \end{cases} \tag{4.4}$$

However, power losses (in all three cases) are not considered in the optimization formula, because they occurred internally in micro-grid, before it contacted macro-station. They are, for simplicity, treated as natural losses in each micro-grid. The optimization formula makes use of power storage loss $PLS_i(t)$ due to storage charging or discharging process as part of power exchange.

To minimize the total power loss, the micro-grids will consider selling/buying power from other micro-grids when the power losses between them are less than those between the micro-grids and the macro-station. To minimize the total power loss, the macro station receives the following information from *micro-grid*$_i$: $W_i(t)$ and $S_i(t)$. $PLG_i(t)$ and $PLS_i(t)$ (the portion already experienced) could be also communicated so that macro-station can calculate the total power losses in the system, but are not needed to macro-station in the optimization process for power exchanging decisions. $PLG_i(t)$ is the percentage of generated power and the loss occurs in the micro-grid alone. $PLS_i(t)$ is partially experienced before contacting macro station, and partially derived by macro-station as the outcome of the optimization process.

When the macro-station receives the information, it helps *micro-grid*$_i$ to find proper neighbor j to exchange power $B_{ij}(t)$. It calculates the corresponding power loss is $PL_{ij}(t)$. The value of $W_i(t)$ will be updated based on $B_{ij}(t)$. The exchange pair $(i,\ j)$ is generated. The action will continue until $W_i(t)$=0 or no proper neighbor exists (e.g., when power loss between available micro-grids is more than between micro-grid and the macro-station). Afterwards, the value of $W_i(t)$ has been updated. Power exchange between micro-grid and macro-station causes power loss $P_{0i}(t)$. Macro station will calculate $B_{ij}(t), B_{0i}(t)$, update $S_i(t)$ and inform *micro-grid*$_i$. *micro-grid*$_i$ will follow and exchange power with *micro-grid*$_j$ and/or the macro-station, and discharge or charge accordingly. Additionally, if power is charged or discharged, $S_i(t)$ and $PLS_i(t)$ will be updated in the micro-grid.

Overall, the input of algorithm are $G_i(t)$ and $D_i(t)$ at each micro-grid, and the outputs are the exchange power pairs $(i,\ j)$ (*micro-grid*$_i$ should exchange power with *micro-grid*$_j$), corresponding power $B_{ij}(t)$, $B_{0i}(t)$, $S_i(t)$, and the sum of power losses $\sum_i PLA_i(t)$.

The macro station will decide how much power $B_{ij}(t)$ should be exchanged among micro-grids, how much power should be discharged or charged, and how much power

$B_{0i}(t)$ to exchange itself with corresponding micro-grid, based on $W_i(t)$ and $S_i(t)$. In a given time slot t (e.g., one hour), the total power loss of the i^{th} micro-grid $PLA_i(t)$ is,

$$PLA_i(t) = PLG_i(t) + PLS_i(t) + PL_{0i}(t) + \sum_j \frac{PL_{ij}(t)}{2}. \tag{4.5}$$

If *micro-grid*$_i$ exchanges power with *micro-grid*$_j$, power loss $B_{ij}(t)$ should not be calculated twice. Therefore, $PLA_i(t)$ includes half of $PL_{ij}(t)$.

When the micro-grids exchange power with others, they will belong to the same coalition. If a micro-grid does not exchange power with other micro-grids, it is a sole micro-grid in its coalition. The power loss function $v(C_l)$ of coalition C_l is,

$$v(C_l) = -\sum_{i \in C_l} PLA_i(t). \tag{4.6}$$

Our research target is to minimize the total power loss. Hence, the objective function is,

$$\begin{aligned} &Maximize \sum_l v(C_l) \\ &s.t. \quad D_i(t) \leq U_i(t) + (1-\beta_i)S_i(t) + \eta_i(t) \quad \forall i \in \mathcal{N}, \end{aligned} \tag{4.7}$$

where $\eta_i(t) = sign(W_i(t))B_{0i}(t) - PL_{0i}(t) + \sum_j (sign(W_i(t))B_{ij}(t) - PL_{ij})(t)$, $sign(W_i(t)) = 1$ if $W_i(t) < 0$, and $sign(W_i(t)) = -1$ otherwise. Therefore, our condition is that (after the preliminary step of meeting own demands first when possible) the demand at each micro-grid does not exceed the sum of the amount of remaining produced power, and stored power, and the power it exchanged with other micro-grids and macro station. Therefore it allows for a non-negative balance to be stored in its power storage for the next time period.

Consider the power loss among micro-grids. Because the voltage among the micro-grids are medium level voltage, the conversion power loss can be neglected. Power transmission will cause PLT. Based on eq. (2.3), if *micro-grid*$_i$ sells power to *micro-grid*$_j$, the power loss function $PL_{ij}(t)$ can be expressed as

$$PL_{ij}(t) = \frac{R_{ij}B_{ij}^2(t)}{U_1^2}, \tag{4.8}$$

where

$$B_{ij}(t) = \begin{cases} \frac{B_{ij}^2(t)R_{ij}}{U_1^2} - W_j(t){:}|W_i(t)| > |W_j(t)| \\ W_i(t) \qquad\qquad :otherwise. \end{cases} \tag{4.9}$$

This is quadratic equation in $B_{ij}(t)$ and therefore the optimal power exchanged between two micro-grids in not necessarily equal to the lower amount among them. The difference, however, is the power loss $PL_{ij}(t)$ due to the exchange. The "buyer" *micro-grid*$_j$ will receive all its needed power $W_j(t)$ if possible, and quadratic equation will only decide how much power the "seller" *micro-grid*$_i$ needs to send. Otherwise *micro-grid*$_i$ (the "seller") cannot meet the demand of *micro-grid*$_j$ (the "buyer"), and the seller only sells $W_i(t)$ to *micro-grid*$_j$. If *micro-grid*$_i$ sells power to *micro-grid*$_j$, the current remaining power $W_i(t)$ will be updated as:

$$W_i(t) = W_i(t) - B_{ij}(t). \tag{4.10}$$

If *micro-grid*$_i$ buys power from *micro-grid*$_j$, $W_i(t)$ will be updated as follow:

$$W_i(t) = \min\{W_i(t) + B_{ij}(t) - PL_{ij}(t), 0\}. \tag{4.11}$$

Therefore, the power loss is experienced at the receiving micro-grid, and not at the "seller" side. The maximum power that *micro-grid*$_i$ could buy is $|W_i(t)|$. In this case, $S_i(t) = 0$, to minimize total power loss. Based on the value of $W_i(t)$, $S_i(t)$ and $PLS_i(t)$ could be updated, and the power that *micro-grid*$_i$ wants to exchange with the macro-station $\delta_i(t)$ could be calculated as per following three cases.

Case 1: If $W_i(t) < 0$, then *micro-grid*$_i$ needs power and $S_i(t)$=0. Therefore, *micro-grid*$_i$ needs to buy power $\delta_i(t) = W_i(t)$ from the macro-station.

Case 2: If $W_i(t) \geq (1 - \beta_i)S_i(t) > 0$, power will be charged and transmitted to the macro-station. Assume that $\mu_i = W_i(t) - (1 - \beta_i)S_i(t)$ and $\lambda_i = S_{max} - S_i(t)$. Therefore, $S_i(t) = \min\{((1 - \beta_i)\mu_i + S_i(t)), S_{max}\}$. In addition, $PLS_i(t) = PLS_i(t) + \beta_i\mu_i$ and $\delta_i(t) = 0$ if $S_i(t) \neq S_{max}$, otherwise $PLS_i(t) = PLS_i(t) + \frac{\beta_i}{1-\beta_i}\lambda_i$ and $\delta_i = \mu_i - \frac{\lambda_i}{1-\beta_i}$.

Case 3: If $(1 - \beta_i)S_i(t) > W_i(t) > 0$ then power will be discharged and transmitted to other micro-grids to meet their demands. Assume that $\gamma_i = S_i(t) - \frac{W_i(t)}{1-\beta_i}$. Hence, $S_i(t) = \frac{W_i(t)}{1-\beta_i}$, $PLS_i(t) = PLS_i(t) + \beta_i\gamma_i$, and $\delta_i(t) = 0$.

In these expressions of, $S_i(t)$ on the right side is the remaining storage after attenuating storage from the power surplus is charged. This storage is augmented after the outcome in the current time period, to provide input storage for the next time period.

If $\delta_i(t) \neq 0$, *micro-grid*$_i$ will exchange power with the macro-station. Three kinds of power losses (PLT, PLG, and PLC) are considered. Based on , $PLT_{0i}(t) = \frac{B_{0i}(t)^2 R_{0i}}{U_0^2}$ and $PLC_{0i}(t) = \alpha B_{0i}(t)$. Similar with, transmission voltages U_0 and U_1 are fixed constants

($U_0 \neq U_1$). Therefore, the power loss between *micro-grid*$_i$ and the macro-station, when $B_{0i}(t)$ has been exchanged, is

$$PL_{0i}(t) = \frac{B_{0i}(t)^2 R_{0i}}{U_0^2} + (\alpha + \theta_0) B_{0i}(t), \tag{4.12}$$

where $B_{0i}(t) = \delta_i(t)$ if $\delta_i(t) \geq 0$, otherwise $B_{0i}(t) = \frac{R_{0i} B_{0i}^2(t)}{U_0^2} + (\alpha + \theta_0) B_{0i}(t) - \delta_i(t)$. α and θ_0 are power loss ratios of conversion and generation of the macro-station.

The operation time duration t is not discussed in this paper. Its impact is expected to be marginal because of relative stability in power demands in short time.

4.3 Coalition Formulation Strategy for Micro-Grids with Power Storage Devices

We now describe coalition formation strategy by macro-station, which makes decision on behalf of all micro-grids. We first introduce a definition from and two rules: *merge* and *split*.

Definition Consider two collections of disjoint coalitions $\mathcal{A} = \{A_1, ..., A_i\}$ and $\mathcal{B} = \{B_1, ..., B_j\}$ formed out of the same players. Their corresponding payoffs are given by eq. (4.7). The payoff of *micro-grid*$_i$ in a coalition is assumed to be $-PLA_i(t)$, which we denote $\eta_i(A) = -PLA_i(t)$ and $\eta_i(B) = -PLA_i(t)$, respectively ($PLA_i(t)$ depends on the coalition created).

Collection $\mathcal{A}$ is preferred over $\mathcal{B}$ by *Pareto order*, i.e. $\mathcal{A} \triangleright \mathcal{B}$, if and only if

$$\mathcal{A} \triangleright \mathcal{B} \Leftrightarrow \{\eta_i(\mathcal{A}) \geq \eta_i(\mathcal{B}), \forall k \in \mathcal{A}, \mathcal{B}\} \tag{4.13}$$

with at least one strict inequality (>) for a player i.

The Pareto order means that a group of micro-grids (players) prefers to join a collection $\mathcal{A}$ rather than $\mathcal{B}$, if at least one player is able to improve its payoff when the structure has been changed from $\mathcal{B}$ to $\mathcal{A}$ without cutting down the payoffs of any others.

Definition Merge: Merge any set of coalitions $\{C_1, ..., C_l\}$ when $\{\cup_{i=1}^{l} C_i\} \triangleright \{C_1, ..., C_l\}$, hence, $\{C_1, ..., C_l\} \rightarrow \{\cup_{i=1}^{l} C_i\}$.

Definition Split: Split any coalition $\{\cup_{i=1}^{l} C_i\}$ where $\{\{C_1, ..., C_l\} \triangleright \cup_{i=1}^{l} C_i\}$, hence, $\{\cup_{i=1}^{l} C_i\} \rightarrow \{C_1, ..., C_l\}$.

The above definitions will help the micro-grids, as players of a cooperative game, to maximize their payoffs, and find the proper micro-grids to form coalitions. We propose coalition formation algorithm for micro-grids and macro-station by exploiting the merge and split operations as shown in Alg. 2.

For $micro\text{-}grid_i$, $W_i(t)$, $S_i(t)$, $PLG_i(t)$ and $PLS_i(t)$ are calculated depending on $G_i(t)$, $S0_i(t)$, and $D_i(t)$. The information I_i ($W_i(t)$, $S_i(t)$, $PLG_i(t)$ and $PLS_i(t)$) is sent to the macro-station. Then $micro\text{-}grid_i$ waits for the response of the macro-station. Macro-station returns ACK message to corresponding micro-grids. If $micro\text{-}grid_i$ does not receive ACK message and if time-out occurs, it will resend its demand to the macro-station. Based on the received information, and the parameters of potential power exchanges among micro-grids, the macro-station generates a set of micro-grid pairs known as Potential Exchange Pair Set of micro-grids (PEPS) $\{(i, j)\}$. Each pair is able to reduce total power loss by exchanging power.

