BRNO UNIVERSITY OF TECHNOLOGY

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF FOREIGN LANGUAGES

ÚSTAV JAZYKŮ

CONTROL OF DECENTRALIZED ENERGY SOURCES AND STORAGE SYSTEMS

ŘÍZENÍ DECENTRALIZOVANÝCH ZDROJŮ ENERGIE A AKUMULACE ENERGIE

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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BRNO 2018

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

Bakalářská práce

bakalářský studijní obor **Angličtina v elektrotechnice a informatice**
Ústav jazyků

Studentka: Valeriia Maksimovich ***ID:*** 189826
Ročník: 3 ***Akademický rok:*** 2017/18

NÁZEV TÉMATU:

Řízení decentralizovaných zdrojů energie a akumulace energie

POKYNY PRO VYPRACOVÁNÍ:

1. Analyzujte v současnosti používané technologie řízení decentralizovaných zdrojů
2. Proveďte průzkum a srovnejte technologie řízení decentralizovaných zdrojů používané různými provozovateli (LDS, Agregátoři, Obchodníci s energií).
3. Proveďte průzkum aktuálních standardů komunikace decentralizovaných systémů.
4. Proveďte analýzu dat z pilotní instalace systému provozovaného v distribuční soustavě, navrhněte a ověřte způsob řízení v prostředí Matlab Simulink.

DOPORUČENÁ LITERATURA:

Dle doporučení vedoucího/odborného konzultanta.

Termín zadání: 9.2.2018 ***Termín odevzdání:*** 1.6.2018

Vedoucí práce: Mgr. Magdalena Šedrlová
Konzultant:

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předseda oborové rady

Abstract

We are living in a century when we can barely imagine life without electricity. The needs of controlling, smart-metering and rearrangements of energy market in Europe raised with penetration of small-scaled power plants, which generate electricity from renewable energy sources. At this step, the following question can be raised, how to provide a reliable, safety and sustainable energy supply whilst minimizing costs and environmental pollution. One way is to introduce decentralized energy sources to the grid.

This thesis mostly deals with the concept of decentralized generation and its penetration to the grid, distribution, accumulation and controlling methods. The thesis will also give the reader overview of several energy market participants, such as energy traders, aggregators and local distribution systems.

Key words

Renewable energy sources, distributed generation, decentralized energy sources, DER, local distributed systems, aggregators, energy traders, photovoltaics, wind power, hydro power, biomass.

Anotace

Žijeme ve století, ve kterém jen těžko dovedeme představit život bez elektrické energie. Vznikajicí malé elektrárny, které vyrábějí elektřinu z obnovitelných zdrojů energie vyvolali potřebu v přisnějším řizení, inteligentním měření a změny Evropského trhu s elektřinou. Hlavní otázka spočívá v tom, jak zajistit spolehlivé, bezpečné a udržitelné dodávky energie a současně minimalizovat náklady a znečištění životního prostředí. Jedním ze způsobů je integrace decentralizovaných zdrojů energie do sítě.

Tato práce se zabývá konceptem decentralizované výroby energie, paralelním provozem s distribuční sítí, akumulací a pokročilými způsoby řízení zdrojů. Práce také poskytuje přehled účastníků trhu s energií, jako jsou například obchodníci s elektrickou energií, agregátoři a lokakní distribuční soustavy.

Klíčová slova

Obnovitelné zdroje energie, decentralizované zdroje energie, DER, lokální distribuční soustava, agregátoři, obchodníci s energii, solární energie, větrná energie, vodní energie, biomasa.

Prohlášení

Prohlašuji, že svoji bakalářskou práci na téma Řízení decentralizovaných zdrojů energie a akumulace energie jsem vypracovala samostatně pod vedením konzultanta a vedoucí semestrální práce a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce. Jako autor uvedené bakalářské práce dále prohlašuji, že v souvislosti s vytvořením této bakalářské práce jsem neporušila autorská práva třetích osob, zejména jsem nezasáhla nedovoleným způsobem do cizích autorských práv osobnostních a/nebo majetkových a jsem si plně vědoma následků porušení ustanovení § 11 a následujících zákona č. 121/2000 Sb., o právu autorském, o právech souvisejících s právem autorským a o změně některých zákonů (autorský zákon), ve znění pozdějších předpisů, včetně hmotných trestněprávních důsledků vyplývajících z ustanovení části druhé, hlavy VI. díl 4 Trestního zákoníku č. 40/2009 Sb.

V Brně dne ....

