Dynamic Economic Dispatch for Multi-Microgrid System using Game Theory

Aidana Kalakova, Electrical and Electronic B.Eng.

Submitted in fulfilment of the requirements for
the degree of Master of Science
in Electrical and Computer Engineering

School of Engineering Department
Electrical and Computer Engineering
Nazarbayev University

53 Kabanbay Batyr Avenue,
Nur-Sultan, Kazakhstan, 010000

Supervisor: Hema Satya Venkata Sivanand Kumar Nunna
Co-supervisor: Prashant Kumar Jamwal

2020

Abstract

The growth of the interest in the Distributed Energy Resources in the Active Distribution Networks, along with the increasing requirements of the customers, leads to the issue of the optimal energy scheduling. Forming of the microgrids for the generation of the local energy can solve this problem by improving the flexibility and reliability of the system by bringing self-supportable systems. Unfortunately, in case of energy excess or demand in the microgrid, the trading should be conducted with the grid at the established prices known as Feed-in tariff and Time-of-use. These prices not optimal for microgrids' trading, as energy generated by microgrid is costing less than the price set by the grid for buying, and more than the price set for selling. Some counties completely eliminated trading with the microgrids, which leads to the significant challenges to the self-controlled operation systems. By combining ideas of the smart grid and microgrid, especially the advantages of two approaches, the Multi-Microgrid system comes into the picture. The Multi-Microgrid system allows energy exchange between the microgrids in the network by sharing the excess energy with those in demand. Nevertheless, the presence of the Transactive Energy Management will not fully solve the issue of the total load and generation difference in the Multi-Microgrid system.

This master thesis work proposes the use of the Dynamic Economic Dispatch for the Multi-Microgrid system with Transactive Energy Management, where Game Theory is used for the identification of the bidding for the microgrids. In the proposed approach Dynamic Economic Dispatch is a way of effective management of the microgrids, with providing secure and economically optimal energy scheduling. Besides, use of the Dynamic Economic Dispatch for the Multi-Microgrid system management will motivate microgrids to participate in the energy auctions, which also leads to the diminution of the difference between the load and the generation in the system. Also, author of work proposes using of three different platforms for energy exchange: trading with the grid, energy trading with centralized structure, and decentralized Transactive Energy management, where the aim is to analyze the results of the different approaches and define the best among them.

Acknowledgment

First of all. I would like to acknowledge my special gratitude towards my supervisors Professor Hema Satya Venkata Sivanand Kumar Nunna and Professor Prashant Kumar Jamwal for their supervision and guidance throughout the duration of my study. With the help of their expert advice, it became possible to write this thesis work and successfully complete the Master of Electrical and Computer Engineering program. I am very thankful for the time they spend in helping me and the discussion that was offered.

Secondly, I would like to express thankfulness to the teaching staff at Nazarbayev University who shared their knowledge with me and whose effort helped me to improve myself in the professional aspect. Besides, I also want to acknowledge the work of the administration staff at the university, whom I want to say thanks to their work.

Thirdly, I want to thank my parents Kalakov Bergen and Kalakova Gulsim, who made the most important help for me, which is namely psychological help and continuous support within all the time of my study. Without their support, I would not able to finish my work, and I am incredibly grateful to my parents. I also want to say thanks to my little sister Akdana and my boyfriend for their support and encouragement throughout this thesis work.

Table of Contents

List of Abbreviations

DN	Distribution Network
AND	Active Distribution Network
DG	Distributed Generator
DER	Distributed Energy Resource
SWOT	Strength, Weaknesses, Opportunities, Threats
EISA	Energy Independence and Security Act
ED	Economic Dispatch
SED	Static Economic Dispatch
DED	Dynamic Economic Dispatch
MMG	Multi-Microgrid
GT	Game Theory
FIT	Feed-in-tariff
TOU	Time-of-use
ODED	Optimal Dynamic Economic Dispatch
AI	Artificial Intelligence
TE	Transactive Energy
DSO	Distributed System Operator
MCP	Market Clearing Price
CNP	Contract Net Protocol
NE	Nash Equilibrium
GA	Genetic Algorithm
STLF	Short-term Load Forecasting
VSTLF	Very-short-term Load Forecasting
MTLF	Mid-term Load Forecasting
LTLF	Long-term Load Forecasting
DNN	Deep Neural Network

List of Figures

List of Tables

List of Publications

1. A. Kalakova, H. S. V. S. K. Nunna, P. K. Jamwal and S. Doolla, "Genetic Algorithm for Dynamic Economic Dispatch with Short-Term Load Forecasting," *2019 IEEE Industry Applications Society Annual Meeting*, Baltimore, MD, USA, 2019, pp. 1-6. (Published)
2. B. Satuyeva, B. Sultankulov, H. S. V. S. K. Nunna, A. Kalakova and S. Doolla, "Q-Learning based Protection Scheme for Microgrid using Multi-Agent System," *2019 International Conference on Smart EnergySystems and Technologies (SEST)*, Porto, Portugal, 2019, pp. 1-6. (Published)
3. A. Kalakova, Y. Amanbek, H. S. V. S. K. Nunna, P. K. Jamwal and S. Doolla, "Feasibility Study of Energy Storage Systems for a Wind Farm: A Case of Ereymentau Region in Kazakhstan," *CPE-POWERENG 2020 14th International Conference on Compatibility, Power Electronics and Power Engineering*, Setubal, Portugal, pp. 1-6. (Accepted for Publication)
4. A. Kalakova, H. S. V. S. K. Nunna, P. K. Jamwal and S. Doolla, "Decentralized Transactive Energy Auction with Demand Response," 2019. (Prepared)
5. A. Kalakova, H. S. V. S. K. Nunna, P. K. Jamwal and S. Doolla, "Dynamic Economic Dispatch using Novel Genetic Algorithm with Short-Term Load Forecasting, IEEE IAS (Submitted, Under review)

Chapter 1 - Introduction

1.1. Background

Integration of Distribution Networks (DNs) leads to the formation of the Active Distribution Networks (ADNs), where each ADN can be presented as large-scale cooperation of the Distributed Generators (DGs), energy storage systems and other generation units. ADNs are the hybrid systems, which can comprise conventional power generation units, such as thermal power generation or hydropower stations, as well as renewable generation facilities [1]. The fundamental goal of the ADNs is the practical and efficient integration of the Distributed Energy Resources (DER) whilst the support of the reliable and securable load dispatching. The tendency in the increasing amount of the DERs in ADNs and power distribution systems, along with the rising customers' requirements for load, results in the issue of optimal energy scheduling in the microgrids [2].

Forming of the microgrids for the generation of local and good quality power brings several benefits, such as improving flexibility, self-supportability, and reliability of the system [3]. Authors in [4] represented the "SWOT" analysis for microgrids, where both advantages and disadvantages were depicted. In the case of benefits, the authors mentioned improving power quality, generation of reliable energy and reduction of distribution losses, enhanced system control, and presence of renewable energy generation in case of transferring to the microgrids. Despite all of the positive aspects, there are still challenges related to switching to the microgrid systems and integration of the DGs. The disadvantages include cases of supply and demand mismatch due to the presence of an increasing amount of the non-dispatchable DG resources, which include wind turbines or solar-powered photovoltaic (PV) panels. Specialists in the energy field propose to reduce the amount of the DGs by replacing it with the backup generation, e.g., liquid propane or diesel generators, which still can support grid independence and will adjust the imbalance between supply and demand [5]. Unfortunately, ecological problems which make themselves to be felt will be only getting worse with the use of the backup systems, as they will cause increasing pollution level; moreover, cost of operation and maintenance of backup generation systems are comparatively higher than those of environmentally friendly DGs [6].

In the survey, conducted by the CIGRE C6.11 study committee regarding development and maintenance of the microgrids, it was found that application of the microgrids includes task management, DG control and data collection, load monitoring, quick reconfiguration of the system and ability to cope with system overloading [7]. Microgrid management is a complicated and challenging problem, where complexity depends on the system configuration and increases with involving non-dispatchable DGs. In work [8], authors suggest transition to smart grids with microgrids on customer-driven basis, where according to the Energy Independence and Security Act (EISA) of US developed in 2007 it is possible to improve interoperability of the primary grid and reduce main system loading by enabling customer to participate in the microgrids control, or demand response to be more specific.

In general, Economic Dispatch (ED) is the way of the effective management of the microgrids, which ensures load distribution among existing generation units by providing secure and economically optimal system scheduling [9]. ED is a part of ADN management and can be referred to as a highly important process, which concurrently embodies several important spheres, including energy storage systems, electric vehicles, generation units, and loads [10]. The problems related to the operation of the microgrids within distributed power systems are known since the first half of the XX-th century and referred to as Static Economic Dispatch (SED). SED is used to deal with technical challenges, such as control of power imbalance, and allocation of power generation among DERs units [9], [11]. Finding an optimal economical solution with minimization of the total operational cost for a microgrid for a single time moment is the way of how SED works. The word "static" in the name of the SED represents the main drawback of the method for the modern systems, as SED follows some operational constraints to solve the optimization problem for a single time moment and can malfunction in case of considerable variation of load through time. The challenge related to the load demand fluctuations is caused by the presence of the ramp rate limits, which cannot be taken into account by SED [11].

An extension of the SED, which is called the Dynamic Economic Dispatch (DED), is known as an optimization task for finding a most economically profitable solution for systems having dynamic nature, in specific dynamically changing microgrid systems with DERs. The benefits of the DED include look-ahead capability for the correct management of power generation units and meet the load demand. At the same time, consider limitations related to the maintenance of balance in the network, such as spinning reserve, transmission lines' power flow limits, bus voltage, and other constraints [11]. With an increasing variety of reserch opportunities and rapid industrialization, which causes issues associated with energy management, the interest in the DED also increases. DED is a broad and deep sphere, with many different and exciting sub-fields inside, which improves on a competitive basis. Improving the communication systems, acceleration of working and responding processes, making system more reliable and safer, as well as making system more controllable and economically profitable are the current directions of the DED development [12].

As it was mentioned earlier, due to the rapid increase in energy consumption all over the world, the paradigm of the smart grid comes into the picture of energy management. The primary purpose of such kind of fast development of the smart grids is mainly caused by three Ds of the modern power systems, which include decentralization, decarbonization, and digitalization [8], [13]. With the improvement of the conventional distribution system, the switch from single microgrid to the Multi-Microgrid (MMG) systems can be observed. The implementation of the MMG system brought many positive aspects into ADNs, including more freedom in the control of system coordination due to the diversification of the MMG components [14] – [16]. The MMG system appealed due to the development of the technologies associated with microgrids and increased dissemination of the microgrids into the power systems. It has changed the traditional distribution systems to the more reliable and faster networks. MMG systems have the ability to effective merging renewable energy sources and new loads, such as EVs, into an existing system, with the ability to partaking tasks between different microgrids. Despite all of the advantages listed above, the main reason of switching to the MMG systems is that coordination inside the MMG can fulfill different targets of the sub-microgrids inside MMG, as well as achieving more extensive goals, such as total performance of the distribution network, total economic profit, and correct resources distribution [15], [17].

1.2. Problem Definition

The rapid growth of the interest associated with the smart grids and microgrids cased the appearance of the concepts related to the combination of advantages of the two systems. The focus is on the creation of a dynamic solution that will have a new idea, which bridges characteristics of microgrid and smart grid, named as an MMG. Usually, energy purchased from or to the grid at prices set by the utility, or there is another option known as FIT (feed-in tariff) and Time-of-use (TOU) prices at which one can sell/buy energy to the power network. Due to the increasing amount of renewable energy generation coming into the picture, the FIT values are coming down and TOU rates are growing up. The meaning of this is any unit of energy generated by microgrid is costing less than the price set by the grid, meaning that it cannot be injected more due to the high initial investments of the microgrids. In some countries, FIT and TOU completely eliminated, as purchasing energy from any microgrid disappears from the grid's market. These situations lead to excess energy in some microgrids, while there are a lot of customers who still purchase their power from the main grid. Thus, with the fundamental changes of the modern energy systems from the primary network, where all of the loads and the generation units were united, to the self-controlled operation systems in the face of the microgrids, significant challenges come into the picture.

The purpose of the MMG system is to find a way to sell excess energy from microgrids to the customers or another microgrid without grid coming into the picture but via using the same infrastructure of the grid. One of the main challenges in MMG systems management is the proper distribution of the energy generation between existing generation units. The concept of the smart grid inside the MMG allows communication between the microgrids, which in turn allows holding of the energy auctions. Energy auctions are the peculiar method of solving increasing load demand issue. Agents of the system, which are the representatives of the microgrids on the sale, should be able to take actions on the "game board" of the auction in the way of the economically optimal and efficient for the microgrid. Policy for the actions taken in the auction mainly depends on the current situation, rules and bidding strategy used, and the steps already made by an agent. The incorrect actions of the agents will be resulted in the low economic efficiency of the microgrid and create lousy behavior of the system. In order to solve this issue, it is required to control actions of the agents in such a way that it will result in the optimal energy scheduling for the MMG system.

1.3. Motivation

One of the main motivations for selecting this topic for the master thesis work was the student's engagement in the Power Engineering sphere, where the current interest is related to the DERs and increasing their amount for the power generation. The reason for this is the environmental concern associated with the conventional generation units, such as coal, oil, or natural gas, which also result in an increasing amount of the air pollution. Unfortunately, penetration of the DERs is not an easy task and required additional work, caused by the randomness of the DERs energy production and its’ surges. The possible solution for this problem became the implementation of the MMG systems, where power fluctuations of the DERs will not affect the main grid.

After making a deep search in the selected direction it was found that there is a lack of works related to the DED for the MMG system, especially with the combined use of the TE management. The current works related to the ED for the MMG available on the Internet consider trading only with the main grid, without the implementation of the TE and not considering the ramp rate limits, which makes optimization system to be static. Here it also should be pointed out, that MMG systems represented in those works do not consider the presence of the DERs in the microgrids and conducts simulations only with considering conventional generation units. The main aim of such works is to minimize the total cost of energy generation in the MMG, by limiting microgrids' self-generation.

After analyzing works and conducting brainstorming, it was decided to propose a new approach related to the MMG systems, viz. DED for the MMG system with the use of the TE management. The presence of the TE in the proposed work will allow microgrids to trade within the system, where DED will ensure the reduction of the total cost for energy generation. Without considering DED for the MMG, the work can be simplified and the ordinary TE market in the MMG system can be conducted. Nevertheless, in this case, work will not contribute anything new. Additionally, the author wants to mention that conducting research with the selected topic will result in the progress related to Power Engineering, and possibly will open new opportunities.

1.4. Aims and Objectives

The main aim of the following work is the implementation of the DEDconstraints of thesystem. With the implementation of DED for MMGs, determination of the generation level of every energy generation unit and proper energy management in the ADN will be done with considering limitations, such as power balance, apparent power flow, spinning reserve, and others. for the MMG framework. The reason for this is that the main objective of the DED is the minimization of the total operation cost and correct energy allocation by taking into account the main

Since DED is a dynamic minimization problem that considers many constraints, it is required to use the method that will be able to find a global or at least sub-global optimal solution. For reaching goals of reducing the fuel cost of power generation by proper DED allocation for the generation units in the MMG system, it was decided to use Game Theory (GT) approach for bidding strategy for the auction between microgrids. GT is a method of decision making for the competing units in the unity system by considering contradictions between groups and their self-interest. Using the GT approach for bidding strategy is the way of controlling energy generation of the microgrids as well as coordination of cooperation between them in the MMG system.

1.5. Contribution

The contribution of this thesis work includes:

- Full literature review on the topics related to the thesis, in particular, Dynamic Economic Dispatch, Transactive Energy management, review of the common auction mechanisms, as well as bidding strategies and the Game Theory.
- Study on mathematical models of the Dynamic Economic Dispatch, k-DA auction mechanisms and Bayesian Game-based bidding.
- Simulation of the agents' communication in the Jade agent development software.
- Simulation if the DED and the Bayesian Nash Equilibrium Game using Matlab.
- Comparing the simulation output of the DED for the MMG system, obtained with the implementation of the different TE markets.
- Investigation of the behavior of microgrids with using the DED with TE management.

1.6. Thesis Outline

Chapter 2 represents a literature review on the topics related to the given master thesis work, which include a review of DED, TE management, GT, as well as auction and bidding mechanisms. The mathematical model of DED, used for the simulation, represented in Chapter 3, where the objective function with the system constraints is represented. Chapter 4 discusses market architectures used for the simulations, namely centralized and decentralized TE markets. Besides, chapter represents the Bayesian Game-based bidding implemented for microgrids' bid/ask price selection. Chapter 5 represents the case study used for the simulation to illustrate the working principle. The simulation results of the entire work are represented in the same chapter, where the discussion and comparison between the different approaches implemented for the simulations are also provided. Finally, Chapter 6 proposes a conclusion of the important parts of the thesis and proposes a direction for future work.

Chapter 2 – Literature Review

2.1. Dynamic Economic Dispatch

ED is characterized as the way toward apportioning levels of the generation of the producing units, to meet the total load in the framework in the most economically profitable way [9]. Chowdhury and Rahman in their work have documented a survey regarding the status of ED in 1990. They have stated that the progress of loading in terms of profit side is going back to 1920s, where the main problem was associated with the proper division of generation between different generation units. Only in 1954, the transmission loss factor was included as a part of the problem of ED for daily generation schedule, concerning the proper coordination of the system in a dispatching domain [18]. ED has appropriately been studied and documented by the majority of researchers and authors in research papers and books related to power system analysis [19] – [21]. Some authors have attempted various techniques for proper control of the system, such a LaGrange based methods, linear or quadratic programming, and Classical ED with Losses, like transportation method, or the technique of continuous minimum cost flow. Some of the authors proposed new heuristic approaches to solve problems related to the real power dispatch. Such kind of technology is based on the integration of natural search techniques and natural selection to the evolutionary algorithms [22].

The ED, in turn, is divided into SED and Optimal Dynamic Economic Dispatch (ODED). The term “static” in the SED states that the calculation is done at a particular time moment. Thus, SED can solve ED for a single load level and will fail in case of significant load variations during a specific time frame. In case of using SED for finding the optimal schedule, it should be taken into account, that there is no any look-ahead ability, and the system will not take into account generators’ ramp rate limits [23].

In the operation of power grids, where an extensive variety of the clients' load requests and the dynamic behavior of the system should be taken into account, it is necessary to study ODED. ODED can be considered as an extension to the existing SED, with the ability to determine optimal schedule with the correct prediction of the system operation over a time horizon with total cost minimization under some operational constraints and aims to find the most economically favorable generation schedule in ADN [24]. ODED can handle problems associated with an unexpected change in the demand in the system in the near future. Thus, it has a look-ahead capability. Besides, ODED considers the ramp rate limit, which is one of the main constraints of the ADN, since it affects the lifetime of the generators. With considering such kind of limitations in the system, solving ODED becomes much more complicated with compare to the SED [25].

The primary stage in the formulation of the ODED problem is the proper initialization of the objective function. Developed objective function should take into account total cost minimization, cost for power losses, emission cost (including CO, SO2, NOx, and others), cost formaintenance, and fuel cost [26]. The second stage in the formulation is the identification system constraints. These constraints can include spinning reserve, ramp rate limits, limits related to the power generation, and other limits, that can be related to the usage of renewable energy sources [26], [27]. Some authors in their work suggest using of the third objective as well in case of formulation of the ODED problems. The third goal called as the improvement of the social benefit, related to the profit maximization of the ordinary customers. Utilization of the third objective is done after power market deregulation, where system should find optimal schedule for the market with reducing income of the large organizations. This objective does not try to bring inequality in the system by discriminating large companies, on the contrary third goal tries to equalize benefits of all sized [28], [29].

Using the ODED can achieve the requirements of the system operators, such as meeting the predicted load demand, minimizing the system operation cost and emissions while considering the physical ramp rate limits of the distributed energy resources [27]. ODED problems can be categorized into two specific ED problems, namely Optimal Control Dynamic Dispatch (OCDD), and DED problems. In comparison to DED, the OCDD reduces the dimensionality of the optimization problem, has more straightforward and straightforward modeling [29]. However, a primitive OCDD problem does not include network losses and covers fewer constraints, which are ramp rates and capacity limits of the generation units [28]. On the other hand, DED minimizes the total cost of system operation by taking into account majority constraints of the system, including spinning reserve requirements, flow-gates limits, and the nodal voltage limits [29].

In the operation of power grids, namely ADN, the DED problem is an optimization problem that concerns the most economical way in power generation by considering load demand and operational constraints. There are many techniques for solving DED problems that help to come up with the lowest cost and achieving the highest degree of reliability of the power system. All of the possible approaches can be classified into three different categories: classical methods, or based on mathematical programming, methods based on artificial intelligence (AI), and the third are hybrid methods [30].

The first category, which is the classical approach, is mainly based on the conventional techniques, which include methods such as non-linear programming (NLP) and linear programming (LP), integer (IP) and dynamic programming (DP), sequential quadratic programming (SQP), transportation method and others. The advantage of those methods is that the efficiency of solutions found by the following methods can be proven mathematically, and they can be applied for large-scale systems and problems [31]. In contradiction to the previous statement, some of the classical techniques have some limitations and have a high possibility of failure to find solutions for problems with non-convex functions. So, processing of the DED problems with using classic technique becomes complicated [32].

To overcome limitations and difficulties related to the classical approach, in recent times, new heuristic approaches have been used to solve a vast amount of optimization problems, including DED, as well as other engineering problems. Some of the methods used for solving include neural networks, evolutionary algorithms, genetic algorithms, game theory and others. This kind of techniques are based on Artificial Intelligence (AI), and they are aimed to find optimal solutions [33].

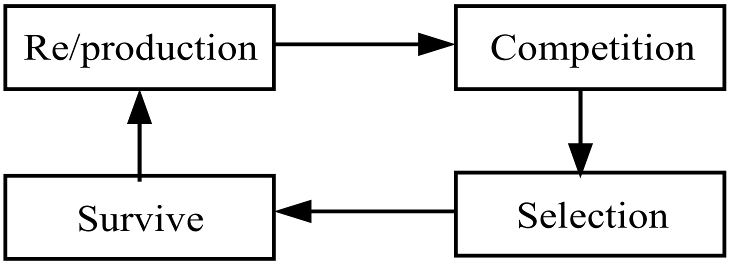

Figure 2.1.1. Darwinian Paradigm

AI is a heuristic search technique adapted and inspired by Darwin’s Paradigm, which is illustrated in Figure 2.1.1, which derives models by providing powerful exploring techniques. The interest in AI is raised due to its ability to solve DED problems in Power Generation. The main advantage for this is that AI itself is independent of the nature of the search, and thus can be implemented in different spheres, just with adapting to the objective function and some required information. Also, AI can be used for solving questions of varying complexity and can have a unimodal form [34].

The third categorical approach for the DED solution is Hybrid techniques. Those techniques are the standard method for real case implementation as they try to overcome drawbacks of the other techniques used one-by-one or alone. In the case of practical application, it is required to use interference of the field base expert or additional approach, as the problems associated with any system stand-alone can include converging optimal solution to the local minima or long computational time. The main working principle of the hybrid techniques is in the combination of two existing approaches for improving the working process of algorithms. Thus, Ongsakul and Ruangpayoongsak at their work proposed the method of combination of simulated annealing method with a genetic algorithm, resulting in GA-SA for solving DED problems. The proposed hybrid system was able to find an optimal solution for the non-linear optimization problem with a non-monotonic and monotonic changing cost function with on-time adjustments of solution finding direction [35]. In general hybrid techniques have a better performance than AI or classical methods used alone. However, it should be taken into account that a random combination of two different technologies will not have resulted in the improved efficiency or accuracy of the proposed system. Besides, the total running time of hybrid models is longer than those for AI techniques or Classical approaches, which is non-acceptable for time-limited condition [36].

2.2. Fundamentals of Agents Theory

In the modern pace, there are increasing trends in smart systems, which leads to the improvement of modern technologies and can be expressed as significant changes. Many organizations all around the world don't want to be left behind and try to improve themselves. Especially it is related to the systems and services used for the day-to-day operations or somehow affecting the comfort of the people. The communication technologies in the power sphere are not the exception in this case [8].

With the fact of the importance of power generation, the implementation of the smart systems to the parts of this sphere also should be taken into account. One of the aspects related to the smartness is the autonomous operation, which eliminates human assistance. Thus, autonomous operation of the microgrid systems should consider self-care, day-to-day operation, as well as the financial sustenance [30]. The care systems are an essential part of the independent operation and should consider the ability of the self-decision making and support connection with other units in the system. Thus, communication of the microgrid with the main grid should be done without any human contribution or other kinds of interruption. At this point, agent theory comes into the picture [37].

The agent theory is the e-learning system, which is proposed to partly or completely eliminate human interaction with the system and make the system self-sustainable. In the case of application of agent theory to the microgrid, the agent will act as the representative of the microgrid in the system, as well as to conduct self-calculation and maintain the system in the working conditions. The additional application of the agents can also include communication with other agents in the system according to the established regulations. The agents follow the instructions preassigned for the system and able to actively participate in the decision-making process. Thus, in the case of the MMG system, the communication between the microgrid will be conducted not by the microgrids' themselves, but via agents' communication [37].

The advantages of using an agent's platform include system automation, where each agent tries to improve itself and can increasingly become a more complex part of the system. Self-care, caused by the intelligence of the agents is the second benefit of the agents' implementation, where the ability to provide fast and more accurate actions is also considered as a part of the agents' environment. The actions taken by the agents are not randomly selected and considered risks associated with the made decision and try to improve the result based on the given opportunities. Besides, the ability of conduction the markets is another advantage of the agents, where agents will act as a microgrids representative [16], [38].

2.3. Transactive Energy Management

With increased interest to DERs, in particular, renewable energy sources, the concept of microgrids came into the picture. Effective management of the microgrids is a challenging task, which should consider challenges related to the economic and commercial aspects. With adding more freedom in the control of system coordination, conventional distribution system switching from single microgrid to the MMG system [16]. There are different structures for energy management for various modes of MMGs, which include structures of decentralized, hierarchical centralized types, and their hybrid. In case of the centralized structure of energy management for the MMG, all data regarding the microgrids in the system, including ramp rate limits, load type, minimum down or uptime, and all other information should be under the disposal of the central system. The primary method of the centralized energy management of MMG should schedule the performance of all microgrids based on the received information. The simple structure of the hierarchical, centralized energy management of the multi-microgrid system can be seen from Figure 2.3.1 [37].

