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An intelligent distributed system for flexible management of variable energy supply and demand in microgrids

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Część I

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Chapter 1

Introduction

Over the recent years, a shift can be observed in the generation of energy production. For years, the production plants were entities positioned central in the grid, growing to meet increasing demands. This saw the change from coal and gas power plants to nuclear plants, but the essential architecture of the grid remained quite central and volatile: the grid depends on few powerful sources and interconnections. The shift came when renewable sources became capable of generating more power and this at an economically viable level. Production became dispersed over a larger number of sources within the grid. The relatively low cost of a low power renewable source (e.g. photovoltaic panels) and the fact that they became economically viable turned them into good investments for companies and even households. This further increased the shift by moving away from a strict consumer-producer network and adding entities that are both consumers and producers. The so called prosumer concept [122], an entity that not only purchases energy, but can also produce and export it to the power grid. This disperses energy production, making it less volatile, but adds new complications in energy management.

Traditional energy management systems mainly work under the assumption of unidirectional flow of energy: from the big production plants to the consumers. They fail to provide a well-suited solution to recent development involving prosumers. In the lower level of the grid, the energy flows from the distribution companies to the loads, located in the leaves of the distribution grid. Generation of energy inside the distributed grid ruins this assumption, as the energy flows bidirectionally. Thus, need for a new management systems appears [97]. This invoked the concept of microgrids: a microgrid can be treated as an aggregated prosumer, which consumes or produces energy. The aggregation of units into a microgrid has lowered the fluctuations than the individual units and such prosumer-like sub-networks can be mainly energy self-sufficient and may work in a so-called island operation mode, but periodically they may buy or sell energy from or to the higher level grid (distribution network). Just as power needs to be balanced in the main grid, the sub-networks also need their own power balancing system: their efficiency increases when they are less dependent on the external network and this calls for good power management.

A microgrid can have multiple generators, from photovoltaic panels and wind turbines to gas microturbines. As these generators are dispersed in the grid, the idea of a decentralized management system arises as a natural solution. The fact that the microgrid deals with lower voltages makes such an approach more feasible. Recently, decentralization of decision making in computer networks is realized more and more often by multi-agent systems [99]. The paradigm of the multi-agent approach for energy management is the core topic of this work. Agents are concepts that can represent a real world object or an abstract concept. The aim of the agents can differ, but usually involves either individual or global optimization. In the power management problem, agents can be associated with devices, like power sources, loads, and energy storages. They have their own knowledge and individual goals defined: some power sources should be given priority in specific conditions, other conditions can require some loads to activate or deactivate. The behavior of the agents has to be defined to achieve these goals. Agents communicate with others in order to ensure security of the energy supply, and to reduce (minimize) unplanned shortages or surpluses. Thus, both sides, the supply and the load devices, take part in resolving imbalances of the energy. This forms a distributed energy management system.

In this work, a multi-agent system was developed to test the possibilities of balancing in short time intervals. The main argument to pursue a multi-agent based approach - apart from the decentralized architecture - is its modularity. There is no need for a central entity. When a new device gets added to the grid, it suffices to have agents properly defined for the new device, but no changes are required to the rest of the system. This results in a very robust system, where the removal or addition of devices is automatically caught and introduction of new devices (e.g. a new power source or power storage unit) does not require any modification to the balancing system.

A multi-agent system is a paradigm that suffers from similar drawbacks to paradigms in artificial intelligence. The system should work autonomously, based on the behaviors implemented. Such systems are very powerful but are difficult to develop: if the system does not behave as expected, it is not always easy to find which behavior in the implementation is the culprit and where the system should be modified. As such, the development of such a system requires a lot of testing and verification. To this purpose, in this work, attention also went to simulating devices present in a microgrid. This involves not only simulation of the sources (photovoltaic panels are dependent on irradiance, wind turbines on wind), but also simulation of user behavior, people using appliances or devices. To this purpose, the case of a planned research institute of "The Conversion of Energy and Renewables" in Jabłonna was used, as this provided an environment were realistic simulations of people's behavior can be envisioned.

The main goal of the multi-agent balancing system is to balance energy, but this has additional constraints: ideally, the use of renewable sources should be maximized, and the cost of the operation of the microgrid minimized. The agents need a mechanism to communicate this, and for this the concept of prices and auction was used. An auction is a well-suited solution to solve the problem where decentralized, autonomous parties tend to realize only their own goals. As in the actual trading, particular entities can reach sub-optimal allocation of the goods in the competitive environment, even without the assumption of the shared knowledge. Thus, in the Agent-based Short-time Power Balancing System for the microgrids, the bargaining of the unbalanced energy is performed in a way that minimizes differences between actual energy production and consumption. To suppress imbalances, the reaction time should be as short as possible. Several type of auctions exist in literature, here a quick auction type was necessary and the one-side first-price sealed-bid auction has been chosen. Another objective in this work is to verify and discuss the application of this particular auction algorithm and to present results of its implementation in a simulated microgrid.

In this work, the applicability of a multi-agent system for short term power balancing is considered. This involves mainly the development of a framework in which simulations can be run, along with a necessary study on how the different devices in the grid behave and how they can be simulated. Studying the feasibility of the agent system is an important step, as the modularity of the agent system lends itself for additional extensions, prediction of future behaviour is one aspect that might allow a microgrid to behave even more optimal. Such extensions are interesting, but cannot be developed with a proper working management system in place.

The outline of the thesis is as follows. In the chapter 2 the basic information about the microgrids, their evolution and the technologies that helped its development are presented.

The problem of power balancing is presented and the balancing with different level of information accessibility is discussed.

Next chapter describes the power management system that was giving the context and environment for the multi-agent system of Short-time Balancing that is the core of this thesis. Description of the subsystems is presented: model of the grid, the long-term planing system, subsystems for energy trading and reliability factor calculators. This chapter also describes the simulators of environment for testing purpose. Supply generator introduces a novel usage field for matched-block bootstrap and power consumption generator is an attempt to simulate human behavior.

The chapter 4 presents the theory of agent approach. The definition of agent is discussed as there is no common agreement over formal definition. Agent framework used in implementation of system is described.

Chapter 5 is presenting the multi-agent system realizing the short-time power balancing. The architecture of the system is presented as well as algorithms of agent operation and the structure of their behavior.

Following chapter presented the experiments and testing of the developed system. Final chapter concludes the thesis.