Valeriia Maksimovich

ACKNOWLEDGEMENT

I would like to thank my advisor, Mgr. Magdalena Šedrlová from the Department of Foreign Languages for guiding me throughout the year and for the advices, feedback and valuable remarques.

My thesis would have been impossible without the advises and support of my research advisor Ing. Michal Vrána from the Department of Power Engineering. I would like to thank for your enthusiasm, academic professionalism, patience and for believing in me.

I would like to thank Faculty of Electrical Engineering and Informatics, especially the Department of Foreign Languages for providing valuable academic knowledge.

Last but not the least, I would like to thank my lovely family. In particular, I would like to thank my parents Tatiana and Evgeny Maksimovich and my little sister Zhanna for the love and support.

MAKSIMOVICH, V. *Řízení decentralizovaných zdrojů energie a akumulace energie.* Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, 2018. 42 s. Vedoucí bakalářské práce Mgr. Magdalena Šedrlová, konzultant Ing. Michal Vrána

1 INTRODUCTION

This thesis will give a reader overview of the concept of decentralized energy resources, its types and control technologies as well as main energy market participants. The whole thesis is divided into four main chapters and consists of theoretical and practical parts. As for the theoretical part, in the beginning of the thesis renewable energy sources are introduced. After that, basic concepts of decentralized energy and benefits of the concept are explained. The following chapter explains the concept of the energy market system in Europe, its participants and their role in the market. The second part of the thesis is a practical during which the author analyzed the data from a simulated model of a local distribution system using MATLAB Simulink. The data for the model was provided by the thesis consultant based on a real household installation located in Brno, Czech Republic.

Nowadays, power engineers from all over the world are dealing with the issue of how to provide secure, reliable and efficient power supply, which will be advantageous from the economic, control and environmental point of view for the individual energy consumers as well as large city facilities. That can be achieved by generating electricity in a decentralized way using decentralized energy sources (DERs). The thesis is primarily focused on decentralized energy systems and describes the concept from the technological and legislative framework. Why is it crucial to introduce renewables to the existing power generating systems? One of the answers can be: to decrease emissions of carbon dioxide (CO_2) and other pollutants, therefore providing a reliable and safe future for our planet. This is a critical task for today because the consequences of environmental pollution can change the climate beyond recognition.

In recent years, the way people generate, distribute and consume energy has drastically changed. Along with the increase of the world's population, the demand on electrical energy has also increased. In comparison with the year 1980, when the world's population was almost half as much, our planet is now inhabited by around 7.55 billion people. In fact, from the beginning of the 18^{th} century, it took 123 years to add 1 billion to the global population. Now, from 1987 to 1999 it took only 12 years. [1] Now, every day approximately 350000 newborn children require reliable, safe and sustainable energy supply. Therefore, it is extremely important to introduce reliable energy management and control technologies and strategies.

1.1 Introducing renewable energy sources

Renewable energy sources or renewables (henceforth referred to as RESs), such as: solar energy, wind energy, biomass, hydro energy, etc. – are energy sources that are continuously renewed in a short time period.

People tend to think that using alternative energy sources for generating electricity is a modern concept, but it is not entirely correct. Renewable energy is the oldest source of energy we use. In fact, RESs have been used for thousands of years. Before Industrial Revolution of the 19th century (when the primary source of energy for industry was coal which was used for heating buildings, generating electricity and rotating of steam engines) renewables were used as a primary source for generating energy. For instance, sailors used wind power to drive ships or ancient Greeks used water wheels to grind grain.

Nowadays the use of RESs is increasing daily due to various of benefits that it has and problems that it solves. As of today, 10 % of the total energy production of the world is produced by RESs (Fig.1). In fact, most of the renewables are unstable and weather dependent and due to their fluctuating nature, they require more control.