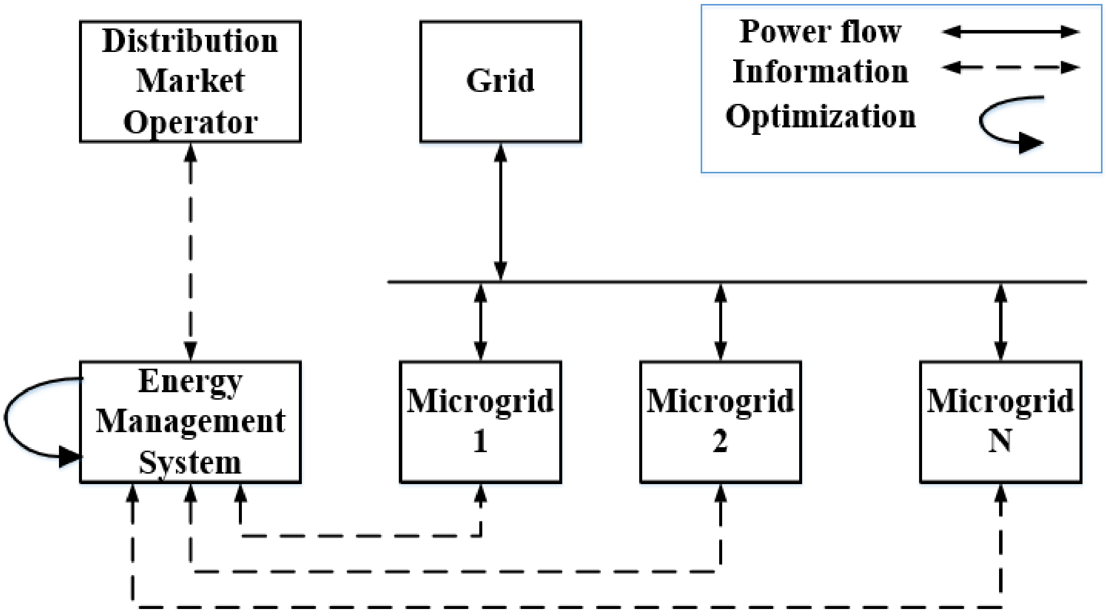

Figure 2.3.1. Hierarchical centralized structure of energy management

The main reason for using such type of energy management is the advantage in the face of global optimization. It can be seen from Figure 2.3.1 that centralized energy management agent has direct access to all microgrid agents and able to perform auction, as well as complete binding process and determine optimal operation for the microgrids for the next time period. It also should be taken into account that using centralized energy management brings benefit in the face of wide system observability, which is very helpful for performing global optimization [38]. Unfortunately, there are some disadvantages of the centralized structure, which are the overhead of requirements in the form of real-time communication, large computational requirements for a single centralized agent, and reduced flexibility of the system [39].

In the case of the decentralized structure of energy management, represented in Figure 2.3.2, it can be pointed out that each microgrid tries to maximize self-benefit and makes scheduling of the activity by itself. There is no proxy agent in the decentralized structure, and each microgrid stays in the direct connection with the distribution market operator and has a direct link to the grid. Due to the lack of the central coordinator communication processes in the decentralized structure more complicated compared to the centralized one [40]. Due to the increasing interest in the privacy, there is an undergoing shift from traditional centralized systems, where the novel approach of implementation decentralized Transactive Energy (TE) market comes into the picture. Decentralized TE auctions can be represented as peer-to-peer energy trading, which also improves the integration of DERs via local balancing between energy demand and supply [41].

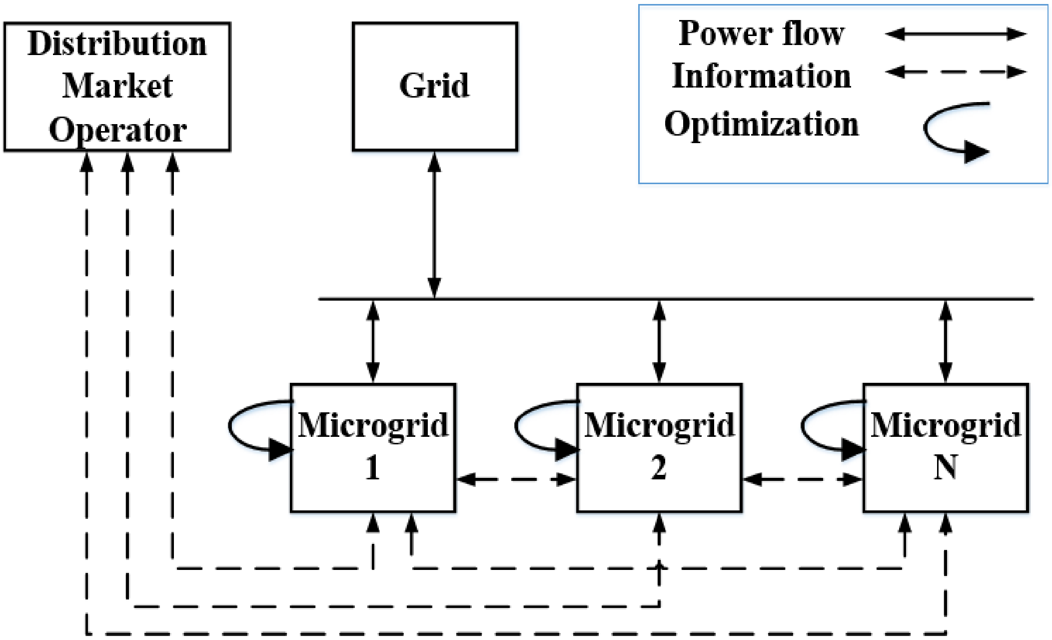

Figure 2.3.2. Decentralized structure of energy management

To ensure safe information exchange and protect the system from cyberattacks, it is recommended to use of the blockchain for decentralized TE auctions. Core design principles of blockchain include decentralization and reliability, wherein the case of the public blockchains anyone can join the system. Blockchain mechanism eliminated necessity in the trusted third party, represented in terms of primary agent or auctioneer in the centralized system. Besides, there are several proved advantages of using blockchain: reducing cost and complexity, reducing error, resilience, and security, as well as creating shared trusted transactions [42], [43].

Meiqin Mao et al. at their work proposed a multi-microgrid system based on hybrid energy management, which represented in Figure 2.3.3. Authors state that the hybrid energy management system takes into account all the disadvantages of both centralized and decentralized systems and tries to avoid them; at the same time, it incorporates all advantages of both systems. Thus, due to the need for coordination between different levels in the hierarchical, centralized system, the coordination between microgrids themselves will not be lost [44].

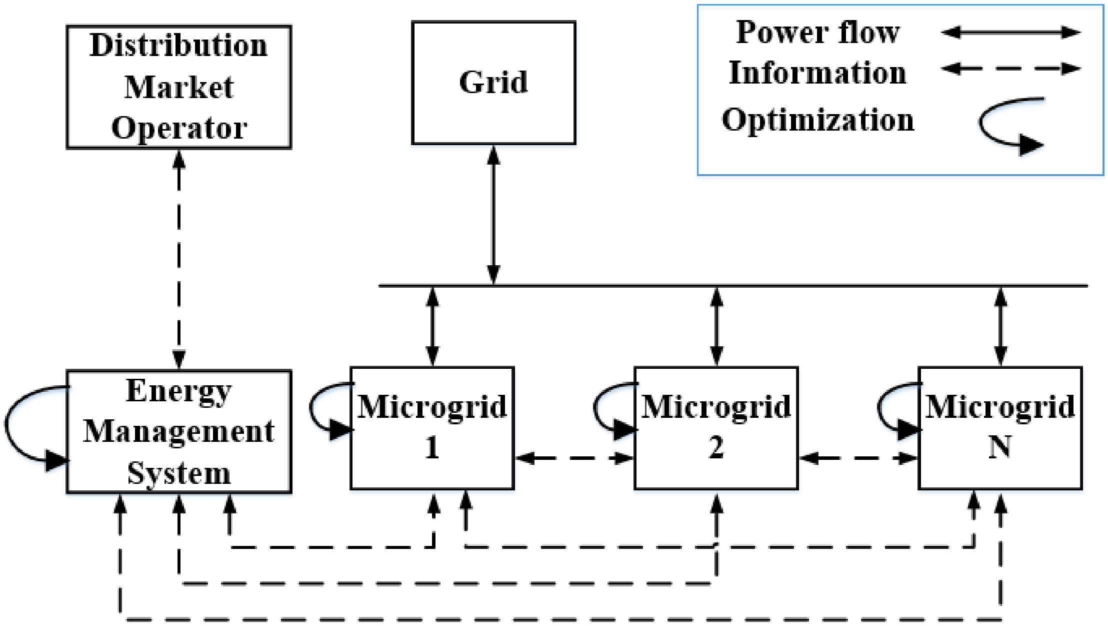

Figure 2.3.3. Hybrid centralized-decentralized structure of energy management

The main advantage of such kind of system combination will give system ability to exchange information at every level and between every level by making the process more optimized. In such type of information exchange economic performance of the overall system will stay at the optimal level [44]. Despite the advantages of the hybrid systems, there are still challenges brought their integration for MMG systems. With increasing connection resources for the microgrid agents, there is increased possibility of failure in case of inconsistency of negotiation results between microgrids communication and central agent decision, which can lead to the collapse of the system [45].

2.4. Auction mechanisms

With introducing microgrids for an onside energy generation, the amount of DERs in the distribution system has been increased. The integration of DERs resulted in decreasing losses in the distribution system, improving safety and reliability, as well as refining power quality [14]. Unfortunately, penetration of DERs resulted not only in a positive way, as it is also lead to the economic and technical challenges related to microgrids management. The presence of the non-dispatchable energy generation resulted in the complication of microgrids' effective management, as the issue of supply-demand mismatch will always be present in the picture [10]. As it was mentioned previously, implementing of the backup power generation, suggested in some papers [5]-[6], is not the effective way of solving problem, as the cost for operation and maintenance, as well as environmental effect of such backup systems also should be taken into account. Due to the mentioned facts, there is a demand for a smarter solution to handle an imbalance in the microgrids. With the increasing level of intelligence of the microgrids, or implementing smart grids concept, it is possible to effectively utilize problems related to the presence of the non-dispatchable DERs in the microgrids. TE is a promising solution, as it has promising potential to lead energy scheduling operations in energy markets [19].

Besides the fact of the transition to the energy markets, the existence of the monopolistic market should be considered. The modern distribution market systems are mainly focused on the benefit of the main grid, where the Distributed System Operator (DSO) is acting as both organized and operator in the market [37]. The purchasing or selling energy in the monopolized markets adds additional constraints for developing proactive prosumers, penetration of DERs, and the formation of the microgrids. The problem associated with the monopolized markets is the fact that microgrids allowed to sell or buy energy only from or to the main grid. The problem is further alleviated by FITs that are significantly lower than the retailed cost of energy and causes a negative impact on small-scale prosumers in distribution systems [39].

Several works in the literature attempt to address the issue related to the old-fashioned operation by conducting an agent-based energy auction [36]. The agents in the energy auctions are intelligent systems that are cooperated with DERs, prosumers, and DR systems. These works suggest using the agents with an embedded level of intelligence to trade energy between each other, where all agents act as peers. The main advantage of such market types is that pool members will determine the cost of energy by abiding by auction protocols. The implementation of a smart contract between auction participants gives the ability to trade with other agents safely. The microgrids can decide whether to participate in the auction as a buyer, in case of the presence of surplus energy, or seller, if there is energy demand [37].

In the context of energy trading, implementation of auction mechanisms can be implemented between microgrids, where dealing with the main grid will be used only as a last resort. Some of the works represented energy auctions for MMG systems without resorting to the main grid, which is called as an isolated energy trading. There is a wide variety of existing auction techniques, which have different properties and balancing strategies, while all of them have an aim to clear the market efficiently. The four most common auction mechanisms are Discriminatory k-DA, Uniform k-DA, Trade Reduction, and Vickrey-Clark-Groves [46].

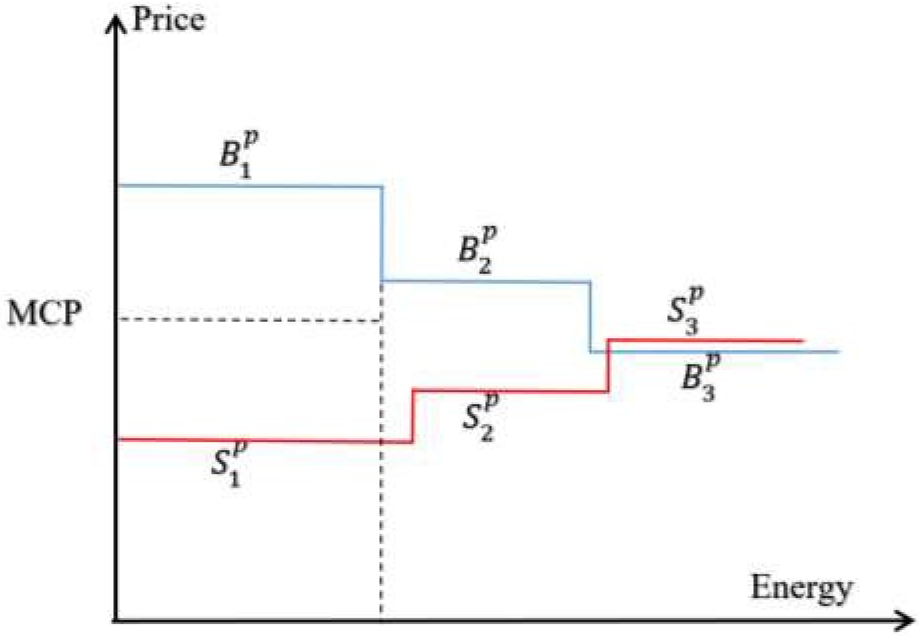

Figure 2.4.1. Discriminatory k-DA auction mechanism

One of the well-known auction types called Pay-as-Bid k-Double auction, or also known as Discriminatory k-DA. In the Discriminatory k-DA auction, both sellers and buyers should submit their bid and ask prices in order to participate in the energy market. Thus, buyers will provide B^p bidding prices, and sellers will offer S^p asking prices. The working mechanism of this auction is following the rule of the natural ordering, which uses numerical sort to categorize the prices, which is represented in Figure 2.4.1. As it can be seen from the picture, the prices submitted by buyers will be sorted in descending order, while sellers' costs will be sorted in ascending order. If buying price B^p is greater or equal to selling price S^p, the trade will take place, where the Market Clearing Price (MCP) will be calculated from Equation (2.4.1). After finding the first MCP, the auction will be continued until the moment when there would not be any intersections between prices or till the end of trading time. The meaning is that price at which energy will be bought or sold will differ for every agent, according to the results of the auction [47].

$$MCP = kB^p + (1-k)S^p \tag{2.4.1}$$

where k is the constant value, predetermined by the market system operator, and typically equal to 0.5.

One of the variations of the Discriminatory k-DA auction mechanism is Uniform k-DA, which also referred to as Double auction. The difference between auctions is that in the Uniform k-DA all the winning agents will trade at the same price, without any discrimination between prices. It also should be noted that MCP, in the case of Uniform k-DA, will be unique and will be calculated once. The Double auction mechanism is similar to the Discriminatory k-DA, as it also uses natural sorting for finding MCP. The mechanism of Double auction is represented in Figure 2.4.2, where the MCP will be calculated from Equation (2.4.2) [47] – [48].

$$MCP = kB_{\gamma}{}^{p} + (1-k)S_{\gamma}{}^{p} \tag{2.4.2}$$

where γ is index, which determines point of the largest break even and satisfies condition $B_{\gamma}{}^{p} \geq S_{\gamma}{}^{p}$.

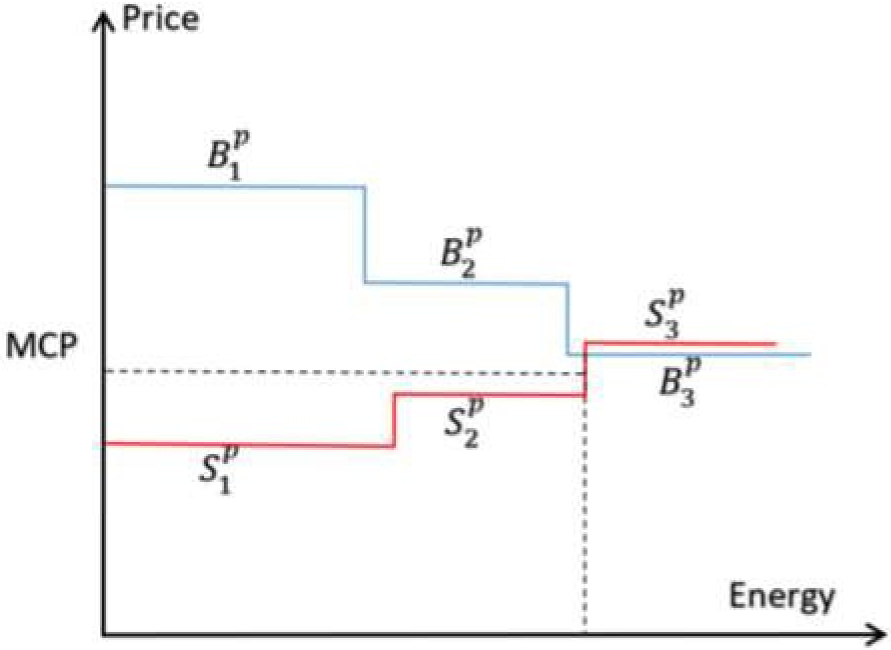

Figure 2.4.2. Uniform k-DA auction mechanism

In the case of Uniform and Discriminatory k-DA auctions, it can be noticed that MCP will be calculated in such a way that the total sum paid by buyers will be equal to those that will be received by sellers. The primary meaning of this is that the market operator of the main auction agent will not receive any amount of money. The Vicrey-Clark-Gloves auction is used to reduce the cheating of agents and maximize the truthfulness of the bidding procedure. Here it also should be noted that MCP will differ for buyers and sellers. The price for selling energy, defined as S^p, will be found from Equation (2.4.3) and price for buying energy, which is B^p, will be calculated from Equation (2.4.4) [49].

$$S^p = \min({S_{\gamma+1}}^p, {B_\gamma}^p) \tag{2.4.3}$$

$$B^p = \max({S_\gamma}^p, {B_{\gamma+1}}^p) \tag{2.4.4}$$

where $S_{\gamma+1}$ and $B_{\gamma+1}$ are ask and bid prices, which follow the largest break-even index and satisfied conditions: $B_\gamma \geq B_{\gamma+1}$ and $S_\gamma \leq S_{\gamma+1}$

The difference between paying and selling prices in the Vicrey-Clark-Gloves auction improve the social welfare of the MMG system, where the difference between prices will be paid as a salary for market system operators (principal-agent) for transmission energy and conduction auction in case of centralized energy management structure. the Vicrey-Clark-Gloves auction mechanism assumes that every agent should be rewarded for work done [50].

The fourth auction mechanism, which is Trade Reduction auction, also tries to maintain truthfulness in agents' bidding and maintain the social welfare of the system. The paying and buying prices on the Trade Reduction auction also different, and their difference is used to pay market system operators for services they have provided. As it can be understood from the name of the auction, the main working principle is based on the limiting number of trades, which will be resulted in increasing competition between auction participants. The typical trade limitation is done to ($\gamma - 1$) number of buyers and sellers; thus, the price for selling and buying prices can be calculated from Equations (2.4.5) and (2.4.6) respectively [51].

$$S^p = {S_{\gamma-1}}^p \tag{2.4.5}$$

$$B^p = {B_{\gamma-1}}^p \tag{2.4.6}$$

Each of the auction mechanisms mentioned above has different characteristics, applicable for different case scenarios. The selection of the correct auction mechanism should be made according to the conditions and requirements of the system. According to [52], an ideal auction mechanism, appropriate for any of the scenarios, should embody four main properties. Main properties include rationality of auction mechanism, explaining actions of sellers and buyers, as well as selection of MCP; budget balance, where payment for market system operator should not be taken into account; economic efficiency, which allows trading for all agents with index less or equal to largest break-even; incentive compatibility, which shows whether auction mechanism supports faithful bidding of agents and thereby contributes to the increase of the equality of profit for both buyers and sellers [53]. Unfortunately, it is not possible to find an ideal auction mechanism according to the theorem of Myerson-Satterthwaite, as no realistic auction mechanism can act as a perfect model. Thus, no auction type will satisfy all four properties. Table 2.4.1 represents comparing analysis of the auction mechanism according to the characteristics of ideal auction [52].

Table 2.4.1. Comparing properties of auction mechanisms

Auction Mechanism	**Auction Rationality**	**Budget Balance**	**Economic Efficiency**	**Incentive Compatibility**
Discriminatory k-DA	Yes	Yes	Yes	No
Uniform k-DA	Yes	Yes	Yes	No
Vicrey-Clark-Gloves	Yes	No	Yes	Yes
Trade Reduction	Yes	No	No	Yes

As can be seen from Table 2.4.1, Discriminatory k-DA and Uniform k-DA are more suitable for conducting TE markets, as they have more positive aspects, rather than negative. The selection of the appropriate auction mechanism is mainly based on the selection principle by asking some questions like “Is it better to be economically efficient rather than be incentive-compatible”. The absence of the incentive compatibility in the auctions can be reimbursed by application bidding strategy that will improve this aspect.

The auction’s properties are established in advance and cannot be changed; they act just as a formulation of the mechanical actions of the auction. They cannot be used as a metric for measuring the efficiency of the mechanism. The metric of measuring effectiveness is a quantitative analysis, which includes the amount of sold and bought energy (in percent) and the amount of cleared inquiries. The method of calculation efficiency of auction mechanism execution is represented in Table 2.4.2 [53].

Table 2.4.2. Metrics of evaluation efficiency of auction mechanisms

Metric	**Method of calculation**
Amount of sold energy (%)	$\frac{\sum_{n=1}^{N_T} D_n^Q}{\sum_{i=1}^{N_S} S_i^Q}$
Amount of bought energy (%)	$\frac{\sum_{n=1}^{N_T} D_n^Q}{\sum_{j=1}^{N_B} B_j^Q}$
Amount of cleared inquiries (%)	$\frac{\sum_{i=1}^{N_B} \frac{B_i^{Clr}}{B_i^Q} + \sum_{j=1}^{N_S} \frac{S_j^{Clr}}{S_j^Q}}{N_B + N_s}$

where,

Metric name	**Explanation**
N_T	Total number of transactions
N_B	Total number of buying agents participated on auction
N_S	Total number of selling agents participated on auction
D_n^Q (kWh)	Amount of energy participated in trade *n* between buyer and seller
S_i^Q (kWh)	Amount of energy put up on auction by selling agent *i*
B_j^Q (kWh)	Amount of energy demanded on auction by selling agent *j*
S_i^{Clr} (kWh)	Amount of energy cleared by transaction for selling agent *i*, where $S_i^{Clr} < S_i^Q$
B_j^{Clr} (kWh)	Amount of energy cleared by transaction for buying agent *j*, where $B_j^{Clr} < B_j^Q$

The main reason for the presence of the metrics of evaluation efficiency for the auction mechanism is the fact that agents who participated in the energy trading market and failed in the auction will be required to trade with the main grid on fix prices. The fix prices for trading with the main grid are TOU and FIT, which are predetermined cost rates and nonbeneficial for microgrids' energy trading. TE auctions are more efficient if they give the ability to exchange energy for more microgrids, as it improves the benefit of the market participants. Within TE auction mechanism selling and buying procedure is more profitable for agents, as trading price is higher than FIT for sellers and lower than TOU for buyers. Higher efficiency of the auction mechanism guarantee interest of more participants, which in turn leads to better operation of energy auctions [47].

2.5. Game Theory and Bidding Strategies

Submission of the efficient bid and ask prices are one of the main interests of the buying and selling agents during participation in the energy auctions. The typical offers of the agents consist of the quantity of required/excess energy for microgrid and their ask/bid prices. The determination of the bid and ask prices are done through the strategy, which is predetermined for the agents and called as a bidding strategy [47]. The primary interest of each agent is the maximization of the self-profit, where submission of the bids for each agent is made without knowing the actions of the other agents. Saying in simple words, every agent acting with some randomness and thus, selected bidding strategy must not only predict some of the moves of the rivals but also follow the rules of the game [54].

2.5.1. Identification of the Game model

The selection of the bidding strategy depends on the type of the game model selected for the formation of the auction and agents' actions representation. The game type chosen for the auction should be simultaneous action type and non-zero-sum. In the game theory, the simultaneous game is the game where actions of the player should not depend on the steps of other players. The primary purpose of this game type is that all agents should submit their bid and ask prices simultaneously, without any preliminary pieces of knowledge of biddings of other players on the game board. Saying, in other words, all the agents should submit their offers at the same time [55]. Simultaneous game is opposite to the sequential game type, as in sequential game agents should be allowed to submit bids by taking turns, which is not fair for all the auction participants. A simultaneous game can be continuous, which means that the game can continue in a new round from scratch, where again, all the players will act simultaneously. An excellent example of a simultaneous game type is the rock-paper-scissors game, where all game participants simultaneously should select one of the given options. In case of the auction, it should be pointed out, that the only restriction given for the agents, is that submitted bids should vary between FIT and TOU [54].

The second characteristic of the game that should satisfy the auction representation is that it should be non-zero-sum. The non-zero-sum games suggest a property that a combination of the player's moves will be not resulted in the loss of his opponents; thus, if one of the buying agents will win the offer, it does not mean that all of the other buying agents will require to lose in the same auction. Here it should be noted that the fact of purchase/selling energy from/to the primary grid in case of loss in the auction is not considered as a paying for the opponent or lose in the auction, but still regarded as a negative aspect for the agents. Majority games in the game theory are non-zero-sum, and the example of this game type is the prisoners' dilemma. In the case of the prisoners' dilemma game, which game matrix is represented in Table 2.5.1, it can be noted that the actions of the other player can have a negative effect on the other player. However, still, the overall sum of the results for the game will not result as a zero [56].

Table 2.5.1. Game matrix of the prisoners' dilemma

	B silent	***B cheat***
A silent	-1 \ -1	-3 \ 0
A cheat	0 \ -3	-2 \ -2

Game matrix represented in the table explains the results of the gamers in case of their actions; thus, if any player will be silent when second is cheating, it will result in his arrest for three years. It also can be noted that in case of the similar actions of players, their results also will be the same: both silent resulted in one year in prison for each while when both cheats resulted in two years of jail. Due to the reason that players' actions also should be selected without preliminary pieces of knowledge of the opposite side, prisoners' dilemma considered as a simultaneous-move game also [56].

Another property that should be considered for conducting the auction is a non-cooperative approach, which is generally can be analyzed within the non-cooperative game theory framework. In the case of the non-cooperative game, each player tries to increase self-profit by finding Nash equilibrium. The focus of the non-cooperative games is in the strategical development of each player, but not the coalition, as each player should make individual actions, without affecting on moves of another player [57]. The details of the non-cooperative game include a sense of the risk associated with the player's actions and information available until the moment of making actions. To be more general, it also can be said that it is possible to implement cooperative game for implementation of the energy auctions, as their approach is much simpler. At the same time, it allows analysis of the group of players as one unit. Unfortunately, using of the cooperative game for the auctions will not provide efficient results, as loss of one player will have resulted on the drop of the whole team, which also lead to the energy trading with the primary grid or monopolized energy market [58].