Chapter 2

Microgrids

2.1 Introduction

Modern society is dependent on the availability of electricity: without it, simple daily routines already become problematic and the modern lifestyle which is based on information flow comes to a halt. The economic impact of power shortages cannot be underestimated: in 2003, a large scale blackout in United States was the indirect cause of 11 deaths, while the cost of its effects was estimated to 6 billion dollars [67]. Theoretical research and practical experience ([14], [15]) show that failures of the power grid and subsequent blackouts will happen one day (they are unavoidable) due to different aspects: weather conditions, constant grow of demand, ageing infrastructure, failures of equipment, economic aspects and human errors. Constant maintenance and development of power grids are the priority to minimize the chance and consequences of failures.

Management of the power grid is complicated – the regulation role of the countries and states is still required to maintain the access to the power of desired quality. In a chain of production and delivery of electricity, there are many companies bounded by internal deals and law regulations. Electric power plants produce the energy, grid infrastructure owners take care for its transfer and consumers pay for both power and transfer based on fixed prices, long term contracts or on market price.

The adjective *smart* has recently become a key word for all attempts to develop information and management systems, for many aspects of life, that would improve living conditions and would be more pro-ecological. There are talks, conferences and reports about smart cities [44, 12], smart transport [119], smart education [104, 103], smart buildings [101], smart regulation [66] and smart grids [82]. The idea of "smart" living is to achieve the balance between the efficiency and optimization of time and resources, and about the sustainability of the situation. The idea of the smart city is an idea of creating an urban environment that will allow for comfortable living by considering economical, infrastructural, educational and social aspects of life. At the same time, the aim is to not forget about the natural environment and the long-term effects of decision making to improve the life conditions of future generations.

The power grids are now facing a revolution. Due to raising ecological awareness, increasing demand and appearance of new technologies, the sector has to move toward less polluting and more flexible power managing. The main technological factors behind the change are the development of renewable power sources and the merging of computer systems with automatic mechanisms of power management. This allowed for new concepts like smart grids, micrograds and prosumers (producer-consumer). Incorporating these concepts, according to [57], is very probable in the future. However, there are still a lot of issues that have to be solved before reliable, safe and trustful micro- and smart- grids appear. In the next sections, these concept will be defined and their impact and importance will be discussed.

2.2 From smart metering to advanced management

In the XXth century the power was mainly produced by large power plants (capacity over 1 GW), which were the most cost-effective of the time. But with time the big increase in power consumption showed that the infrastructure is barely sufficient. The use of electricity started growing, especially in peak hours (during the day), which forced producers to maintain a spinning reserve. This is an amount of power that can be quickly delivered to the network by increasing the output of the running power sources. In addition, there are non-spinning reserves , power that can be delivered by switching on additional power plants to compensate for the peak usage; these are fast reacting power plants, usually based on gas-turbines. Maintaining both large spinning reserves and non-spinning reserves is very costly. The non-spinning reserves have to be ready for operation with the deficit in the network appears, and there has to be sufficient redundancy of power production abilities in the grid. Attempts to equalize the usage within a day were made by introducing peak and off-peak tariffs. As this was adopted by a small group of users, it did not manage to remove the fluctuation of power consumption.

The smart revolution started with introducing new methods of measuring the power and the ability to send that information via digital system. In XXth century, the power meters installed in every building were measuring the usage of power and the counter was manually checked at regular times (e.g. every year) to determine how much power was used. Nowadays *smart meters* are being installed; they can automatically send information to the power companies, in almost real time, making it possible to differentiate the tariffs during a shorter time period. According to EU directive, by 2020, 80% of the consumers should be equipped with smart meters, but some governments and power companies want to achieve 100% by that time [27]. There are many advantages of introducing smart meters: real-time information about power usage, no necessity to check manually power usage, easier to find and eliminate illegal power consumption, faster handling of problems and equipment failures and the possibility of having different tariffs for different times of the day. Disadvantages of smart meters are: the initial cost of changing technology has to be paid, possible interference of the meter with domestic equipment [118] and doubts about security of stored information from smart meters. The last argument relates to privacy issues and is the most problematic one. Studies have shown that it is possible to distinguish what devices are operating from the properties of the current and consequently it can be determined what person in a household is doing [32]. Power companies and various organizations try to develop a scheme that would ensure privacy of power consumers.

The smart meters' ability for real time power measuring allows for more advanced pricing schemes: with high frequency metering there can be hourly tariffs or even real-time power pricing. Such schema would allow to match the cost of power with the demand/supply balance in the grid, which in turn could revolutionize the energy market and the way the energy is consumed. Presently, only big energy users and producers can actively participate in the energy market. Retailers (households, small companies) do not have that possibility and up to now most of them have one or two tariffs (peak and off-peak). As a result, the only incentive to save energy is to switch off unnecessary devices or change the equipment for more energy saving one. If there would be a possibility to differentiate the price depending on the current demand/production ratio it would give the users a reason to actively shift the consumption toward cheaper time, in the process reducing global power peaks. The benefit would be in more stable power parameters and less power reserves necessary. This idea is the basis for demand side management (DSM) [9]. Demand side management encourages the users to change their behavior or manage the controllable devices to optimize the time and amount of usage of electric energy. This might be done directly, by allowing a computer system to schedule the operation time of devices, or indirectly by giving incentives to the user by demonstrating the price of energy or other type of indicators. Financial incentive is the most common one and easily understandable, but as research of Robert Cialdini show in [18] an even better incentive is the feeling of being in competition (e.g. between neighbors).

Knowing the real time price of the energy depending on demand and supply, an advanced management can be introduced on the demand site, but also on the production side. The production side benefits from a more detailed structure of power usage as this allows to create more detailed and exact profiles of energy usage and produce accordingly. What is more, actions taken by power consumers make it easier for production side, as the price mechanism tends to make sure the actions eliminate sudden peaks of power.

Smart metering is a part of a *smart grid*, which is a concept of introducing exchange of information between different elements of an electrical grid (consumers, producers and storage units). Thanks to that, control and coordination of supply and demand of energy can be introduced to ensure quality of electric power in the grid, to reduce the cost and to promote renewable energy sources. Smart grid solutions span over all levels of networks and touch many different aspects of power production, distribution and transmission. Connection to computer systems is a way to introduce advanced management systems that can optimize and personalize the power usage. It gives broader control over elements of the grid and introduces automatic management using different methods of artificial intelligence. Such systems are already implemented; one example of such an improvement is a smart lighting system for the cities developed by Siemens [109], and installed e.g. in Jelenia Góra [112]. It allows to dim each street light separately to avoid lighting empty streets at night, while automatic sensors can increase the luminosity of street lamps when vehicle or human appears on the street.