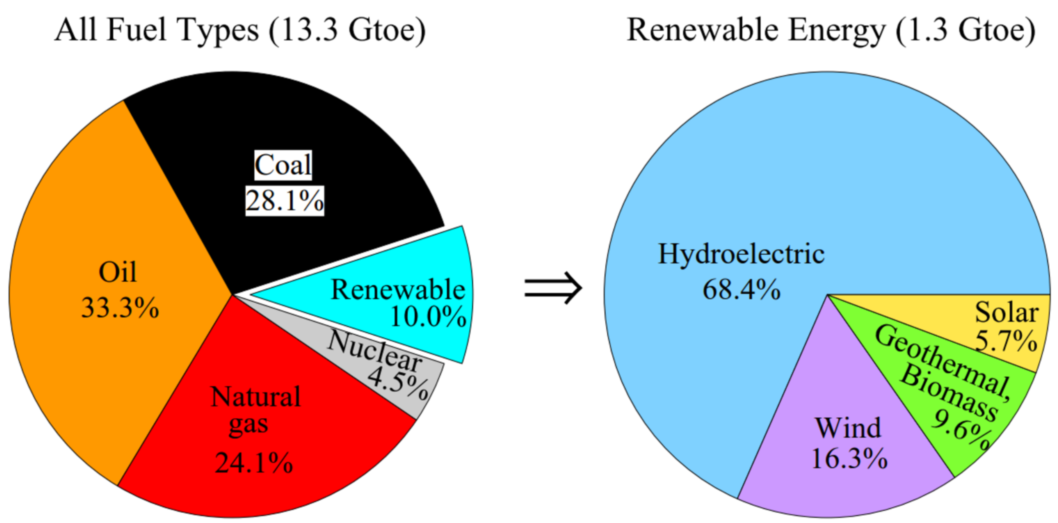

Figure 1 Chart showing global energy consumption in percentage in 2016 (retrieved from www.bp.com)

2 DECENTRALIZED ENERGY

2.1 Definition of Decentralized Energy

World Alliance for Decentralized Energy (WADE) defines Decentralized Energy or Distributed Generation as: *"Electricity production at or near the point of use, irrespective of size, technology or fuel used - both off-grid and on-grid."* [2], which means that DE generates electricity close to the place where it will be utilized. Decentralized energy is a technology which links together small, grid-connected distributed energy sources (DERs), which are located within the electric distribution system near the end user of power, with conventional power plants, which are located far away from the point of use.

2.2 Decentralized Energy vs Centralized Generation

Member countries of the European Union are moving from a highly-centralized to the more decentralized energy systems. These systems include distributed generation, energy accumulation and active involvement of consumers to the energy management through demand response and flexibility.

Generation of energy using the decentralized generation concept is exactly the opposite of generation from conventional power plants, such as large nuclear and fossil fuel power stations and thermal power station, which are centralized. The location of power station is often chosen with regards to variety of economic, environmental, geographic and geological factors, as well as safety and environmental requirements. For example, fossil fuels plants are built away from cities to prevent air pollution. Conventional power stations are usually located far away from the point of use and therefore require reliable transmission means to transfer electricity over long distances at high voltage to deliver it to the consumer.

2.3 Benefits of Decentralized Energy Systems

Decentralized energy solves a variety of problems and offer economically and environmentally beneficial solutions. A natural byproduct of burning any fuel to generate electricity is heat. Besides electrical energy generation, nuclear and thermal power stations also produce significant amount of heat. In comparison with electricity, which can be transported through transmission lines without significant amount of losses, heat cannot be transported over long distances due to large amount of losses, which are increasing with distance. Therefore, the heat generated during the production of electrical energy is dissipated in the environment (lost without applying). As a result, not whole energy potential is used during energy generation. The distributed energy systems (DESs) make it possible to *utilize waste heat* by locating smaller power plants close to where heat is required, using combined heat and power (CHP) technologies. Waste heat can be used to heat buildings as well as for manufacturing processes which require heat, for instance steelmaking.

The second important advantage of DESs is significant reduction of transmission and distribution energy losses due to the location of generators. Table 1 shows the losses which occur during transmission of energy from traditional, centralized power stations. The overall losses between the power station and end customer is in the range from 8 to 15 %.

Table 1. Electrical energy losses during transmission. Taken from: IEC document "Efficient Electrical Energy Transmission and Distribution" (2007) www.schneider-electric.com

%	Place where the losses occurred
1-2%	Step-up transformer from generator to transmission line
2-4%	Transmission line
1-2%	Step-down transformer from transmission line to distribution network
4-6%	Distribution network transformers and cables

DERs also make it possible to use different concepts of generation, accumulation and transmission of energy, such as: Micro grids, Virtual Power Plants or Smart Grids. Regardless of which type of decentralized technology a city uses, it is easier for the customer to *control or generate energy* or even sell the energy back to the grid and vice versa buy electricity from the grid. Moreover, the use of DERs reduce *the impact on the environment* through the use of alternative energy sources.

2.4 Challenges of Decentralized Energy Systems

DESs face different types of barriers, such as technological, economic, social.
According to the European Committee on Industry, Research and Energy (ITRE) [3], the main technological barriers of DESs are:

- need of forecasting since DERs usually have fluctuating nature and due to intermittent and unplanned production,
- security of supply,

- upgrading network infrastructure, adaptation for DESs requirements,
- needs of demand response and flexibility (inviting customers to participate in the energy market),
- need of energy accumulation.