With the information mentioned above, regarding the transactive energy management structure, another property of the game also should be considered. The fourth property is the information type represented in the game board, which can be imperfect or perfect information type. The difference between those two states is evident, as, in the perfect information game, at least one player will have all information regarding actions of other players, while in the imperfect information game, no one will now current actions of other players [59]. The reason for choosing a property for the game also depends on the type of energy management selected for the system. Thus, in the case of the centralized transactive energy management system the perfect information type game should be used, as all information regarding the offers, as well as the status of all microgrids in the system will be submitted to the DSO, which is also considered as a part of the game. Following the same logic, it should be said that imperfect information game should be considered in case of the decentralized transactive energy system, as no one in the system will have access for information regarding the offers and other staff regarding the microgrids. Information regarding the features of the game in accordance with the selected energy management system represented in Table 2.5.2.

Table 2.5.2. Game features

Energy management type	Simultaneous action	Non-zero-sum	Non-cooperative approach	Perfect information	Number of players
Centralized	Yes	Yes	Yes	Depends on player	N
Decentralized	Yes	Yes	Yes	No	N

According to the features required for the game, that should be used for conducting the auction, as well as a bidding strategy; it can be noted that the most suitable basement is the Bayesian Games. The Bayesian game theory is the only one that satisfies all the features mentioned above, as well as a privilege represented as an ability to change the rules of the game according to the required conditions. The meaning of this is that it is possible to create the auction game by using the structure of the Bayesian game as a fundament [60].

2.5.2. Bayesian Games

The Bayesian Games, which are the part of the Game Theory, are the games where information shared between the game participants is not complete for all the players. An excellent example of this is the closed auction, where players do not know the bid values submitted by other players; however, they still can have a conviction regarding those values. The reason for having those convictions are used to find out winning bid value for the players, where beliefs are represented as probability distribution between the possible benefits. The primary strategy of each player will be based on the "common prior assumption," as the modeling of the action plan should be based on some of the prior knowledge or random selection. The assumption of the players that will have a direct effect on their future actions can be changed and updated according to the Bayes rule [60], [61].

Similarly to all other games in the Game Theory, the best decision for each player in the Bayesian Games is following Nash Equilibrium strategy. The main characteristic of the Nash Equilibrium is that the action will have the best possible outcome for everyone, where it is given that all strategies of all other players played. Here it should be noted that, for some cases, there can exist a chance of having several Nash Equilibriums or situations where there cannot be Nash Equilibrium at all. The analog Nash Equilibrium is used in the Bayesian Game and called as a Bayesian Nash Equilibrium strategy, which aims to maximize the total profit for every player by given all possible actions of other players, and according the beliefs of the player [61].

2.5.3. Bidding Strategies

For simplicity, in order to explain possible bidding strategies, a four-player game can be considered. Two players in the game will be buyers, whilst two others will be sellers. In all auction systems, each seller should submit his bid against all other sellers; similarly, each buyer bid against all other buyers on auction. Due to the absence of bidding information of other auction participants, the new bidding rate for each player can be identified based on his previous bid in the auction. The changing factor of the bids can be determined according to the preferences of the player. All of the bidding strategies are considered as a part of the Game Theory, as they also found as a part of the selected game. In the Bayesian normal-form game, each player does not need to assume moves of each rival but can view all of the opponents as one team, against which he is playing [62].

The possible bidding strategies include random bidding strategy, bidding strategy based on the preference factor of the player, best-offer approach, and market-power bidding strategy. In the case of the random bidding, strategies ask/bid prices are selected using uniform or random distribution without any plan and neglecting the market's situation with history. The random sampling of bid/ask prices made by random sampling between 0.01$/kWh and 0.99$/kWh, with adding selected value to the cost of energy generation, calculated for each microgrid differently [63].

The second bidding strategy based on the preference factor assumes that each agent's bid/ask price always should be more/less than the MCP of the previous market period. The bidding plan believes that results on the auction for each of the agents should be more efficient, due to the reason that buyers will try to submit higher prices, while sellers will try to provide higher rates. By considering the fact that MCP will be calculated from scratch for every market punctuation, it should be mentioned out with the preference factor bidding; the average MCP should not fluctuate too much. The behavior of the bidding model also assumes some distribution, where μ (mean) selected to be 0.2, and σ (standard deviation) should be 0.15 [64].

Bidding strategy based on the best-offer approach is used as a typical part of the Game Theory. The best-offer approach allows submission of the bid or ask price only in case if the participant is sure that it will win according to the assumptions made by the player. The strategy for payoff determined by Equation (2.5.1) in case of the agent is seller and Equation (2.5.2) for buyer [65].

$$\pi_i^{Strtg} = \begin{cases} C_i^{Strtg} & if\ C_i^{Strtg} < C_{others}^{Strtg} \\ 0 & otherwise \end{cases} \tag{2.5.1}$$

$$\pi_i^{Strtg} = \begin{cases} C_i^{Strtg} & if\ C_i^{Strtg} > C_{others}^{Strtg} \\ 0 & otherwise \end{cases} \tag{2.5.2}$$

Similarly, from the side of the agent *i*, the strategy for all other agents will be calculated by Equitation (2.5.3) if the agent is seller, and Equation (2.5.4) if the agent is the buyer [65].

$$\pi_{others}^{Strtg} = \begin{cases} C_{others}^{Strtg} & if\ C_{others}^{Strtg} \leq C_i^{Strtg} \\ 0 & otherwise \end{cases} \tag{2.5.3}$$

$$\pi_{others}^{Strtg} = \begin{cases} C_{others}^{Strtg} & if\ C_{others}^{Strtg} \geq C_{i}^{Strtg} \\ 0 & otherwise \end{cases} \tag{2.5.4}$$

The rule of the natural ordering in the bidding strategy assumes that player with the best offer should win in the auction, or at least not to lose. The aggregate amount of the opponent players has higher possibility to offer the best price, rather than one player, and that's why an individual player always should try to submit not equal and higher than all other buyers, or lesser than all other sellers [65].

Last but not the least bidding strategy is the market-power based bidding. The main difference of the fourth approach is the dependence on the historical data of the market, as well as the identification minority side on the current market. Thus, in case if the number of buyers is assumed to be less than the number of sellers, the market is supposed to be a buyers' market, where buyers will have more privileges. The same is working in the opposite way, where the market can become sellers' market. The changes come not only to the name but also to the bidding process. In case of the market called to be sellers' one, the privilege given for sellers will be to select ask prices without assuming any competition, which is represented in Equation (2.5.5), while for buyers bid prices found according to Equation (2.5.2). In case if the market called to be buyers' market, buyers would submit their bids according to Equation (2.5.5), whereas sellers will use Equation (2.5.1) [66].

$$\pi_{i}^{Strtg} = C_{i}^{Strtg} \tag{2.5.5}$$

As in the case of any technique, bidding strategies can be compared between each other, which is represented in [64]. According to the result described in work, it can be noted that best-offer bidding strategy results performance is better compared to the rest three techniques. The best-offer approach allows submission results, where the reason that performance will be tuned as a being near-ideal. Second place after best-offer bidding strategy is based on random bidding, which plan use random process. The results found for market-power auction and preference factor auction shows that amount of energy sold and bought on the market will not exaggerate 50% in the best case, which also makes the rest of the trade with the primary market. By relying on results provided in [52], it can be said that using a best-offer bidding approach will have resulted in more optimal outcomes in selling energy on the energy market.

2.6. Short-Term Load Forecasting

The coordination of the DGs within ADN is a complex task, which can be divided into several unique control techniques. Those control techniques include DED, Load Forecasting, Hosting Capacity and other aspects of the power systems operation [22]. To control the operation of the power system the decision procedure is primarily based on some preliminary predictions or subject matter experts. These decisions include increasing or decreasing generation operation costs, coordination of operation of network control facilities, and others. Moreover, those decisions should be economically and technically beneficial [34]. Planning of optimal hour-to-hour and day-to-day operations of the ADN framework depends on different aspects of the system and requires estimation of the load in the system in advance. This task for ADNs is called as Short-term Load Forecasting (STLF) [67]. Therefore, STLF is one of the key control techniques in ADNs.

The forecasting of the load plays a significant role in terms of establishing a secure and economically feasible power framework. The load forecasting in its turn can be classified into four categories: Very short-term Forecasting (VSTLF), STLF, Mid-term Load Forecasting (MTLF) and Long-term Load Forecasting (LTLF). The type of forecasting depends on the desired accuracy of the prediction and type of system planning that is used for forecasting. The prediction of the very short term typically done for the power markets, where extreme accuracy is required for the deregulated auctions, typically prediction of load in the next trading period. On the other hand, the MTLF and LTLF are done to predict the loading of the system for week to months, and months to years ahead. Typically, those types of load predictions are not so accurate, but they are helpful for configuration of future pricing [68]. The STLF predicts load for several hours or day ahead period and is commonly used to schedule the network operations. Therefore, the STLF is the most important forecasting technique required for the control of ADNs [67].

Srivatsava et al. state that there are four main categories of STLF: Statistical Technique, Artificial Intelligence, Knowledge-Based Expert Systems and Hybrid Techniques [68]. The ST approaches are represented in the form of the complicated mathematical model of load relationship with several input factors. These methods include Multiple Linear Regression method, Exponential Smoothing, Stochastic Time Series, Adoptive Load Forecasting and some others [69]. The ST is more useful in the case of MLTF and LTLF. As an example, Alfares et al used Exponential smoothing in comparison with Multiple Linear Regression for day-to-day load forecasting for the whole year period, which shown precise prediction throughout the year. Here, it should be taken into account, that the accuracy of the prediction was based on the averaging of the load during the day period [70]. However, in the case of the shorter-term prediction Statistical Technique is not so efficient, and it is not recommended to use them in case of the non-linear systems, such as renewable energy sources or non-linear load types in the system [71].

Artificial Intelligence is a comparatively new technique type used in the research related to STLF. Computational techniques in the Artificial Intelligence typically refer to the fuzzy systems, evolutionary computation, artificial neural networks, swarm intelligence algorithms, and others [71]. The Fuzzy logic has a good performance, however, in the case of unsupervised learning neural networks shows better results [72]. Neural networks are systems modeled after the implementation of the basic working principle of the connection of the neurons. Neural networks become one of the frequently applied technique for load forecasting in recent years [73].

The knowledge-based expert system is a rule-based method, that makes decision-based on the subject matter expert opinion [74]. This method is useful in case if unpredictable or sudden occasions have a place. Thus, in case of some weather conditions, where the data-driven system fails due to the unknown circumstances, the knowledge-based system comes into the picture [75]. A good example can be the Earth day, where people turn off electricity for an hour and in this case, the load should be estimated by experts. This type of system can be viewed as a machine version of the expert in the field, but it is not recommended to use every time [74].

The hybrid system is a commonly used method for real-life implementation of load forecasting and used to overcome drawbacks of the other techniques used one-by-one or alone. This type of approach is a combination of two or more different techniques. The most typical combination is particle swarm optimization, fuzzy neural networks and knowledge-based expert system [76].

Chapter 3 – Dynamic Economic Dispatch

3.1. Objective function for the microgrids

The aim of the DED problems is minimization of the total operation cost with considering system constraints. The system used for the work consists of the conventional and renewable energy generation units, which are the generators based on fossil fuel and wind power generation units. It also should be pointed out, that DED problem is applied for the MMG system, where total operation cost of each microgrid should be calculated. The constraints considered in the system for solving DED problem include ramp rate limits for conventional generation units, conventional power plant and wind power generation limits, spinning reserve and limits of the power flow in the lines.

Each individual microgrid in the MMG system will have similar objective function, which in represented as following, where main aim is to find parameters for minimization of the total operation cost:

$$\min TC_{i_T} = \sum_{t=1}^{T} \Big[\sum_{j=1}^{N} [FC_{i,t}(P_{j,t}) + MC_{i,t}(P_{j,t}) + EC_{i,t}(P_{j,t}) + C_i(P_{w,j,t})] - P_{i,t}^{auct} C_{i,t}^{Strg}\Big] \qquad 3.1.1$$

where TC_{i_T} is the total cost of operation of microgrid i (\$); $P_{i,t}^{auct}$ is the total amount of power required/excess for i^{th} microgrid at time t (\$/kW); T is the cycle of the DED scheduling; N is the number of generation units in the i^{th} microgrid; m is the number of the microgrids in the system. When microgrid has an excessive amount of power, it participates in the auction as a seller, and in case if it requires power it participates as a buyer; thus, the $C_{i,t}^{Strg}$ (\$/kW) can change according to the situation and can be found as:

$$C_{i,t}^{Strg} = \begin{cases} MCP & \text{, if microgrid is seller and his ask price won in the bidding} \\ TOU & \text{, if microgrid is seller and his ask price lost in the bidding} \\ -MCP & \text{, if microgrid is buyer and his bid price won in the bidding} \\ -FIT & \text{, if microgrid is buyer and his ask price lost in the bidding} \end{cases} \quad (\$/\text{kW})$$

The Equation (3.1.1) is subject to the set of functions:

a. Cost of fuel:

$$FC_{i,t}(P_{j,t}) = a_j + b_j P_{j,t} + c_j P^2_{j,t} \qquad 3.1.2$$

where a_j, b_j, c_j are the coefficient units of the cost for fuel of the j^{th} fuel (conventional) generation unit in the i^{th} microgrid, $P_{j,t}$ is the power output of the j^{th} generation unit during t time interval (kW).

The cost function was selected to be quadratic as in general thermal generation units, without considering valve-point effect.

b. Cost for maintenance of fuel generation units:

$$MC_{i,t}(P_{j,t}) = K_j \times P_{j,t} \qquad 3.1.3$$

where K_j is the cost for maintenance of j^{th} conventional generation unit ($/kW) of i^{th} microgrid.

c. Cost of emissions of fuel generation units:

$$EC_{i,t}(P_{j,t}) = \omega_j (P_{j,t})^2 + \tau_j P_{j,t} + \upsilon_j \qquad 3.1.4$$

where ω_i, τ_i, υ_i are the coefficients of the CO_2 emission coefficients of i^{th} microgrid.

d. Generation cost of wind power:

$$C_i(P_{w,j,t}) = aI^P P_{w,j,t} + G^E P_{w,j,t} \qquad 3.1.5$$

where I^P is the cost of investing money to the wind turbine ($/kW) and similar for assumed to be similar for all wind turbines; G^E is the cost for maintenance and exploitation of the wind turbine ($/kW); $P_{w,j,t}$ is the power generated by the j^{th} wind turbine in the time period t; α is the coefficient for the time allocation of investment money with interest rate r, found as:

$$\alpha = r/|1 - (1+r)^{-N}|$$

Due to the presence of the multiple microgrids in the system, the total operation cost should be optimized for each of them. By adding the existence of the auction to the system picture, the cost of selling excessive amounts of energy became more profitable for the agents, which means that the generation of additional energy also should be considered as a concept for reducing total operation cost for microgrids. The correctly chosen strategy for energy generation should also consider the possibility of losing on the auction and selling/buying energy to/from the main grid.

Authors in [33] propose updating of the objective function by adding weight coefficients for the subjective parameters. With supplementing the weight coefficient, the total operation cost of the microgrid will be minimized based on the priority given for the parameters and make more generation environmentally friendly by paying attention toward emission and fuel cost functions. Unfortunately, it is not possible to implement this technique in the DED with the MMG system, in particular auction-based energy trading. The main reason for this is that it is not possible to append cost function related to the energy sold/bought on the auction, as one of the trading principles includes independent decision for participation in trading. In connection with this, all of the parameters in the objective function should have equal priority for honest results.

3.2. Constraints of the DED

The DED problem aims to find the optimal operation parameters with total cost minimization. Any optimization problem related to the power sphere should satisfy the power demand of the network and follow the constraints. The main reason for following constraints of the system whilst solving the optimization problem is the control of the process and keeping a particular system's limits. In case if the solution found by solving an optimization problem will not satisfy the demand of the specific time interval, or power generation will not satisfy the ramp-rate limits, the problem is not considered as solved.

Thus, the minimization of the total operation cost also should consider the constraints of the network. The constraints of the network.:

1. Power generation limits:

$$P_{i,j,t}^{min} \leq P_{i,j,t} \leq P_{i,j,t}^{max} \qquad 3.2.1$$

where $P_{i,j,t}$ is the active power generated by j^{th} conventional generation unit of the i^{th} microgrid at time t (kW); $P_{i,j,t}^{min}$ and $P_{i,j,t}^{max}$ are the lower and upper limits of the j^{th} conventional generation unit of the i^{th} microgrid (kW).

$$Q_{i,j,t}^{min} \leq Q_{i,j,t} \leq Q_{i,j,t}^{max} \qquad 3.2.2$$

where $Q_{i,j,t}$ is the reactive power generated by j^{th} conventional generation unit of the i^{th} microgrid at time t (kW); $Q^{min}_{i,j,t}$ and $Q^{max}_{i,j,t}$ are the lower and upper limits of the j^{th} conventional generation unit of the i^{th} microgrid (MVar).

2. Wind turbines generation limits:

$$P_{i,w,t} = \begin{cases} 0 \text{ for } v_t < v_{min} \text{ and } v_t > v_{max} \\ P_r \frac{v - v_{min}}{v_r - v_{min}} \text{ for } v_{min} < v < v_r \\ P_{w,r} \text{ for } v_r < v < v_{max} \end{cases} \qquad 3.2.3$$

where $P_{i,w,r}$ is the rated power output of the wind generation units (kW) of the i^{th} microgrid, v_r is the rated speed for wind turbine (m/s), v_{min} is the wind speed required to start power generation by wind turbine (m/s), v_{max} is the cut-out speed for the wind turbine (m/s).

3. Ramp rate limits:

$$R^{down}_{i,j}\Delta T \le P^{t+1}_{i,j} - P^{t}_{i,j} \le R^{up}_{i,j}\Delta T \qquad 3.2.4$$

where ΔT is the transition time between the time periods (h); $R^{down}_{j,i}$ and $R^{up}_{j,i}$ are the ramp down and ramp up transition limits of the j^{th} conventional generation unit of the i^{th} microgrid (kW/h); $P^{t+1}_{i,j} - P^{t}_{i,j}$ is the difference in generation between transition periods time t and $t+1$ of the j^{th} thermal generator of the i^{th} microgrid (kW).

The presence of the ramp rate limits is one of the main reasons for called problem not Static, but Dynamic Economic Dispatch. The reason of this fact is that main difference between DED and SED not only in dynamic time changing but also the presence of the look-ahead capability for the solving of the optimization problem, which is not available in the SED.

4. Power flow limits of the transmission lines:

$$-P^{max}_{l} \le P_{l,t} \le P^{max}_{l} \qquad 3.2.5$$

where P^{max}_{l} is the maximum available power transmission capacity of line l (kW); $P_{l,t}$ is the power flow between nodes (or agents) on the l line l at time t (kW).

5. Voltage limits at the busses:

$$V^{min}_{i,j} \le |V_{i,j,t}| \le V^{max}_{i,j} \qquad 3.2.6$$

where $V^{min}_{i,j}$ and $V^{max}_{i,j}$ are the minimum and maximum voltage limits at the j^{th} bus of the i^{th} microgrid (p.u.); $V_{i,j}$ is the voltage at the j^{th} bus of the i^{th} microgrid at time t (p.u.).

6. Spinning reserve of the conventional generation units:

$$SpR_{i,j,t} = \max\left(RP^{u}_{i,j}, P^{max}_{i,j} - P^{t}_{i,j}\right) \quad 3.2.7$$

where RP^{u}_{i} is the 17% of the maximum limit of the power rated for the conventional generation unit (kW).

The $SpR_{i,j,t}$ is the spinning reserve of the conventional generation unit, which is defined as a surplus capacity that is available for power generation level expansion. The spinning reserve's capacity relies on different factors in the real life, which include parameters of the generation unit, the torque that can be applied to the rotor of the generation turbine, maximum rated power, etc.

7. Power balance

$$\sum_{i=1}^{m} P_{i,t} = P^{Dem}_{i,t} + P^{Loss}_{t} \quad 3.2.8$$

where $P^{Dem}_{i,t}$ is the demand of the i^{th} microgrid forecasted for the t time interval (kW); $P^{Loss}_{i,t}$ is the losses of the i^{th} microgrid during the t time interval (kW).

Chapter 4 – Transactive Energy Management and Markets

4.1. Markets' architecture for energy trading among microgrids

Multi-agent system management is a cooperation of two or more intelligent agents within an MMG system. The definition of the agent of the microgrid is not similar to the actual agent, as it implies the automatization of the microgrid and autonomous actions due to the change in the environment. The agents themselves are the intellectual systems used for system analyzing and representation of the microgrid on the map. Proactive actions of the agents allow microgrids to support social connections in the MMG environment (interaction with other microgrids in the system) and follow goal-oriented direction. The key features of the agent include data collection and transmission, as well as representation of the microgrid on the energy market (if it is applicable).

The agent-oriented programming is one of the best ways to implement secure data transmission and its access for the agents via encapsulation of the data files and timely market-monitoring. It also should be noted that the fact of adding the energy markets to the picture of the MMG system should affect the agent's operations, as ignoring or postponing messages related to the auctions are not allowed for the modeling of the agents' behavior. In the case of the development of the intelligent system, all possible responses and behavior of the agent should be considered, as well as all possible areas of their application. Areas of agents' application in the MMG systems can include simulation of the energy auctions, control of the microgrid's actions, system automation and protection, monitoring of the circumstances available in the system and its diagnostic. The purpose of the multi-agent system can be focused on energy management, creation of the smart MMG system, optimal scheduling of the distributed energy resources, analysis of the MMG system and control of the microgrids' actions. Aside from the simulation and implementation of the energy auction, the multi-agent system can also be used to control the separate units and transfer for the island mod operation of the microgrid.

Multi-agent system structure in the transactive energy management enables reciprocal negotiation between the agents in the execution of the energy auctions by abiding by the protocol for the coordination of the agents' actions. The Contract Net Protocol (CNP) is a set of rules, which is determined for the communication and fair coordination of the agents in the MMG network. Traditional CNP can be represented as a concise process with a predetermined set of rules or steps for efficient interaction of the agents. The rules in the CNP can vary according to the system specification or goal of the predetermined task.

As was mentioned in the literature review chapter, there are different structures of the transactive energy management system that can be used for the implementation of energy auctions. The interest of this master thesis is to implement centralized and decentralized energy auctions and compare their results. For the realization of the energy markets, it decided to select a continuous discriminatory k-DA auction mechanism, which represented in Figure 2.3.1. The Gantt Chart of every time interval within Transactive Energy Management time depicted in Figure 4.1.1. As can be seen from the figure, every time interval of the MMG energy management is break up in three periods, which are the self-discussion period, market period, and period of energy transmission between the microgrids. The first period, which is the self-discussion time interval, is the period where microgrids calculate their DED and decide regarding participation/refuse in/from the auction, and in case of participation, microgrids should identify their bid/ask prices. The second period is designed for the market itself, where buyers and sellers submit their offers and wait for the decision regarding winners of the auction. The third period is used for the transmission of energy between the winners of the auction, while the microgrids that lose should trade with the main grid.

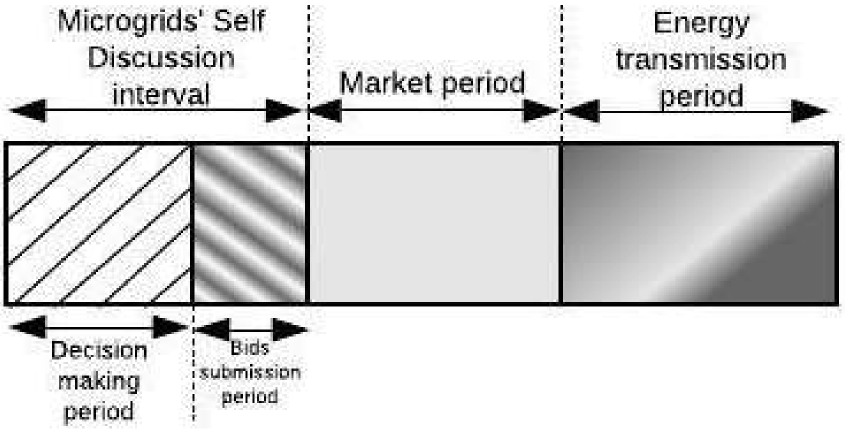

Figure 4.1.1. Gantt Chart for one block of time

4.1.1. Centralized energy market architecture

The first market architecture proposed in the manuscript is the centralizes energy auction, which is created based on the hierarchical-centralized structure of energy management. The structure of the energy management used for the manufacturing of the auction is represented in Figure 2.3.1. The design of the centralized auction implies the conduction of auction on a level different from a microgrid. The meaning of this is that microgrids are not the direct participants of the energy auction, and MMG Load and Generation Agents are those who receive information regarding bid/ask prices and the amount of excess/required amount of energy. The meaning of this is that market and microgrids level are separated, which can be seen from Figure 4.1.2.