2.3 From microsources to microgrids

Renewable power sources are perceived as a solution that can help fight climate change. The renewable power sources are sources that produce energy from natural processes, such as sun power, water, wind, waves, etc. These power sources have the advantage of having non exhaustible fuel. The disadvantage lies in the unpredictability of production and sometimes short lifespan of the devices. The production costs of the devices tend to be very high, mainly due to the usage of rare minerals and advanced components, and the production process can be polluting, which is not desirable.

Prosumer is a concept that was originally defined in economy as a junction between words professional and consumer. It was adapted by the energy sector as a junction of the words producer and consumer. A prosumer is a unit that internally produces and consumes energy. As the production and consumption of the power within the prosumer grid do not always balance, a prosumer can be seen by the external grid as a source that delivers energy to the grid or as a load that consumes it, depending on a current power flow. Idea of the prosumers is usually connected with small area grid connected to microsources, mainly renewables. Such configuration has a rational economical explanation: the cost of construction of such facility are smaller than expected revenue. Due to the small production and consumption abilities such prosumer would be exchanging very limited amounts of power with external power grid. If management of power and planning is included in prosumer management (e.g. not drawing power from external power grid in peak hours) the prosumer can actively help power grid to maintain good quality of power and decrease the use of reserves.

Usually prosumers are small energy units and individually they do not impact a lot on an overall balance of the grid. In a big mass they can impact, but due to the internal management of energy they may create fewer problems to control systems of the big power plants than completely uncontrolled small individual users, like e.g. residential homes.

A microgrid is a group of consumers, producers, prosumers or energy storage devices located on small area that can operate autonomously. The microgrid usually constitutes a low (400/230V) or medium (1 kV - 60 kV) voltage network. Very often, microgrids are equipped with power sources (e.g. gas microturbines, micro wind turbines, photovoltaic panels) or power storage (e.g. batteries, flywheels). Such infrastructure poses a big challenge to the management of energy, as the balance has still to be maintained. In spite of that, microgrids have a number of advantages, especially when equipped with small energy sources (renewables or not) and when there is a possibility to store power, even in limited amount. A characteristic feature of a microgrid is that it can be treated as one entity from the point of view of the larger network. This work considers the power issues inside a microgrid, for discussion of additional advantages of using microgrids see [57]. The projects that are being realized, connected to microgrid research, are described in [39].

In a microgrid, it is necessary to balance the production and consumption of power to maintain the quality factors of the electric current; these guarantee the safety of the devices in the microgrid.

A microgrid can work in "synchronous mode", meaning that it is connected to a larger grid and exchanges power with it. However, microgrid can work disconnected from the main grid; this is a so called "island mode". Microgrid can be in such state when the external grid is unavailable or if it is possible to perfectly balance production and consumption of electricity internaly. This mode is beneficial, as it optimizes the energy in the microgrid and, in case of using renewable sources of energy) operates at the lowest cost: any exchange of power with the external network means paying for power transfers and usually the price of energy is more profitable for larger, external grid. It also offers security and failsafe benefits, as the microgrid is not dependent on the external grid. While in practise it may not be possible to operate all the time in island mode, it is the desirable target for the microgrid. In island mode, an abundance of power production in the microgrid should be solved either by wasting energy or limiting production; whereas a shortage of energy, should result in some of the consuming devices to be switched off according to importance or preference. The difficulty is that a decision has to be made and it should follow the constantly changing conditions in the grid. The faster the decision is made, the less power is wasted and the safer the devices are. Power produced by some renewable sources (especially micro sources, which might lack the ability to manage their current production level) fluctuates dynamically due to sudden changes in e.g. wind and solar irradiance. Predictors, to some extent, can forecast the production and help minimizing the imbalances, but the predictions are not perfect. Consumption of energy is also very changeable and often unpredictable, especially in small microgrids, where a single device can make a noticeable difference in overall power usage. This means that the actions of a single person can make a noticeable disruption from a typical daily power usage profile.

A microgrid is not just a smaller version of a macrogrid. The physical effects in low-voltage grids are different than in high voltage grids that have enough inertia. Moreover, a possible autonomous (island) operation of a microgrid requires solving of additional problems. For example, subsistence of the frequency, which is normally controlled by the external grid, has to be solved. In the island operation mode a microgrid often does not have enough power to support a usual load all the time; there should be a mechanism of switching off the loads with lower priorities.

Limited information about the amount of consumption and production is a problem for balancing. The consumption is changeable in time: it is the sum of consumption of a number of small devices, where each of them may have different usage patterns. While patterns and cycles, such as daily or weekly, are usually visible in the amount of power usage, the exact amount can only be predicted roughly.

The production is the sum of the decisions of all producers which operate in the microgrid. They may or may not know how many producers are present in total and decide to participate in balancing, but in any case they can only estimate the amount of power produced by all other sources. The information shared between producers is a property of a used scheme, which can depend on the level of cooperation, the size of the microgrid or other factors, such as cost of power production, ownership, regulations, etc. In microgrids with one owner, there can be full cooperation with full flow of information; allowing for central balancing to be used. When competition of producers is present, the flow of information may be constrained to the minimal level that is necessary for the process. When a microgrid is limited to few buildings, it is helpful to know the physical limitations of the units to predict the amount of produced power.

To manage the energy, it is important to understand specificity of the microgrids. There are many features that discern microgrids from big power systems. The issue has been discussed in detail in [51]. Essential features for functioning microgrids as semi-autonomous power systems include the use of power electronic converters, the use of specific control systems, and it requires the ability to communicate within the microgrid. Another fundamental feature of microgrids is installation of renewable energy sources, which is of great importance from the point of view of environment protection. Most of the microsources are connected to microgrids via power electronic converters, which also provides them with required control abilities. These abilities are also necessary from the point of view of ensuring security and proper level of reliability of supply.

The key issue is control of the microgrid operation and requirements for protection of the microgrid functioning. Particularly it concerns such tasks as voltage regulation, frequency regulation, power flow control, and voltage stability. These issues are especially significant during island operation. It is also important for a microgrid to have an ability to change smoothly the state from the synchronous operation mode to the island operation mode or vice versa.