Power exchange among different micro-grids pairs from PEPS causes different power losses. Hence, we need a function to help the macro-station to find the proper micro-grid pairs to exchange power, so as to minimize the total power loss. The "Reducing power loss per Unit Power" (RUP) of *micro-grid*$_i$ and *micro-grid*$_j$ for the micro-grid pair can deal with this problem. If *micro-grid*$_i$ exchanges power with *micro-grid*$_j$, the function is expressed below,

$$RUP(B_{ij}(t)) = \frac{PL_{0i}(t) + PL_{0j}(t) - PL_{ij}(t)}{B_{ij}(t)}. \tag{4.14}$$

This function represents potential extra payoffs (reducing power loss) per unit exchange power for the coalition, if *micro-grid*$_i$ joins the coalition. $PL_{0i}(t)$ and $PL_{0j}(t)$ represent power loses if the same power $B(i,j)$ was exchanged with macro station by both micro-grids, in the current coalition. Merging them could replace these two by power exchange between them, with power loss $PLij(t)$. Higher values of RUP mean saving more power per unit power. Therefore, based on eq. (4.14), the micro-grids can make the best decisions to merge their coalitions. For instance, assume that there are two coalitions (1 and 2); micro-grid a chooses one of them to join so as to reduce power loss. Also assume that the micro-grid a could exchange power with micro-grid b which belongs to the coalition 1, and micro-grid c which belongs to the coalition 2. The demands of the micro-grids are W_a=10, W_b=-11, and W_c=-13. Therefore, exchange powers are B_{ab}=B_{ac}=10, and corresponding power losses are $PL_{ab}(B_{ab})$=2, $PL_{ac}(B_{ac})$=1.5, $PL_{0a}(B_{ab})$=3, $PL_{0b}(B_{ab})$=4, and $PL_{0c}(B_{ac})$=3. Hence, $RUP(B_{ab})$=0.5, $RUP(B_{ac})$=0.45. Based on RUPs, micro-grid a will join the coalition 1, so as to minimize the total power loss.

The macro-station calculates RUP (eq. 4.14) of PEPS and sorts PEPS in descending order according to RUP, and considers the first element (i, j) from PEPS if PEPS is not empty. It generates exchange power pair (i, j) and exchange power $B_{ij}(t)$. Coalitions

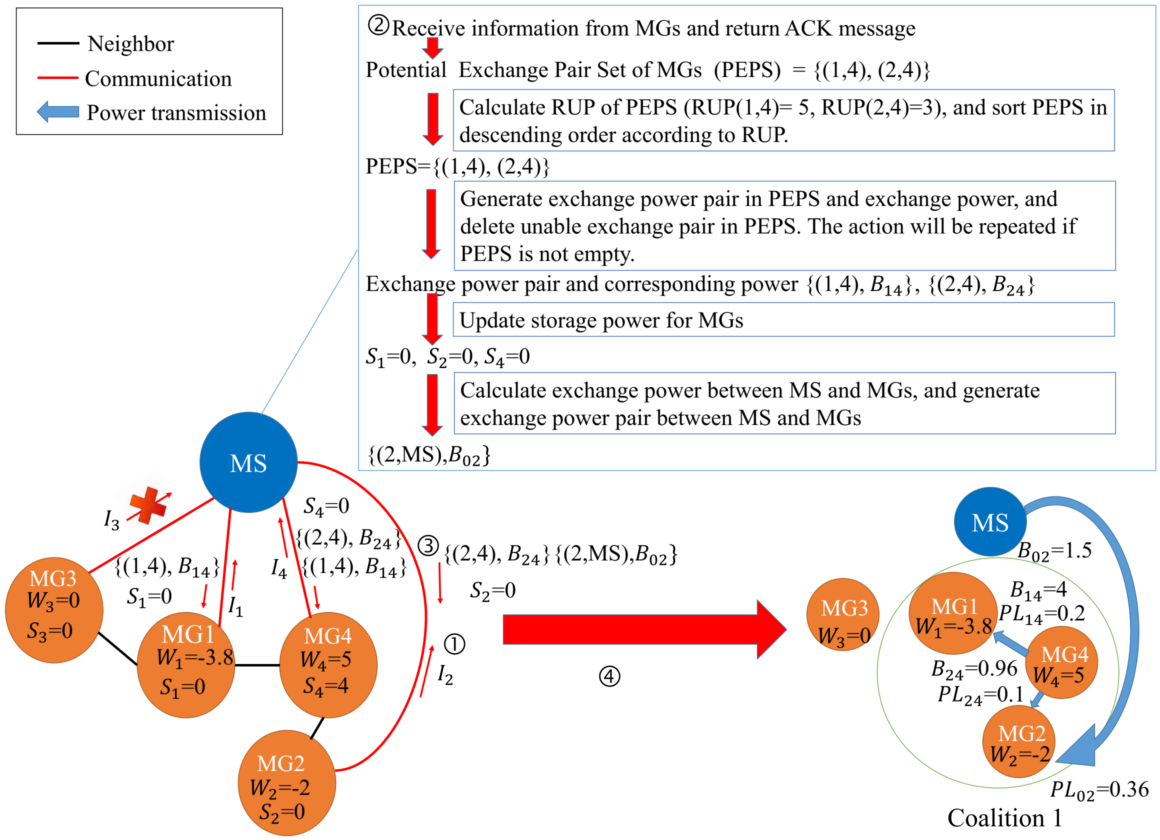


Figure 4.1: A simple example showing how the algorithm 1 lead to power exchange between micro-grids and macro-station with minimized power loss.

containing *micro-grid*$_i$ and *micro-grid*$_j$ will be merged. If $|B_{ij}(t)| = |W_i(t)|$ then the macro-station deletes the pairs in PEPS that i belongs to, because its demand becomes 0. $W_i(t)$ and $W_j(t)$ will be updated based on $B_{ij}(t)$. This action will continue until PEPS is empty. At this stage, micro-grids that still need power $(W)_i(t) < 0)$) will receive it from macro-station. Macro-stations with excessive power $(W)_i(t) > 0)$) will store them in own storage devices.

For instance, assume that there are 4 micro-grids (MG1 to MG4) and a macro-station (MS). In Fig. 4.1 (Copyright ©2014IEEE) the negative sign means the MGs need power to meet the demands of the users, zero means supply is equal with demand, positive means the MGs need to sell power to others. Assume that S_1=0, S_2=0, S_3=1, and S_4=3. First, the MGs send their information to the MS, and receive ACK message from the

MS. Next, when the MS receives the information, the unordered set PEPS {(1,4), (2,4)} is generated. Then the MS calculates the RUP of PEPS, and sorts PEPS in descending order according to RUP. Assume that RUP(1,4) = 5 and RUP(2,4) = 3. Hence, PEPS is {(1,4), (2,4)}. Thus MG1 and MG4 could calculate exchange power before MG2 and MG4. Next, the MS gets pair (1,4) from PEPS to generate exchange power pair $(1, 4)$ and exchange power B_{14} = 3.8. When MG1 and MG4 exchange power, demand of MG1 will be met. Hence, MG4 will discharge and transmit power to meet W_1, and this process will cause PLT and PLS. After power exchanging, W_1=0, PL_{14}=0.2, and W_4 = 0.97. Because demand of MG1 is met, the MS deletes MG1 from PEPS. Then pair $(2, 4)$ is taken from PEPS with B_{24} = 0.96 (considering PLS of MG4). After that W_4 = 0 and W_2 = -1.14. Then delete MG4 from PEPS. It causes PEPS to be empty. When PEPS is empty, the MS generates storage power for micro-grids (S_i = 0). After that the MS generates exchange power pair between macro-station and micro-grids ({(MS,2)}), and calculates the exchange power between the MS and the micro-grids (B_{02}=1.5). The MS will then send exchange pair and exchange power to corresponding MGs. MG1 receives {(1,4), B_{14}} and S_1 = 0. MG2 receives {(2,4), B_{24}}, {(2,MS), B_{02}} and S_2 = 0. MG4 receives {(1,4), B_{14}}, {(2,4), B_{24}} and S_4 = 0. Based on these pairs and demands, the MGs form coalition (MG2, MG1, and MG4), and exchange power with others or/and the MS.

After the merge and split operations in Alg. 2, the network becomes a partition composed of disjoint coalitions, and no coalition may have any incentive to perform further merge or split operation (the partition is *merge-and-split proof*). The micro-grids will find the coalition where they obtain most profits and join it. The algorithm can be re-applied when demand loads in the micro-grids change, to guarantee that the micro-grids may maximize their respective profits. We now show that our proposed algorithm is stable and convergent.

Definition A coalition C: $= \{C_1, ..., C_k\}$ is $\mathbb{D}_{hp}$-stable if the following two conditions are satisfied.

(a) for each $i \in \{1, ..., k\}$ and for each partition $\{P_1, ..., P_l\}$ of the coalition C_i: $v(C_i) \geq \sum_{j=1}^{l} v(P_j)$.

(b) for each set T $\subseteq \{1, ..., k\}$: $\sum_{i \in T} v(C_i) \geq v(\cup_{i \in T} C_i)$. [59]

Lemma 4.3.1 *The coalition formed by the proposed algorithm is $\mathbb{D}_{hp}$-stable.[21]*

Lemma 4.3.2 *In the studied ($\mathcal{N}$,v) micro-grids coalition game, the proposed scheme converges to the Pareto optimal $\mathbb{D}_{hp}$-stable partition, if such a partition exists. Otherwise, the final partition is merge-and-split proof. [21]*

Our solution is Pareto optimal. Hence, the merge and split operations will help the micro-grids to maximize their utilities (minimize the total power loss), until the $\mathbb{D}_{hp}$-stable situation occurs. In this situation, no micro-grid can decrease its total power losses without increasing other micro-grids' total power losses.

By using our algorithm, the micro-grids could exchange power among themselves instead of with the macro-station so as to alleviate power loss. After exchanging power, some generated power could be stored in the micro-grids.

4.4 Experimental Results

In this section, we present some experimental results to verify the effectiveness of our algorithm. The performance of our proposed scheme is compared with that of the non-cooperative scheme used in [36]. In the non-cooperative scheme, the micro-grids only exchange power with the macro-station and they cannot exchange power with the other micro-grids. Our considered simulation scenario comprises a power distribution grid topology, and the area is 10×10 km^2. The macro-station is placed at the center of the grid, and the micro-grids are deployed randomly in the topology. The resistance between the micro-grids is the same as that between the macro-station and any micro-grid, and its value is set to $R = 0.2$ Ω per km. The fraction of power transmission α is set to 0.02 according to the assumptions made in [58]. For simplicity, θ_i and β_i are regarded as constant in our simulation. Similar to the assumption made by [21], the power demand D_i of $micro\text{-}grid_i$ is derived from a Gaussian distribution between 10 MW and 316 MW. The power generation G_i is obtained from a Gaussian distribution between 10 MW and 316 MW. Assume that the capacity of power storage device is 200 MW, and the minimum storage power is 10 MW. The voltage values of U_0 and U_1 are set to 50 kV and 22 kV, respectively, which represent practical values in a variety of smart grid distribution networks [58]. The prices of a unit power loss are set as $w_1 = 1$ and $w_2 = 3$ [1]. In our proposal, the users send the information to the corresponding micro-grids, and the micro-grids also exchange the information to other micro-grids or the macro-station if necessary. Assume the micro-grids can communicate with the macro-station though an optical backbone network, capacity of which is 100Mbps. For simplicity, each micro-grid is assigned to meet the demands of 100 users. The length of packets from the users to the

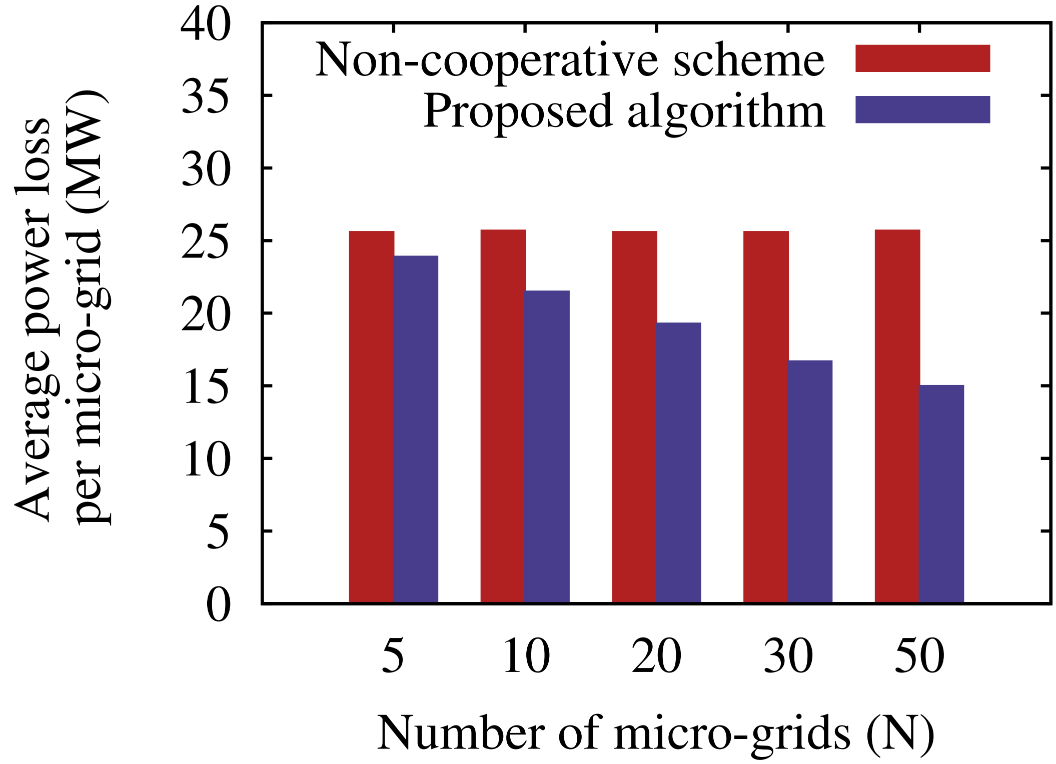


Figure 4.2: Comparison of the average power loss in the non-cooperative scheme and our proposal.

micro-grid is set to 102 bytes, and the length of packets exchanged among the micro-grids is set to 112 bytes [60]. The simulation results are presented in the remainder of this section.