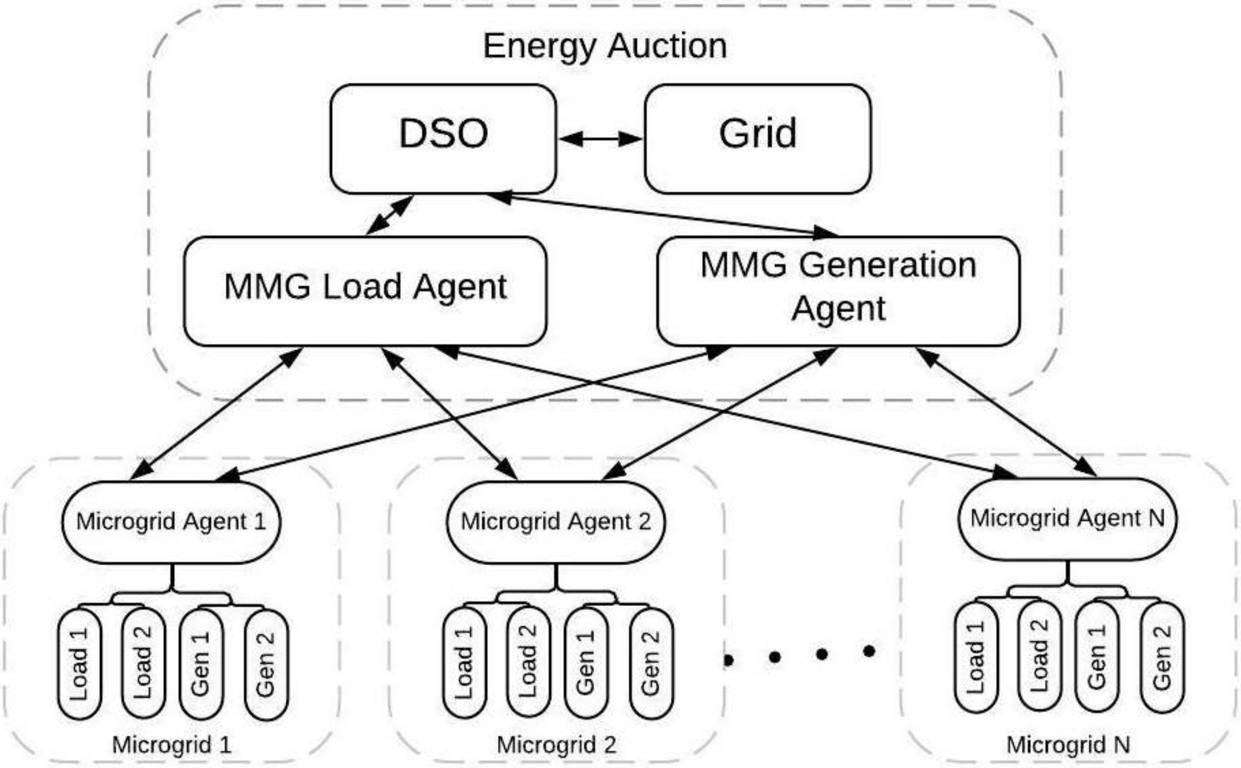

Figure 4.1.2. Centralized energy market for MMG system

The top level of the system represented in Figure 4.1.2 is the market for energy trading, where DSO is acting as both organized and operator in the market, and responsible for matching total excess generation and demand in the MMG system. The DSO in the market level should identify the matching between the agents by conducting the continuous discriminatory k-DA auction. The bottom level of the system is the microgrids, where each one tries to match their generation and load and identify correct resource management.

Each of the microgrids has its own Microgrid Generation (MG Gen) and Load (MG Load) agents, who collect information regarding generation and load and send it to the Microgrid Agent. The Microgrid Agent identifies the situation for the next period, with the calculation of the DED, and identifies status for the microgrid in the auction. The information should be further submitted to the DSO agent, which is acting as the organizer of the market, via MMG Load and Generation Agents, who break submitted offers into pieces of equal size for the simplification work of the DSO. Here it also should be noted that FIT and TOU prices, which are the buying and selling prices of the main grid, are constant and not efficient for the microgrids' trading. The trading with the grid takes place in case of losing in the auction and having no other option. Thus, if the microgrid is submitted offer as a seller to the auction and his offer lost in comparison with others, those microgrids will trade with the grid at FIT. Similar case happens with buyers, who lost in the auction, and have to trade with the grid at TOU price. The relation among FIT, TOU, and MCP always follow the correlation represented by Equation (4.1.1). With the fact of presence trading with the main grid, one of the characteristics of the efficient auction is the minimizing trading with the grid and obtaining the maximum benefit from conducting the trading between the microgrids.

$$\mathrm{FIT} < \mathrm{MCP} \le \mathrm{TOU} \tag{4.1.1}$$

The market can be conducted with different time intervals, which usually selected to be 15, 30, or 60 min, where it is assumed that all parameters will be constant within the time block. The list of steps of the system in case of centralized energy management is the following:

Step 1: DSO sends messages to the microgrids in the MMG system regarding the beginning of the new period.

Step 2: Microgrid Agents collect data regarding load and generation from the MG Load and MG Gen Agents.

Step 3: Every microgrid conducts self-calculation and identifies the status of the microgrid, where it should decide regarding participation in the auction as a buyer/seller or not participate at all.

Step 4: Microgrid Agents submits information to the corresponding MMG Agent according to the status of the microgrid, where buyers submit offers to Load Agent and sellers to the MMG Generation Agent.

Step 5: MMG Load and MMG Generation Agents analyze received information and create sub-agents for representation fixed amount of energy each, which are further submitted to the DSO.

Step 6: DSO receives sub-agents with the bid/ask prices, and if the number of selling and buying sub-agents is not equal, it requests a missing amount from the Grid. When the number of selling and buying sub-agents is equal, DSO conducts the auction.

Step 7: After conducting the auction, DSO submits information to the Microgrid Agents via MMG Load and MMG Generation agents.

Step 8: Winner microgrids transmit energy between each other and lost one's trade with the Grid.

4.1.2. Decentralized energy market architecture

The second market architecture proposed in the manuscript is the decentralizes energy auction, which is created based on the decentralized structure of energy management, which is represented in Figure 2.3.2. The name of the design of the auction speaks for itself, as it does not rely on the central unit for conducting the auction. The distinctive feature of the decentralized auction is the conduction of auction on the microgrids' level, where microgrid can be not only a participant of the auction but also a conductor. The structure of the Decentralized auction for the MMG system can be seen from Figure 4.1.3.

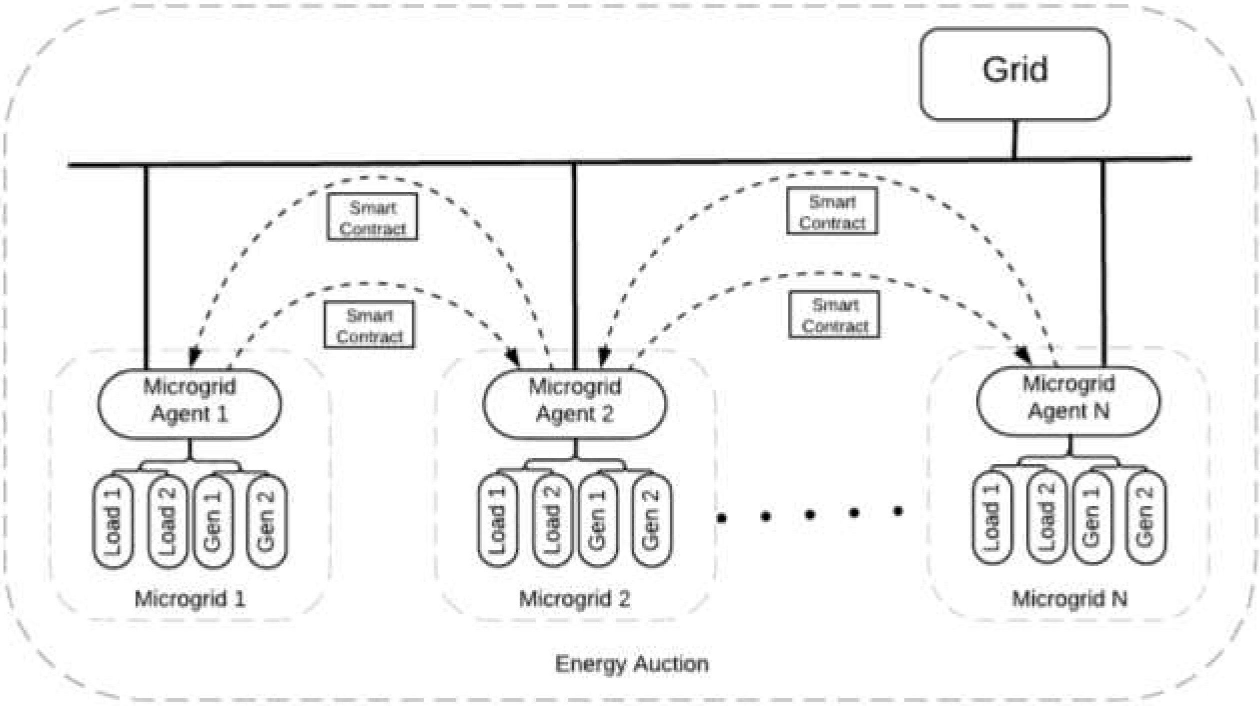

Figure 4.1.3. Decentralized energy market for MMG system

The reason for conducting decentralized auctions is in the problems that sometimes can be associated with centralized systems, which include:

1. Failure of the central agent, that can lead to the inability of conducting TE auctions.
2. All the auction participants must estimate the level of trust to the central agent, who is acting as an auctioneer. The reason for this is that auctioneer may be in conspire with some units (microgrids).
3. In the centralized auctions, the main agents are represented in terms of a large and controllable system (DSO), which also can ask a fee its' work (ex. conducting the auction).
4. Sometimes the agents selected for the energy transmission between each other by the DSO is located at a long distance between each other, which can cause a transmission loss.
5. There is no guarantee of the safe information exchange when microgrids' agents submit/receive information to/from the main agent.

To ensure safe information exchange and protect the system from cyberattacks, the decentralized auctions can use the blockchain for auction mechanism. The fact that core design principles of blockchain include decentralization and reliability, as well as the elimination of the necessity in the trusted third party (auctioneer in the centralized system). And as it was mentioned earlier, using blockchain provides advantages in the face of reducing error and improving security, as well as trusted energy transactions [42]. There are 6 key features of the blockchain: decentralization, smart contracts, privacy, tokenization, secure and insurance of stable work.

If any microgrid will require energy trading with another microgrid it should follow some procedure, which is specially assigned for the peer-to-peer energy trading. The list of steps of the system in case of decentralized energy management with the blockchain mechanism is the following:

Step 1: Each microgrid collects data regarding load and generation from the MG Load and MG Gen Agents.

Step 2: Everyone in the system creates a smart contract, where bids should be included.

Step 3: The decentralized TE auction starts, where all Microgrid Agents in the system send their smart contracts to the neighboring agents.

Step 4: Each microgrid collects several amounts of incoming smart contracts and acts as an auctioneer, trying to solve discriminatory k-DA auctions.

Step 5: After solving auctions, the agent should find the public key to ensure energy transmission from buyer to seller.

Step 6: Auctioneer notifies seller and buyer agents regarding accepting the transaction and indicated the public key to the system.

Step 7: If the agent did not receive any notification within the Market period, it will be automatically denoted as losing on the auction and necessity in trading with the main grid.

4.2. Bayesian Game based bidding

With the fact of incomplete information in the auction, where the participants can have only assumptions regarding actions of other players and use of the discriminatory k-DA auction type, it should be noted that the Bayesian games, or "games of incomplete information" perfectly fit the conditions. In addition to the chosen auction type, the bidding strategy will follow the first price sealed-bid auctions. The reason for this is the strategic form of the bidding, where players submit their bids simultaneously, without the ability to increase or decrease their value after they have seen the bids of other players. Implementation of the Bayesian games is the common method for honest allocation of the goods between players in the auction with a variation of the good amounts for individuals. The definition of the Bayesian game can be represented in the form of structure:

- The $\mathcal{J}$ number of players in the auction
- Each player *i* in the game has a set S_i of possible actions
- Each player *i* has a set $\theta_i \in \Theta_i$, knows as a type, or convictions of the player regarding convictions of other players, about the convictions of other players, and it is infinite times
- Payoff functions for the auction participants, where for each player *i* there is $u_i(s_1, \dots, s_{\mathcal{J}}, \theta_1, \dots, \theta_{\mathcal{J}})$
- Probability distribution $p(\theta_1, \dots, \theta_{\mathcal{J}})$ over the state of minds of players

The common knowledge in the Bayesian game, which shared between all players, is the probability distribution, a possible state of mind of other players, and the payoff functions. With the given data it is possible to calculate anticipated payoff for player *i* with θ_i state of mind:

$$U(s_i', s_{-i}(\cdot), \theta_i) = \sum_{\theta_{-i}} p(\theta_{-i}|\theta_i)\, u_i(s_i', s_{-i}(\theta_{-i}), \theta_i, \theta_{-i}) \qquad 4.2.1$$

According to the theorem of the repeated games, which include auctions, if the game has a unique Nash Equilibrium (NE), then there is a unique subgame perfect NE. The meaning of this is that the NE is independent on the past outcomes of the game in case of the repeated game. The $s(\cdot)$ strategy can be called as NE only in case if for all $i \in \mathcal{I}$ and $\theta_i \in \Theta_i$ will satisfy condition:

$$s_i(\theta_i) = \max \sum_{\theta_{-i}} p(\theta_{-i}|\theta_i)\, u_i(s'_i, s_{-i}(\theta_{-i}), \theta_i, \theta_{-i}) \qquad 4.2.2$$

In the auction, each player should submit a bid or ask price b_i, depending on the chosen status (buyers/seller) in the block of time, where the payoff can be found as:

$$U_i(\boldsymbol{b}, \boldsymbol{v}) = \begin{cases} v_i - b_{clr} & , if\ b_i > b_j \\ 0 & , else \end{cases} \qquad 4.2.3$$

where **b** and **v** are the vectors of bids and valuations, b_{clr} is the clearing bid price for the auction, and the bidding of other players assumed to be uniform in the range $[0, v_{max}]$.

The i^{th} bidder's best response received in case of receiving maximum payoff:

$$b_i^*(v_i) = \arg\max \int_o^{V_{max}} U_i(\boldsymbol{b}, \boldsymbol{v}) f_v(v_j) dv_j = \qquad 4.2.4$$

$$= \arg\max (v_i - b_i) \Pr(b_i > b_j(v_j)) + 1/2 (v_i - b_i) \Pr(b_i = b_j(v_j))$$

In order to find out the specific result, the bidding strategy of the players should be restricted to affine form:

$$b_i(v_i) = \alpha_i + \beta_i v_i \qquad 4.2.5$$

With inserting Equation (4.2.5) to Equation (4.2.4) we obtain the following:

$$\Pr(b_i > b_j(v_j)) = \Pr(b_i > \alpha_j + \beta_j v_j) = \Pr\left(v_j > \frac{b_i - \alpha_j}{\beta_j}\right) = \frac{b_i - \alpha_j}{\beta_j v_{max}}$$

$$0 = \frac{d(v_i - b_i)\left(\frac{b_i - \alpha_j}{\beta_j}\right)}{db_i} = v_i - 2b_i + \alpha_j$$

$$b_i^*(v_i) = \begin{cases} \frac{v_i + \alpha_j}{2} & , if\ v_i \geq \alpha_j \\ \alpha_j & , if\ v_i < \alpha_j \end{cases} \qquad 4.2.6$$

where α_j is the MCP of the previous period/assumed strategy of the opponents, v_i is the valuation of i^{th} player.

The best response of the buyers and sellers in the auction according to the Bayesian NE is represented in Figure 4.2.1.

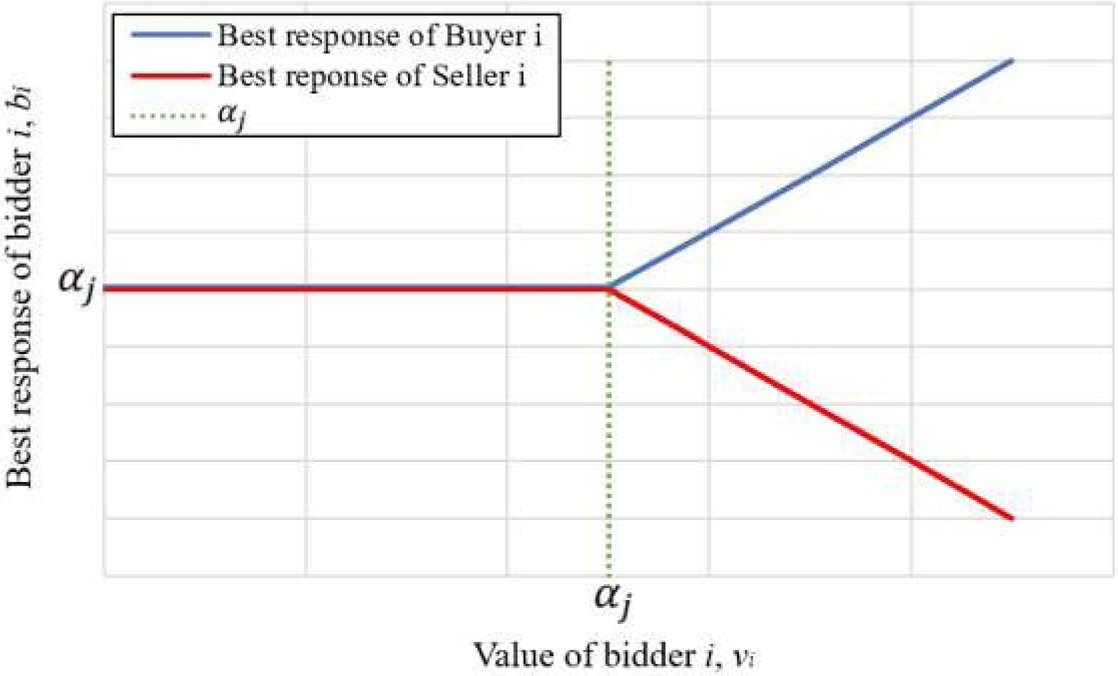

Figure 4.2.1. i^{th} player's best response

Chapter 5 – Case Study Simulation

5.1. The Proposed Approach for solving DED

The approach presented in the thesis work will be used to solve the DED for the MMG system in centralized and decentralized manners. For both approaches, each of the microgrids in the MMG system should perform local DED, which is executed in the Self-Calculation period, and represented in the Gantt Chart as the first part of the block of time in Figure 4.1.1. With the fact of the multi-objective problem for solving the DED, the Self-Calculation period should be subdivided into the stages, which will include kind of consensus between the microgrids for sharing part of the self-data between the whole MMG system.

The Self-Calculation part of each microgrid will include 3 stages, which should be performed in order:

1. Stage 1: Applying the data-sharing regarding the load in the system, between the agents. The data regarding the generation is not part of the sharing information, while past data is available for all the agents. The reason for performing the first stage is the partial data sharing, which aimed to reach a consensus for the problem between all microgrids in the MMG.
2. Stage 2: Each microgrid determine its future status in the system, and microgrids determine their future bid/ask prices by using Bayesian Nash Equilibrium Strategy (Game Theory).
3. Stage 3: After deciding with bidding for the next period each microgrid runs the DED for itself with using Genetic Algorithm (GA). After running the DED buyers and sellers will determine the offers they will send to the auction.

Here it also should be noted that running the self-calculation part for the microgrid is done differently for each block of time, and running the DED in the Stage 3 of the self-calculation period does not give the final result of the system, since the cost of selling/buying energy will be known only after conducting the auction. To say in more accurate words, the meaning of this is that the DED is used to determine the energy generation for the thermal generators for the next period with the assumption that microgrid will win in the auction.

Additionally, the DED will be conducted for the MMG system without considering the trading between the microgrids. The reason for this is the comparing presence of the GT based TE management in the DED for MMG system with ordinary DED, where each microgrid will try to optimize itself separately.

The Genetic Algorithm (GA) is the AI-based method that can be used as a proposed approach for solving the DED problem. The use of any of the AI techniques for the DED is more advantageous compared with any hybrid and classical techniques, which is proven in Chapter 2 - Section 1. The main working principle of the GA based on the random search strategy and the flowchart of GA is represented in Figure 5.1.1.

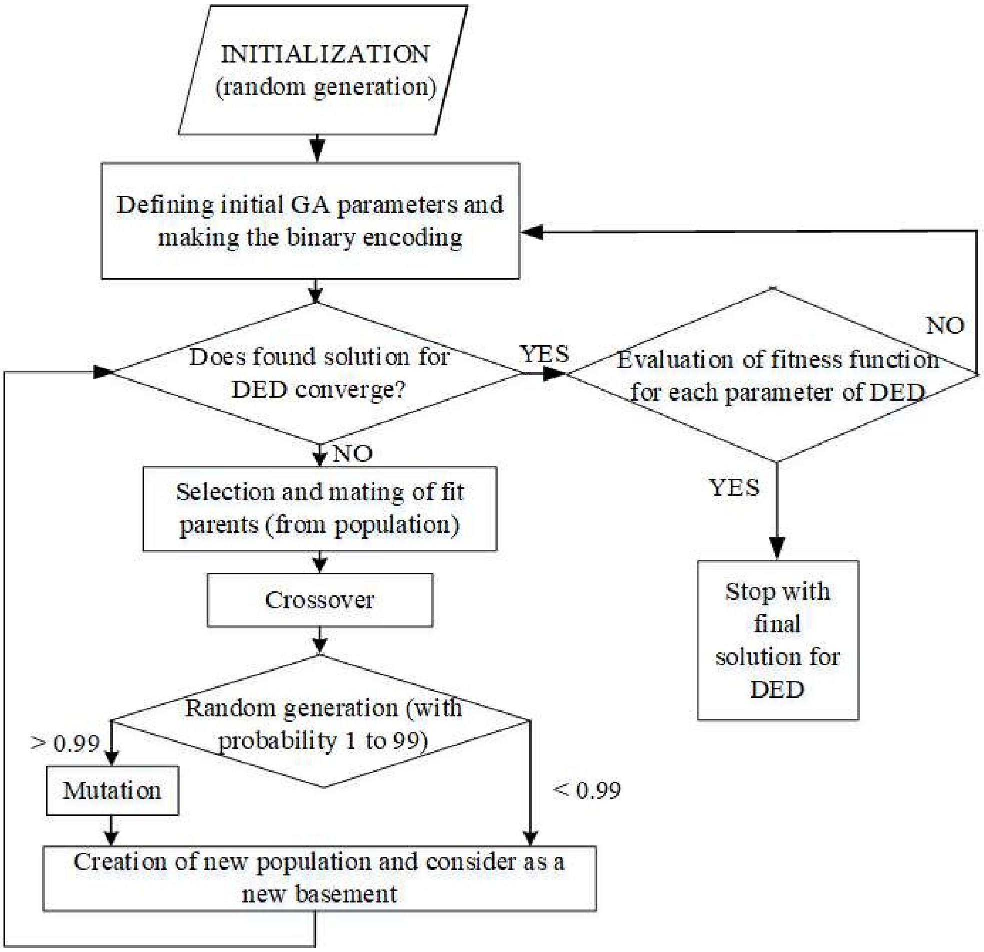

Figure 5.1.1. Flowchart of the GA

According to the procedure represented in Figure 5.1.1, the fact of working with binary can be noticed. The reason for this is that GA works only with data encoded to the binary format and represented as the genomes. The genomes, or also population, are the data used for finding a solution to the problem and represented in the form of the binary numbers of a specific length. The first step of the GA is the random generation of initial parameters (first population), or the first possible solutions to be more specific. The next step in the algorithm is checking the convergence of the found solutions according to given constraints in the system. If a found solution is within the limits, it is required to evaluate the fitness function for the found parameters (Equation 3.1.1). If the found solution will not converge, then two operations will be conducted, namely mutation and crossover.

$$Chld_1 = [(\alpha_{IR})Prnt_1 + (1 - \alpha_{IR})Prnt_2] \quad 5.1.1$$

$$Chld_2 = [(1 - \alpha_{IR})Prnt_1 + (\alpha_{IR})Prnt_2] \quad 5.1.2$$

Crossover operation is used for the formation of new solutions (children), based on the previous generation. The crossover operations for the creation of two children are represented in Equations (5.1.1) and (5.1.2). The first step in the crossover operation is the random generation of α_{IR} number in the range [0, 1], which is further used as the influence ratio of parents for the creation of a new population.

The mutation operation is more optional comparing to crossover and performed with a 1% probability. The reason for this is that mutation is used for evaluation of the new generation, which will be fully opposite to the parents' generation and creates a new line if the previous generation did not show a good performance.

5.2. Case Study

The main aim of the following work is to enable DED with a centralized and decentralized TE auction platform with the Bayesian NE based bidding. In order to demonstrate the working principle of the proposed models, the MMG with DER will be considered. The power-related markets are conducted in intervals of 1 hour, that also called as a 1-hour time bocks. Each day consists of 24-time blocks, it is assumed that auctions are conducted in each time interval for the subsequent unit. For convenience, we will consider 1 day for showing the proper work of DED.

The IEEE 37-bus system was selected for analyzing the efficiency of the proposed work. For the simulation of the DED for MMG system with Game Theory-based TE, some modifications of the system were conducted, and the proposed system can be seen in Figure 5.2.1. The system used to find the optimal power generation schedule for the MMG system. The system parameters for the thermal generators of the microgrids are represented in Table 5.2.1.

Table 5.2.1. System Parameters for Microgrid's Thermal Generation Units

Bus Number	a	b	c	P_G^{min} (MW)	P_G^{max} (MW)
707	10	1.50	0.0170	40	270
722	0	1.00	0.0095	30	250
710	5.2	1.75	0.0175	50	280
738	0	1.2	0.0162	70	320
740	7.0	1.00	0.0083	60	300

The parameters for maintenance and emission cost, in their turn, are represented in Table 5.2.2.

Table 5.2.2. Parameters for Emission and Maintenance for Thermal Generation Units

Bus Number	K ($/kWh)	ω	τ	υ
707	19.2	0.0200	- 0.0100	25.313
722	19.2	0.0207	- 0.0055	22.983
710	19.2	0.0270	- 0.0100	25.505
738	19.2	0.0226	- 0.0055	24.700
740	19.2	0.0291	- 0.0050	24.900

From Figure 5.2.1 it can be seen that there are 4 microgrids in the system, which have not only traditional thermal generation units but also use wind generation. The generation cost of wind power calculated using Equation (3.1.5). For the particular case study, the interest rate *r* of the wind generation unit used to be 5.05%. The lifetime of the wind turbines selected to be the same for every wind turbine and used to be equal to 25 years, as it is the approximate working time of the wind turbine. Here it also should be noted that wind power will not be generated according to the requirements of the microgrid, and will depend only on the wind speed, meaning that it will not be controlled by the microgrid's operator. The parameters for wind power generation for wind turbines are represented in Table 5.2.3.