Protection systems applied in microgrids have to be specific with regard to connecting microsources via power electronic converters, low level of short-circuit power in island operation states and bi-directional power flows in microgrid branches. Protection systems installed in microgrids have to work properly in the case of faults appearing both in the microgrid and in the external distribution network.

In the microgrid island operation mode, control systems have to take into account the inertia of the different types of the microsources. Microsources have differenct response time and their time to change the production level varies between devices. It is especially significant during frequency regulation in the island operation mode of a microgrid. One of the most important feature is also the Demand Side Management (DSM) function when controllable loads exist in the microgrid. Supply reliability is a strict requirement for a microgrid to work in the island operation mode. For methods developed to control the load see e.g. [21, 42, 79].

The concept of a microgrid is based on the fact that there is a cooperation or at least non-hostility among the participants in the microgrid. It is automatically fullfilled when all sources and loads in the microgrid belong to the same owner. Then there are no conflicting views, no problems with distributing the profits from producing the energy or sharing the costs of buying additional energy. This is actually the case considered in this paper, where it is assumed that the whole infrastructure belongs to a single owner. However, the described approach of treating devices as independent agents can be also applied in a many-owner microgrid, providing that economic result of the whole grid operation is the common goal.

2.4 Power balancing

A microgrid in general can consist of producers, consumers and prosumers. Each of these can be controllable or uncontrollable. Uncontrollable devices are those which are not manageable by the grid or by a management system, to this category are included most of the power consuming devices and small renewable power sources (in which power production depends on weather conditions). It is important to note that controllable/uncontrollable in this context are considered in relation to a management system: a lamp is controllable by a person, but as we do not want the system to decide to switch it on or off, for the system it is an uncontrollable device. The balancing problem reverts to a decision problem of setting the operating point of controllable devices in the microgrid, so that supply and demand are equal according to equation (2.1). To simplify a model, all uncontrollable devices can be aggregated to a single value: this value is either 0 (perfect balance of uncontrollable devices), positive (behaves as producer) or negative (behaves as consumer), but this aggregated value is not constant over time.

The power sources have physical limitations: a minimal and maximal operating point, a time necessary for changing the operation point, etc. Managing a controllable power source means deciding if the device will be active in the next time period ($s_i(t_k)$), and if so, determine the amount of power it will provide.

Balancing should make the amount produced ($s(t_k) = \int\limits_{t \in t_k} s(t)dt$), for a given time ($t_k$), equal to the amount that can be consumed ($d(t_k) = \int\limits_{t \in t_k} d(t)dt$) at that time. The real energy balancing is a continuous process, but from the operational point of view it can be quantified to a number of short time periods t.

$$\sum_{i=0}^{n} s_i(t_k) = \sum_{j=0}^{m} d_j(t_k) + L(t_k),\ t_k \in T \tag{2.1}$$

where $n \in N$ is the number of active producers and $m \in M$ is the number of active consumers. The losses of power during transmission ($L(t_k)$) are not considered: they are relatively small for microgrids, their amount depends on network structure and while their absence does not influence the theoretical solution, it does allow for a simplification of the model.

There has been many papers dealing with problem of power balancing, see for example [54]. However, as pointed out in [122], due to a dynamic generation and demand of the electric power, and need to obtain the power balance, the grids with renewable energy sources require application of even more complex control systems. They are usually called the energy management systems (EMS). These systems often include such modules as a control module oriented to optimization of the grid operating costs, a module cooperating with the distribution grid operator, and a module ensuring reliable supply of energy. Balancing is possible due to the existence of controllable devices (their operation point can be changed by the energy management system (EMS), which is further discussed in chapter 3) and the ability of switching off or on a part of the consumption. In most real life installations, a microgrid is connected to an external power grid, which can provide or absorb a large amount of power. In large power grids, a constant reserve of production power is kept in order to cover occurring imbalances.

The problem of balancing a microgrid is of interest to many research teams. General architectures of energy management systems might be found in [122], [96] and [97]. Details of the algorithm of the market based short-time balancing is described in chapter 5 and can also be found in [81].

The problem of power balancing is slightly different on each level of the power grid. Balancing power in the high voltage network can benefit from big aggregation of consumption. There the daily and weekly cycles dominate [56] and the inertia of the grid is much larger. In microgrids, the changes in consumptions still have visible cycles, but the random behavior plays a bigger role and the inertia of devices is smaller. This requires fast decision making regarding changing the operation point of sources and consumers in the grid. That poses a computation challenge, especially when the number of nodes is large and an energy management system has to balance the energy in all nodes, considering also all the physical limitation of the devices within a defined time period.

Effective balancing requires some kind of communication or a schema of cooperation between the producers of energy. The most straightforward schema is the centralized management: it is then possible to have one predictor of demand (e.g. that which gives the smallest errors), based on which the plan for production is made and the system distributes the power production. Centralized systems offer the possibility of optimal production distribution [116], possibly considering multi-criteria decision making. Centralized systems unfortunately have a number of different disadvantages: sensitivity to central controller failure, poor scalability, and requirement of full control over the sources. Full control may not be a problem in microgrids with a single owner, but may be unacceptable in a general situation. A centralized system might also not be able to consider specific preferences of the source owners or might give unacceptable results when a source owner happens to actively make decisions on its own (although that should not happen in a well designed system).

Non-centralized solutions have been also developed and showed promising results. Agent-based power balancing systems are quite a popular approach. Due to the intrinsic characteristics of the agents, these system are distributed. A classification of different energy management schemes for agent-based systems can be found in [100]. Agents can represent single devices, nodes in the power grid, subsets of nodes or even single microgrids. The presented categories of management schemes are: central-hierarchical control structure, distributed-hierarchical control structure, and decentralized control structure (peer-to-peer relation). The hierarchical organization of agents introduces an order and defines agent's functions in optimization and decision making. This can speed up the processing of the data, by dividing and distributing the tasks for calculation. The hierarchy can handle power distribution in a similar way as centralized systems. Completely decentralized control structures are extremely robust to failures and can quickly adapt to changing conditions. However, because there is a larger exchange of data and negotiation, such systems tend to operate slower, which might be the cause of imbalances not being resolved in time.

The last group of control systems are the ones based on market structures. The market is the central element of the balancing process, but the participants decide what kind of offer is placed on the market. In such approaches, money and cost functions play the role of ordering the power from most desired sources (i.e. cheapest and most efficient) down to the sources that are used only in emergency (i.e. more expensive power systems). Presentation of market based energy control systems can be found in [122, 81, 120].