In line with needs of technological upgrades of energy system, there are also the economic issues. In some cases, highly decentralized electricity generation without use of fossil fuels can be more expensive in comparison to large, centralized systems with conventional power plants. Nevertheless, electricity costs depends on the DER technologies and also on the type of the renewable resource. For instance, wind, hydro and geothermal energy are considered to be the most cost-effective.

European Committee on Industry, Research and Energy (ITRE) is also states that people have a lack of relevant and adequate information about DESs, about the economics and technical feasibility of different solutions alike. [3]

2.4 DESs components

DESs comprise small-scale power generation units or storage technologies (typically in the range of 3 kW to 50 MW) located within the electric distribution system at or near the end user. [3] A visual representation of DES is showed on the Figure 2.

According to the European Committee on Industry, Research and Energy (ITRE), [3] DESs involves three main components:

- Distributed generation (DG) – comprises small scale energy generators and CHP units as well as large fossil-fired power plants
- Energy storage units (also known as accumulation units)
- Demand response (DR) – programs aimed to move energy consumption by customers according to the load diagram of the day in order to decrease costs
- Energy management system (EMS)
- Communication technologies between individual DERs

Detailed explanation of the concepts above will be provided in the relevant chapters.

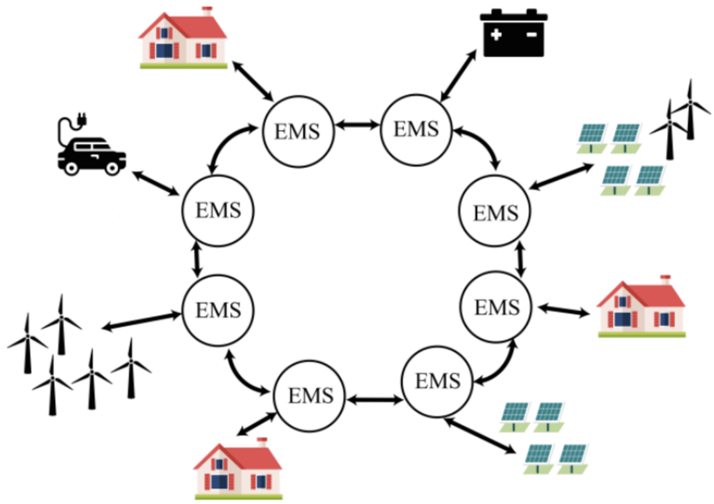

Figure 2. An example of decentralized electricity system (retrieved from the research made by Vrana M. Smugala, Mastny, Moravek „Control of Hybrid Energy Systems and Evaluation of Integration into Virtual Power Plant" Department of Electrical Power Engineering Brno University of Technology).

3 OVERVIEWS OF RENEWABLE DERs

As was mentioned above, decentralized renewable energy sources are located near the point of use. In this chapter, all possible decentralized renewable energy sources which can be used in the Czech Republic will be presented with existing possibilities to perform control. Furthermore, limitations during the control process will be presented in this chapter.

It is crucial to distinguish between decentralized and centralized renewable energy, because if the technology is renewable it does not mean that it is used in DES. An example of conventional centralized renewable energy system can be a large photovoltaic power stations or land based large-scale wind farms. In comparison with that we will consider installations such as local wind turbine located near residential house or office building and roof top wind turbine. The potential DERs are listed below:

- Solar photovoltaic (PV) panels (roof top PV or land based)
- Small wind power systems (roof top wind turbines or land based)
- Small hydro power plants
- Biomass and biogas technology
- Geothermal energy

However, not all DERs can be used in The Czech Republic due to its location, natural resources, insufficient intensity of sunlight, costs factors, etc. The most efficient and effective DERs, which are currently available at the Czechs market are: solar photovoltaic systems, wind power systems, hydro power and biomass firing power plants. In the next chapter the sources listed above will be considered.

3.1 Photovoltaic (PV) panels

Solar power can be converted into another form of energy, such as electrical or thermal energy. Solar thermal power and Photovoltaic are technologies under which the conversion from solar power to useful energy is performed directly. On the other hand, bioenergy and hydropower are indirect manifestations of solar energy.