Table 5.2.3. Parameters for Wind Generation Units

Bus Number	I_i^P ($/MW)	G_i^E ($/MW)
724	16.34	22.79
728	15.97	23.08

744	16.49	22.23
735	16.22	22.68
741	14.25	23.70

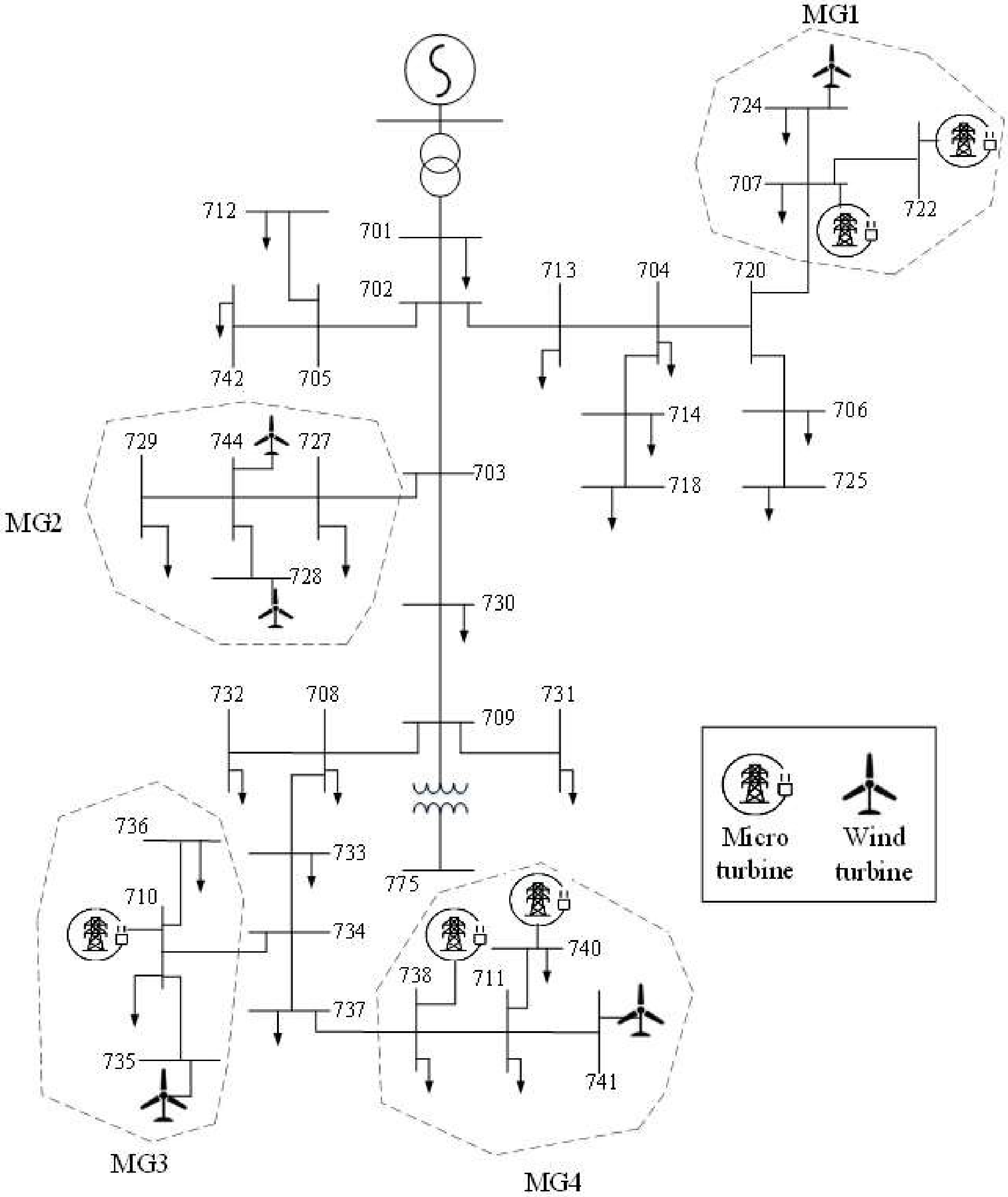

Figure 5.2.1. IEEE 37-bus system with 4 microgrids

The system in the case study is used for providing an example of the application of the proposed technique for solving DED for the MMG system with TE auctions using GT bidding. The case study will be used for the simulation of two types of TE energy auctions, namely centralized and decentralized (see Figures 4.1.2 and 4.1.3). The results of the simulation will be compared with each other.

5.3. Deep Neural Network for STLF

Neural Network is a computing system inspired by neurons' connections in the human brain; it also specified as a separate prediction class. Neural Network, which also called as an Artificial Neural Network, is a kind of a system that tries to find correct prediction by constantly updating itself.

Deep Neural Network (DNN) is also one of the Artificial Neural Networks, which is merely speaking is an ordinary NN, but with several hidden layers. Hidden layers in DNN are used for the deep characterization of the data due to the fact that hidden layers used for extraction of features. Using of DNN allows system to obtain more information, which is resulted in improved capability of the system in terms of data prediction. The structure of ordinary DNN is represented in Figure 5.3.1.

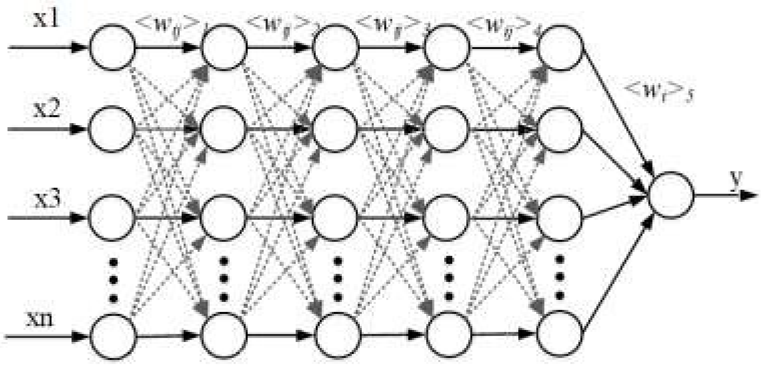

Figure 5.3.1. Deep Neural Network with 4 hidden layers

From Fig. 1 it can be observed that there are several amounts of hidden layers, where each of them implements the so-called transformation of the data. The transformation itself is associated with finding correct parameters of layers' weights. Those weight values for each layer should be correctly mapped according to the training of the DNN. The model selection associated with DNN parameters found through the validation process, and overall accuracy should be checked by testing process. DNN have an incredible advantage when processing large amount of data and thus able to learn features of high-level in the step manner. On the other side, accuracy associated with

DNN for STLF generally does not exceed 75%. Additionally, in case of using a plenty number of samples in training set, overall efficiency of the system can decrease.

The output y, in Figure 5.3.1, updates are done based on the following model:

$$y = f_N(k + \sum_{i=1}^{H4} < w_i >_5 \ < h_i >_4) \tag{5.3.1}$$

where k is the margin of the resulting layer and $< h_i >_4$ is a result of the i^{th} node in the fourth layer:'

$$< h_i >_4 = f_N(< c_i >_4 + \sum_{i=1}^{H3} < w_{ij} >_4 < h_i >_3) \tag{5.3.2}$$

where $< c_i >_4$ is a margin (edge) of the i^{th} node of the fourth layer and $< h_i >_3$ is a result of the i^{th} node for the next layer:

$$< h_i >_3 = f_N(< c_i >_3 + \sum_{i=1}^{H2} < w_{ij} >_3 < h_i >_2) \tag{5.3.3}$$

where $< c_i >_3$ is a margin of the i^{th} node of the layer number three and $< h_i >_2$ is a result of the i^{th} node for the next layer:

$$< h_i >_2 = f_N(< c_i >_2 + \sum_{i=1}^{H1} < w_{ij} >_2 < h_i >_1) \tag{5.3.4}$$

where $< c_i >_2$ is a margin of the i^{th} node of the layer number two and $< h_i >_1$ is a result of the i^{th} node in the primary layer, also called as an opening layer:

$$< h_i >_1 = f_N(< c_i >_1 + \sum_{i=1}^{H1} < w_{ij} >_2 x_i) \tag{5.3.5}$$

where $< c_i >_2$ is a margin of the i^{th} node in the primary levelling cover and x_i is the i^{th} input. f_N is the activation function used in the DNN. In this work sigmoid function is used as an activation function:

$$f_N = \sigma(x) = \frac{1}{1 + e^{-x}}$$

Simulation of the STLF using DNN was conducted using Weka 3.8.4 program.

5.4. System Overview and Assumptions

In order to give more clear representation of the approach represented in the master thesis work, the overview of the system simulated within one time period is represented in Figure 5.4.1. As it can be seen from the figure, each microgrid in the MMG system performs decision making process, where the STLF, Bayesian Game and DED are conducted. Conduction of the aforementioned processes are the essential part for identification correct bid/ask prices, as well as determination of amount of energy to offered/requested energy on TE auction. The reason of conduction the STLF is the identification of the load in the microgrid for the proper simulation of the DED.

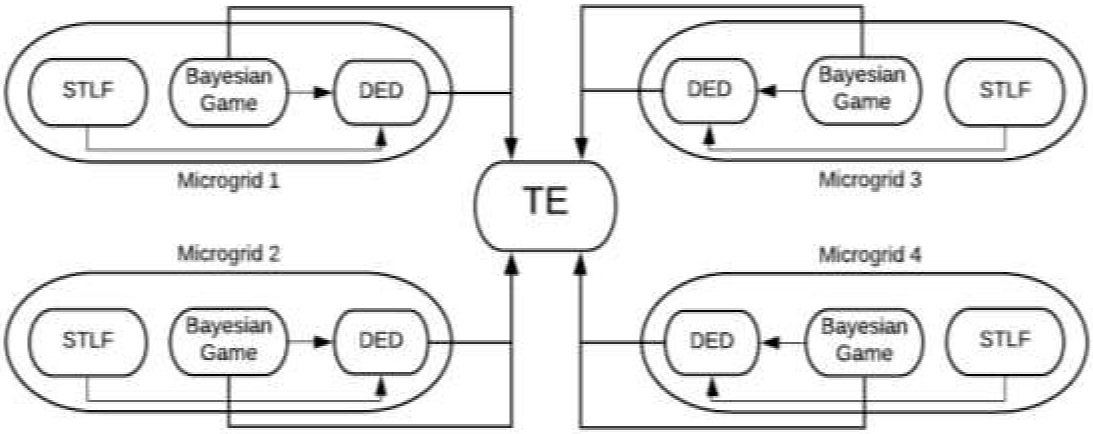

Figure 5.4.1. Overview of the whole system for one time period

It can be seen from the Figure 5.3.1, that the first step in the decision making for each microgrid is conduction of the STLF. After conduction the STLF every microgrid will have information regarding the future load. With having this information on hands, it is possible to executing the self-DED without considering participation in the auction, which will be explained further in the Case 1 in 6.1.1 sub-part of the Chapter 6. In order to participate in the TE auction, agents should identify bids, which is known after running the Bayesian Game and finding the Nash Equilibrium according to settled assumptions for each agent separately. After finding proper bid/ask prices, agents are able to run the DED, where it will be possible to identify amount of energy that will be generated by the thermal generation units. The amount of generation is found according to the information known by the agent. The amount of energy generated by the microgrid cannot be less than the requirements of the agent (where exception is the case where load exceed the maximum generation limits), and cannot be more than the 60-65% of the total load required for the MMG system. The DED uses bids identified by the game as an assumption that microgrid will win in the auction and motivates the microgrid to generate energy to participate in the auction.

In order to ensure that approach proposed in the work will be executed properly, there are several assumptions that should be considered. The assumptions for this work are following:

1. It is considered that energy transmitted between the microgrids in the MMG system is exchanged without any losses.
2. It is always possible to make proper connection between the microgrids, as well between any microgrid and the main grid.

3. Information shared between the agents will always reach the receiving point and will not be interrupted somehow. The meaning of this is that information that will be send by any agent will not be lost somewhere and will arrive without any changes.
4. The results found by the STLF will be considered as an actual data, without any difference between them in the future.

Chapter 6 – Results and Discussion

6.1. Results of DED for MMG

6.1.1. Case 1: Self DED for each Microgrid without TE market

In order to draw a parallel between different cases and analyze the results obtained during simulation of DED for MMG with GT, it is also required to obtain simulations of DED for each of the microgrids without the presence of the TE markets, where energy trading will be available only between the microgrid and the main grid. The results of the simulation are obtained separately for each of the microgrid, where DED was simulated using Matlab and communication between an agent and the main grid operator was conducted using the Jade program.

Table 6.1.1. Simulation Results for Microgrid 1 in Case 1

Time block	Microgrid 1				
	L1 (724) (kW)	L2 (707) (kW)	WT1 (724) (kW)	G1 (707) (kW)	G2 (722) (kW)
1	213	276	137	175,1	176,9
2	240	282	142	188,2	191,8
3	273	296	161	201,7	206,3
4	271	297	180	199,8	203,2
5	289	313	169	214,8	218,2
6	265	318	132	227,6	223,4
7	226	303	120	212,6	208,4
8	225	293	135	197,6	193,4
9	217	296	130	185,7	197,3
10	198	285	158	170,7	182,3
11	203	277	130	170,5	179,5
12	196	273	139	164,6	165,4
13	189	270	147	153,5	158,5
14	194	261	137	160,0	158,0

15	172	243	126	145,2	143,8
16	181	249	129	142,9	158,1
17	176	251	137	137,9	152,1
18	164	258	122	148,5	151,5
19	175	273	124	163,5	160,5
20	181	276	123	159,6	174,4
21	184	278	139	162,2	160,8
22	192	280	135	161,9	175,1
23	199	287	128	173,9	184,1
24	214	284	132	172,3	193,7

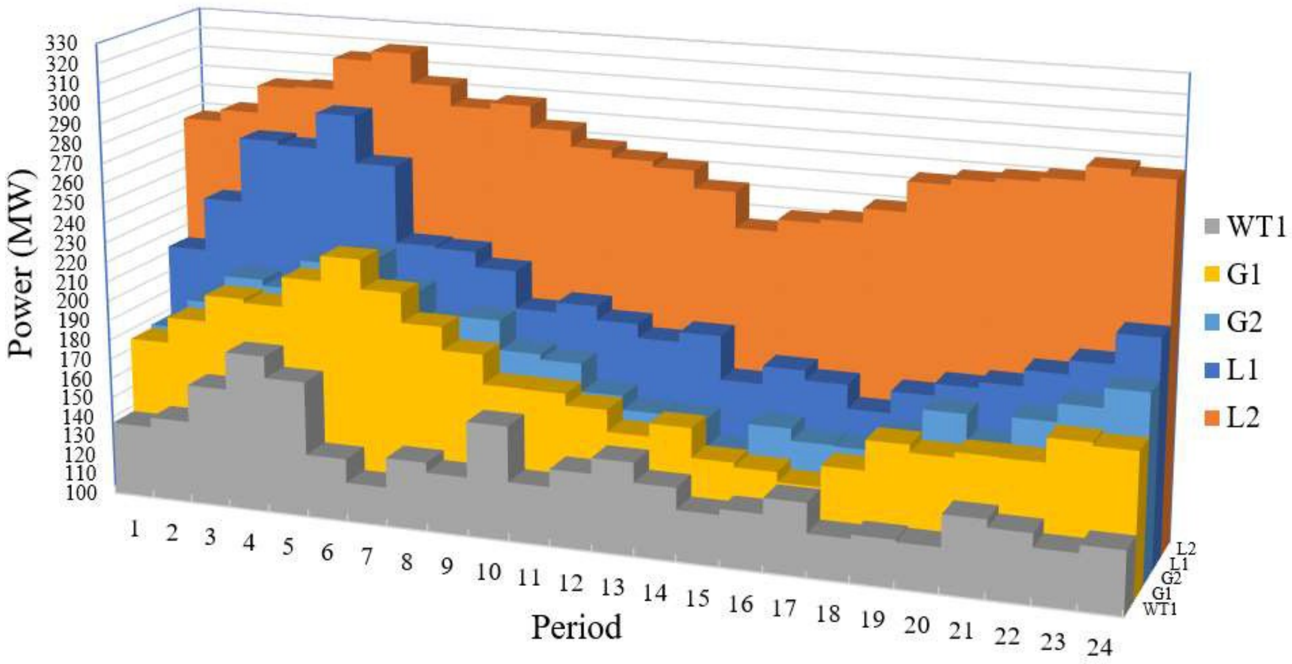

Figure 6.1.1. Power generation and load graph for Microgrid 1 in Case 1

The results of the simulation of the DED for Microgrid 1 are represented in Table 6.1.1 and Figure 6.1.1. As the main aim of the DED is to minimize the total generation cost of the system within the selected time period, it also should be noted that the Wind Turbines generation cannot be changed and depend only on the wind speed of the time period, according to the assumption of this work. From the simulation results for Microgrid 1, the total generation of the unit exceeds the total load of the unit in some of the time periods. With the fact of absence of the trading between the microgrids in the MMG system, the total cost of the generation for the Microgrid 1 will be calculated with considering trading with the main grid, or sale of energy in this special case. The total cost for the Microgrid 1 is equal to \$315,09 where trading with the main grid was conducted in 4th, 7th, 8th, and 10th time blocks.

From Figure 5.2.1 it can be noted that there are no thermal generation units in the Microgrid 2, which automatically removes the need of conducting the DED with the fact of trading possibility only with the main grid. The load and the wind generation parameters of the Microgrid 2 represented in Table 6.1.2 and Figure 6.1.2.

Table 6.1.2. System schedule for Microgrid 2 in Case 1

Time block	Microgrid 2			
	L1 (729) (kW)	L2 (727) (kW)	WT1 (728) (kW)	WT2 (744) (kW)
1	257	172	133	134
2	269	183	140	140
3	268	189	146	169
4	279	198	151	184
5	286	194	170	167
6	299	203	143	139
7	297	191	128	122
8	284	184	137	133
9	271	182	130	127
10	265	173	142	151
11	269	161	128	132
12	263	157	133	137
13	258	152	145	146
14	251	147	136	136
15	240	143	127	125

16	245	142	128	127
17	241	146	121	120
18	243	168	113	132
19	254	173	123	120
20	262	179	128	127
21	273	183	137	138
22	278	184	135	136
23	282	179	130	129
24	281	177	131	129

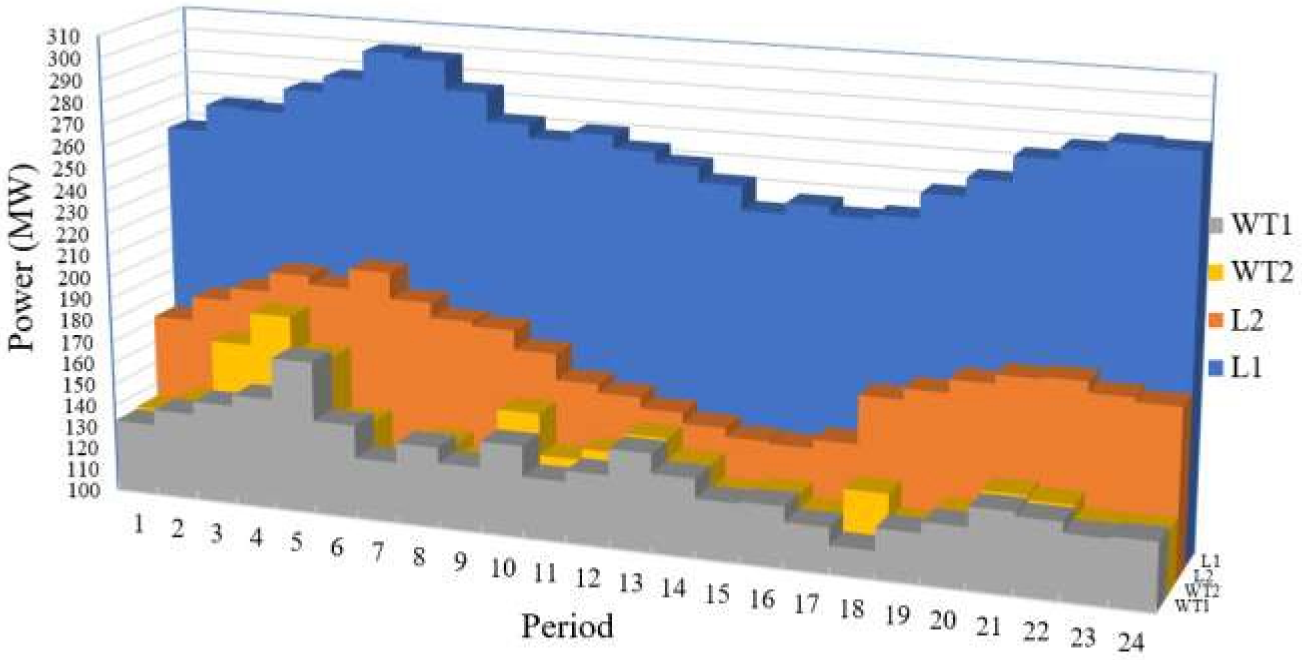

Figure 6.1.2. Wind power and load graph for Microgrid 2 in Case 1

From Figure 6.1.2, represented above, it can be noted that the total load for the unit exceeds the entire generation in each time period. With the fact of trading with the main grid, the microgrid will not have another chance to buy energy with TOU price, which is set by the grid. The final cost for Microgrid 2 in 24 hours, including the cost of wind energy generation and buying energy from the main grid, is $317,97. The trading with the grid conducted in every period of simulation, in case of the second microgrid, where the amount of purchased energy is not less than 100 kWh.

Table 6.1.3. Simulation Results for Microgrid 3 in Case 1

Time block	Microgrid 3			
	L1 (710) (kW)	L2 (736) (kW)	WT1 (735) (kW)	G1 (710) (kW)
1	139	158	130	167
2	145	152	141	156
3	133	143	159	141
4	138	147	136	151
5	130	172	168	166
6	125	173	137	181
7	136	185	125	196
8	139	197	134	202
9	142	193	131	204
10	137	207	153	195
11	146	194	141	210
12	158	199	132	225
13	163	204	151	218
14	174	198	139	233
15	179	182	121	240
16	177	176	125	228
17	171	167	115	223
18	165	162	127	208
19	163	157	131	193
20	157	149	129	178
21	144	153	132	165
22	137	161	137	161
23	132	164	123	173
24	142	163	127	178

The results of the simulation of the DED for Microgrid 3 are represented in Table 6.1.3 and Figure 6.1.3. It can be noted that the total generation of the microgrid transcends the demand of the unit in several time periods, especially in the 3rd, 5th, and 6th-time blocks, where it is more than required for at least 20kWh. The total cost of the generation for Microgrid 3 is equal to $224,62.

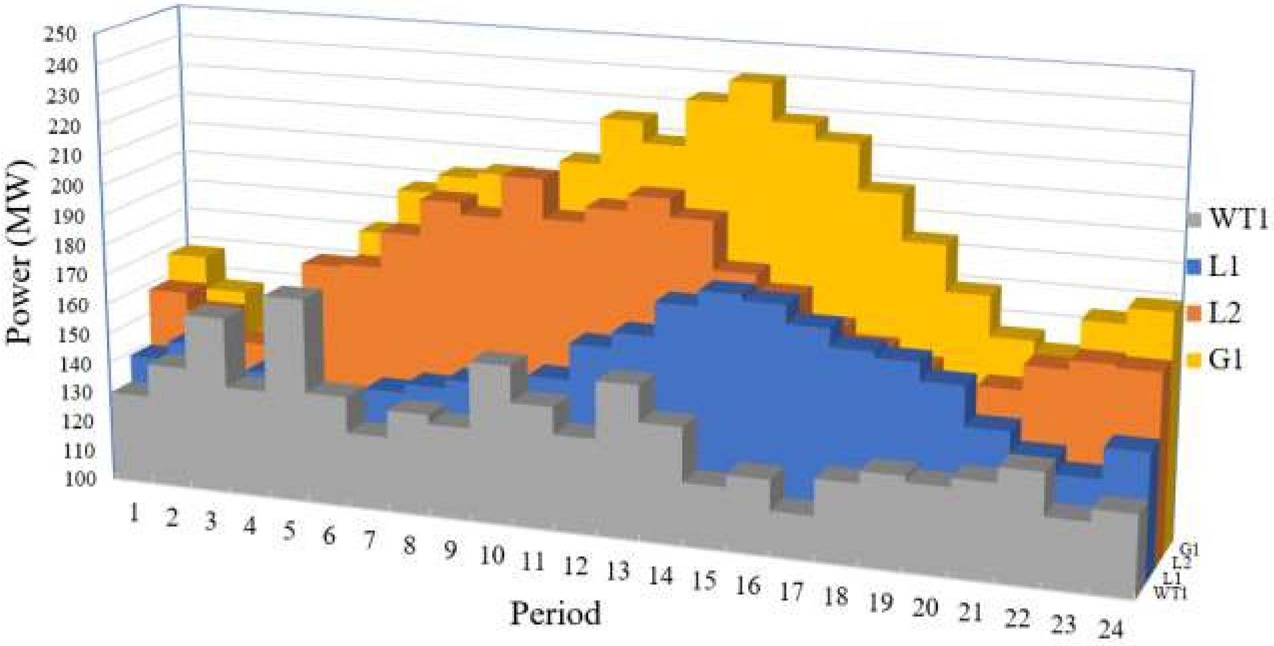

Figure 6.1.3. Power generation and load graph for Microgrid 3 in Case 1

The results of the simulation of the DED for Microgrid 4 represented in Table 6.1.4 and Figure 6.1.4. The generation of the microgrid varies according to the demand of the unit, with the fact of the overgeneration and energy requirement in some periods. The trading with the main grid in case of the fourth microgrid is done in both directions, meaning that microgrid represented itself in the role of the buyer in some time blocks, and seller in others. As it was mentioned earlier, trading with the main grid can be done only by following conditions set up by the grid, where trading prices are TOU and FIT. The final cost for the Microgrid 4 in 24 hours, including energy generation and trading in the auction, is $472,16. The agent acting as a seller in the 2nd block, and as a buyer in the 6th and 7th-time blocks.