2.5 Power storage and electric vehicles

The presence of the power storage units, e.g. batteries, can facilitate the balancing, as they provide a time and power buffer for the management system. Power storage units are generally much faster than controllable power sources when it concerns changing the amount of taken or given energy. Extremely fast operating storage units such as flywheels can smooth the sudden peaks of power and compensate for short power loses. Large enough capacity of power storage devices in the microgrid can solve a lot of issues, even completely eliminating the imbalances. Detailed analysis of influence of power storage can be found in

[123]. Storing the power unfortunately results in loses of power, a high cost of installation of storage units and, in some cases, a necessity of replacing them relatively often. In microgrids, large capacities of storage units are not common mainly due to high costs of their installation and maintenance. The most frequently considered devices are batteries, flywheels and superconductors.

Battery is a device that aim is to convert the chemical energy into electric energy thanks to the process of an electrochemical oxidation-reduction [53]. Battery is a general name for different type of such power storage: non-rechargeble (primary batteries), rechargeable (secondary batteries), reserve batteries and fuel cells. The exhaustive description of architecture, operation and properties of batteries can be found in [53].

Flywheel is an old concept of device that is used to store energy for short time and equalize peaks of energy that otherwise are difficult for balancing. Peaks of energy are costly to cover with energy from external network and they can damage devices if not handled properly. In island mode operation of microgrid device as flywheel is very useful, as it can absorb and give in very short time large amount of power. The flywheel starts quickly to loose the energy (the flywheel used as an example in this project the flywheel loses it's power after 12,5 second), which makes it unsuitable for long term storage, but this time is enough to allow for smooth transfer from synchronized mode of microgrid to island operation mode. In synchronized mode flywheel would be a device to deal with very short imbalances as its reaction time is the shortest of all available devices. Also the short charging time (in used example it can charge to 100% of the capacity in 20 seconds) makes it perfect for shaving power peaks and filling sudden deficits of energy. Flywheels are much more durable, their average life time reaches over 20 years, there is no limit on the number of charge and discharge cycles, the efficiency of the device reaches 99,8%. All rotating elements work in vacuum which minimizes the amount of friction. Due to short time of keeping power flywheel cannot be treated as battery units. Batteries have much less life expectancy, but can keep the power for longer periods.

Superconducting Magnetic Energy Storage (SMES) is a relatively new concept of a power storage unit, in practice used more as a mechanism to improve and control power quality than to store power. It uses magnetic field to store power using superconducting coil cooled to low temperatures [114]. There is a number of problems that still have to be overcome to make this technology mature and usable for large scale, but the advantages of the technology seems interesting: very short delay during charge and discharge and very high power output (although for a very short time).

The power storage units are very useful in maintaining the balance in grids. Having large enough storage can solve a lot of current issues with power quality and production. Presently the storage capabilities are marginal in comparison to the usage, but if microgrids are considered there is a space for enhancing the operation of microgrid using affordable storage units. Especially promising is an idea of electric vehicles that could have a double function: as a means of transport and as a mobile power storage unit.

Electric engine appeared just after invention of electricity. For short time electric vehicles were considered a future of transport [5], e.g. the first fuel cell car was made in 1966 by General Motors [22]. Then, for many years gasoline powered cars were the vast majority on the road. Due to the increasing fuel prices and the heightened awareness of ecological situation the search for cleaner and alternative engines started. The electric vehicles or hybrids have become more and more accessible. Their price is dropping and the technology is developing. The availability of private renewable microsources opens possibilities for cheap exploitation of an electric vehicle, using locally produced power.

Electric vehicles do not directly pollute, the pollution is emitted to the atmosphere during production of a car and during generation of electricity that is stored in vehicle's battery. Such emissions tend to be smaller than the everyday usage of a car, when considered over the average lifetime of a car. Furthermore, such pollution is much more easy to limit as there are single points of modernization: the power plants. Electric vehicles are more silent and reduce the noise pollution that, although often underestimated, directly influences the well being of people, especially in urban spaces. The biggest barrier of the electric cars is the lack of recharging stations that limits the range of such vehicles. The special term *range anxiety* [22] describes the uneasy feeling of not being able to reach a desired destination due to range limitations of an electric car. This is still the case, even though some of the electric cars have their range and speed often not worse than those of conventional fuel-powered models, e.g. Tesla Roadster has range of 390 km on one charge [69]. On the other hand due to the elasticity of electric engines (power usage in stationary traffic is minimal) such cars are much more efficient in high-traffic conditions. Technologically the limits are set by the capacity and physical properties of the power storage units (e.g. weight and size). The most popular storage, which are the batteries are using high density materials which make them heavy, the number of charging-discharging cycles is often limited and density of the power is fairly low [22]. The use of such batteries has to be especially supervised due to the materials and components used for its production. The speed of charging creates a second barrier, as charging a battery takes longer than refueling a car. The speed of charging is defined by the architecture of the battery and standard of the connector. The network of charging stations (or points of exchanging batteries) is still very limited which poses the barrier for the development of these types of vehicles.

The most popular are now so called plug-in hybrid electric vehicle (PHEV), which can be defined as hybrid vehicles which have a battery storage (at least of 4kWh), can recharge its battery (most commonly from standard socket) and can drive for some time (at least 10 miles) on electricity not using any fuel [41]. From power grid point of view, such cars are power storage units: when they are charged they consume energy, but when they are connected to the network they can give the power to the grid. That can have wider usage for power management.

There are many country-level projects which aim is to boost more environmental friendly technologies, e.g. British government gave additional £37 million on building charging stations for electric vehicles [20]. Taking into account all pros and cons of electric vehicles, most car manufacturers consider in their long-term planning shifting to hybrid or fully electrical vehicles due to uncertain future of fuel prices and its availability.

The ongoing research in field of electric vehicles focus on: the development of efficient charging stations, using electric cars as mobile power storage units that can help balancing the power grid [123] and technological advances in field of power storage units.

2.6 Theoretical basics of production side management

In this thesis the focus is placed on production side management (PSM): the power sources and power storage units have to decide when and how much power should be produced to balance the power, maintain good quality of power in the network and gain adequate profit. The problem is complicated even when not all the physical limitations are considered, the decision about production is taken under a big uncertainty as neither the production of other power units nor the exact consumption is known. The national grids have enough inertia to allow the single producer to manage the power production level, the consumption is aggregated enough to make it foreseeable, adding to that a system of reserves creates a system that works. But when microgrids are considered the situation becomes more complicated.