According to the data from PV barometer [5], in the years from 2015 to 2016 the European leaders in photovoltaic energy production were Germany, Italy, UK, France and Spain. While Germany produced twice as much PV power as Italy, which took second place in PV electricity generation. In the year 2016, Germany produced 41 340.0 MWp, while Italy produced 19 274.1 MWp, the Czech Rep. generated 2 047.4 MWp which takes eighth place in PV electricity generation. Solar power technologies in The Czech Republic are commonly used and available. In fact, the Czech Republic since the year 2008 ranks high in solar power capacity per capita in the EU. PV modules are usually mounted on the roofs or facades of buildings and any surplus energy is sold to the grid. PV systems contain batteries and deliver electricity generated during the day to the property in the evening. PV systems can be installed in remote areas and operated in island mode.

PV works on the principle of direct conversion of photons to electricity. This process is called the photovoltaic effect. The PV cell is mainly made of silicon (Si), the second most abundant element on Earth. Silicon is semiconductor material which is widely used for integrated circuits. 90% of all solar cells today are made of Silicon. The most efficient and the most expensive PV is *monocrystalline silicon solar PV*. These PV cells are mainly made of extremely pure monocrystalline silicon (Si), with a single crystal lattice structure. Other types of PV cells are: *polycrystalline solar cells* and *thin film solar cells.*

From the point of view of connection there are three types of systems: off-grid systems, hybrid systems and grid-connected systems. There are several energy market participants, which require different type of connection. For instance, local distribution systems can be operated in island mode and can be grid connected. One of the main advantages of the hybrid systems is the access to power from the grid (in case of high demand) and the possibility to disconnect and generate electricity in island mode. In grid-connected systems a battery for storing electricity is not required (energy surplus is sold directly to the grid without accumulation).

3.2 Small - scale wind power systems

The EU is one of the leading regions on generation power from wind energy. According to the global wind statistics, in 2017, EU countries generate 169,319 MW from wind installations, which is the second largest annual installed capacity by country after China. [6] Wind energy along with hydro energy are the main renewable energy sources in the EU.

A small wind turbine is a wind turbine used for microgeneration of electrical energy, as opposed to large conventional wind turbines with high power output. Small wind power systems are currently available from many manufacturers and range in size from 1 to 200 kW. Like other renewable technologies, small wind turbines produce clean, ecological power for residential houses or small businesses. In the EU liberalized energy market, under condition of the specific licenses, electrical energy consumers can be an energy market participant and actively take part in energy generation or provide a demand response.

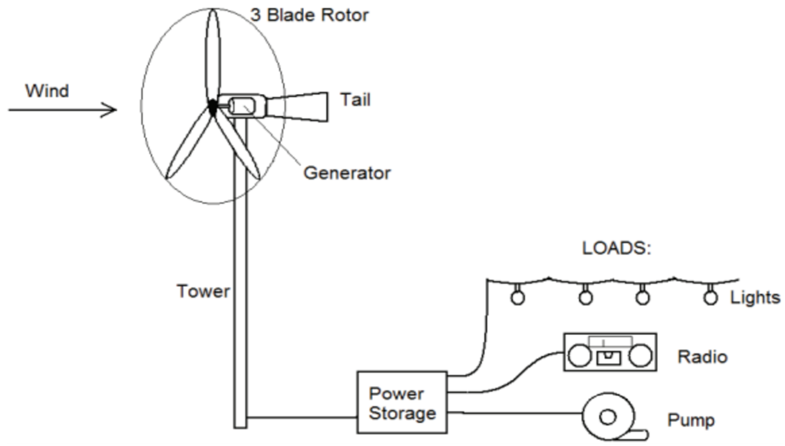

Figure 3. Schematic diagram of a small wind turbine power system (retrieved from www.intechopen.com).

A simple wind turbine consists of three main parts, which are shown in Figure 3: blades, shaft (rotor) and generator. The working principle of a wind turbine is based on rotation of the blades caused by wind. When the blades are moving, mechanical energy causes the rotor to spin. The rotor is attached to the shaft, which also spins. The generator then produces electrical current by transferring from rotational energy to electrical energy. In advanced wind installations there are more components, such as yaw mechanisms, electrical controllers, cooling units, etc.

There are various design solutions of wind turbines. Small and micro wind turbines can be constructed in horizontal axis (HAWT) or vertical axis (VAWT) design. Most small wind systems manufactured today are horizontal wind turbines with two or three blades. However, some vertical axis wind turbines, such as savonius or darrieus types are also used.

We can divide wind power plants according to the connection to the grid. Grid connected wind turbine generators (WTGs) and stand-alone WTGs. Small-scale grid connected WTGs which provide electricity for remote houses, farms and small buildings will now be introduced. As was mentioned before, there is no need for batteries to accumulate energy, because all the generated electricity is fed into the grid. During low demand periods, for example at night, if the wind turbine generates more electrical energy than the household needs, the excess can be sold to the grid.