Fig. 4.2 (Copyright ©2014IEEE) demonstrates the average power loss per micro-grid for varying number of the micro-grids from 5 to 50 in case of the non-cooperative scheme and our proposal when $\theta_i = 0.05$ and $\beta_i = 0.01$, respectively. From the results depicted in the figure, in the non-cooperative scheme, the power loss per micro-grid does not improve (in fact does not change) because the micro-grids only obtain power from the macro-station. On the other hand, in our proposal, the average power loss is improved substantially with the increasing number of the micro-grids. The reason behind this performance improvement in case of our proposal can be credited to the coalitions formed

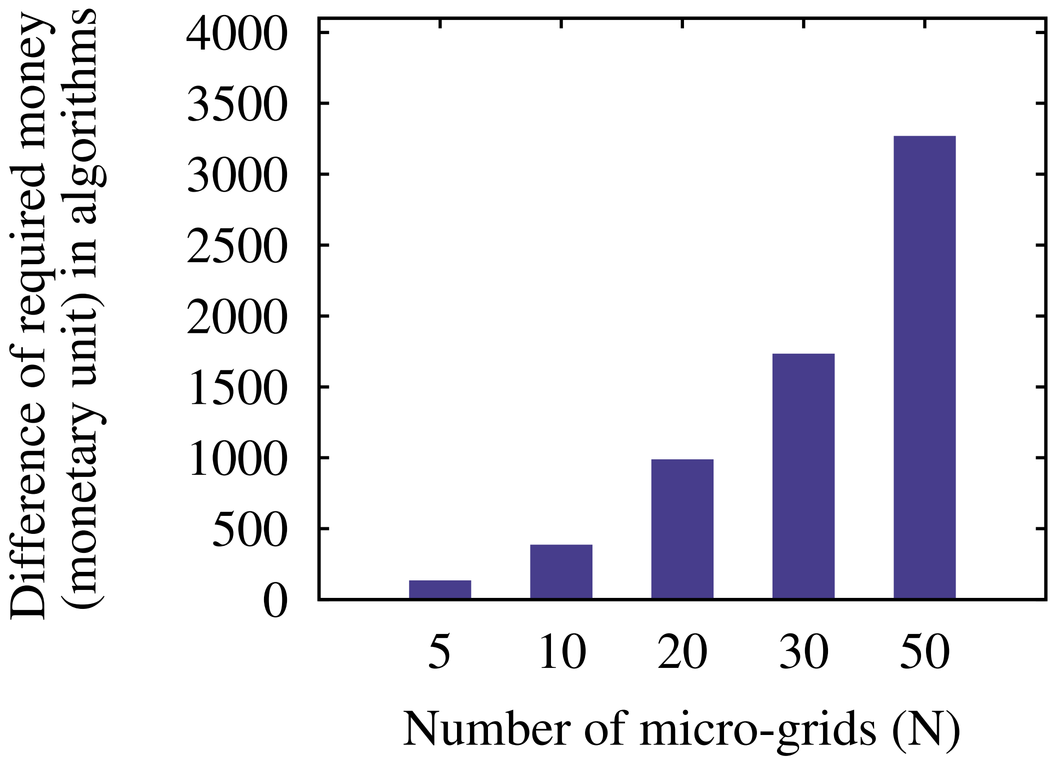


Figure 4.3: A mount of saved money in our proposal is employed.

by the micro-grids with the objective of optimally alleviating the power loss. When the micro-grids could successfully form coalitions, they could exchange power with other micro-grids instead of the macro-station leading to the reduction of the average power loss.

Fig. 4.3 (Copyright ©2014IEEE) demonstrates the difference of the money required for purchasing power in case of the non-cooperative scheme and that in our proposal. As demonstrated by the figure, when the number of micro-grids increases, the difference of the required money (i.e., saved money by using our proposal) becomes larger. This is because in the non-cooperative case, surplus power in off-peak time is sold to the macro-station. In addition, during peak time (when the supply power is less than the demands of users), the micro-grids buy power from the macro-station. These lead to PLT and PLC. However, in our proposal, the micro-grids can form coalitions and they could exchange power with

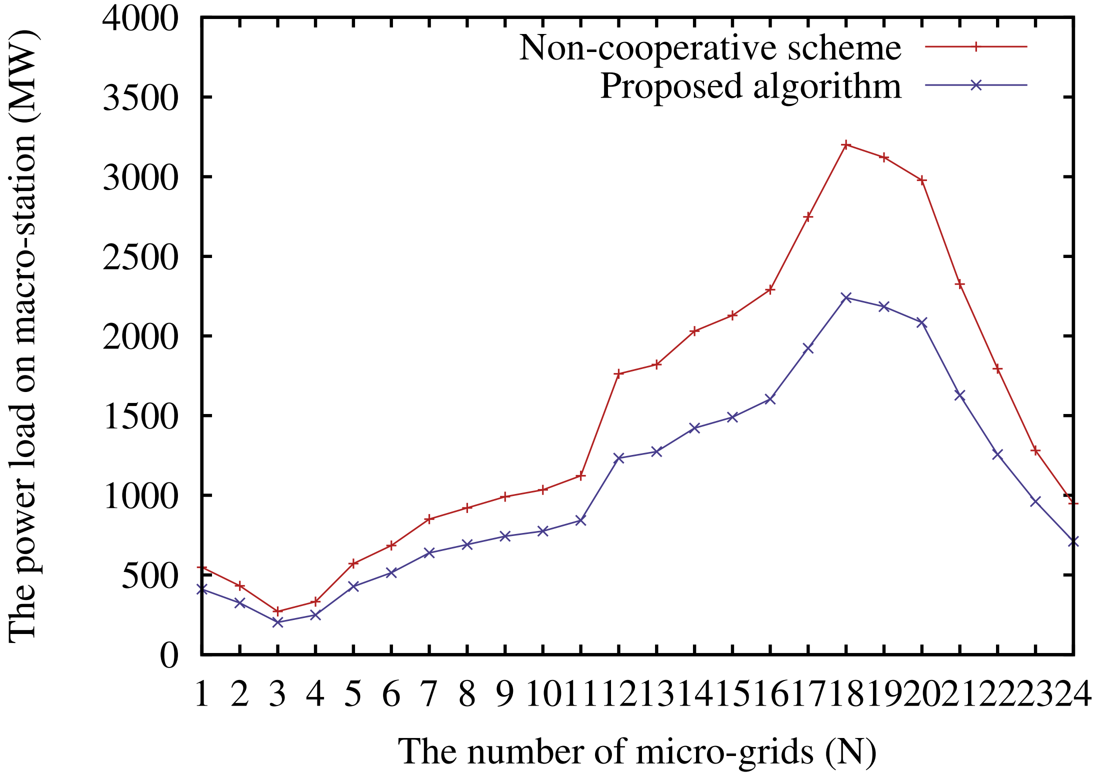


Figure 4.4: The power load on the macro-station in the non-cooperative case and our proposal.

other micro-grids. Additionally, the power loss among the micro-grids is lower than that between the micro-grids and the macro-station. Hence, the amount of total power losses in our proposal is lower than that in the other case. Furthermore, the micro-grids in our proposal can buy power in lower unit power price through the micro-grids coalitions. Thus, this presents an incentive to the users in terms of a chance to save money by using our micro-grids coalitions based proposal.

Fig. 4.4 (Copyright ©2014IEEE) depicts that the micro-grids want to buy the power from the macro-station for N=20 micro-grids in both the considered schemes. Assume that the peak period in a day is from 12 PM to 9 PM. Furthermore, the situations of the micro-grids are considered to remain fixed since their initial random deployment in the simulated grid. Although in both schemes, the micro-grids have the power storage devices

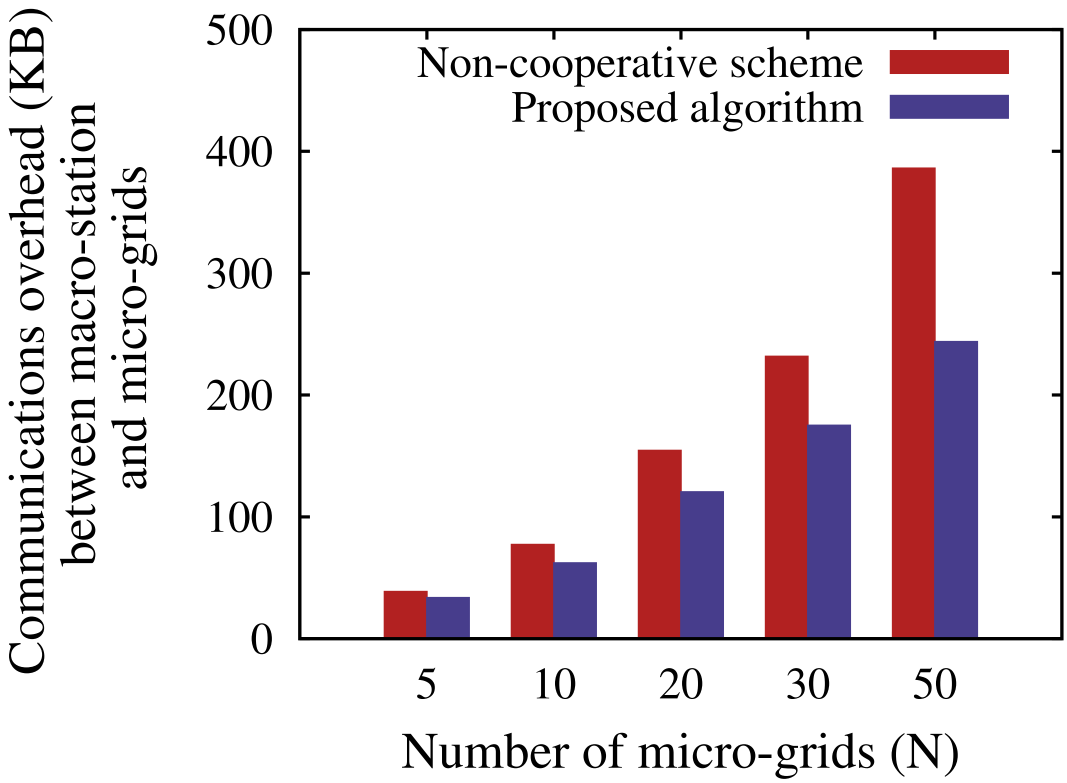


Figure 4.5: The communications overhead between the micro-grids and the macro-station in the non-cooperative case and our proposal.

that they could charge in off-peak time and discharge in peak time, note that compared with the non-cooperative case, the result achieved by our proposal (i.e., the burden in terms of the power load inflicted upon the macro-station) is lower. It is because the micro-grids in our proposal can buy power from neighboring micro-grids instead of the macro-station while the micro-grids in the non-cooperative case the micro-grids can only exchange power with the macro-station. The results presented so far demonstrate that both the users and the macro-station can obtain benefits from forming coalitions through our proposed scheme.