The biggest cost for owners of uncontrollable microsources (like wind turbines, water turbines, photovoltaic panels) is the installation of devices and maintenance. The exploitation cost are neglectable, so the best strategy for the owner is to produce as much as

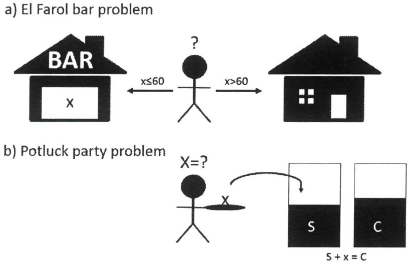

Figure 2.1: Graphical representation of El Farol bar problem (a) and Potluck problem (b), S is a total supply and C is the value of consumption.

possible. The power that is overproduced is sent to the power grid (assuming the microgrid is not in island mode), but this mainly occurs when the weather conditions are good but it does not coincide with the power peak time.

The owners of controllable power microsources (like micro gas turbines, reciprocating engines on biogas or cogenerations units) are in different situation. In this case producing power or even operating in idle state means using the fuel, which has to produced or purchased. Considering that the switching on and off of the power source might take time (depending on the characteristic of the device) the first decision of the micro power source owner is when to switch the source on and then at what operating point. If the owner is operating the microgrid in island mode, there decisions are crucial for proper operation of the microgrid. There are a number of methods and strategies to solve this issue, an author's method is described in chapter 5. Some of them are centralized, treating the power production as multi-criteria optimization problem (considering cost, fairness and special requirements of the owners of the microsources), other solutions consider more distributed approach where owners have to cooperate or compete to reach the balance of power. Because the solution presented in this work is distributed, a deeper analysis of such an approach will be presented.

In a distributed approach, the amount of public information and what information are being exchanged is an important issue. For various reasons, as e.g. safety, competition, willingness to make profit, the producers tend to keep certain information private. The lack of information exchange can make it impossible to perform balancing. Such situation was considered by Brian Arthur in [6], where a method to deal with such ill-defined problem is suggested. It was called the El Farol Bar problem. The extension of this problem which is a simplified balancing of demand and supply, the Potluck [26], considers the supply and demand equalization with almost lack of information exchange. This problem will be discusses further in section 2.6. Discussion about this topic was presented in [94].

2.6.1 El Farol Bar Problem

The El Farol Bar problem (or Santa Fe Bar Problem) was introduced by Arthur in 1994 [6]. The problem was inspired by a real bar in Santa Fe, which was very popular on Thursday nights. But if too many people decided to go to the bar to enjoy the music, it was too crowded. Arthur defined the problem as follows. If there are not more than 60 people in the bar, the people inside enjoy being there. Otherwise they feel better at home. This problem is illustrated in Fig. 2.1(a). So a participant is considered a winner if she/he goes to the bar while it is not crowded, or if she/he stays at home when the bar is crowded. In the El Farol Bar problem, the participants' goal is to win as many times as possible, where

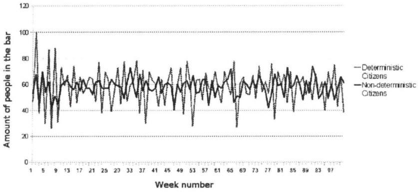

Figure 2.2: Attendance to the El Farol bar of deterministic and non-deterministic citizens.

the goal function $g_i(t)$ of i-th participant in the t-th night is defined by:

$$g_i(t) = \begin{cases} 1 & \text{if (go to the bar and the bar not crowded)} \\ & \text{or (not go and the bar is crowded)} \\ 0 & \text{if (not go and the bar not crowded)} \\ & \text{or (go and the bar is crowded)} \end{cases} \tag{2.2}$$

The participants do not know how many of them are in the city, they are not communicating with each other and they have no idea what other people want to do. The only information available to them is the historic attendance: each participant knows how many people were in the bar during the last weeks. In a problem defined as such, there is no win-win solution - when in the bar there are 60 people, the ones remaining at home loose, when there are 61 people in the bar, these 61 people loose.

In this scenario, there is not enough data to make a deductive, rational decision, which makes the problem ill-defined. In [6], an inductive reasoning scheme is proposed. This is an idea taken from psychology: people are very often facing ill-defined problems and humans cope with this situation by looking for patterns and similarities in other situations. If a person would be asked the reason for going to the bar, possible answers could be: "last week it was empty so this week it will be the same", "last week it was full, so this week it will be empty" or just "because I want to go". From the game theory and mathematical analysis point of view these answers are not reasonable, but due to lack of information they are as good as any other. Humans often do not analyze all possible actions deeply, but make shortcuts and take non-optimal decisions, sometimes due to undefined reasons. It is logical from the evolution point of view, as taking decisions fast has been more crucial for survival, than being indecisive and not performing any actions. Arthur (in [6]) assumed that each person has its own way of predicting the attendance in a bar – they have a set of simple predictors. The predicted attendance might be: an average of the last few weeks; the same as last week; the same as 3 days ago (cycle detector) or an assumption that the bar will always be half empty. Each person also knows the attendance from few last weeks. So a going or not-going decision depends on the known history of attendance and ones own hypothesis. What is more, participants can choose their predictors from a pool, according to the success rate of a considered predictor (how many times it gives a good advice). Surprisingly, the simulations show that the attendance in the bar is oscillating around the chosen maximal comfortable number of the participants in the bar. An example of the bar attendance in this problem is presented in Fig. 2.2. Arthur called it inductive reasoning method and defined it as follows. When there is a lack of knowledge to take a reasonable decision, one should use simple models that worked best in the past, and after each iteration of the process evaluate the models.

An interesting feature of this approach is that starting from some defined conditions and following totally deterministic rules, the outcome is a sequence of attendance that resembles a stochastic process. The amount of people in the bar is oscillating around 60.

It is explained by the fact that citizens choose the predictors that performed best, this creates a self-regulating system where the number 60 is a natural attractor.

It is worth to notice that if the citizens know how many of them are in the city, they can solve the problem quite easy by coming to the bar in cycles. This solution was described in [52].