As far as hybrid wind system are concerned, this arrangement means that the system is connected to the distribution grid but can be disconnected and operated independently. Small hybrid WTGs can be used in smart grids, DES or LDS in combination with other electricity generation units, for instance, a small solar panel. Hybrid systems require more control and participation in operation from other energy market subjects (aggregators, operators, energy traders or other subjects).

3.3 Small hydro power systems

Hydro power plants represent the largest share of renewable energy sources in the EU. Moreover, hydropower accounts for about 20 % of global electricity production which makes it the largest source of renewable energy on earth. [8]

Small-scale hydropower (SSH) is a power plant which generates small amounts of electricity. Usually its capacity varies from 5 to 10 MW (in some countries even less), which can be a good economical source of energy for small communities.

The terms micro-hydro and pico-hydro (see
Table 2) are used for very small generation capacity power plants (up to 100 kW). By using these kind of power plants, it is possible to power small isolated communities.

Table 2 Classification of small-scale hydropower. Adapted from SINGH, D. (2009): Micro Hydro Power Resource Assessment Handbook. New Delhi, India: Renewable Energy Cooperation- Network for the Asia Pacific (RECAP).

Type	Power Output	Applicability
Small	1 – 10MW	Small communities with possibility to supply electricity to regional grid.
Mini	100 kW – 1MW	Small factory or isolated communities.
Micro	5 – 100kW	Small isolated communities.
Pico	<5kW	1 – 2 houses.

Hydro power plants can be installed near buildings with close proximity to the running stream. If the stream has sufficient head and flow rate and it is impossible to build reservoir, the hydro system is operated as *run of river* type of hydro power plant. The turbines blades are rotating directly from a stream. This is a most cost-effective solution of hydro power plant since there is no need to build a reservoir.

Power generation from hydro plant depends upon 2 main factors: head (vertical drop) and water flow. Head is created by the difference in height between the water intake and the turbine. The higher vertical drop is, the more kinetic energy will be produced and converted into electrical energy. All hydro power systems consist of the following components: penstock (channel or pressurized pipeline used to carry delivered water), water turbine (used to convert the kinetic energy into a mechanical energy) and electrical generator (to convert mechanical energy into electricity).

The choice of turbine depends on the flow rate and the head. For the purpose of generating electricity in small amounts, reaction and impulse types of the turbines can be used depending on the stream type. Reaction types require low head and high flow rate and impulse operates at high head. Usually Francis and Kaplan turbines are more suitable in small scale power generation since they do not require large head.

However, in mountainous areas, the water from the high-level stream can be delivered to a Pelton turbine, the water flow can be controlled by a valve. The generated power can be stored for periods of high demand. Fluctuating demand can be backed up by using a load controller or by varying the water supply to the turbine. Micro hydro power plants in combination with solar PV panels can create sustainable system since the speed of the water is higher in spring and autumn when solar irradiation is lower. [9] Stored electricity from micro hydro systems can be also used as a backup in case of failures.

3.4 Biomass and biogas as the energy sources

According to the publication of Czech power company ČEZ biomass is the second largest renewable source in the Czech Republic after hydro power stations. More than 17% of overall green energy is generated by combustion of biomass. Biogas takes third place and generates more than 5% of all energy produced from renewable energy sources. [10]
Biomass has been used in the form of wood for millennia and was the main source of energy before fossil fuels were discovered. Biomass is a diversified energy source, it can produce

electricity, heat transport fuel and also it can be stored. Biomass can be used as a decentralized energy source provided that source of biomass and a conversion plant are in close location with each other. Biomass conversion plants for heat and electricity generation are available in the Czech Rep. in variety of scales, powers and price ranges.
Biomass can be used for heat or electricity generation. Using biomass for electricity generation usually involves burning (or combustion). For the combustion process the efficiency is estimated at 25-35%. Residual energy (65-75%), which is produced in the form of heat, remains unused. This problem can be solved by combined heat and power generation (CHP). The heat generated during the generation of electricity can be used for heating.
The following forms of biomass are mainly used in the Czech Republic: wood waste from forest residues (branches, stumps, wood bark) or industrial residues (sawdust, wood chips, shavings), agriculture wastes (cereal straw, organic or vegetable residuals, manure) and energy crops (wheat, maize, spelt).