Fig. 4.5 (Copyright ©2014IEEE) plots the communications overhead for varying numbers of micro-grids. When the micro-grids exchange power with the macro-station, they need to send packets (i.e., power demand, current situation, and so forth) to the macro-

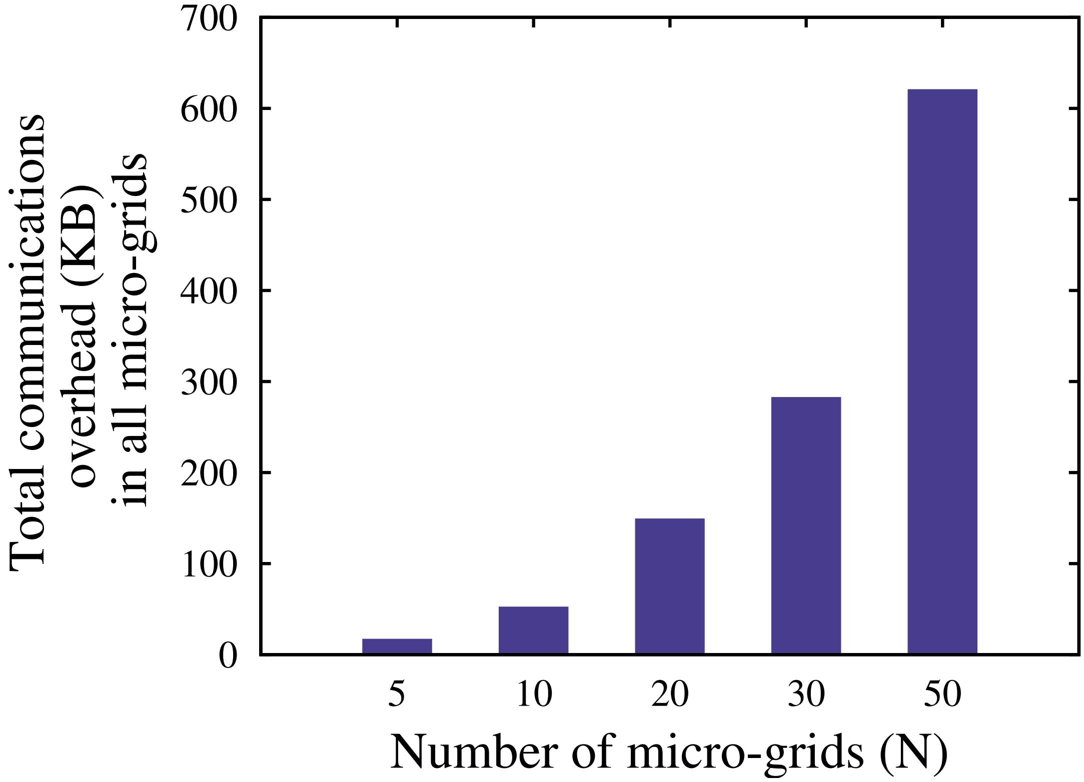
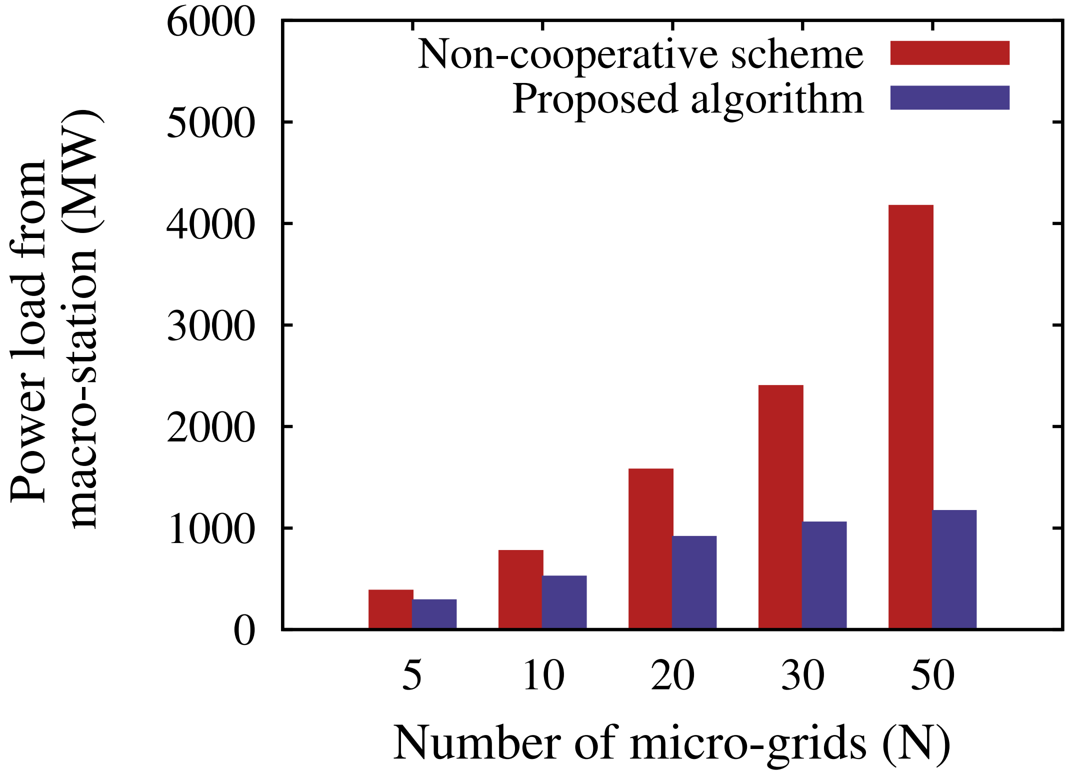


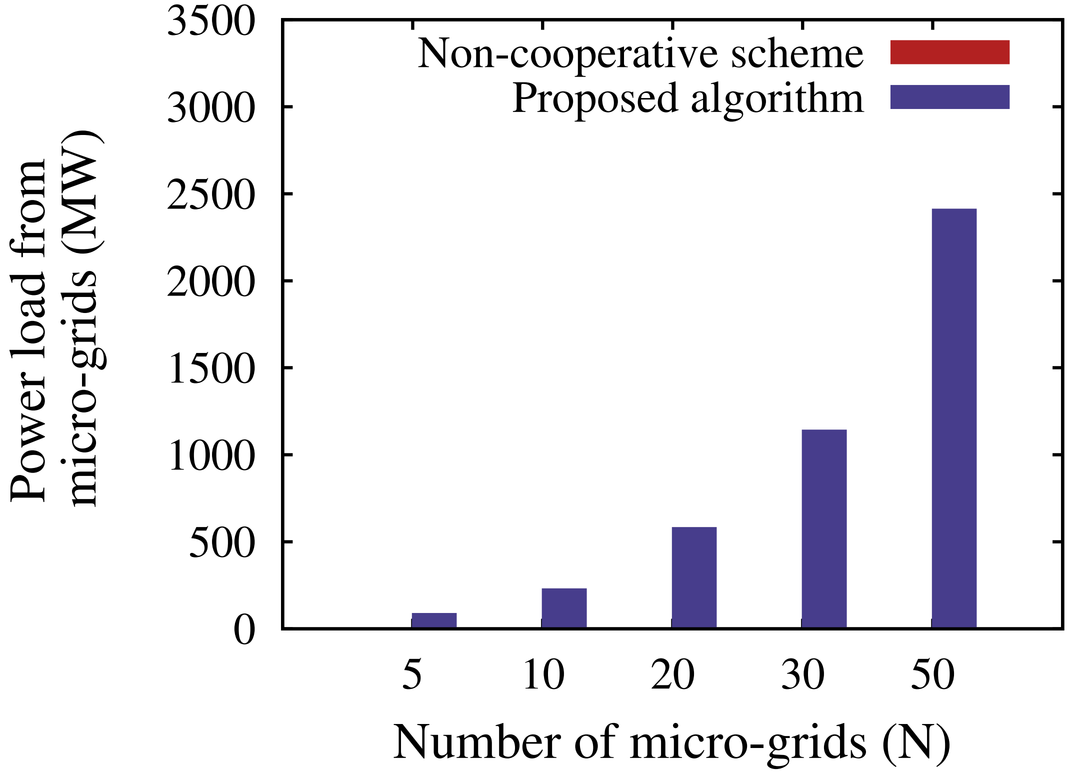
Figure 4.6: The total communications overhead experienced by all the micro-grids for varying numbers of micro-grids in our proposal.

station. From the figure, it should be noted that with increasing number of the micro-grids, more bandwidth is consumed. However, the communications overhead of both the schemes are not much when compared with the available bandwidth of the communication infrastructure of the considered power grid. Moreover, compared to the non-cooperative case, the micro-grids in our proposal can form coalitions and exchange the power with other micro-grids instead of the macro-station resulting in less messages exchange with the macro-station.

To evaluate the communications overhead due to the negotiations amongst the micro-grids to form coalitions, Fig. 4.6 (Copyright ©2014IEEE) plots total communication overheads in all the micro-grids for varying numbers of micro-grids. It is worth noting that the non-cooperative scheme does not consider such negotiations amongst micro-grids.