2.6.2 Potluck Problem

The Potluck problem was described and defined in [26]. A potluck is a party where every guest brings some food for everyone to eat. If the food is in excess, the guests feel uncomfortable, as their food has to be thrown away. On the other hand, if there is a deficiency of the food, guests are hungry and unhappy. The perfect situation would be to have the exact amount of food, but the appetites of the guests depend on many factors and can vary between parties. So, without communication guests have to guess the total amount of food they have to bring, not knowing what strategy other guests will adapt, see Fig. 2.1(b) for an illustration.

In the Potluck problem, the goal function is to balance the supply and demand. Assuming that demand is something out of control, the goal function of l-th guest can be defined as, see [26]:

$$g_l(t) = \begin{cases} 1 & \text{if } \sum_{i=0}^{n} s_i(t) = \sum_{j=0}^{m} d_j(t) \\ 0 & \text{if } \sum_{i=0}^{n} s_i(t) \neq \sum_{j=0}^{m} d_j(t) \end{cases} \tag{2.3}$$

The notations are explained in Table 2.1. A guest is in the winning position when the sum of supply is equal to the sum of demand. But a guest has no means to communicate with other guests to inquire about the amount of food they plan to bring or the food they want to eat. This lack of information makes the problem ill-defined, where the rational reasoning does not help in winning of any of the guests. Enumula and Rao ([26]) define rational reasoning as applying the best strategy in given situation, that is with the assumption that the consumption level will be the same in future as in the last time. This show that it leads to increased oscillation of supply. If all guests make this assumption, they will take similar decisions, which will lead to an exaggerated change in the supply of food and the balance is never reached. The way to prevent it is by introducing different strategies for each of the participants, hoping that at least to some extent the *undersupply* and oversupply will cancel each other out.

A method to deal with this problem is also presented in [26]. It is a non-rational approach similar to the inductive reasoning described in [6]. As was mentioned before, rationality, according to Enumula and Rao [26], is to apply the best strategy according to the present knowledge. In the Potluck problem, the rational action is to act as if the supply has not changed since the last party. The non-rational approach is to allow participants to take an action that is assuming a certain change in the future supply (usually not explained by analysis of the problem). Participants have a set of simple predictors with assigned weights, that forecast the level of consumption. The decision is made on the basis of a weighted sum of predictors response (weighted majority algorithm). After each party, the predictors are evaluated and weights are adjusted accordingly. Enumula and Rao [26] called it a non-rational learning algorithm. In the cited article, prediction of supply side is not considered.

Enumula and Rao claim in [26] that the Potluck problem is a generalization of the El Farol Bar one. But actually the point of view of decision-makers and the goal functions are different in both problems. The personal goal function in the El Farol Bar problem is given by equation (2.2). It is clearly an egoistic goal, which does not consider the well-being of other participants. Decisions of a participant are influenced by the actions of others, which can be interpreted as influencing the decision-maker, but it is not done intentionally. A participant has no intention to make the bar full or not, because in both situations there is a possibility of winning. Arthur [6] underlined that participants are independent agents, that are following their goals, even not being aware how many of participants are in the system.

In the Potluck problem, the goal function is to balance supply and demand, as described by equation (2.3). The goal can be defined as a global goal function which means that it is a type of a social welfare function. Unlike the El Farol Bar problem, it does not consider a personal gain or loss, but the sum: all participants win or lose. In the El Farol problem, if the bar is crowded, the people in the bar loose, but the people that did not go to the bar win. An analogy to social welfare in the El Farol Bar problem would be the situation where the citizens are trying to reach 60 people in the bar every week, and in case when there are more (or less) attendees everyone looses.

The question arises if these problems are really equivalent even though the goals of the participants are different. The methods of approaching them are similar, but the problems' complexities change when some exchange of information is introduced. In case of a personal goal, adding knowledge about the decisions of others (by communication) only introduces complications in decision making: the agent has to actively make effort to be in the winning position. To clarify this statement a following scenario can be considered: there are 100 participants in the El Farol bar problem, but just 99 of them has some media of communicating their decisions, e.g. announcing it on the social network. None of them knows what the 100th participant will decide, and this participant does not know the decisions of others. By communicating each other, the participants can agree to perform a schema that will ensure fair amount of winnings for each agent. They can agree that 59 of them are going to the bar and 40 staying home (the agents that are going to the bar can change every week, which would mean introducing going to the bar in cycles). This is a solution where the winner group is the largest, independent of the decision made by the isolated person. But it requires of participants to make concessions for some kind of social fairness. In the original problem agents are assumed to be myopic and egoistic, which does not allow them to cooperate. So, seeing the situation, participants staying home will be willing to change their decision. If this happens, the situation will change again and the decisions of the participant will also change. That would trigger a set of changes that would lead to an apparently chaotic behavior. A stopping condition may be applied, e.g. it might be the time (an hour of going to the bar is defined) or the number of decision changes. When the decision making process is closed the number of citizens in the bar is very likely to be not optimal. The outcome will show pseudo stochastic oscillations around the number of 60 people going to the bar, even when almost everything is known. In the Potluck problem the behavior in this scenario is different. Information about the amount of food brought by 99 out of 100 people suggest their predicted consumption level and all participants try to minimize the error of prediction. After a number of iteration the 99 participants can predict the production level of the 100th participant and consider his decision. Imbalance is still present, but the oscillations are relatively smaller. Socially aware agents are more likely to cooperate, make concessions and negotiate their decisions. Introduction of communication to the problem makes it possible to reason rationally.

2.6.3 From Potluck to power balancing

Table 2.1 presents a comparison of the theoretical El Farol Bar problem, the Potluck problem and a practical problem of power balancing. The problems seem very similar, but a quick analysis shows main differences which cause that distinct methods of facing these problems have to be considered. The theoretical problems are very simplified and constrained. The most limiting constraint is that agents are banned from exchanging infor-

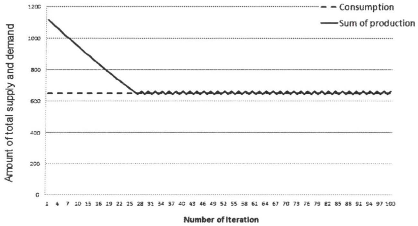

Figure 2.3: Potluck problem simulation with linear consumption, with n=100.

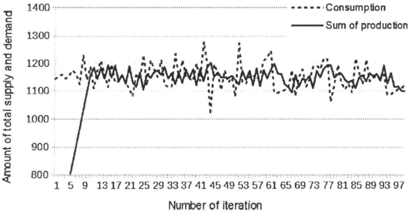

Figure 2.4: Potluck problem simulation with random consumption, with n=100.