To serve an energy demand in distributed generation, biogas can be burned simultaneously with natural gas, which is not a renewable source. Natural gas.org states that this gas *«is one of the leading energy sources for distributed generation. Because of the extensive natural gas supply infrastructure and the environmental benefits of using natural gas»*. [11]
There are many ways in which natural gas and biogas can be used to generate electrical energy. For instance, for combustion of biomass or natural gas in household's small biomass/natural gas-fired combustion engines can be used. They consist of a steam generation unit, usually boiler where gas is burned to heat water and produce steam and then turns a turbine to generate electricity. Another technique for producing electricity from gas is using a small gas turbine where instead of steam, hot gases turn a turbine to generate electricity.
The Czech Rep. have a potential in using biogas, it can be used near farms and where some agricultural processes are carried out, since biogas is produced from raw materials such as agricultural and municipal, green or food wastes, manure or sewage.

Biogas can be produced via various of methods, one of them is the anaerobic digestion process. Anaerobic digestion is a decomposition of organic substances (manure, plants, sludge) in closed tanks without oxygen access. The following types of biomass commonly used for biogas production: livestock excrements (solid or liquid manure), phytomass (silage, parts and roots of plants) wastes arising from agro-food industries (dairies, slaughterhouses, distilleries), specific wastes (meat and bone meal), domestic and urban wastes.

4 CONTROL METHODS OF DERs

Decentralized energy systems with high penetration of non-constant and stochastic DERs require more precise energy control. Generated power control methods that can be implemented to various renewable energy power plants are presented in this chapter. A smart electrical grid have many types of loads and generators (from conventional nuclear or hydro power plants located far away from the load, to small scale wind or PV farms located near a point of use). Generators must be properly controlled to maintain reliable operation of the system.

Crucial factors to be considered in a proper integration of distributed energy resources into a grid include stability, protection, and operational restrictions to ensure stable operation after faults, load changes, and other network disturbances.

4.1 Control of photovoltaic power plants

The main goal of all PV systems operation is to obtain maximum power output. However, there are several factors which can affect power output of cells. Nominal power (output) of photovoltaic systems is strongly depends on several factors: solar irradiation, temperature, the angle of the sunlight, etc. Cell temperature and solar irradiation levels directly affect system power output, high solar irradiation means increased power output. PV cell performance decreases with increasing temperature. The amount of solar irradiation strongly depends on the cloud covering and the location.

In order to guarantee that the PV system constantly operates on its maximum power point, specific electronic circuits known as maximum power point tracking (MPPT) are used to control power output. [12]

The technology called Active Power Control of PV inverters enables regulation of PV frequency and power reference tracking.

In conclusion, it could be stated that it is possible to control PV cells in full-scale but there are restrictive weather conditions (such as cloudy days), which cannot be controlled or changed.

4.3 Wind turbine power control methods

This section explores the control techniques for small wind turbine control systems. Wind turbines are designed in such a way that they can reach maximum output power at wind speeds around 15 m/s. It is not reasonable to design wind turbines which operate at strong wind. Conventional wind turbines are not designed for extreme rotational speeds since high angular velocity might cause structural damages. A wind turbine needs to be controlled to optimize its output. There are several factors that need to be controlled: the rotational speed of a turbine, turbines orientation and the generator's speed. Regulation of power in wind turbines is important to avoid damage in case of strong winds. If wind speed is exceeded the power must be limited, there are many ways to achieve it; the power control systems are able to optimize the power output of a wind system.

Maximum power of small wind turbine is achieved when rotor is pointed directly into the wind flow. The following two techniques are used to control the power in small and micro turbines (up to 1.5 kW). The first solution contains wind vane used to maintain orientation of rotor towards the wind to increase power (see Figure 4 on the right). The second technique comprises control of blades revolutions by yawing the rotor out of the wind in case of maximum wind speed to decrease power (see Figure 4 on the left).