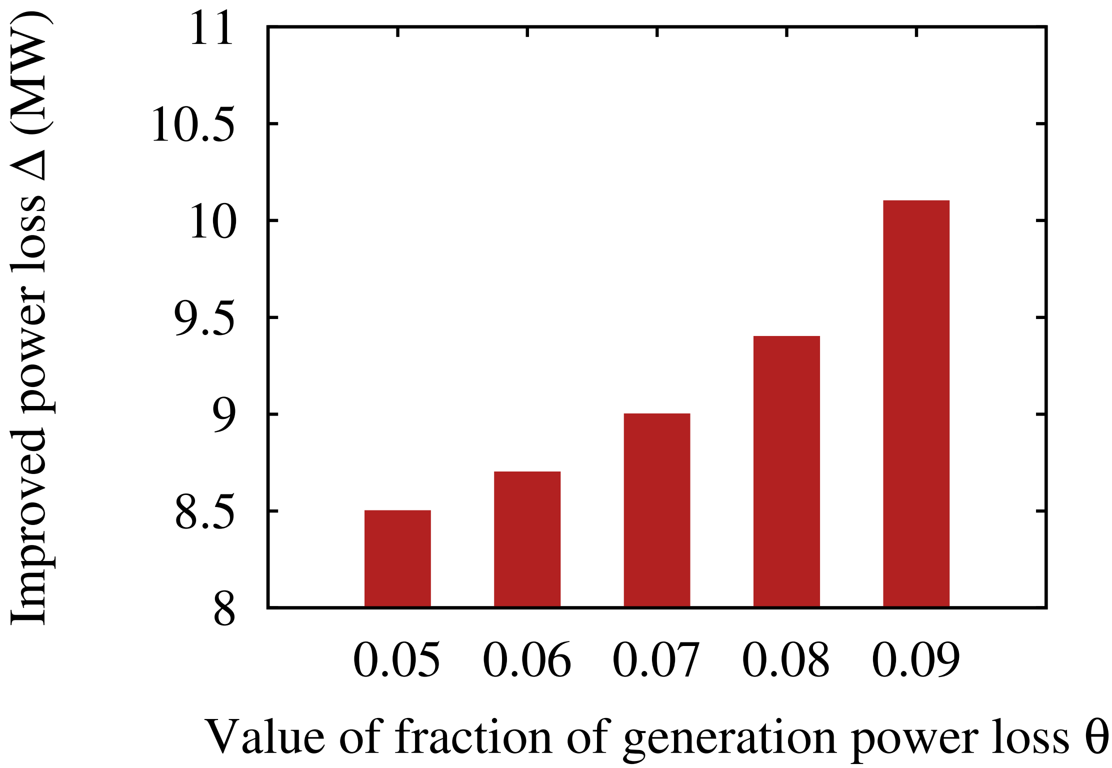


(a) Average power load from macro-Station

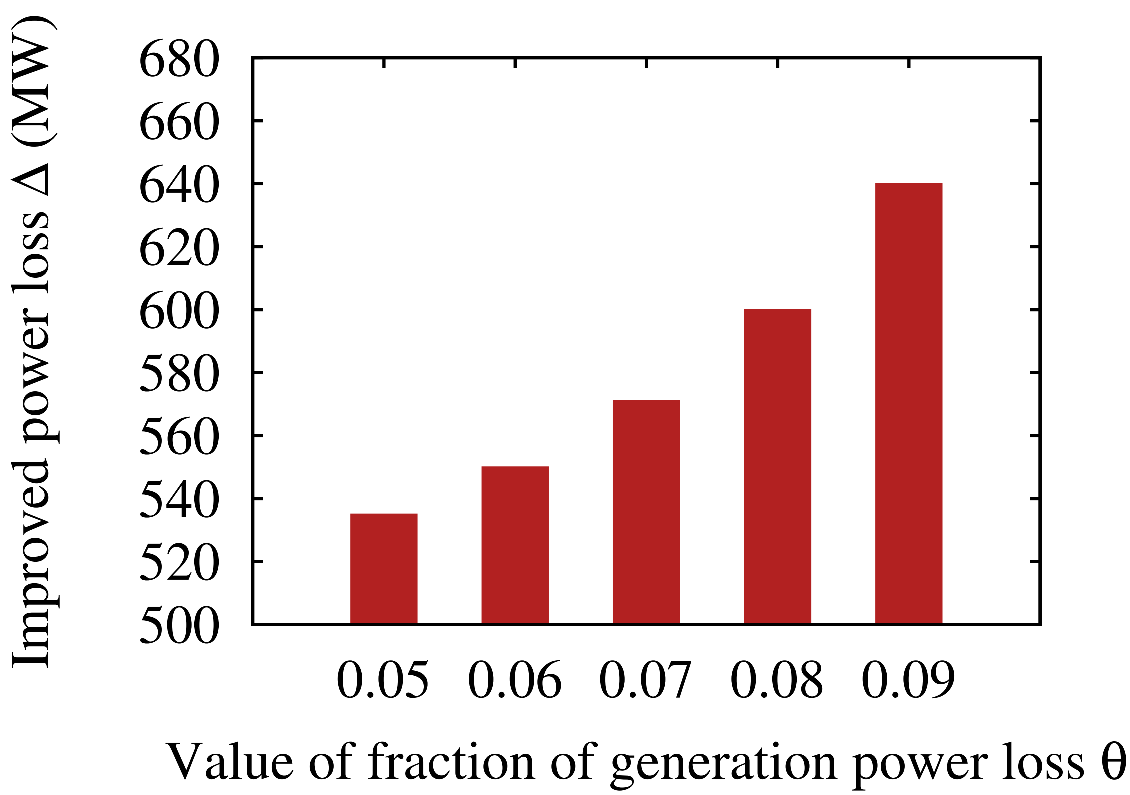


(b) Average power load from micro-grids

Figure 4.7: Average power load from macro-station and micro-grids

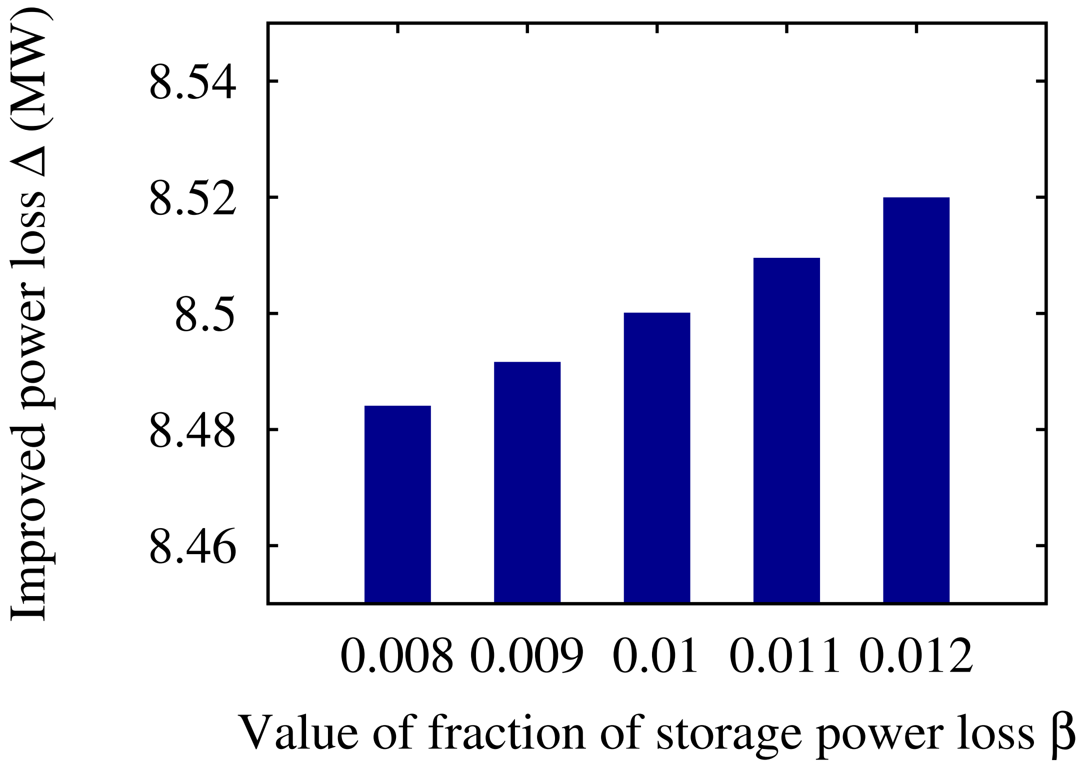


(a) Number of micro-grids = 5

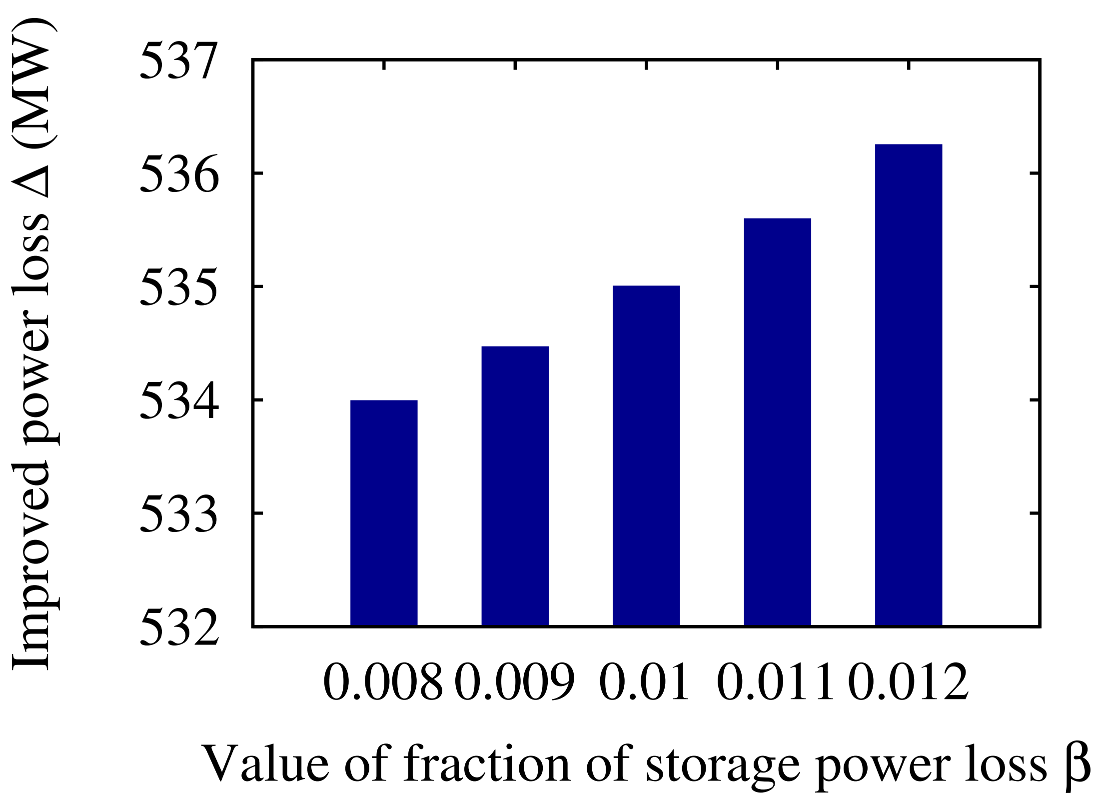


(b) Number of micro-grids = 50

Figure 4.8: Improved power loss in different parameter θ environment



(a) Number of micro-grids = 5



(b) Number of micro-grids = 50

Figure 4.9: Improved power loss in different parameter β environment

The micro-grids sent offer to their neighbors so as to form coalitions, based on the power exchange pair $(i,\ j)$. Then by using our proposed scheme, the micro-grids form coalitions so as to maximize their payoffs. When the coalitions are formed, the micro-grids belonging to the same coalition communicate with other micro-grids and exchange power with them. With increasing number of the micro-grids, the total communication overhead becomes larger as shown in Fig. 4.6. However, even for a significantly high number of micro-grids (e.g., 50), the total communications overhead experienced in all the micro-grids is approximately 600 KB, which does not affect much the available bandwidth on the considered system.

Fig. 4.7 (Copyright ©2014IEEE) demonstrates that the macro-station in the non-cooperative case needs to supply more power for the micro-girds to meet their demands than that in our proposal. The reason is that in the non-cooperative case, micro-grids only obtain power from the macro-station (it is the reason why the values of the non-cooperative case in Fig. 4.7(b) are zero) and it causes high power loss while by using our algorithm micro-grids could exchange power with others instead of macro-station so as to reduce power loss. Therefore, the proposed algorithm helps the macro-station to decrease the peak of power generation and improve efficiency of power.

Figs. 4.8 and 4.9 (Copyright ©2014IEEE) show the improved power loss, Δ, which is the power loss difference between our proposal and the non-cooperative case when the fraction of power generation parameter θ and the fraction of power storage parameter β are changed, respectively. In Fig. 4.8, θ is varied and β is fixed, and in Fig. 4.9, β is varied and θ is fixed. From these figures, we can find that the results are positive. It means that our proposed algorithm save more power than that in the non-cooperative case. The reason is that the non-cooperative case did not consider how to minimize the total power loss of the whole smart grid network, whilst our algorithm considers how to reduce the total power loss. Hence, our results are better than the non-cooperative case results in the same simulation environment.

4.5 Summary

In this chapter, we propose a centralized power distribution greedy algorithm for micro-grids that have power storage device.

- Firstly, the algorithm can help the micro-grids to form coalitions with their neighbors so as to minimize power loss.
- Secondly, the proposed algorithms also permits the micro-grids to make decisions on whether to form or break the coalitions while maximizing their utility functions through alleviating the power losses due to power generation, transmission, conversion, storage.
- Thirdly, the stability and convergency of the solution are proved.
- Finally, we make the numerical simulation. Though the simulation results, the effectiveness of the algorithm is demonstrated.

Algorithm 2 Power Exchange and Minimize Power Loss Algorithm. (Input: $D_i(t)$, $G_i(t)$, Output: exchange power pairs (i, j), $B_{ij}(t)$, $S_i(t)$, $B_{0i}(t)$, and $PLA_i(t)$)

BEGIN
For *micro-grid*$_i$
Calculate $PLG_i(t)$, $S_i(t)$, $W_i(t)$ and $PLS_i(t)$ based on eqs. (4.2), (4.3), and (4.4), respectively.
Send $W_i(t)$, $PLG_i(t)$, $S_i(t)$, and $PLS_i(t)$ to the macro-station
For the macro-station
Loop
Receive $W_i(t)$, $PLG_i(t)$, $S_i(t)$, and $PLS_i(t)$ from *micro-grid*$_i$.
Return ACK message.
Generate PEPS, calculate RUP of PEPS, and sort PEPS order in descending according to RUP.
While (PEPS is not empty)
Get first element $(i,\ j)$ from PEPS, generate exchange power pair $(i,\ j)$ in PEPS, and calculate power loss $PL_{ij}(t)$ and exchange power $B_{ij}(t)$, based on eqs. (4.8) and (4.9), respectively.
If $(|W_i(t)| = |B_{ij}(t)|)$
Delete potential exchange pair that i belongs to.
Else
Delete potential exchange pair that j belongs to.
Endif
Update $W_i(t)$, based on eqs. (4.10) and (4.11).
Send $(i,\ j)$, $B_{ij}(t)$ to *micro-grids* i and j.
Endwhile
Based on exchange power pair(s), set coalitions of the micro-grids by using $Merge$ and *Split* operations.
Update $S_i(t)$ and $PLS_i(t)$, and generate $\delta_i(t)$, based on cases 1 to 3.
Based on eq. (4.12), calculate $B_{0i}(t)$ and $PL_{0i}(t)$.
Calculate $PLA_i(t)$, based on eq. (4.5).
Send $S_i(t)$ and $B_{0i}(t)$ to *micro-grid*$_i$.
Endloop
For *micro-grid*$_i$
Exchange power $B_{ij}(t)$ with *micro-grid*$_j$, store power $S_i(t)$ and exchange power $B_{0i}(t)$ with the macro-station.
END

Chapter 5

Power Loss Minimization Method: A decentralized Approach

5.1 Introduction

The algorithms in Chapters 3 and 4 are centralized algorithms. It means that the micro-grids need to send information to the macro-station, wait the response from the macro-station, and exchange power with their neighbors based on the response. Although the results of those algorithms are global optimal, the centralized algorithms have some short-coming. For instance, security, stability of the system. Moreover, the algorithms cannot work in the micro-grids system without data center. Therefore, we propose a decentralized algorithm for the smart grid system without data center. In this case, the micro-grids exchange information with their one-hop neighbors, find the proper neighbors and exchange power with them so as to reduce the power loss. From the numerical results, we can find that although the average power loss of our decentralized algorithm is slightly more than that of the centralized algorithm, the communication overhead of our algorithm is less than that of the centralized algorithm.