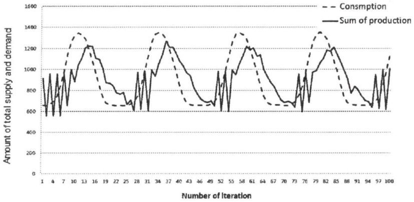

Figure 2.5: Potluck problem simulation with sinusoidal consumption, with n=100.

mation. The Potluck problem can be expanded with additional constraints that resemble physical limitations that are present in the power balancing problem (e.g. minimal operating point, maximal operating point, latency of operating point change, etc.), but these do not significantly change the problem considered: it is still an ill-defined decision problem, the additional constraints do not simplify nor complicate it.

Here, the aggregated device is assumed to be a consumer, in order to avoid a situation of overproduction by uncontrollable producers. Such situation needs special actions (e.g. removing an uncontrollable producer, wasting power, etc.), which are not common situations in the typical balancing problem.

In the Potluck problem, lack of information about power production is equally problematic as lack of knowledge about its consumption. Tests have been made using a non-rational learning algorithm with different consumption patterns: the performance of the algorithm with a random consumption is shown in Fig. 2.4, with a fast changing sinusoid consumption in Fig. 2.5 and with a linear consumption in Fig. 2.3. Several categories of predictors have been used in the calculations:

Table 2.1: Comparison between problems of El Farol, Potluck and power balancing.

Symbol	El Farol Problem	Potluck Problem	Energy balancing
T	set of weeks	set of weeks	set of time periods
N	set of participants	set of guests	set of suppliers
M	equal to 1	set of consumers	set of energy consumers
$s_i(t)$	binary decision of going or not	amount of brought food by i-th guest	amount of energy produced by i-th supplier
$d_j(t)$	constant	amount of food expected by consumer j	amount of energy demanded by consumer j in time t
$S(t) = \sum_{i=0}^{N} s_i(t)$	total attendance in the bar in a week t	amount of food brought to the party	amount of energy produced by all suppliers
$D(t) = \sum_{j=0}^{M} d_j(t)$	constant	total demand of food	total consumption
$P_i(t)$	prediction of the attendance to the bar in a week t	prediction of the amount of total consumption in a week t	prediction of total consumption in time t

- average demand over the last k periods,
- randomly chosen value of demand from the last k periods,
- choosing the demand from $t - k$ period, this predictors are cycle detector, it can detect cycles of 2, 3, 5 periods,
- mirror image around the average of the last k periods,
- the same as the previous period,
- trend over the last k periods,
- median of the last k periods,
- weighted solution over the last k periods - the random k weights are chosen: $w_1, w_2, \ldots, w_k$, where $\sum_{i=1}^{k} w_i = 1$ and the prediction is calculated as: $\sum_{i=1}^{k} D(t-i)w_i$.
- the smallest value of demand out of the two last periods,
- the larger value of demand out of the two last periods.

It is clear that a less changeable consumption makes it easier to reduce imbalances, as predictors work better. However, even for linear consumption agents could not fully balance demand and supply. The oscillations are still visible.

The reason for this is that suppliers use the same algorithm and therefore take similar decisions based on the same information, which in turn leads to overcompensation. This is logical, as a supplier has no knowledge of other suppliers and tries to solve the imbalance by itself. In some situations (e.g. the oscillations in the linear case) the result can be improved by introducing additional conditions to the agents' logic, but such specialization would decrease overall performance in the general case. A better solution is to allow for communication between the suppliers.

There are many ways in which such communication can be introduced. The simplest case considers publishing information for all agents. One way to prevent big oscillations is to limit the number of suppliers that can change their decision, such that not all suppliers will react to the imbalance. This automatically limits the total change. It can be achieved by introducing tokens to tell a supplier that it is allowed to change its output, and publishing which agents have the tokens in the given iteration. Preferring certain suppliers over others becomes a matter of a central body that has to decide how the tokens are distributed. Another way of preventing big oscillations is by introducing direct communication between the suppliers. This can lead to bilateral and multilateral negotiations, which permit for rational reasoning. In a similar way, a solution with an ordering of suppliers can be introduced, and the agents higher in hierarchy would be privileged to change their supply. In both last approaches, preference of a supplier can be decided by all the suppliers, using the information they share, without a central decision body.

Realistically, a rotation of the suppliers should be introduced, based on various factors, such as e.g. the cost of supply. To dynamically adjust the ordering, a market scheme can be adopted: prices will introduce a certain order. Exchanging information about the price and defining a cost of imbalance (the bigger the difference between supply and demand the higher the cost) is a simple market based scheme for balancing. Considering such approach requires concessions from participants, but also allows for rational decision making and leads to almost perfect balancing.

The goal function in real life power balancing is much more complex than in the artificial, theoretical problems. Comparing the goal functions (equations (2.1) and (2.3)) can give impression that they are the same. But in many of the described models the criterion is to maximize the profit or minimize the cost of producing energy ([81, 117]), where achieving balance is just one of the conditions. Often, only microgrids that have a connection to the external power network are considered. Such a reserve (the external network is not a constraining factor in this case: it can supply or receive any amount of power) is ensuring that the balance can always be achieved, which facilitates the decision making. Under such conditions, the problem of balance is not the primary one and the goal function focus usually on profitability of the power production. The concept of a microgrid is fairly new. Pointing out that it can generate a revenue can motivate further development of this technology and construction of microgrids. When the island mode operation of the microgrid is considered, the power balancing becomes crucial for safety of the devices and the network itself.

In the Potluck and the El Farol problems decisions must be taken in discrete time intervals and need many iterations to allow the learning algorithms to adjust the predictors. After each iteration the outcome is calculated – the amount of people in the bar or amount of food on the party. The power balancing problem is in reality a continuous process, but it is often quantified to allow computer algorithms to cope with. The shorter the quantification time, the more small changes can be balanced, leading to smaller loses and better security of the grid. However, shortening of the balancing time has also its limits; as the change of the operation point of the devices requires time. Different devices have varied times of reactivity regarding their operation point change, which makes it impossible to derive the optimal minimal length of a time period in general. It can be approximated when the real set of devices that are installed in the defined microgrid is known. At present, for energy management system, the time periods may be 10 minutes, 5 minutes, but seldom less than 1 minute. Of course, the minimal physical time depends on the set of devices, but that can be evaluated only experimentally.