Table 6.1.4. Simulation Results for Microgrid 4 in Case 1

Time block	Microgrid 4					
	L1 (711) (kW)	L2 (738) (kW)	L3 (740) (kW)	WT1 (741) (kW)	G1 (738) (kW)	G2 (740) (kW)
1	145	196	292	129	253,6	250,4
2	141	191	304	143	267,9	261,1
3	145	204	331	121	282,9	276,1
4	163	221	342	162	290,2	273,8
5	178	227	356	171	305,0	285,0
6	189	218	369	135	320,0	300,0
7	191	214	362	123	320,0	300,0
8	193	191	352	135	308,0	293,0
9	192	184	347	129	305,7	288,3
10	191	171	341	147	290,7	273,3
11	189	169	337	131	287,6	276,4
12	185	166	325	138	273,4	264,6
13	181	160	316	142	259,8	255,2
14	168	161	307	133	255,8	247,2
15	160	169	303	120	264,9	247,1
16	157	167	297	126	252,6	242,4
17	153	169	292	119	250,0	245,0
18	145	163	286	127	235,2	231,8
19	131	168	282	123	227,5	230,5
20	129	177	277	126	226,9	230,1
21	133	178	275	136	232,8	217,2
22	144	183	282	137	241,6	230,4
23	147	189	291	127	255,9	244,1
24	150	197	290	130	256,7	250,3

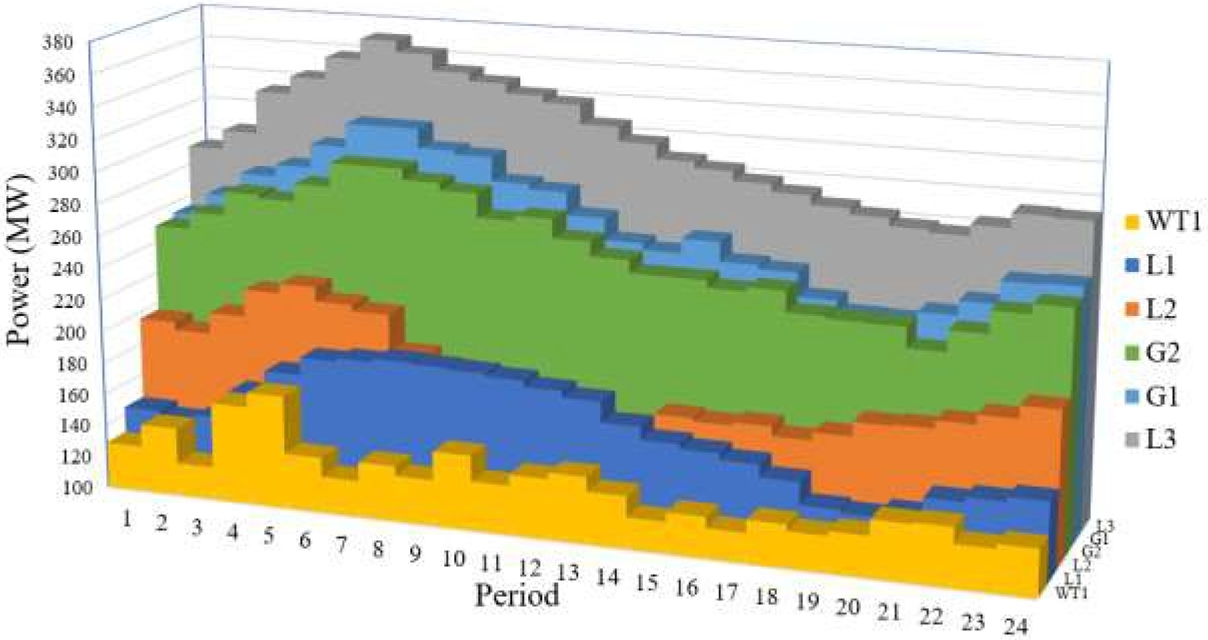

Figure 6.1.4. Power generation and load graph for Microgrid 4 in Case 1

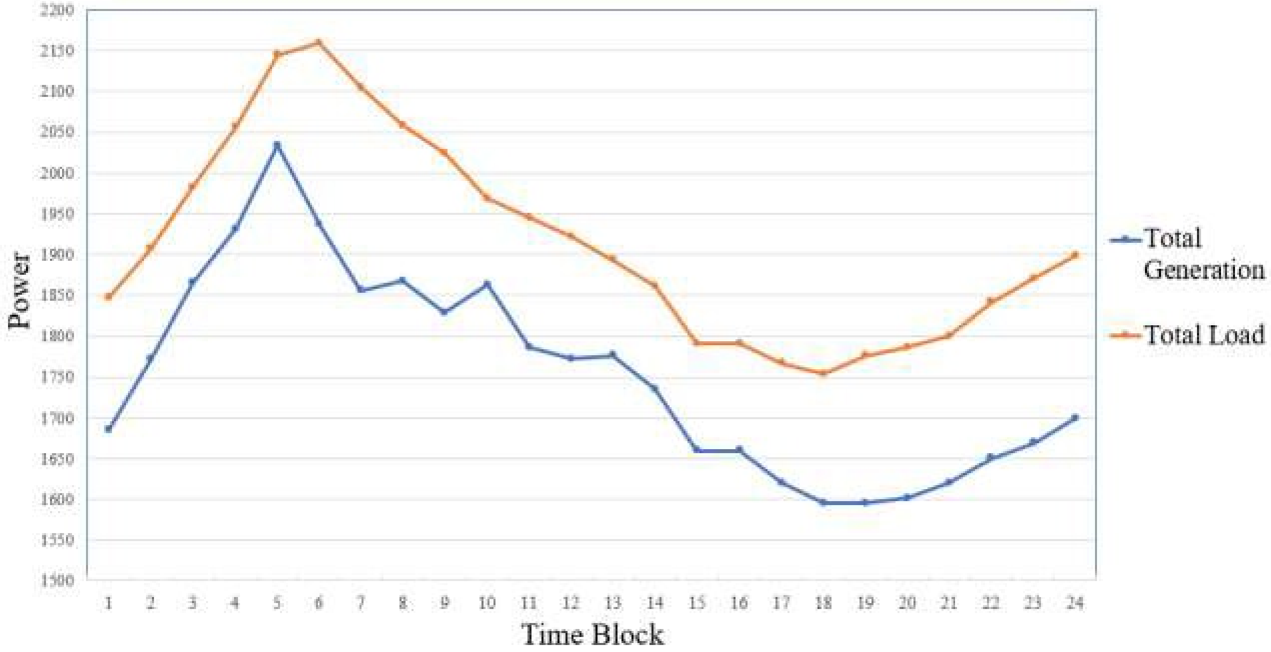

Figure 6.1.5. Difference between generation and demand for Case 1

The contrast between the total demand and generation in the MMG system in Case 1 can be seen from Figure 6.1.5. The difference in the system represented in the figure does not consider the effect of energy trading with the main grid and represents only the microgrids' load and generation. Here it also should be pointed out, that the use of the DED for each microgrid reduced the total cost for each of the microgrid in the maximum manner, which was possible without trading with other microgrids. The difference between the demand and the generation is in the range of 100-200 kW and varies for each time block.

6.1.2. Case 2: DED for MMG system with centralized TE market

The architecture of the DED for the MMG system with a centralized TE market is based on the hierarchical-centralized structure of energy management, which is represented in Figure 2.3.1. As it was mentioned earlier, the design of the auction mechanism implies separation of the auction with the microgrids, which means that microgrids are not the direct participants in the energy trading. Besides, there are still some factors that should be considered with the centralized system for DED for MMG system for each individual microgrid:

- Conduction self-Bayesian games for identification the optimal bidding strategy
- Identification of the optimal amount of energy to be offered/purchased during the auction
- Identification role in the auction
- Conducting self-DED

The purpose of the auction in the DED for the MMG system is to minimize the total operation cost for each of the microgrid separately and the whole MMG system. The key feature of conducting the DED is to motivate the units to participate in the auction and optimize the self-behavior. The centralized TE market is conducted by the main agent, which is called the DSO, and plays the role of the auction conductor, market-administrator, and controlling unit. In addition to the mentioned, the DSO is also considered as the main agent for controlling the security in the market against data access from the outsiders. The sniffer diagram of communication in the market for one block of time is represented in Figure 6.1.6.

To evaluate the efficiency of the proposed system, a model represented in the case study was simulated. The buying and selling prices of the main grid were selected to be 2,5 cents/kWh and 4 cents/kWh, respectively. The selling and buying prices of the main grid were selected in the way, which is not optimal for the energy trading for the microgrids. The bid and ask prices of the agents can vary in the range between selling and buying price. The bidding strategies of the agents are selected according to the results of the Bayesian Nash Equilibrium games, where agents make assumptions regarding other players in the system. Additionally, it should be noted that in the centralized TE market system the MLA agent share data regarding the load requirement in the whole MMG system between every agent, for more accurate game prediction.

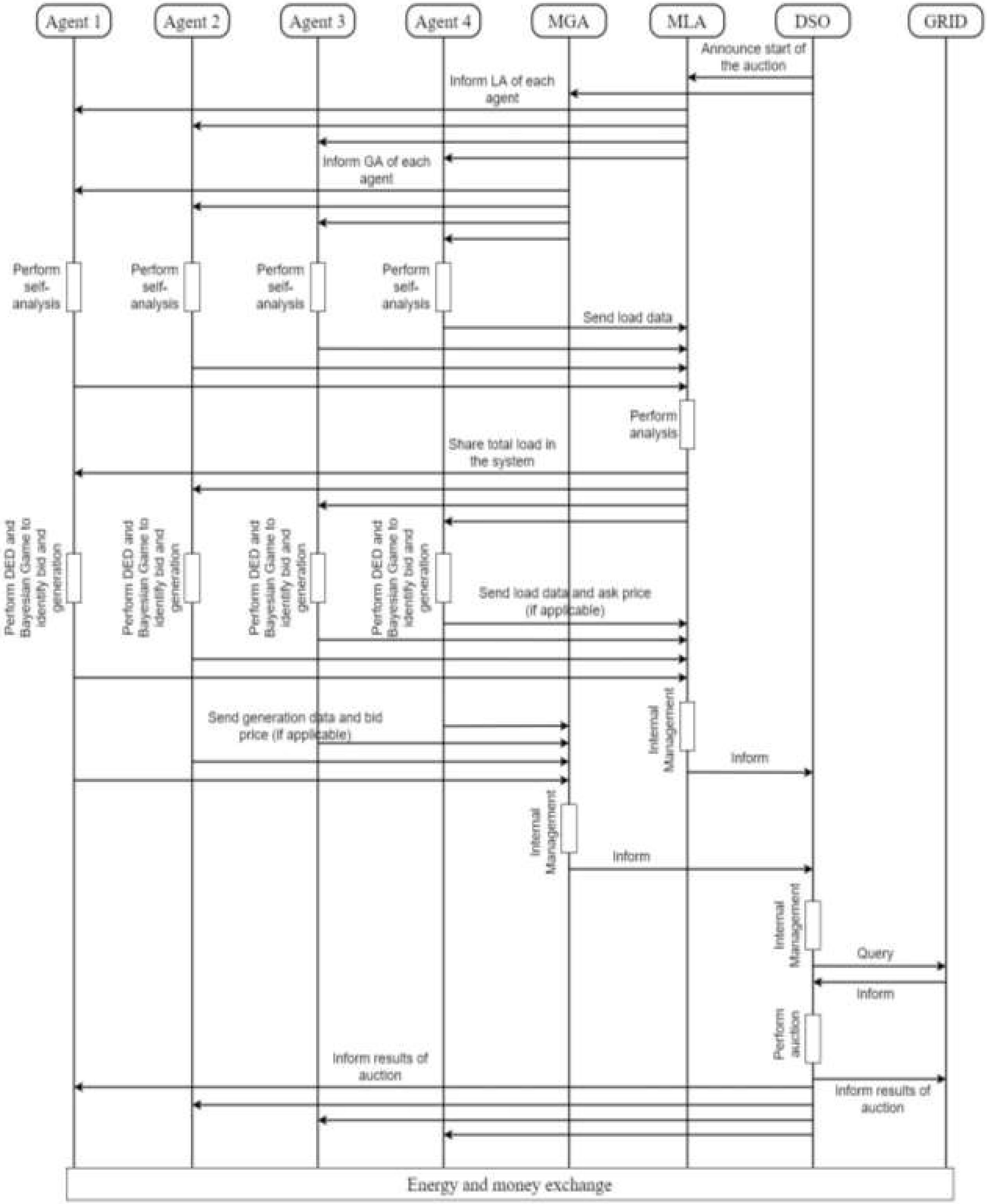

Figure 6.1.6. Sniffer diagram for the centralized TE market for one block of time

The results of the simulation are obtained separately for each of the microgrid, where DED was simulated using Matlab and communication between an agent and the main grid operator was conducted using the Jade program.

Table 6.1.5. Simulation Results for Microgrid 1 in Case 2

Time block	Microgrid 1				
	L1 (724) (kW)	L2 (707) (kW)	WT1 (724) (kW)	G1 (707) (kW)	G2 (722) (kW)
1	213	276	137	235,1	230,2
2	240	282	142	226,8	228,0
3	273	296	161	232,3	220,8
4	271	297	180	227,9	220,3
5	289	313	169	225,0	229,0
6	265	318	132	250,0	270,0
7	226	303	120	250,0	270,0
8	225	293	135	248,9	261,0
9	217	296	130	247,3	262,4
10	198	285	158	222,3	240,4
11	203	277	130	246,0	234,0
12	196	273	139	245,0	231,8
13	189	270	147	226,5	228,2
14	194	261	137	216,6	232,2
15	172	243	126	229,7	232,3
16	181	249	129	216,2	234,7
17	176	251	137	219,6	236,6
18	164	258	122	221,8	226,0
19	175	273	124	232,2	213,7
20	181	276	123	220,5	216,1
21	184	278	139	212,8	221,6
22	192	280	135	227,2	227,5
23	199	287	128	238,8	241,5

24	214	284	132	243,0	234,9

The results of the simulation for Microgrid 1 are represented in Table 6.1.5 and Figure 6.1.7. The assumptions in the simulation were the same as in Case 1. The difference in the system was the motivation of the agents to participate in energy trading in order to reduce the total generation cost, calculated by the DED. The trading was conducted with other microgrids in the system, while trading with the grid was done only in case of loss in the auction. The total cost for Microgrid 1 was calculated to be $309,9.

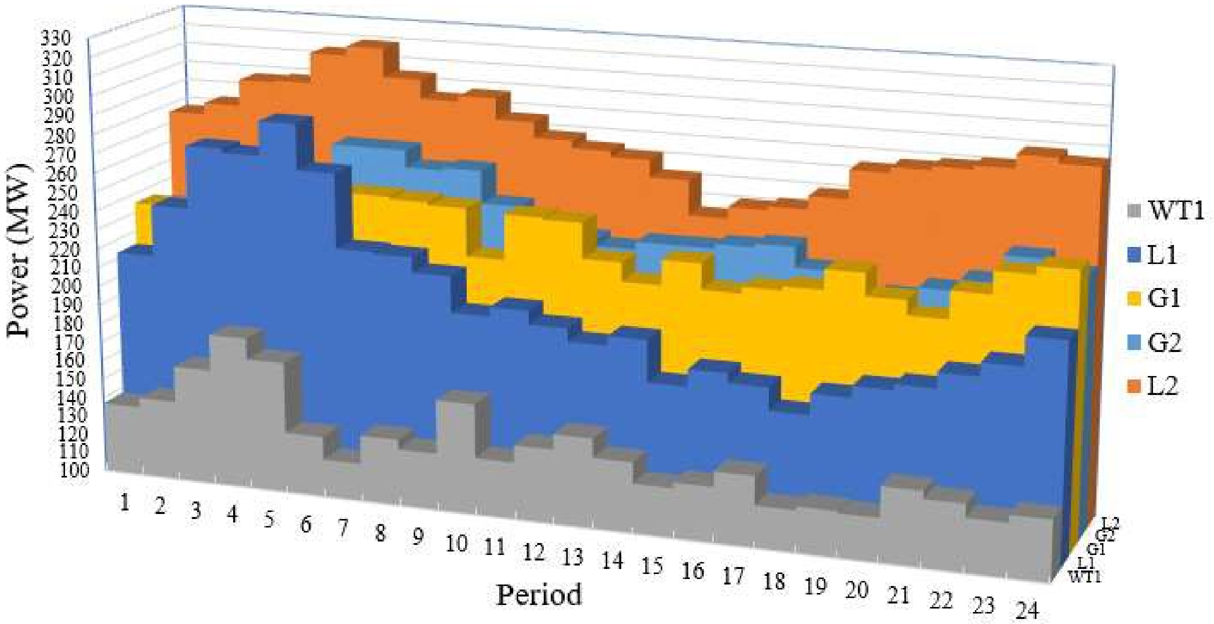

Figure 6.1.7. Power generation and load graph for Microgrid 1 in Case 2

Due to the reason of the absence of the thermal generation units in the Microgrid 2, which also can be seen from Figure 5.2.1, there is no difference in the wind generation and total load in the unit, between Case 1 and Case 2. The main difference between the cases is the energy trading procedure, which is conducted between the microgrids in the second case and can be seen from Table 6.1.2 and Figure 6.1.2. The total cost for the Microgrid 2 in the new energy trading conditions was calculated to be $287,92.

The results of the simulation for the Microgrid 3 are represented in Table 6.1.6 and Figure 6.1.8. The motivation of the unit is similar to other microgrids in the system, which leads to participation in energy trading in every time period. The result of Case 2 for Microgrid 3 is the total cost of the generation, which is equal to $219,97.

Table 6.1.6. Simulation Results for Microgrid 3 in Case 2

Time block	Microgrid 3			
	L1 (710) (kW)	**L2 (736) (kW)**	**WT1 (735) (kW)**	**G1 (710) (kW)**
1	139	158	130	214,9
2	145	152	141	234,9
3	133	143	159	252,2
4	138	147	136	241,4
5	130	172	168	252,0
6	125	173	137	280,0
7	136	185	125	280,0
8	139	197	134	268,5
9	142	193	131	272,5
10	137	207	153	244,5
11	146	194	141	247,1
12	158	199	132	244,8
13	163	204	151	223,4
14	174	198	139	233
15	179	182	121	240
16	177	176	125	228
17	171	167	115	221,4
18	165	162	127	218,0
19	163	157	131	229,7
20	157	149	129	227,8
21	144	153	132	220,6
22	137	161	137	226,7
23	132	164	123	240,6
24	142	163	127	245,1

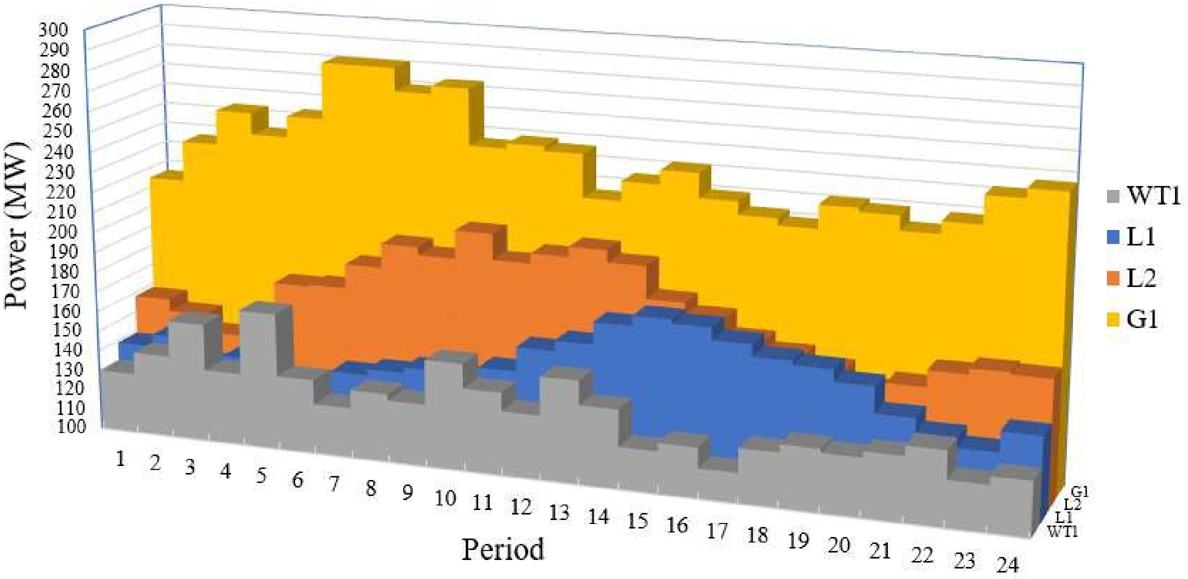

Figure 6.1.8. Power generation and load graph for Microgrid 3 in Case 2

The results of the simulation for Microgrid 4 presented in Table 6.1.7 and Figure 6.1.9. With the fact of the largest load in the system, represented in the fourth unit, the expenses for the generation similarly very high, which also was able to be noted in Case 1. The participation of an agent in the energy trading was done in both directions, as a buyer, and as a seller. The final cost for the Microgrid 4 in 24 hours, including energy generation and trading in the auction, is equal to $468,72.

Table 6.1.7. Simulation Results for Microgrid 4 in Case 2

Time block	Microgrid 4					
	L1 (711) (kW)	L2 (738) (kW)	L3 (740) (kW)	WT1 (741) (kW)	G1 (738) (kW)	G2 (740) (kW)
1	145	196	292	129	275,9	255,5
2	141	191	304	143	290,9	247,6
3	145	204	331	121	305,9	253,1
4	163	221	342	162	320	260,4
5	178	227	356	171	320	275,4
6	189	218	369	135	320	300
7	191	214	362	123	320	300

8	193	191	352	135	320	289,9
9	192	184	347	129	320	272,4
10	191	171	341	147	311,6	252,4
11	189	169	337	131	297,1	266,9
12	185	166	325	138	282,5	255,5
13	181	160	316	142	269	246
14	168	161	307	133	254,4	248,6
15	160	169	303	120	258,9	253,1
16	157	167	297	126	246,5	248,5
17	153	169	292	119	253,3	241,7
18	145	163	286	127	240,3	226,7
19	131	168	282	123	238,2	219,8
20	129	177	277	126	236	221
21	133	178	275	136	226	224
22	144	183	282	137	237,7	234,3
23	147	189	291	127	251,3	258,7
24	150	197	290	130	263,7	263,3

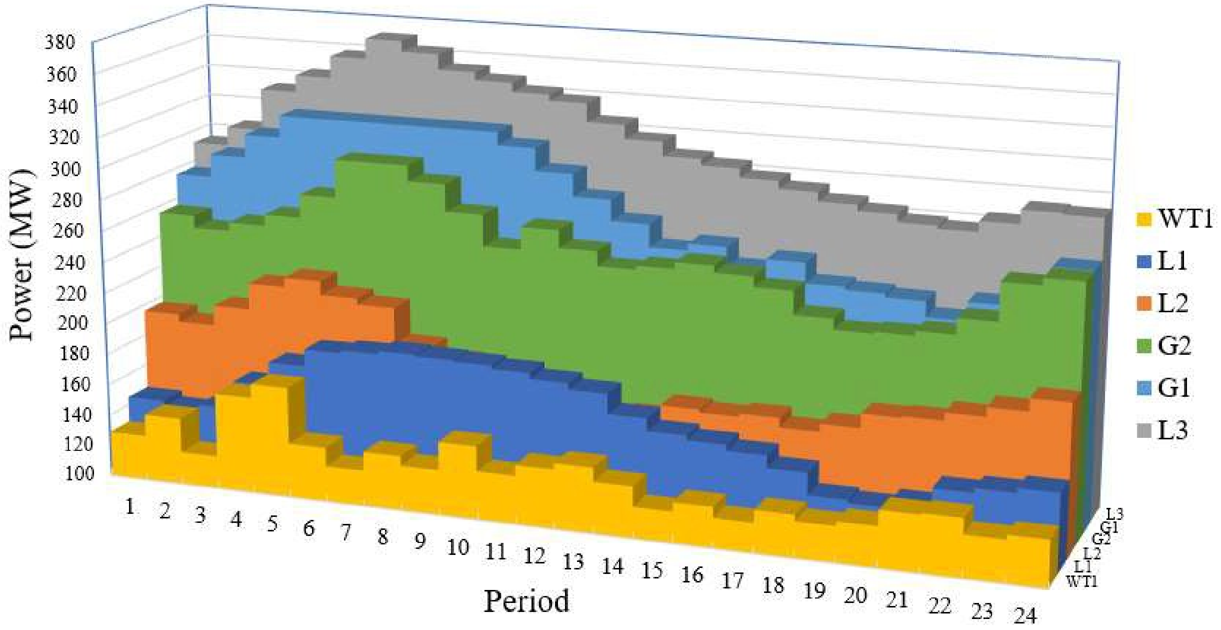

Figure 6.1.9. Power generation and load graph for Microgrid 4 in Case 2

The difference between the total demand and generation in the MMG system in Case 2 can be seen from Figure 6.1.10. It can be noticed that the effect of the energy trading results in reducing the gap between load and generation, where the use of the DED for the microgrids also affects the cost of energy production. There are still some variations, which lead to trading with the main grid, however, it is still a required condition for the proper functioning of the system.