5.2 System Model

In this section, our proposed model will be considered. As shown in Fig. 1.1, we consider that there are three layers in our model. The primary power station (macro-station) is the first layer. It could exchange power with the secondary power station (micro-grid). For simplicity, assume that the macro-station has enough power to meet the demands of the micro-grids and receive the surplus power from the micro-grids. Following as our previous work, each micro-grid is linked to the macro-station directly. The micro-grids are the second layers in our model. Comparing with the macro-station, they could be deployed nearer to customers. Therefore, the customers could be linked to the micro-grids directly. The micro-grids support power to the customers so as to meet the demands of them. And they will exchange power with their neighbors or the macro-station, when supply and demand are unequal. Because they just know the location of their neighbors, a distributed algorithm is to be proposed. The algorithm could help the micro-grids to find proper partner so as to minimize the total power loss of the smart grid. The smart meters are installed in equipment of the customers. Therefore, they can send the demands of the customers to the micro-grids. Finally, the customers, who obtain power from their respective micro-grids, form the last layer of our considered system.

Let $\mathcal{N}$ denote the set of the micro-grids and $N = |\mathcal{N}|$. In the given time period (e.g., one second), for $micro\text{-}grid_i$, we define real function $W_i(t)$ as the current remaining power of $micro\text{-}grid_i$ and it can be expressed as follows:

$$W_i(t) = G_i(t) - D_i(t). \tag{5.1}$$

where $G_i(t)$ and $D_i(t)$ are the generation power of $micro\text{-}grid_i$ and the demands of the customers which are linked to *micro-grid*$_i$, respectively. It means that *micro-grid*$_i$ wants to obtain power to meet its demand ($W_i(t) < 0$), *micro-grid*$_i$ has a power surplus to sell ($W_i(t) > 0$), or its supply equals its demand ($W_i(t) = 0$). The micro-grids can be divided into two types, namely "sellers" and "buyers". The "sellers" have surplus to sell while the "buyers" need additional amount of power to meet the demands of the customers. If the current remaining power of *micro-grid*$_i$ is zero ($W_i(t) = 0$), *micro-grid*$_i$ is considered to be either a "seller" or a "buyer", and it cannot affect the result. In fact, the demand of customers $D_i(t)$ and production power $G_i(t)$ are always considered as random numbers in the real smart grid networks. As a consequence, the value of $W_i(t)$ is accordingly considered as a random number with a certain observed distribution.

When $W_i(t) \neq 0$, *micro-grid*$_i$ will exchange power with other micro-grids or the macro-station. It will cause power loss. For simplicity, two kinds of power losses will be considered in our model. The first one is Power Loss due to Transmission (PLT). The other power loss is Power Loss due to Conversion (PLC).

First, the power loss between two micro-grids are considered. Based on eq. 2.3, if *micro-grid*$_i$ transmits power to *micro-grid*$_j$, the power loss function $PL_{ij}(t)$ can be expressed as follows.

$$PL_{ij}(t) = \frac{R_{ij} Q_{ij}^2(t)}{U_1^2}, \tag{5.2}$$

where R_{ij} is the resistance of the distribution line between *micro-grid*$_i$ and *micro-grid*$_j$. U_1 denotes the transfer voltage between *micro-grid*$_i$ and *micro-grid*$_j$ and it is less than U_0. In this model, we do not consider the power loss of transforming between *micro-grid*$_i$

and *micro-grid*$_j$. Also, $Q_{ij}(t)$ is defined as.

$$Q_{ij}(t) = \begin{cases} \frac{Q_{ij}^2(t)R_{ij}}{U_1^2} - W_j(t) : |W_i(t)| > |W_j(t)| \\ W_i(t) \qquad\qquad : otherwise. \end{cases} \tag{5.3}$$

If *micro-grid*$_i$ sells power to *micro-grid*$_j$, the current remaining power $D_i(t)$ will be updated as:

$$W_i(t) = W_i(t) - Q_{ij}(t). \tag{5.4}$$

If *micro-grid*$_i$ buys power from *micro-grid*$_j$, $W_i(t)$ will be updated as follow:

$$W_i(t) = \min\{W_i(t) + Q_{ij}(t) - PL_{ij}(t), 0\}. \tag{5.5}$$

After exchanging power with other micro-grids, if $D_i \neq 0$, *micro-grid*$_i$ will exchange power with the macro-station. In this process, we consider two kinds of power losses, namely PLT and PLC. If *micro-grid*$_i$ wants to sell $D_i(t)$ to the macro-station ($D_i(t) > 0$) or buy $D_i(t)$ from the macro-station ($D_i(t) < 0$), we are able to express the power loss $PL_{0i}(t)$ as follows.

$$PL_{0i}(t) = \frac{R_{0i}Q_{0i}^2(t)}{U_0^2} + \alpha Q_{0i}(t), \tag{5.6}$$

where R_{0i} is the distribution line resistance between the macro-station and *micro-grid*$_i$, the voltage of power transfer between the *micro-grid*$_i$ and the macro-station is U_0, and α is a fraction of power loss caused by voltage conversion. For simplicity, α is treated as a constant. $Q_{0i}(t)$ is the power that *micro-grid*$_i$ wants to buy or sell. The value of $Q_{0i}(t)$

is any of the following.

$$Q_{0i}(t) = \begin{cases} \frac{Q_{0i}^2(t)R_{ij}}{U_0^2} + \alpha Q_{0i}(t) - W_i(t) & : \quad W_i(t) < 0 \\ W_i(t) & : \quad otherwise. \end{cases} \tag{5.7}$$

Based on eqs. (5.2) and (5.6), in a given time slot t, the total power loss of the i^{th} micro-grid $PLA_i(t)$ is,

$$PLA_i(t) = PL_{0i}(t) + \sum_j \frac{PL_{ij}(t)}{2}. \tag{5.8}$$

If *micro-grid*$_i$ exchanges power with *micro-grid*$_j$, power loss $PL_{ij}(t)$ should not be calculated twice. Therefore, $PLA_i(t)$ includes half of $PL_{ij}(t)$.

Our research target is to minimize the total power loss. Hence, the objective function is,

$$\begin{aligned} & Minimize \sum_i PLA_i(t) \\ & s.t. \quad D_i(t) \leq G_i(t) + \eta_i(t) \quad \forall i \in \mathcal{N}, \end{aligned} \tag{5.9}$$

where $\eta_i(t) = sign(D_i(t))Q_{0i}(t) - PL_{0i}(t) + \sum_j (sign(D_i(t))Q_{ij}(t) - PL_{ij}(t))$, $sign(D_i(t)) = 1$ if $D_i(t) < 0$, and $sign(D_i(t)) = -1$ otherwise. Therefore, our condition is that the demand at each micro-grid does not exceed the sum of the amount of remaining produced power and the power it exchanged with other micro-grids and the macro-station.

5.3 Algorithm for power exchange

In Section 5.2, the model and functions are discussed. Based on these functions, the total power loss of smart grid could be calculated. However, unlike centralized algorithm, the micro-grids do not acquaint the total information. They just know the locations of one-hop neighbor(s) and exchange power with it/them.

At the beginning of time slot t, $micro\text{-}grid_i$ receives $W_i(t)$ from the customers. To meet $D_i(t)$, $micro\text{-}grid_i$ generates power $G_i(t)$. If current remaining power of $micro\text{-}grid_i$ $W_i(t) \neq 0$, $micro\text{-}grid_i$ will exchange power with its neighbor(s). The $micro\text{-}grid_i$ will exchange information of $W_i(t)$ with its neighbors. Based on the remaining power of neighbors, $micro\text{-}grid_i$ generates a set of Potential Exchange power Neighbors (PEN). This set means that if $micro\text{-}grid_j \in PEN$, $micro\text{-}grid_i$ has opportunity to exchange power to $micro\text{-}grid_j$. If PEN of $micro\text{-}grid_i$ has more than one element, it needs to choose proper neighbor to exchange power, so as to minimize the total power loss. The "Reducing power loss per Unit exchanged Power" (RUP) of $micro\text{-}grid_i$ and $micro\text{-}grid_j$ for the micro-grid pair can deal with this problem. If $micro\text{-}grid_i$ exchanges power with $micro\text{-}grid_j$, the function is expressed below,

$$RUP(Q_{ij}(t)) = \frac{PL_{0i}(t) + PL_{0j}(t) - PL_{ij}(t)}{|Q_{ij}(t)|}. \tag{5.10}$$

This function represents potential extra payoffs (reducing power loss) per unit exchange power, if $micro\text{-}grid_i$ joins the coalition. $PL_{0i}(t)$ and $PL_{0j}(t)$ represent power loses if the same power $Q_{ij}(t)$ was exchanged with macro-station by both micro-grids, in the current coalition. Merging them could replace these two by power exchange between them, with power loss $PL_{ij}(t)$. Higher values of RUP mean saving power per unit power. Therefore, based on eq. (5.10), the micro-grids can make the best decisions to merge their coalitions.

The $micro\text{-}grid_i$ calculates RUP (eq. 5.10) of PEN and sorts PEN in descending order according to RUP. Then, $micro\text{-}grid_i$ considers the first element j from PEN, if PEN is not empty. $Micro\text{-}grid_i$ sends $D_i(t)$ to $micro\text{-}grid_j$, waits for the response from $micro\text{-}grid_j$ unless time-out occurs. If $micro\text{-}grid_i$ receives "accept" response from $micro\text{-}grid_j$, it will exchange power with $micro\text{-}grid_i$, based on $W_i(t)$ and $W_j(t)$, delete j from PEN, and update $W_i(t)$. $Micro\text{-}grid_j$ will be deleted when $micro\text{-}grid_i$ is waiting for the response from $micro\text{-}grid_j$ and time-out occurs, or the response is "reject". At the same time, $micro\text{-}grid_i$ receives offers from its neighbors as well. If $micro\text{-}grid_i$ is waiting the response from the first element of PEN j and receives the offer from other neighbor $k(k \neq j)$, the status of $micro\text{-}grid_k$ will be set as "hold" and the hold message is returned. The neighbor k will not be deleted until time-out occurs. The above action will not repeated until $W_i(t) = 0$ or PEN is empty. After exchanging power with one-hip neighbors, $W_i(t)$ has been updated by the quantities of exchanged powers. If $W_i(t) \neq 0$, $micro\text{-}grid_i$ will exchange power with the macro-station. For instance, assume that there are one macro-station (MS) and five micro-grids (MG1 to MG5) (5.1, copyright ©IEEE 2014). RUP_{12}=1.2, RUP_{23}=2, RUP_{34}=3.5, and RUP_{45}=4. Based on those RUPs, MG1 will send offer to MG2, MG2 will send offer to MG3, MG3 will send offer to MG4, and MG5 will send offer to MG4. Because MG4 sends offer to MG5 and waits the response, MG4 will send "hold" to MG3. In the same manner, MG3 and MG2 send "hold" to MG2 and MG1, respectively. When MG4 receives response from MG5, they will exchange power.

Because PL_{45}=0.2, Q_{45}=1.3. After that W_4=W_5=0 and MG4 sends "reject" to MG3. When MG3 receives "reject", it will activate the offer of MG2 and exchange power with MG2 (Q_{23}=3). Therefore, MG1 receives "reject" from MG2, after power transmission between MG2 and MG3 (W_2=W_3=0). Finally, MG1 will exchange power with the MS ($Q_{01} = 3.5$).

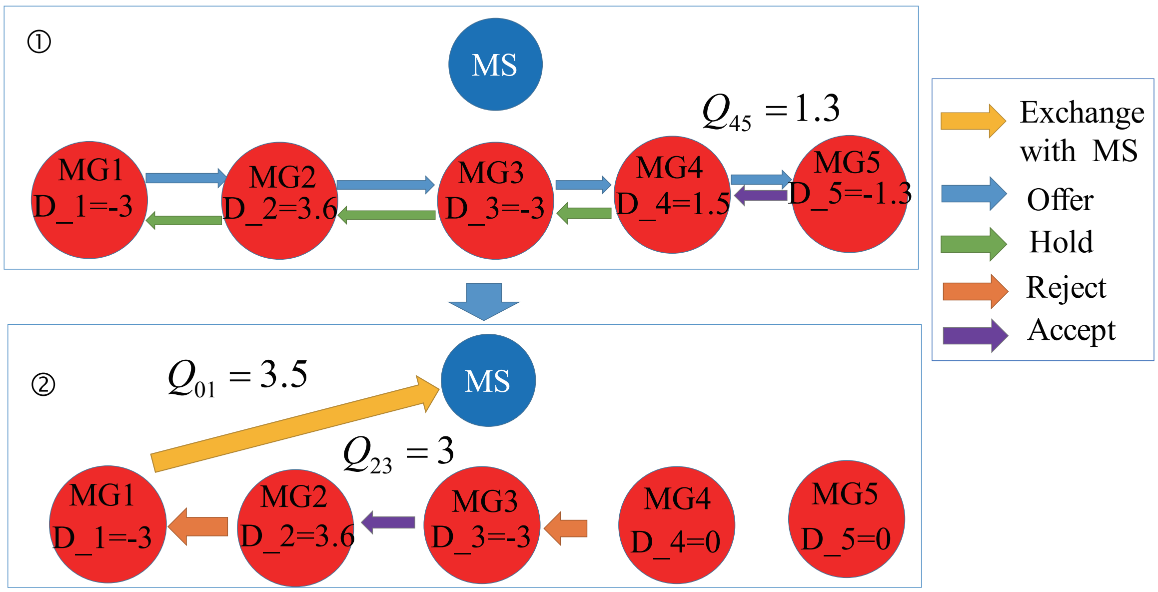


Figure 5.1: A simple example showing how the algorithm 3 leads to power exchange between micro-grids and macro-station with minimized power loss.

Theorem 5.3.1 *The solution of Algorithm 3 is Pareto Optimal.*

Proof Assume that the solution $(a_1, a_2, ..., a_N)$ is not Pareto Optimal. Therefore, there exists a micro-grid $l \in N$ least, which can adjust its action a_l to a_l^* so as to augment its utility while utilities of others will not be diminished. In other words, $u(a_l, a_{-l}) < u(a_l^*, a_{-l})$. Because the algorithm could help micro-grids to find the most proper neighbors and exchange power so as to maximize their payoff, micro-grids cannot augment their utilities through change the solution of the algorithm. Therefore, $u(a_l, a_{-l}) \geq u(a_l^*, a_{-l}) \quad \forall a_l^* \in A_l$. This result contradicts the previous assumption that the solution is not Pareto Optimal.

5.4 Performance Evaluation

In this section, simulation results are presented to evaluate the effectiveness of our proposed algorithm. The performance of our proposed scheme is compared with that of a distributed algorithm that the micro-grids will choose the nearest neighboring micro-grid to exchange power, and our previous centralized work GT-CFS. Our considered simulation scenario comprises a power distribution grid topology, area of which $10 \times 10\ km^2$. The macro-station is placed at the center of the grid, and the micro-grids are deployed randomly in the topology. Each micro-grid is linked with its one-hop neighbouring micro-grid and the macro-station. Similar to the assumption made by, the power demands of the customers $D_i(t)$ of $micro\text{-}grid_i$ is derived from a Gaussian distribution between 10 MW and 316 MW. The power generation $G_i(t)$ is obtained from a Gaussian distribution between 10 MW and 316 MW. The resistance between the micro-grids is the same as that between the macro-station and any micro-grid, and its value $R = 0.2\ \Omega$ per km. The fraction number of power conversion $\alpha = 0.02$ according to the assumption in. The voltage values of U_0 and U_1 are set to 50 kV and 22 kV, respectively, which represent practical values in a variety of smart grid distribution networks. The prices of the each of the unit power are set as $w_1 = 1$ and $w_2 = 3$. The simulation results are presented in the remainder of this section.

Fig. 5.2 (Copyright ©2014IEEE) depicts the average power loss per micro-grid for varying number of micro-grids from 5 to 50 in case of a distributed algorithm that micro-grids will find the nearest micro-grid to exchange power and our proposed algorithm.

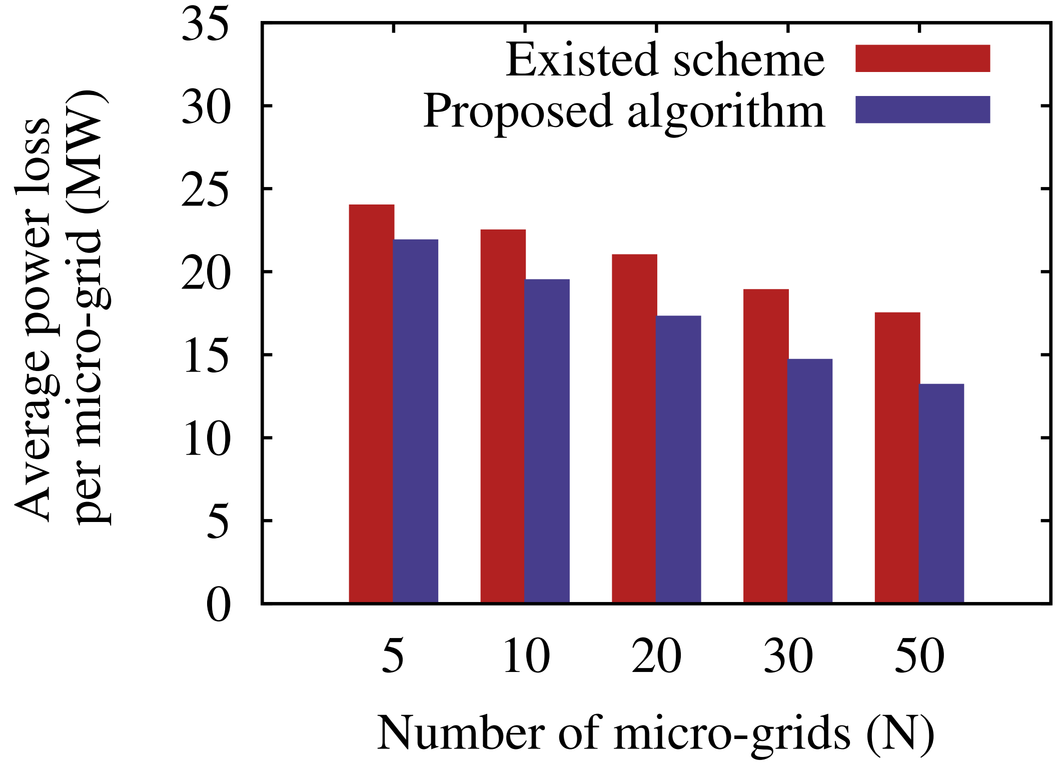


Figure 5.2: Comparison of the average power loss in the nearest-neighbor-find scheme and our proposal.

The results in the figure indicates that when the number of micro-grids increases, the power losses decrease. However, the result of our proposed algorithm is less than that in nearest-neighbor-find algorithm. The reason is that in our algorithm the total power loss is considered, global optimal is better than local optimal. By using out proposal, the micro-grids could find the proper one-hip neighbors to exchange power, so as to minimize the total power loss.

Fig. 5.3 (Copyright ©2014IEEE) demonstrates the percentage of cost saving using our proposal compared with the nearest-neighbor-find algorithm. As shown in the figure, when the number of micro-grids increases, the percentage becomes bigger. This is because our proposal could help micro-grids to find proper neighbor so as to minimize the total power loss and saving the money. Hence, our algorithm will help the entire power grid to

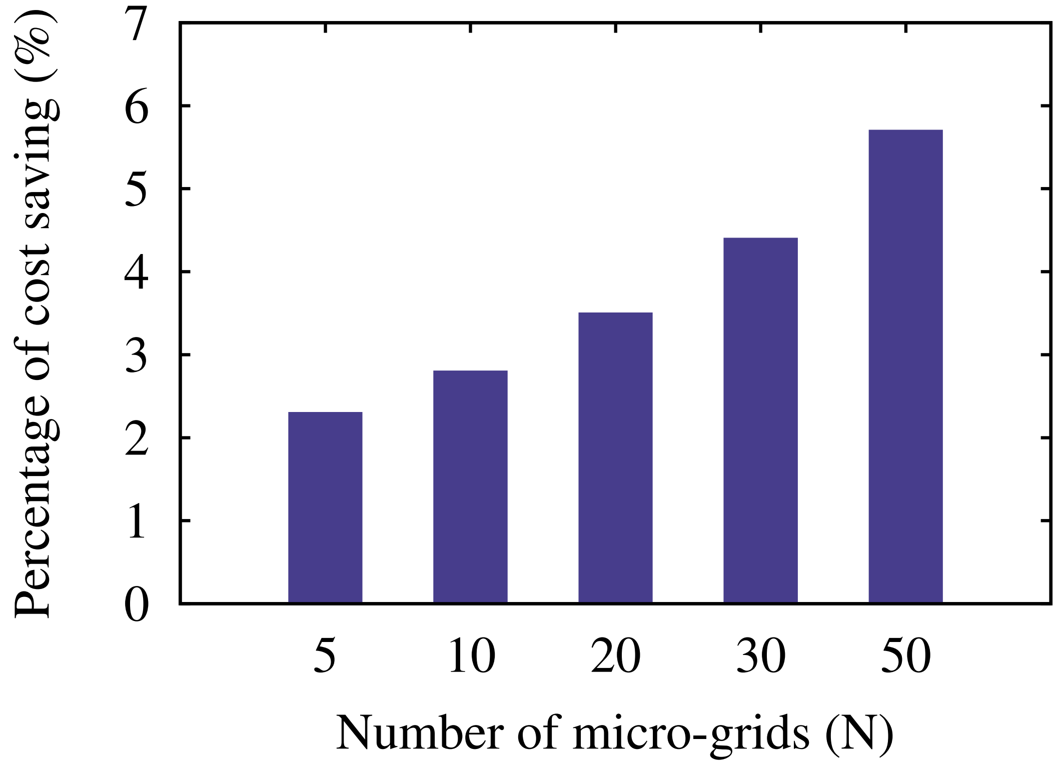


Figure 5.3: The percentage of cost saving using our proposal compared with the distributed nearest-neighbor-find algorithm.

save a significant amount of money in contrast with the nearest-neighbor-find algorithm.

Fig. 5.4 (Copyright ©2014IEEE) demonstrates that the macro-station in the nearest-neighbor-find case needs to supply more power for the micro-girds to meet their demands than that in our proposal. The reason is that in the nearest-neighbor-find case, micro-grids only exchange power with the nearest one-hip neighboring micro-grids and it did not consider the total power loss while by using our algorithm micro-grids could exchange power with others so as to reduce the total power loss. Higher power loss will cause higher power load from the macro-station. Therefore, the proposed algorithm helps the macro-station to decrease the peak of power generation and improve efficiency of power.

Next, let us consider the comparison in centralized algorithm and our proposal. In centralized algorithm, the micro-grids will send demands to the data center (e.g., macro-