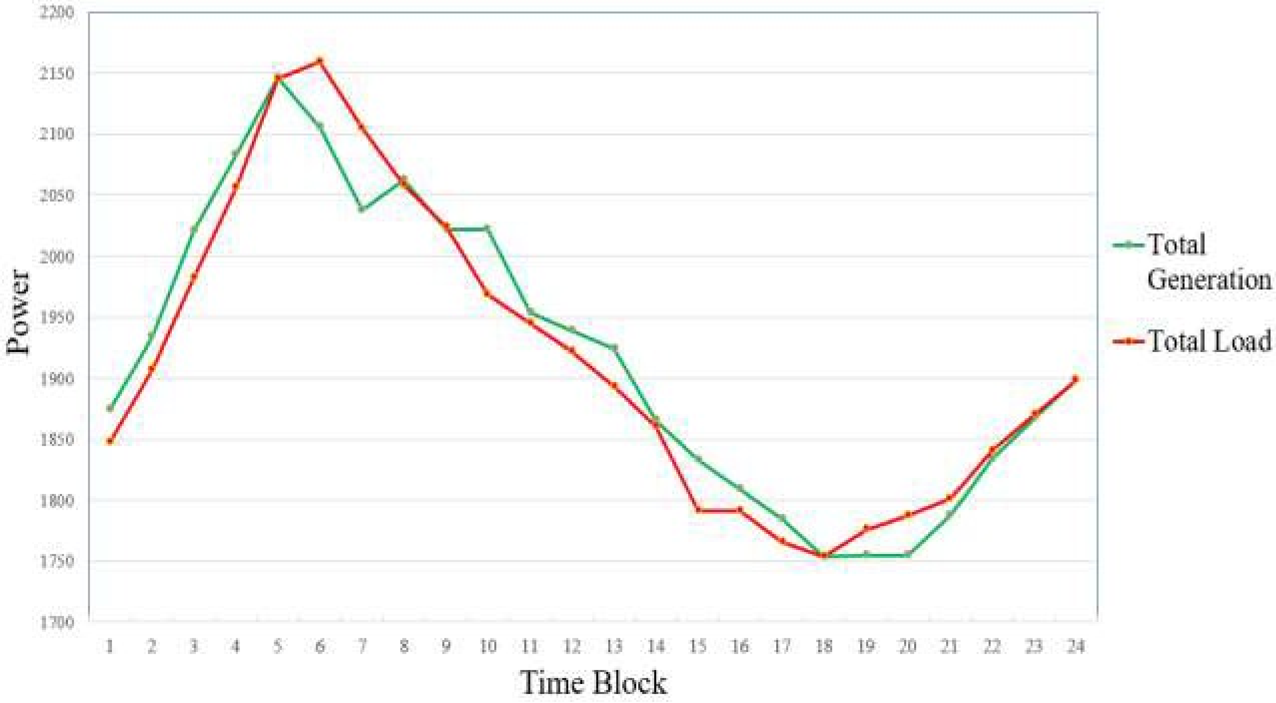

Figure 6.1.10. Difference between generation and demand for Case 2

Table 6.1.8 represents the results of the simulation of the auctions with the case study data, and self-decisions of the microgrids based on the DED and Bayesian Game. The cost represented in Table 6.1.8 of the energy import/export for microgrids was calculated as the average of all bid/ask prices for the corresponding microgrid using Equation (6.1.1) in case of the buyer, and (6.1.2) in case of the seller.

$$P_{MG,B} = \frac{P_{B1} * E_{B1} + P_{B2} * E_{B2} + \cdots + P_{BN} * E_{BN}}{E_{B1} + E_{B2} + \cdots + E_{BN}} \tag{6.1.1}$$

$$P_{MG,S} = \frac{P_{S1} * E_{S1} + P_{S2} * E_{S2} + \cdots + P_{SN} * E_{SN}}{E_{S1} + E_{S2} + \cdots + E_{SN}} \tag{6.1.2}$$

Table 6.1.8. Auction Simulation Results for Case 2

Blk	MG	Export/ Import	Cost	Export/ Import from Grid	Blk	MG	Export/ Import	Cost	Export/ Import from Grid
1	1	-113,3	3,26	0	13	1	-142,7	3,04	+23,7
	2	+162	3,27	0		2	+119	3,15	0
	3	-47,9	2,85	+26,6		3	-7,4	2,50	+7,4
	4	-27,4	3,28	0		4	0	0,00	0
2	1	-74,8	3,10	+13,6	14	1	-130,8	3,12	+4,8
	2	+172	3,23	0		2	+126	3,14	0
	3	-78,9	3,23	0		3	0	0,00	0
	4	-45,5	3,01	+13,6		4	0	0,00	0
3	1	-45,1	3,19	0	15	1	-173	3,03	+42
	2	+142	3,24	0		2	+131	3,20	0
	3	-135,2	3,05	+38,3		3	0	0,00	0
	4	0	0,00	0		4	0	0,00	0
4	1	-60,2	3,19	0	16	1	-149,9	3,06	+17,9
	2	+142	3,22	0		2	+132	3,13	0
	3	-92,4	3,15	+10,6		3	0	0,00	0
	4	-16,4	2,50	+16,4		4	0	0,00	0
5	1	-21	3,22	0	17	1	-166,2	3,07	+18,6
	2	+143	3,22	0		2	+146	3,15	0
	3	-118	3,21	+1,4		3	+1,6	3,15	0
	4	-5,4	3,31	0		4	0	0,00	0
6	1	-69	3,24	0	18	1	-147,8	3,15	0
	2	+220	3,48	-53		2	+166	3,15	-0,2
	3	-119	3,36	0		3	-18	3,18	0
	4	+21	3,26	0		4	0	0,00	0
7	1	-111	3,33	0	19	1	-121,9	3,19	0
	2	+238	3,48	-43		2	+184	3,29	-21,4

	3	-84	3,42	0		3	-40,7	3,23	0
	4	+24	4,00	-24		4	0	0,00	0
8	1	-126,9	3,35	0	20	1	-102,6	3,25	0
	2	+198	3,37	0		2	+186	3,38	-32,6
	3	-66,5	3,35	+4,3		3	-50,8	3,25	0
	4	-8,9	3,36	0		4	0	0,00	0
9	1	-126,7	3,24	0	21	1	-111,4	3,25	0
	2	+196	3,29	-2,4		2	+181	3,31	-14
	3	-68,5	3,36	0		3	-55,6	3,28	0
	4	+1,6	3,30	0		4	0	0,00	0
10	1	-142,7	3,16	0	22	1	-117,7	3,26	0
	2	+145	3,27	0		2	+191	3,29	-7,6
	3	-53,5	2,60	+46,2		3	-65,7	3,27	0
	4	-8	2,50	8		4	0	0,00	0
11	1	-130	3,20	0	23	1	-122,3	3,30	0
	2	+170	3,21	0		2	+202	3,31	-2,1
	3	-48,1	3,12	+8,1		3	-67,6	3,32	0
	4	0	0,00	0		4	-10	3,30	0
12	1	-146,8	3,13	+16,6	24	1	-111,9	3,25	0
	2	+150	3,21	0		2	+198	3,27	0
	3	-19,8	3,20	0		3	-67,1	3,29	+1
	4	0	0,00	0		4	-20	3,29	0

6.1.3. Case 3: DED for MMG system with decentralized TE market

The third case for the DED for the MMG system is based on using the decentralized structure of energy management, which can be seen from Figure 2.3.2. The design of the auction mechanism implies auction conduction in the microgrids' level, where any microgrid can be either auctioneer or buyer/seller. The information exchange in the case of the decentralized TE market is done through the sharing of smart contracts. The implementation of a smart contract between auction participants gives the ability to trade with other agents safely, without worrying about being hacked or interrupted by anyone or anything. The procedure in case of the decentralized system is not too much different for each microgrid's self-discussion interval. The meaning of this is that each unit should conduct a self-Bayesian game for identification of the bidding strategy, conduction of self-DED and finding the optimal amount of energy to offer during the auction according to the result of self-discussion.

There are many reasons for using the decentralized system:

1) There is no central unit, which can fail at some time period and make the impossible conduction of the auction.
2) There is no need to estimate the level of trust to some central agent, which can conspire with some specific units.
3) In some of the centralized TE markets, DSO may charge a fee for the work done. This issue cannot arise in the case of the decentralized system.
4) In the case of the decentralized TE, transmission losses are minimized due to the fact of approving energy exchange mainly between peers allocated closely to each other.
5) Using the blockchain in the decentralized system guarantees reliable trade platform, which cannot be attacked from the outside, and ensure safe information exchange between the units.

With the fact mentioned above, there is a rising interest in the new decentralized systems, represented in for of P2P energy trading. The balancing between the demand and supply in the novel approach allows improved integration of the DERs, and safe information exchange. The decentralized system is considered as protected from the cyberattacks, whereas there is still open access for joining the system. Authors in [40] proved several advantages of using blockchain with the decentralized TE management, which include reducing cost and complexity of the system, reducing error and transmission losses, improved security, as well as presence of the trusted transactions.

Similarly, to the centralized system, the main purpose of conducting the DED for the MMG in the decentralized system is to minimize the total operation cost through the motivation of the microgrids to participate in the energy auction. The sharing of data regarding the load in the system should be done prior to starting the auction for more accurate game prediction. To evaluate the efficiency of the proposed system, a model represented in the case study was simulated. The sniffer diagram of communication in the decentralized market for one block of time is represented in Figure 6.1.11.

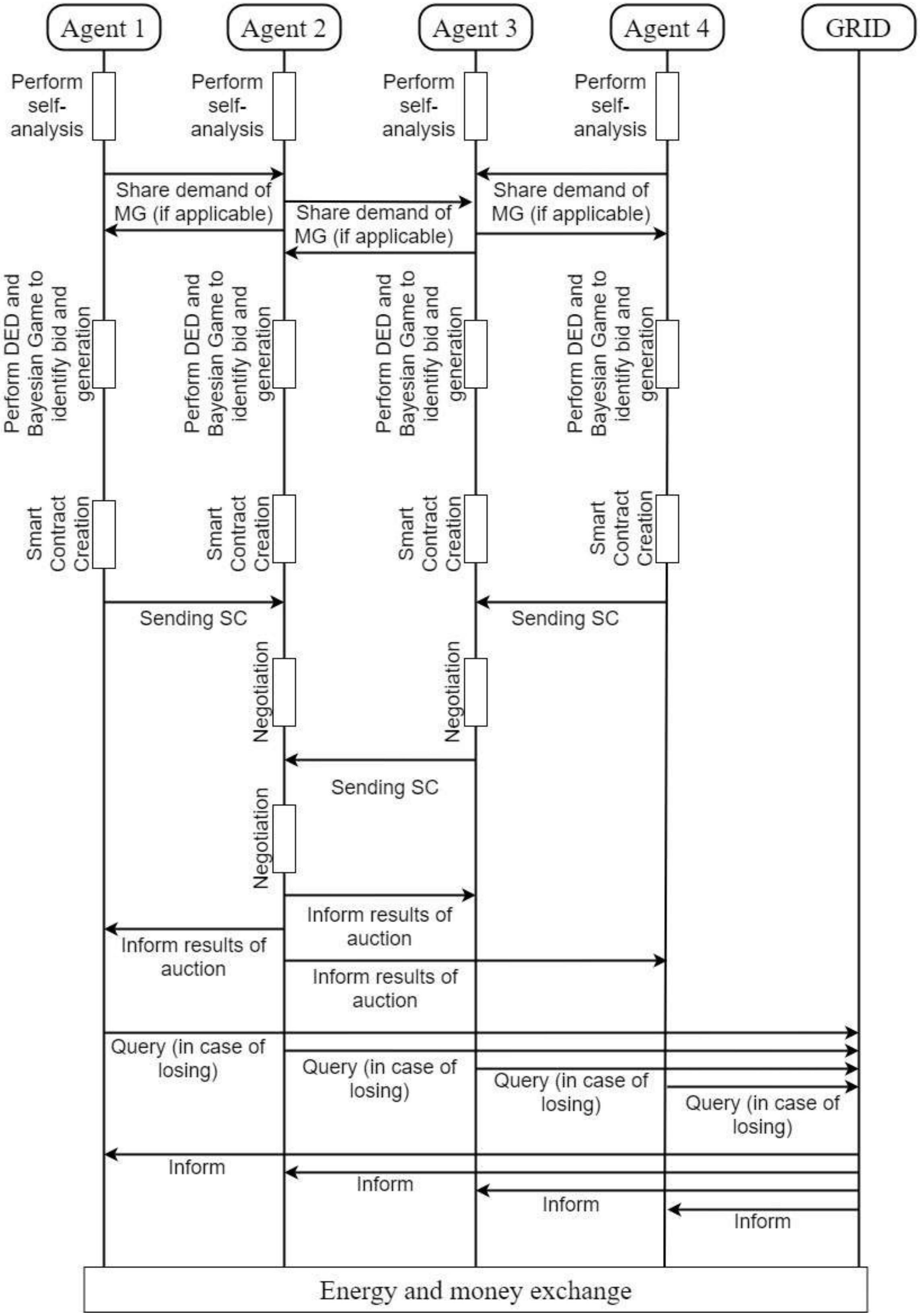

Figure 6.1.11. Sniffer diagram for the decentralized TE market for one block of time

The results of the simulation are obtained separately for each of the microgrid, where DED was simulated using Matlab and communication between an agent and the main grid operator was conducted using the Jade program.

Table 6.1.9. Simulation Results for Microgrid 1 in Case 3

Time block	Microgrid 1				
	L1 (724) (kW)	L2 (707) (kW)	WT1 (724) (kW)	G1 (707) (kW)	G2 (722) (kW)
1	213	276	137	225,1	220,2
2	240	282	142	216,8	214,0
3	273	296	161	212,3	210,8
4	271	297	180	217,9	220,3
5	289	313	169	225,0	239,0
6	265	318	132	250,0	270,0
7	226	303	120	250,0	270,0
8	225	293	135	248,9	261,0
9	217	296	130	247,3	262,4
10	208	285	158	222,3	240,4
11	203	277	130	238,0	234,0
12	196	273	139	245,0	227,8
13	189	270	147	224,5	210,2
14	194	261	137	216,6	227,4
15	172	243	126	210,7	212,3
16	181	249	129	213,2	220,7
17	176	251	137	209,6	233,6
18	164	258	122	221,8	226,0
19	175	273	124	232,2	233,7
20	181	276	123	229,5	238,1
21	184	278	139	222,8	224,6
22	192	280	135	227,2	232,5
23	199	287	128	238,8	242,5

24	214	284	132	243,0	234,9

The results of the simulation for Microgrid 1 in the decentralized TE market are represented in Table 6.1.9 and Figure 6.1.12. The total cost for Microgrid 1 was calculated to be $308,37, where the money for 24 fours was decreased by participation in the energy trading and DED calculation. The trading with the main grid also can be conducted in case of surplus/lack of the energy resources after the end of the market period, or loss in the auction.

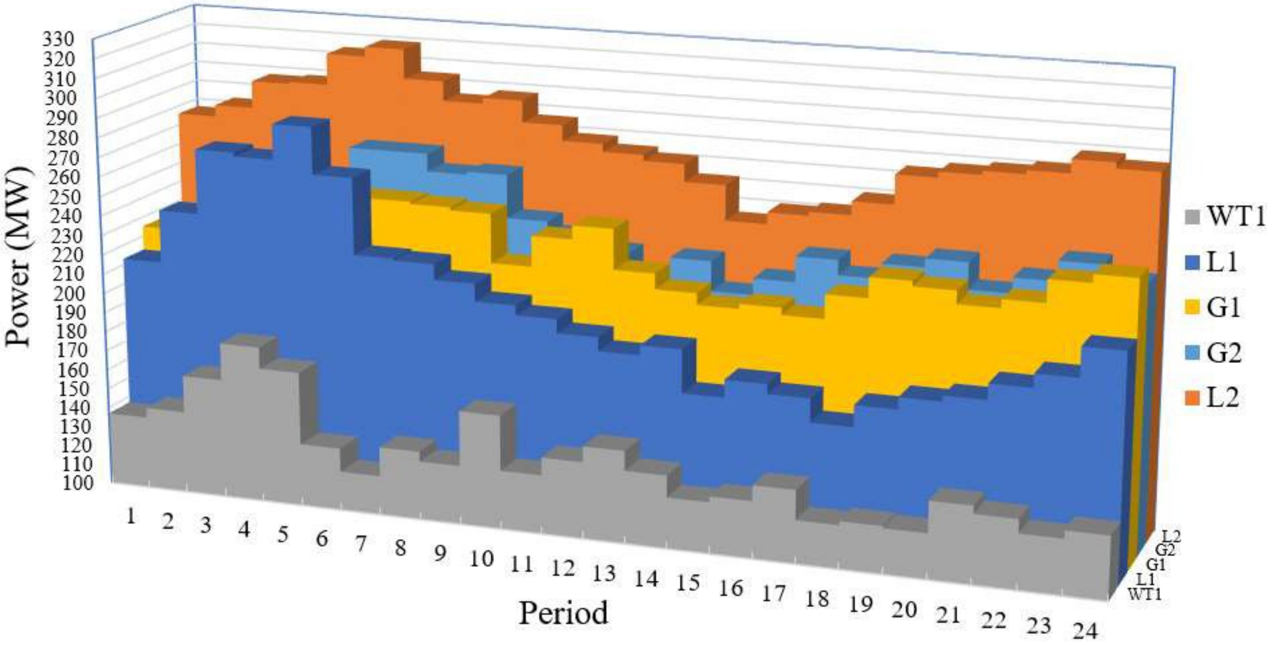

Figure 6.1.12. Power generation and load graph for Microgrid 1 in Case 3

As it was said previously, there is no difference in the wind generation and total generation in case of the second microgrid in the Case 3, Case 2 and Case 1. The reason for this is absence of the thermal generation in the microgrid, which also can be pointed out from Figure 5.2.2. The energy generation and load for the 2nd microgrid can be seen from Table 6.1.2 and Figure 6.1.2. The total cost for the microgrid in the new energy trading conditions was calculated to be $286,48, which include energy trading procedure.

The simulation results for the Microgrid 3 represented in Table 6.1.10 and Figure 6.1.13. The motivation of the microgrid to participate in the energy trading is similar to other microgrids in the system, namely reducing total generation cost within the whole time period. The result of simulation for the Microgrid 3 is the total cost of the generation, which is equal to $219,23.

Table 6.1.10. Simulation Results for Microgrid 3 in Case 3

Time block	Microgrid 3			
	L1 (710) (kW)	L2 (736) (kW)	WT1 (735) (kW)	G1 (710) (kW)
1	139	158	130	214,9
2	145	152	141	234,9
3	133	143	159	248,2
4	138	147	136	241,4
5	130	172	168	252,0
6	125	173	137	280,0
7	136	185	125	280,0
8	139	197	134	268,5
9	142	193	131	272,5
10	137	207	153	244,5
11	146	194	141	247,1
12	158	199	132	240,8
13	163	204	151	222,4
14	174	198	139	233
15	179	182	121	240
16	177	176	125	228
17	171	167	115	221,4
18	165	162	127	218,0
19	163	157	131	229,7
20	157	149	129	227,8
21	144	153	132	221,9
22	137	161	137	229,7
23	132	164	123	240,6
24	142	163	127	245,1

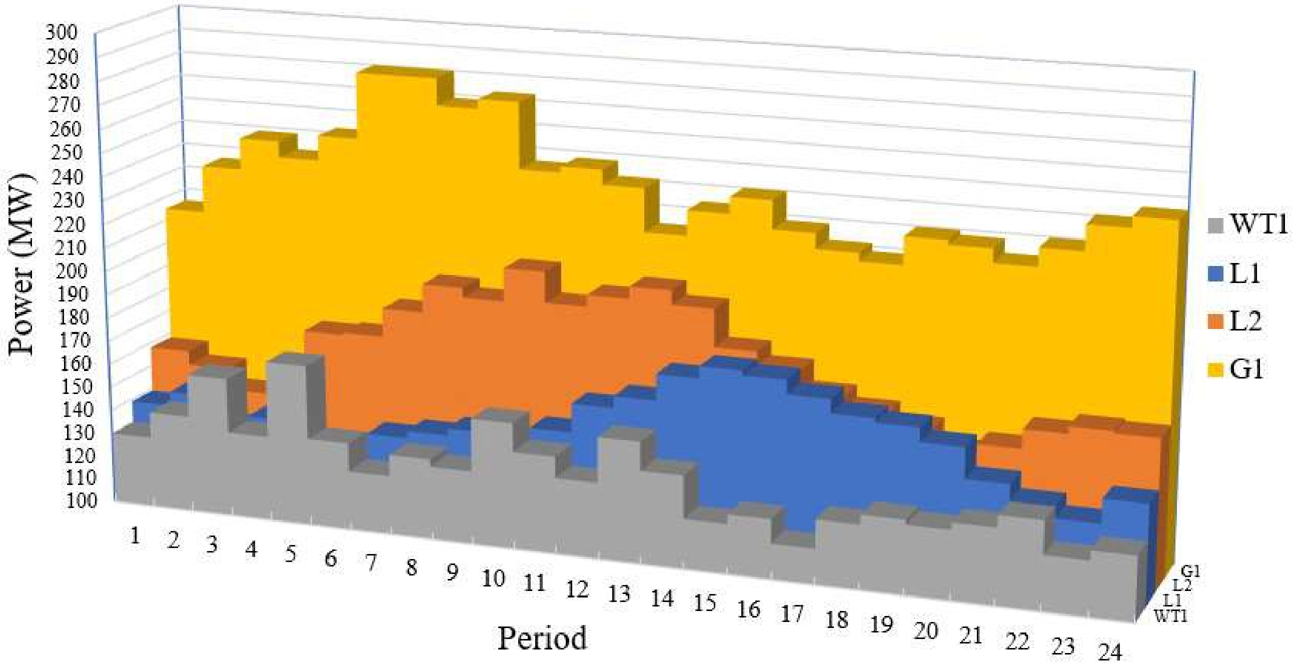

Figure 6.1.13. Power generation and load graph for Microgrid 3 in Case 3

Table 6.1.11 and Figure 6.1.14 represent simulation results for Microgrid 4, which has the largest load and generation in the MMG system. The expenses for the microgrid reciprocally very high. As well as in previous cases, the unit participated in the auction as both buyer and seller. The total cost resulted in simulation for the Microgrid 4 is equal to $467,95.

Table 6.1.11. Simulation Results for Microgrid 4 in Case 3

Time block	Microgrid 4					
	L1 (711) (kW)	L2 (738) (kW)	L3 (740) (kW)	WT1 (741) (kW)	G1 (738) (kW)	G2 (740) (kW)
1	145	196	292	129	275,9	250,5
2	141	191	304	143	290,9	247,6
3	145	204	331	121	305,9	253,1
4	163	221	342	162	310	260,4
5	178	227	356	171	316	273,4
6	189	218	369	135	320	300
7	191	214	362	123	320	300
8	193	191	352	135	320	289,9

9	192	184	347	129	318	274,4
10	191	171	341	147	303,6	252,4
11	189	169	337	131	297,1	266,9
12	185	166	325	138	282,5	255,5
13	181	160	316	142	269	246
14	168	161	307	133	254,4	248,6
15	160	169	303	120	258,9	253,1
16	157	167	297	126	246,5	248,5
17	153	169	292	119	253,3	241,7
18	145	163	286	127	240,3	226,7
19	131	168	282	123	238,2	219,8
20	129	177	277	126	236	221
21	133	178	275	136	226	224
22	144	183	282	137	237,7	234,3
23	147	189	291	127	251,3	258,7
24	150	197	290	130	263,7	263,3

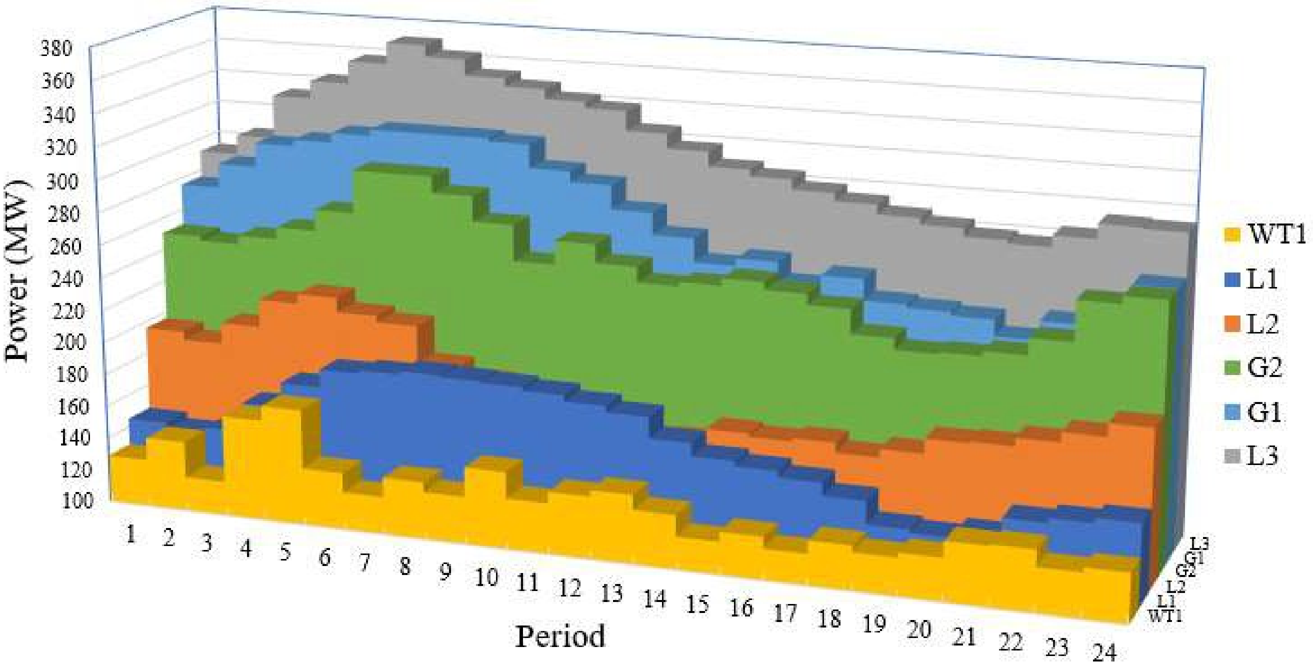

Figure 6.1.14. Power generation and load graph for Microgrid 4 in Case 3

The difference between the total load and generation in the MMG system in Case 3 is represented in Figure 6.1.15. The gap between the demand and energy production reduced due to the decentralized system, where the main trading is done mainly between the neighboring units. The use of the DED for the MMG system resulted in the reduction of the total cost, compared with Case 1. Here it also should be noted that the high variation between the load and generation inthe 6th and 7th-time blocks, is the result of the load that exceeds the generation limits. To say it in more simple words, all of the thermal generation units are working on their maximum capacity during 6th and 7th-time intervals, while the excess load is supplied by the main grid.

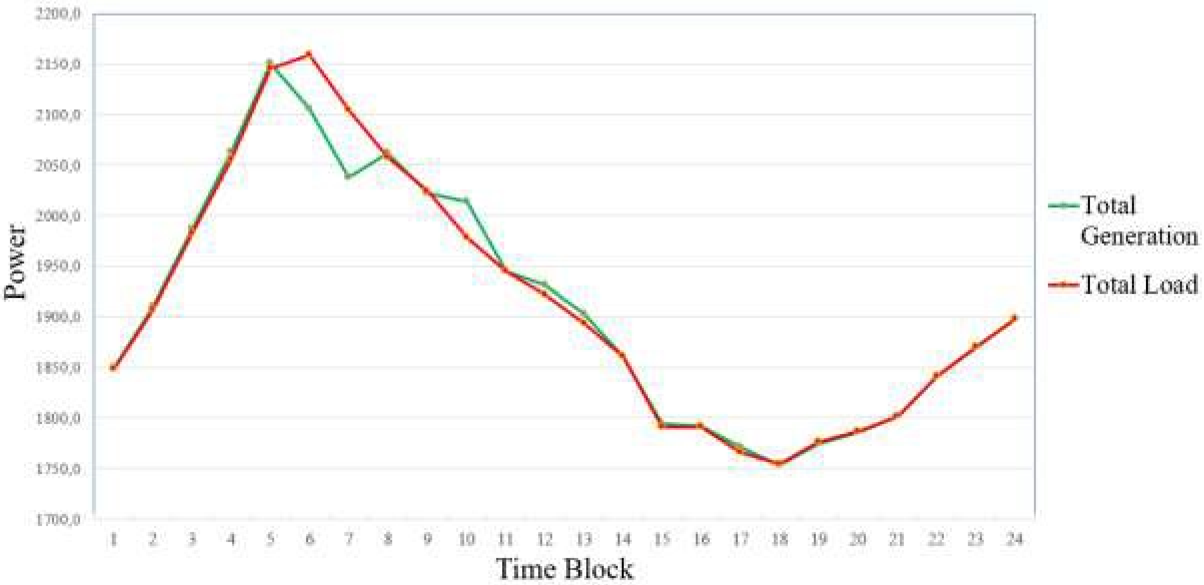

Figure 6.1.15. Difference between generation and demand for Case 3

Table 6.1.12 represents the results of the simulation of the auctions with the case study data. The costs for selling/buying energy represented in the Table 6.1.12 were calculated using the average of all bid/ask prices using Equation (6.1.1) in case if a microgrid is a buyer, and (6.1.2) in case if the unit is a seller.