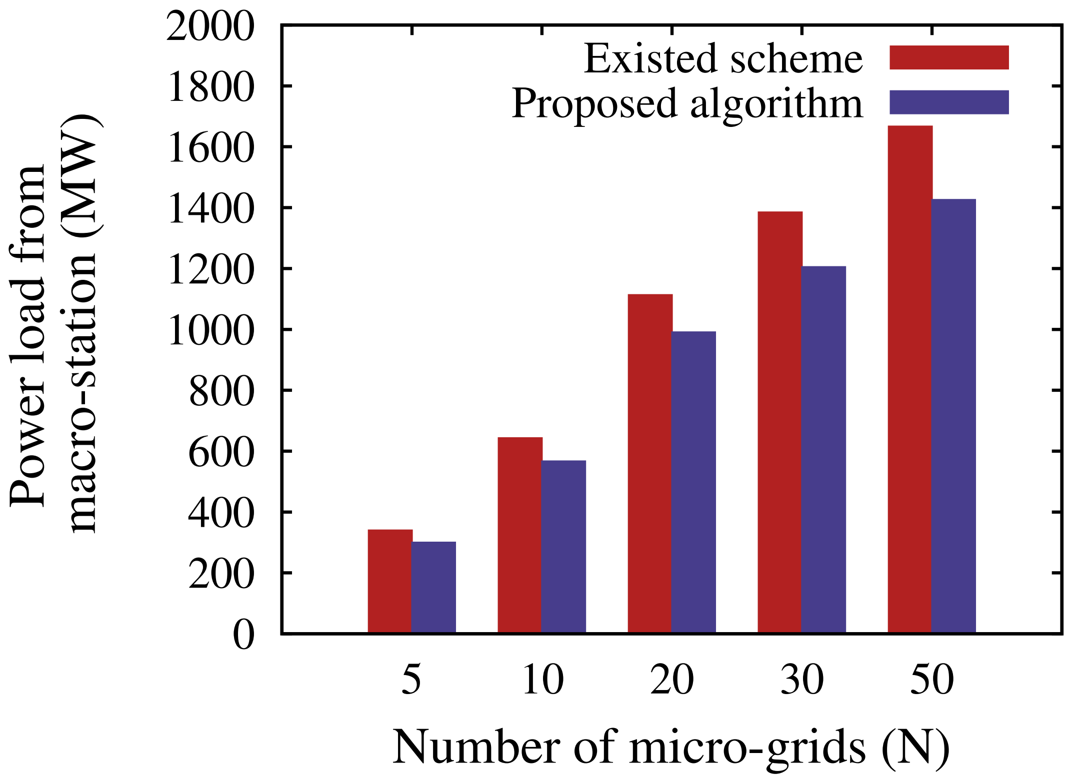
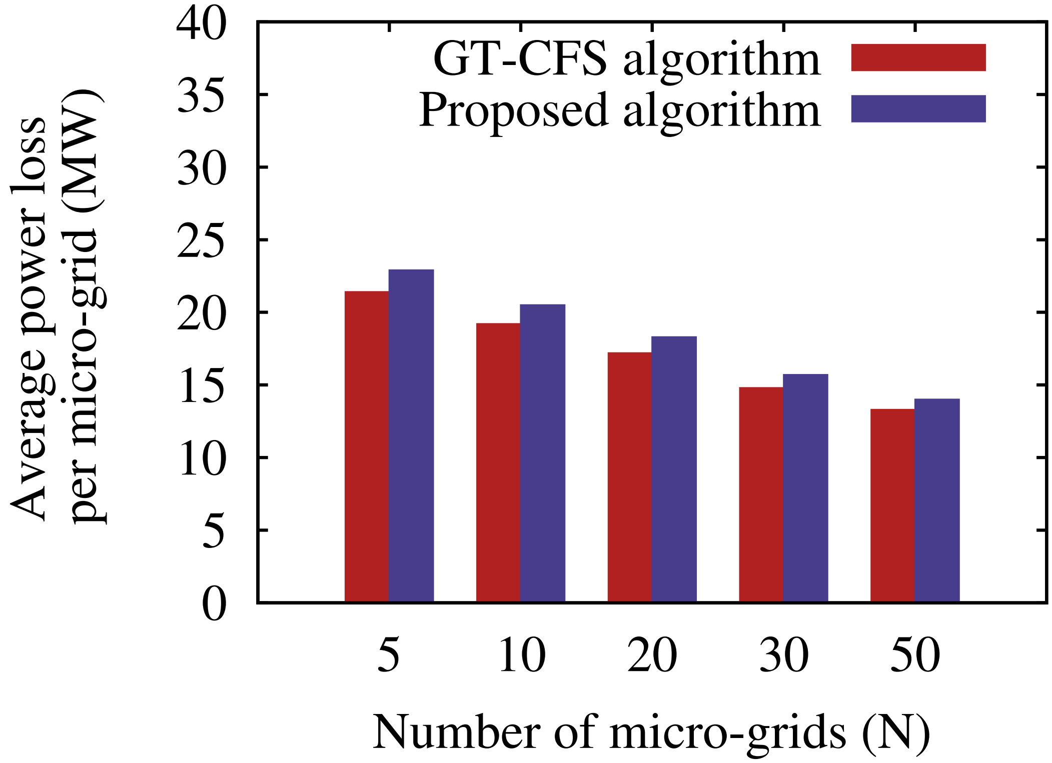
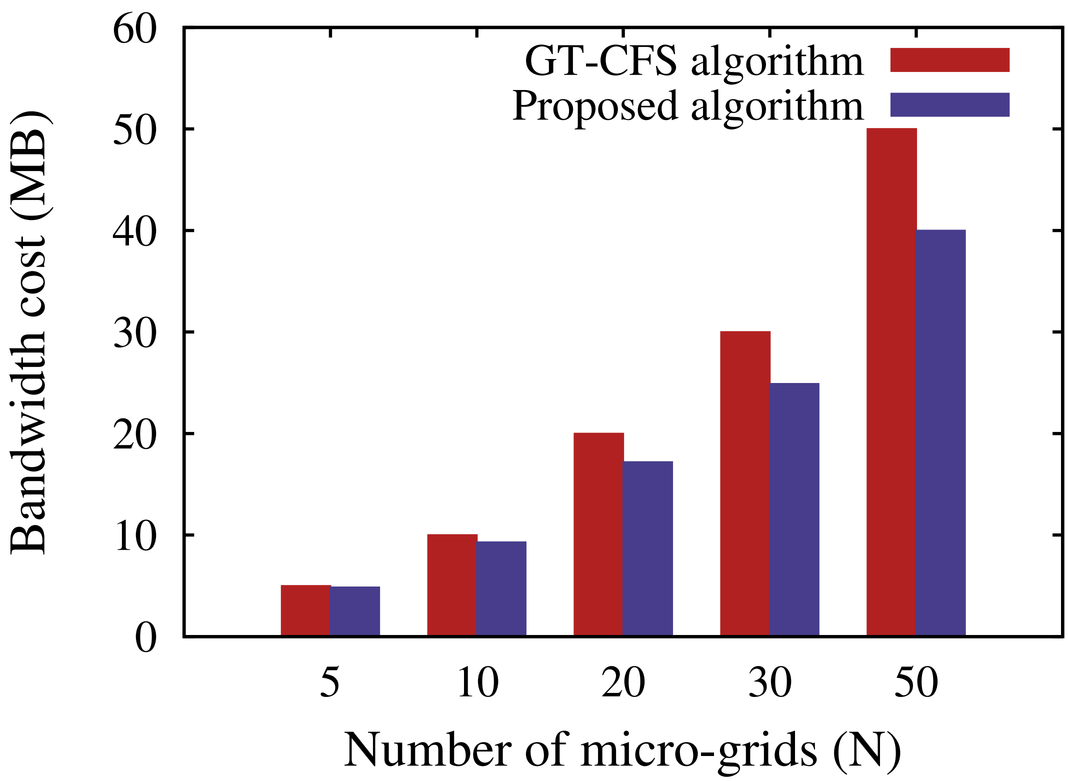


Figure 5.4: The power load on the macro-station in nearest-neighbor-find case and our proposal.

station). The macro-station will help all the micro-grids to find proper neighbors, as it knows all the information of the micro-grids. However, in distributed system, the micro-grids only know the demands of one-hip neighbors. By using our proposal, the micro-grids will send the demands to one-hip neighbors so as to minimize the total power loss. If the time-out occurs, the micro-grids will give up this neighbor and try to exchange power with other neighbors. And it could add power loss. Therefore, the average power loss in our proposal is sightly more than that in centralized algorithm (e.g., GT-CFS). The fig. 5.5(a) (Copyright ©2014IEEE) talks about it. In the other hand, because the micro-grids do not send information to the data center, the communication bandwidth cost in our proposal is less than that in the centralized algorithm. Therefore, from Fig. 5.5(b) (Copyright ©2014IEEE), we can see that the communication bandwidth cost in our proposal is less



(a) Average power loss



(b) The bandwidth cost

Figure 5.5: The comparison in GT-CFS and our proposal.

than that in our previous work GT-CFS. It means that by using our algorithm, more micro-grids could share the fixed bandwidth by using our proposal than that in GT-CFS.

5.5 Summary

In this chapter, we propose a novel decentralized power distribution algorithm for the micro-grids. Our proposal allows the micro-grids to make coalitions so as to minimize the total power loss. At first, the micro-grids exchange information with their neighbors. After that the micro-grids will find the potential exchange neighbors and send exchange offer to them. Based on the demand of users, the micro-grids will automatically decide whether they want to form coalition with their neighbors by using the algorithm. When the coalitions are formed, the micro-grids in the same coalition will exchange power with others. Finally, in contrast with the nearest-neighbor-find algorithm and our previous work, the performance of our proposed algorithm is shown.

Algorithm 3 DISTRIBUTED POWER EXCHANGE ALGORITHM OF MICRO-GRIDs (Input: $W_i(t)$, $G_i(t)$, Output: $Q_{ij}(t)$, $Q_{0i}(t)$, and $PLA_i(t)$)

```
BEGIN
 for each micro-grid i
 Loop
   Calculate D_i(t), based on W_i(t), G_i(t) (eq. 5.1)
   While (D_i(t) ≠ 0)
    Send information of D_i(t) with its neighbors.
    Generate PEN, calculate RUP of PEN and sort PEN
    While (D_i(t) ≠ 0 and PEN is not empty)
      Get first element of PEN j
      If (j.status==hold and time-out occur)
       Delete j from PEN
      Else
       Send offer to micro-grid_j and wait response
       while (time-out does not occur)
         If (the response from j ==“accept”)
          exchange power with j, calculate Q_ij(t), PL_ij(t) based on eqs. 5.2, 5.3, update
D_i(t) and delete j from PEN.
         Endif
         If (receive offer from neighbor k and k ≠ j)
          k.status=hold and send “hold” to k
         Endif
       Endwhile
      Delete j from PEN
      Endif
    Endwhile
    If (D_i(t) ≠ 0)
      Calculate Q_0i(t), PL_0i(t) based on eqs. 5.6 and 5.7 and D_i(t)=0
    Else
      If receive offer from neighbor l
       Send “reject” to the neighbor l
      Endif
    Endif
   Endwhile
 Endloop
END
```

Chapter 6

Conclusion

6.1 Summary and Discussions

As a new kind of power grid, the smart micro-grid can adjust power production depending on the demands of users. However, when the supply power of the micro-grid is less than the demand of users, power will be transmitted among the micro-grids so as to meet the demands. Power distribution causes power loss. Therefore, how to minimize the power loss is the most important thing for the power distribution algorithm. In this thesis, we focus on proposing the power distribution algorithms so as to improve the efficiency of power. The primary contributions of this dissertation are listed as follows:

- We introduce the smart micro-grid in Chapter 2. Moreover, literature review is also introduced in this chapter. After that we point out the reasons of power distribution in the smart micro-grids. We will propose the algorithms to solve the power distribution problem in thesis. At the end of this chapter, propose power loss formulations are given so as to help we to propose the algorithms in the next chapters.

- In Chapter 3, we proposed a novel game theoretic coalition formulation strategy dubbed GT-CFS for distributed micro grids. Our proposal allowed the micro-grids to form coalitions so that the power loss is minimized when power is transmitted from a micro-grid to other micro-grids or the macro station. The propose GT-CFS also allows the micro-grids to make decisions on whether to form or break the coalitions while maximizing their utility functions through alleviating the power loss within power transfer. To prove the stability and optimality of GT-CFS, we made mathematical proofs. After that, we make an analysis on determining an optimal number of micro-grids required for a given area. Through simulation results, the effectiveness of GT-CFS is verified. Comparative results demonstrate its superior performance, in contrast with the non-cooperative model and the conventional model, in terms of a significant reduction of the average power loss per micro-grid.

- To optimally reduce the total power losses in such a power grid system, in Chapter 4, we propose a greedy coalition formation algorithm, which allowed the macro-station to coordinate mutual power exchange among the micro-grids and between each micro-grid and macro-station. Our algorithm optimized the total power losses across the entire power grid, including the cost of charging and discharging power storage devices, and power losses due to power transfers. The algorithm creates exchange pairs among the micro-grids giving priority to pairs with higher power loss reduction per exchanged power unit. Through computer-based simulations, we demonstrated that the proposed approach significantly reduces the average power loss compared with the conventional non-cooperative method. The simulations also demonstrated that the communications overhead of our proposal (due to negotiations aimed at forming coalitions) does not significantly affect the available communication resource.

- We proposed a distributed algorithm is proposed in the Chapter 5. By using this distributed algorithm, the micro-grids only exchanged information with their one-hop neighbours. After that power be distributed in the smart grid so as to meet the demands of users. We made mathematical proofs that the distributed algorithm is stable, convergent and near-optimal. Then through computer simulations, we demonstrate that the proposed algorithm can lead to near-optimal result for alleviating the average power loss per micro-grid and reduce the communication overhead significantly in contrast with the centralized approach.

6.2 Future Directions

In this thesis, we developer theoretical models for analytical study of power distribution and power loss minimization in smart micro-grids. The possible future works are as fellows:

Notice that the theoretical models and closed-form results for smart micro-grids power distribution developed in this thesis hold only for power distribution among one-hop neighbours, so one of our future research directions is to explore theoretical models in a more flexible scenario, where not only one-hop but k-hop ($k \geq 2$) neighbours will be considered as power transmission partners to take advantage of power distribution among smart micro-grids.

Since all theoretical models in this thesis had one macro-station models, it would be interesting to further extend the developed theoretical models to analyse the power distribution and power loss minimization in k macro-station power grids.

Other interesting future direction is to consider more kinds of power loss in our models. For instance, power loss due to transmission between smart micro-grids and the users. Moreover, we will consider real industrial smart micro-grids model.

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