Table 6.1.12. Auction Simulation Results for Case 3

Blk	MG	Export/ Import	Cost	Export/ Import from Grid	Blk	MG	Export/ Import	Cost	Export/ Import from Grid
1	1	-93,3	3,27	0	13	1	-122,7	3,20	+10,1
	2	+162	3,27	0		2	+119	3,27	0

	3	-47,9	3,28	+1,6		3	-6,4	3,26	0
	4	-22,4	3,21	0		4	0	0	0
2	1	-50,8	3,32	+3,2	14	1	-126	3,22	0
	2	+172	3,32	0		2	+126	3,22	0
	3	-78,9	3,28	0		3	0	0	0
	4	-45,5	3,33	0		4	0	0	0
3	1	-15,1	3,20	0	15	1	-134	3,24	+3
	2	+142	3,22	0		2	+131	3,26	0
	3	-131,2	3,20	+4,3		3	0	0	0
	4	0	0	0		4	0	0	0
4	1	-50,2	3,17	0	16	1	-132,9	3,24	+0,9
	2	+142	3,21	0		2	+132	3,25	0
	3	-92,4	3,18	7		3	0	0	0
	4	-6,4	3,21	0		4	0	0	0
5	1	-31	3,13	+5,4	17	1	-153,2	3,24	+5,6
	2	+143	3,24	0		2	+146	3,27	0
	3	-118	3,24	0		3	+1,6	3,19	0
	4	+0,6	3,21	0		4	0	0	0
6	1	-69	3,19	0	18	1	-147,8	3,21	0
	2	+220	3,05	-53		2	+166	3,21	-0,2
	3	-119	3,26	0		3	-18	3,22	0
	4	+21	3,26	0		4	0	0	0
7	1	-111	3,25	0	19	1	-141,9	3,26	0
	2	+238	3,05	-67		2	+184	3,27	-1,4
	3	-84	3,30	0		3	-40,7	3,28	0
	4	+24	3,25	0		4	0	0	0
8	1	-126,9	3,28	+4,3	20	1	-133,6	3,28	0
	2	+198	3,28	0		2	+186	3,28	-1,6
	3	-66,5	3,23	0		3	-50,8	3,29	0
	4	-8,9	3,26	0		4	0	0	0

9	1	-126,7	3,36	0	21	1	-124,4	3,25	+0,3
	2	+196	3,36	-0,8		2	+181	3,25	0
	3	-68,5	3,34	0		3	-56,9	3,24	0
	4	+1,6	4,00	-1,6		4	0	0	0
10	1	-127,7	3,11	+36,2	22	1	-122,7	3,26	+0,4
	2	+145	3,33	0		2	+191	3,26	0
	3	-53,5	3,29	0		3	-68,7	3,26	0
	4	0	0	0		4	0	0	0
11	1	-122	3,26	0	23	1	-123,3	3,28	0
	2	+170	3,27	0		2	+202	3,28	-1,1
	3	-48,1	3,31	+0,1		3	-67,6	3,28	0
	4	0	0	0		4	-10	3,32	0
12	1	-142,8	3,17	+8,6	24	1	-111,9	3,23	0
	2	+150	3,21	0		2	+198	3,24	0
	3	-15,8	3,20	0		3	-67,1	3,24	0
	4	0	0	0		4	-20	3,22	+1

6.2. Discussion

This part of the work represents the discussion regarding the simulated results, in particular, the comparison of different approaches represented in this chapter. The simulation results, namely the total generation cost, found by the DED for the MMG, and the generation schedule found for each microgrid in the system, are found for three different cases: without the TE market, with centralized and decentralized TE management. The results are depicted in Figures 6.1.1-6.1.15 and Tables 6.1.1-6.1.12 respectively. Here, it should be noted, that in case of absence of the TE auctions in the first case used for the simulation the all trading processes with excess energy and demand in the microgrids were conducted only with the grid, based on the FIT and TOU fix prices.

The focus of the work was to show a dynamic solution that will have a new idea, which bridges characteristics of microgrid and smart grid, named as the MMG system, and implement the DED approach as a motivation for TE auction participation. The results represented in the previous parts can be used for the analysis of the self-controlled operation system in the face of the microgrid in the different operation conditions. The second and the third cases used for the simulation have a purpose to find a way to sell excess energy from one microgrid to another in the MMG system, without trading with the grid (except the cases without having other options).

The results of the simulation of the first case, where DED was used to optimize the individual cost for each microgrid without considering and implementation of the TE market, the total operation cost for the whole MMG system was equal to \$1329,84. As energy trading was done with the grid, there was a striking difference between the MMG system's total load and generation, which can be noted from Figure 6.1.5. The situation regarding demand and generation is completely different in the case of the second and third simulation cases, where the DED for the MMG was simulated using centralized and decentralized TE respectively. The total operating cost in the second case was equal to \$1286,51, and \$1282,03 in the third case. From this, it can be noted that the presence of the TE auction resulted in the optimization of the total generation cost for 3,5-4%, which is the noticeable effect when the cash is not calculated in hundreds, but thousands.

The yearly savings in case of using decentralized TE management, comparing with the results found in the second case, is equal to \$1,635.2. With considering fact that the average cost for 1 kW is about 3cents, this amount of money can be considered as big saving. Besides, the main attention should be considered on the generation in the second and third cases. The difference between the demand and generation, represented in Figure 6.1.15 for Case 3, shows that the use of the decentralized TE market has a better effect on the optimal energy schedule. The trading with the grid was conducted due to the generation limitation in the 6th and 7th-time blocks, while in the other periods' total load and generation in the MMG system in Case 3 was approximately the same. Unfortunately, the same things cannot be said for the results received from Case 2. Besides, it should be mentioned that there are additional positive effects of using decentralized energy management systems, including improved social welfare of the MMG system, secure information, and energy exchange for the privacy of the participants, as a result of using blockchain, and system consensus with the auction results.

Chapter 7 – Conclusion and Future work

7.1. Conclusion

This master thesis work represents a DED for MMG system using 3 different platforms for energy exchange, namely trading with the grid, centralized energy trading, and decentralized TE management. The main aim was to analyze the results of the different approaches and define the best among the proposed ones. The use of the TE markets, in the case of both centralized and decentralized systems, has proven their efficiency in comparing with the grid trading, due to the fact that the presence of the DED with auction motivated unit to participate in the energy trading.

The model represented in the case study of the thesis was established using the IEEE 37-bus system with the modifications for four microgrid units and DERs for the formation of the ADN. The Jade program was used to perform the agent communication in the MMG system and enable the conduction of the energy trading based on the results of the auctions. The DED and the bidding strategy based on the Bayesian Game were executed using the Matlab platform. The presence of the TE management system has proven the efficiency of the DED for the MMG system, comparing with the self-improvement of each unit in the represented framework. The purpose of the MMG system was to find a way of balancing the total load and generation in the system without a grid coming into the picture but using the same infrastructure. The DED and the Bayesian Game were used to solve one of the main challenges in the MMG system management, which is the proper distribution of the energy generated between the existing generation units. The agents of the system tried to take action in a way that will be economically optimal and efficient for the microgrids, respectively.

The third case implemented in the simulation has proposed an advanced platform for P2P energy trading without the participation of the authorized third-party, called as a main agent and auctioneer, as in the second case of the work. The use of the blockchain for implementation of the decentralized double auction helped to eliminate the single point of attack, guaranteed secure information exchange and provided legal transactions between all prosumers in the network. From the results of the simulations, it is recommended to implement the DED for MMG with decentralized TE management in order to improve the efficiency of the energy transaction, with the elimination of the transmission losses, and removing the dependence on the third party in the auction. From the results of the simulation, it also can be found, that implementation of the DED for the MMG with GT, in particular the Bayesian Game for the bidding, will lead to the improvement of the social welfare and efficient energy trading with reducing the cost of the energy production.

7.2. Future work

The future work related to the topic of the thesis includes the development of the DED for MMG with Demand Response. Demand Response is a technique that will allow reshape the load curve and shift some part of the load from the peak hours to another time. From the third case represented in the simulation part of the thesis, in particular from Figure 6.1.15, it can be noted that there are some time periods where the total load in the MMG system exceeds the total generation, while all generation units work for their maximum. By using the Demand Response technique, it will be possible to reshape the load curve and get rid of the enlargement of the generation capacities.

In addition to the mentioned above, the author plan to include the energy storage systems to the proposed model of the work, which will lead to improving the reliability of the system, where the cost for the battery storage and energy from the battery will be substantially lower than the cost set by the grid. The use of the battery storage systems will allow consideration of the Electric Vehicles in the system, which also can act as storage systems. The use of Electric Vehicles as the mobile batteries will also lead to the independence of the MMG system from the main grid, as well as an increasing amount of the DERs.

The implementation of the techniques mentioned above will be resulted in the vast increase of the versatility of the system and find more precise solutions to the power imbalance issues caused by the DERs.

Bibliography/References

[1]. X. Hua, C. Yuxi, W. Jian and V. Agelidis, "Design of energy dispatch strategy of active distribution network using chance-constrained programming," *2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Brisbane, QLD, 2015, pp. 1-5.

[2]. L. Strezoski, I. Stefani and B. Brbaklic, "Active Management of Distribution Systems with High Penetration of Distributed Energy Resources," *IEEE EUROCON 2019 -18th International Conference on Smart Technologies*, Novi Sad, Serbia, 2019, pp. 1-5.

[3]. L. Meng, M. Savaghebi, F. Andrade, J. C. Vasquez, J. M. Guerrero and M. Graells, "Microgrid central controller development and hierarchical control implementation in the intelligent microgrid lab of Aalborg University," *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Charlotte, NC, 2015, pp. 2585-2592.

[4]. S. Q. Kazmi, A. Waheed Khawaja, Z. M. Haider, Tauheed-ur-Rahman and S. M. A. M. Kazmi, "Voltage Stability of Wind Turbine Based Micro Grid Using Simulation Platforms," *2019 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET)*, Istanbul, Turkey, 2019, pp. 1-6.

[5]. S. Zhu, L. Geng, J. Zheng, X. Wang, D. Choi and Y. Li, "Selection method of transformer interconnecting distributed generation and distribution networks," *2009 Transmission & Distribution Conference & Exposition: Asia and Pacific*, Seoul, 2009, pp. 1-4.

[6]. H. S. V. S. K. Nunna and S. Ashok, "Optimal management of microgrids," *2010 IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply*, Waltham, MA, 2010, pp. 448-453.

[7]. C. D'Adamo, S. Jupe and C. Abbey, "Global survey on planning and operation of active distribution networks - Update of CIGRE C6.11 working group activities," *CIRED 2009 - 20th International Conference and Exhibition on Electricity Distribution - Part 1*, Prague, Czech Republic, 2009, pp. 1-4.

[8]. J. Malinowski, "Adoption of the Energy Independence and Security Act of 2007," *Conference Record of 2010 Annual Pulp & Paper Industry Technical Conference*, San Antonio, TX, 2010, pp. 1-5.

[9]. M. Mutlaq and S. Kumar R., "Environmental Economic Dispatch of Thermal Power Plants in Saudi Arabia: A Case Study," *2019 Industrial & Systems Engineering Conference (ISEC)*, Jeddah, Saudi Arabia, 2019, pp. 1-5.

[10]. C. Rooks, X. Kou and F. Li, "Interval Optimization for Robust Economic Dispatch in Active Distribution Networks Considering Uncertainty," *2019 International Conference on Smart Energy Systems and Technologies (SEST)*, Porto, Portugal, 2019, pp. 1-6.

[11]. J. P. Chiou, C. F. Chang and C. C. Wang, "Hybrid Differential Evolution for Static Economic Dispatch," *2014 International Symposium on Computer, Consumer and Control*, Taichung, 2014, pp. 950-953.

[12]. G. Chen, C. Li and Z. Dong, "Parallel and Distributed Computation for Dynamical Economic Dispatch," in *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 1026-1027, March 2017.

[13]. L. Herenčić *et al.*, "Overview of the main challenges and threats for implementation of the advanced concept for decentralized trading in microgrids," *IEEE EUROCON 2019 -18th International Conference on Smart Technologies*, Novi Sad, Serbia, 2019, pp. 1-6.

[14]. Firdaus, Umar and O. Penangsang, "Economic dispatch of multi microgrid systems with renewable energy sources using particle swarm optimization," *2016 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, Lombok, 2016, pp. 595-600.

[15]. J. S. Ren, K. T. Tan, B. Sivaneasan, P. L. So and E. Gunawan, "Energy management of a multi-agent based multi-microgrid system," *2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Hong Kong, 2014, pp. 1-6.

[16]. H. Xing, A. Qian, Y. Peng and W. Xiaohong, "The research on coordinated operation and cluster management for multi-microgrids," *International Conference on Sustainable Power Generation and Supply (SUPERGEN 2012)*, Hangzhou, 2012, pp. 1-3.

[17]. G. Zheng and N. Li, "Multi-Agent Based Control System for Multi-Microgrids," *2010 International Conference on Computational Intelligence and Software Engineering*, Wuhan, 2010, pp. 1-4.

[18]. Jizhong Zhu *et al.*, "Two stage approach for economic power dispatch," *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, Pittsburgh, PA, 2008, pp. 1-5.

[19]. B. Hu, B. Ye, X. Wang, L. Dai, Y. Chen and M. Zhang, "Low carbon economic dispatching for power system integrated with large scale photovoltaic power generation," *2017 IEEE Conference on Energy Internet and Energy System Integration (EI2)*, Beijing, 2017, pp. 1-6.

[20]. Liu Yong and Shang Tao, "Economic dispatch of power system incorporating wind power plant," *2007 International Power Engineering Conference (IPEC 2007)*, Singapore, 2007, pp. 159-162.

[21]. Warsono, D. J. King and C. S. Ozveren, "Economic Load Dispatch for a power system with renewable energy using Direct Search Method," *2007 42nd International Universities Power Engineering Conference*, Brighton, 2007, pp. 1228-1233.

[22]. M. Singh, Deepika and M. Kumar, "Economic load dispatch calculator," *2014 6th IEEE Power India International Conference (PIICON)*, Delhi, 2014, pp. 1-6.

[23]. C. Chiang, "Genetic Algorithm for Static Power Economic Dispatch," *2009 WRI World Congress on Computer Science and Information Engineering*, Los Angeles, CA, 2009, pp. 646-650.

[24]. X. S. Han and H. B. Gooi, "Optimal dynamic dispatch in short-term hydrothermal generation systems," *2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.00CH37077)*, Singapore, 2000, pp. 1231-1236 vol.2.

[25]. Z. L. Lyu, X. Q. Wang and Z. X. Yang, "Optimal dynamic dispatch of pareto frontier for microgrid based on MOIBBO algorithm," *2017 IEEE Power & Energy Society General Meeting*, Chicago, IL, 2017, pp. 1-5.

[26]. F. S. Abu-Mouti and M. E. El-Hawary, "Optimal dynamic economic dispatch including renewable energy source using artificial bee colony algorithm," *2012 IEEE International Systems Conference SysCon 2012*, Vancouver, BC, 2012, pp. 1-6.

[27]. L. Zhao and Z. Wu, "The Day-Ahead Economical Optimal Dispatch for Independent Community Microgrid," *2018 International Conference on Power System Technology (POWERCON)*, Guangzhou, 2018, pp. 1306-1313.

[28]. C. Lin, W. Wu, X. Chen and W. Zheng, "Decentralized Dynamic Economic Dispatch for Integrated Transmission and Active Distribution Networks Using Multi-Parametric Programming," in *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 4983-4993, Sept. 2018.

[29]. C. He, H. Wang and X. Cao, "Optimal dynamic load dispatching with the coordination of wind farm and AGC units," *2014 IEEE PES General Meeting | Conference & Exposition*, National Harbor, MD, 2014, pp. 1-5.

[30]. K. Chanc, N. Subrahmanyam and M. Sydulu, "Dynamic Economic Dispatch by Equal Embedded Algorithm," *2006 International Conference on Electrical and Computer Engineering*, Dhaka, 2006, pp. 21-24.

[31]. R. S. Wibowo, K. R. Firmansyah, N. K. Aryani and A. Soeprijanto, "Dynamic economic dispatch of hybrid microgrid with energy storage using quadratic programming," *2016 IEEE Region 10 Conference (TENCON)*, Singapore, 2016, pp. 667-670.

[32]. R. S. Wibowo, K. R. Firmansyah, N. K. Aryani and A. Soeprijanto, "Dynamic economic dispatch of hybrid microgrid with energy storage using quadratic programming," *2016 IEEE Region 10 Conference (TENCON)*, Singapore, 2016, pp. 667-670.

[33]. A. Kalakova, H. S. V. S. K. Nunna, P. K. Jamwal and S. Doolla, "Genetic Algorithm for Dynamic Economic Dispatch with Short-Term Load Forecasting," *2019 IEEE Industry Applications Society Annual Meeting*, Baltimore, MD, USA, 2019, pp. 1-6.

[34]. R. Samadi and J. Hamidzadeh, "Dynamic economic dispatch solving in power systems using imperialist competitive algorithm," *2014 International Congress on Technology, Communication and Knowledge (ICTCK)*, Mashhad, 2014, pp. 1-6.

[35]. W. Ongsakul and N. Ruangpayoongsak, "Constrained dynamic economic dispatch by simulated annealing/genetic algorithms," *PICA 2001. Innovative Computing for Power - Electric Energy Meets the Market. 22nd IEEE Power Engineering Society. International Conference on Power Industry Computer Applications (Cat. No.01CH37195)*, Sydney, NSW, Australia, 2001, pp. 207-212.

[36]. Z. Liang and J. D. Glover, "A zoom feature for a dynamic programming solution to economic dispatch including transmission losses," in *IEEE Transactions on Power Systems*, vol. 7, no. 2, pp. 544-550, May 1992.

[37]. S. Aznavi, P. Fajri and M. Rasheduzzaman, "Hierarchical Energy Management Strategy for a Community of Multi Smart Homes," *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, Washington, DC, 2018, pp. 176-181.

[38]. T. Kovaltchouk, A. Blavette, J. Aubry, H. B. Ahmed and B. Multon, "Comparison Between Centralized and Decentralized Storage Energy Management for Direct Wave Energy Converter Farm," in *IEEE Transactions on Energy Conversion*, vol. 31, no. 3, pp. 1051-1058, Sept. 2016.

[39]. M. A. F. Ghazvini, D. Steen and L. A. Tuan, "A Centralized Building Energy Management System for Residential Energy Hubs," *2019 International Conference on Smart Energy Systems and Technologies (SEST)*, Porto, Portugal, 2019, pp. 1-6.

[40]. A. Dowrueng, J. zum Hingst, A. Mbuy, E. -. Wehrmann and H. -. Beck, "Decentralised Energy Management System with comprehension of fluctuated renewable energy resources," *2009 International Conference on Clean Electrical Power*, Capri, 2009, pp. 316-319.

[41]. U. Sangpanich, "A novel method of decentralized battery energy management for stand-alone PV-battery systems," *2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Hong Kong, 2014, pp. 1-5.

[42]. S. Chen, B. Guo, H. Yan, Q. Qin, B. Li and B. Qi, "Application and Prospect of Integrated Energy Interoperability Management System Based on Blockchain," *2019 IEEE International Conference on Energy Internet (ICEI)*, Nanjing, China, 2019, pp. 421-425.

[43]. K. Nakayama, R. Moslemi and R. Sharma, "Transactive Energy Management with Blockchain Smart Contracts for P2P Multi-Settlement Markets," *2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA, 2019, pp. 1-5.

[44]. M. Mao, Y. Wang, L. Chang and Y. Du, "Operation optimization for multi-microgrids based on centralized-decentralized hybrid hierarchical energy management," *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Cincinnati, OH, 2017, pp. 4813-4820.

[45]. T. Ming, W. Deng, J. Wu and Q. Zhang, "A hierarchical energy management strategy for battery-supercapacitor hybrid energy storage system of electric vehicle," *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, Beijing, 2014, pp. 1-5.

[46]. W. Zhong, K. Xie, Y. Liu, C. Yang and S. Xie, "Auction Mechanisms for Energy Trading in Multi-Energy Systems," in *IEEE Transactions on Industrial Informatics*, vol. 14, no. 4, pp. 1511-1521, April 2018.

[47]. Xiaofeng Liu and Hua Cao, "Uniform price versus discriminatory auctions in bond markets: A experimental analysis based on multi-agents system," *2011 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce (AIMSEC)*, Dengleng, 2011, pp. 1791-1794.

[48]. S. Oren, "When is a pay-as bid preferable to uniform price in electricity markets," *IEEE PES Power Systems Conference and Exposition, 2004.*, New York, NY, 2004, pp. 1618-1620 vol.3.

[49]. M. Babaioff and N. Nisan, "Concurrent auctions across the supply chain", *Proceedings of the 3rd ACM conference on Electronic Commerce - EC '01*, 2001.

[50]. L. Xiang, G. Sun, J. Liu, X. Wang and L. Li, "A discriminatory pricing double auction for spectrum allocation," *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, Shanghai, 2012, pp. 1473-1477.

[51]. M. Khorasany, Y. Mishra and G. Ledwich, "Market framework for local energy trading: a review of potential designs and market clearing approaches", *IET Generation, Transmission & Distribution*, vol. 12, no. 22, pp. 5899-5908, 2018.

[52]. J. Lin, M. Pipattanasomporn and S. Rahman, "Comparative analysis of auction mechanisms and bidding strategies for P2P solar transactive energy markets", *Applied Energy*, vol. 255, p. 113687, 2019.

[53]. P. Yan and X. Wang, "The Mechanism Design of Multi-attribute Auctions," *2008 International Seminar on Business and Information Management*, Wuhan, 2008, pp. 299-302.

[54]. L. Du, Q. Chen and N. Bian, "An Empirical Analysis of Bidding Behavior in Simultaneous Ascending-Bid Auctions," *2010 International Conference on E-Business and E-Government*, Guangzhou, 2010, pp. 249-251.

[55]. M. Dramitinos, G. D. Stamoulis and C. Courcoubetis, "An innovative decision support system for bidding in simultaneous ascending auctions," *Seventh IEEE International Conference on E-Commerce Technology (CEC'05)*, Munich, Germany, 2005, pp. 414-417.

[56]. D. Chang, H. Wang and Z. Wu, "Maximum principle for non-zero sum differential games of BSDEs involving impulse controls," *Proceedings of the 32nd Chinese Control Conference*, Xi'an, 2013, pp. 1564-1569.

[57]. Chengke Zhang, Jingguang Gao, Zejiang Liu and Feiqi Deng, "Nash equilibrium strategy of two-person bilinear-quadratic differential game: a recursive approach," *2006 6th World Congress on Intelligent Control and Automation*, Dalian, 2006, pp. 1075-1079.

[58]. F. A. Giraldo and J. Gómez, "The evolution of neural networks for decision making in non-cooperative repetitive games," *2013 8th Computing Colombian Conference (8CCC)*, Armenia, 2013, pp. 1-6.

[59]. J. Lu, X. Wang, D. Wang and Y. Wang, "Parallel Monte Carlo tree search in perfect information game with chance," *2016 Chinese Control and Decision Conference (CCDC)*, Yinchuan, 2016, pp. 5050-5053.

[60]. N. D. Duong, A. S. Madhukumar and D. Niyato, "Stackelberg Bayesian Game for Power Allocation in Two-Tier Networks," in *IEEE Transactions on Vehicular Technology*, vol. 65, no. 4, pp. 2341-2354, April 2016.

[61]. M. Rayati, M. Toulabi and A. M. Ranjbar, "Optimal Generalized Bayesian Nash Equilibrium of Frequency-Constrained Electricity Market in the Presence of Renewable Energy

Sources," in *IEEE Transactions on Sustainable Energy*, vol. 11, no. 1, pp. 136-144, Jan. 2020.

[62]. S. Ganzfried and Q. Sun, "Bayesian Opponent Exploitation in Imperfect-Information Games," *2018 IEEE Conference on Computational Intelligence and Games (CIG)*, Maastricht, 2018, pp. 1-8.

[63]. X. Huang and Z. Wang, "Analysis of Bidding Strategies of Generation Companies by Evolutionary Game Theory," *2009 Second International Conference on Information and Computing Science*, Manchester, 2009, pp. 62-65.

[64]. Jing Tang, Jianxin Lin, Qiaolin Ding and Yan Zheng, "A new optimal bidding strategy in power market," *2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific*, Dalian, 2005, pp. 1-5.

[65]. W. El-Baz, P. Tzscheutschler and U. Wagner, "Integration of energy markets in microgrids: A double-sided auction with device-oriented bidding strategies", *Applied Energy*, vol. 241, pp. 625-639, 2019.

[66]. S. P. S. Mathur, A. Arya and M. Dubey, "A review on bidding strategies and market power in a competitive energy market," *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, Chennai, 2017, pp. 1370-1375.

[67]. V. Dehalwar, A. Kalam, M. L. Kolhe and A. Zayegh, “Electricity load forecasting for Urban area using weather forecast information,” 2016 IEEE International Conference on Power and Renewable Energy (ICPRE), Shanghai, 2016, pp. 355-359.

[68]. X. Sun, Z. Ouyang and D. Yue, “Short-term load forecasting based on multivariate linear regression,” 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, 2017, pp. 1-5.

[69]. Moghram and S. Rahman, “Analysis and evaluation of five short-term load forecasting techniques,” in IEEE Transactions on Power Systems, vol. 4, no. 4, pp. 1484-1491, Nov. 1989

[70]. A. C. Caminero, S. Ros, R. Hernndez, A. Robles-Gomez and R. Pastor, “Load Forecasting Mechanism for e-Learning Infrastructures Using Exponential Smoothing,” 2011 IEEE 11th International Conference on Advanced Learning Technologies, Athens, GA, 2011, pp. 364-365.

[71]. S. E. Papadakis, J. B. Theocharis and A. G. Bakirtzis, “Fuzzy short-term load forecasting models based on load curve-shaped prototype fuzzy clustering,” 1999 European Control Conference (ECC), Karlsruhe, 1999, pp. 2023-2028.

[72]. Wei Dinq, Fu-Gui Dong and Shang-Dong Yang, “Load forecasting based on clustering analysis using fuzzy logic,” 2005 International Conference on Machine Learning and Cybernetics, Guangzhou, China, 2005, pp. 2640-2645 Vol. 5.

[73]. S. Singh, S. Hussain and M. A. Bazaz, “Short term load forecasting using artificial neural network,” 2017 Fourth International Conference on Image Information Processing (ICIIP), Shimla, 2017, pp. 1-5.

[74]. W. Kong, Z. Y. Dong, D. J. Hill, F. Luo and Y. Xu, “Short-Term Residential Load Forecasting Based on Resident Behaviour Learning,” in IEEE Transactions on Power Systems, vol. 33, no. 1, pp. 1087-1088, Jan. 2018.

[75]. Falvo, Lamedica, Pierazzo and Prudenzi, “A Knowledge Based System for Medium Term Load Forecasting,” 2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition, Dallas, TX, 2006, pp. 1291-1295.

[76]. X. Jin, J. Wu, Y. Dong and D. Chi, “Application of a Hybrid Model to Short-Term Load Forecasting,” 2010 International Conference of Information Science and Management Engineering, Xian, 2010, pp. 492-497.