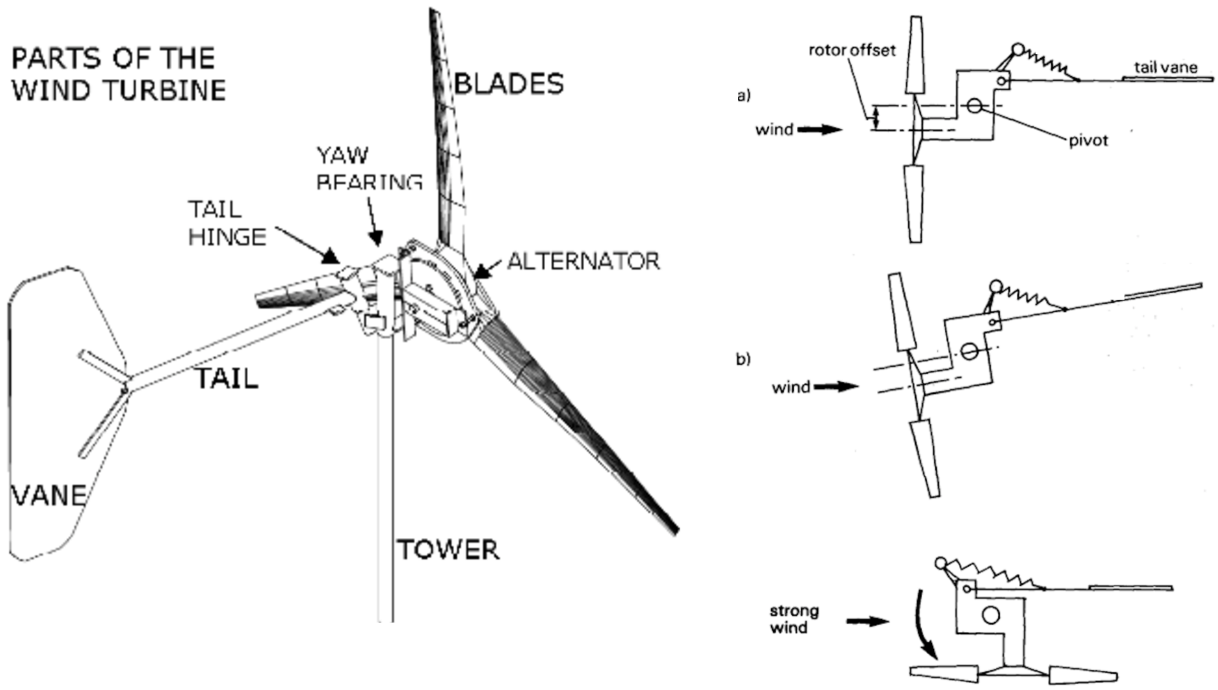

Figure 4. On the right: illustration of parts of a small wind turbine. On the left: a- normal operation, b- low efficiency c- rotor stops when wind reaches max. speed (from www.ve.mzf.cz, www.fao.org).

There are more power output control methods, for example pitch control and stall control methods. Pitch control system is an active form of control where operation is based on monitoring of input power and in a case where overspeed occurs, the system rotates the blades around its axis and therefore changes its aerodynamic efficiency. After a sensor detects the appropriate wind speed, the system again rotates the blades and adjust the power according to the demand.

The stall control system is a passive type of power control, there are no moving parts in the rotor. In this system, the blades do not rotate around its axis, it is fixed to the rotor. Wind turbines are equipped with brakes, which if it is necessary slow down rotation of the blades. When overspeed occurs, turbulence is created at the ends of the blades. As the wind speed increases, the angle of affecting the blades also increases, until it starts to slow down gradually.

4.2 Control of hydro power plants

One of the most challenging issues arising in water turbines due to the inherent fast and stochastic nature of the load is the active power balance and control.
One of the factors we can control in a water turbine is the amount of water that enters the turbine. The flow rate Q can be controlled therefore the output active power can be changed. Digital flow controller (DFC) can be used for the flow rate control. DFC is an automatic controller which can monitor speed, frequency, power and water level. It is also possible to

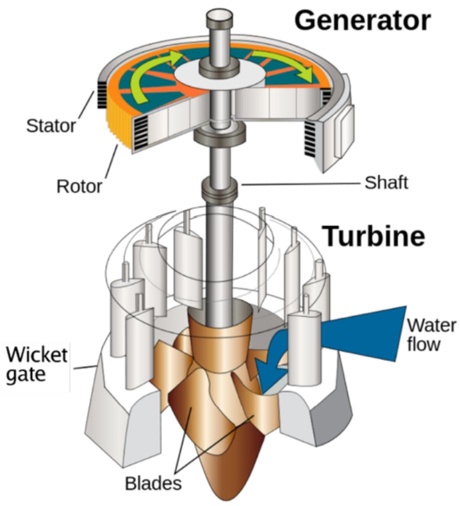

Figure 5. Basic structure of hydroelectric power plant. Adapted from Mastný (2015) «Fundamentals of Energy Processes and Electricity Generation»

control (change) the amount of water entering the turbine by manipulating the wicket gates (see Figure 5)

In run-of-river hydro power plans it is impossible to control the amount of generated power since flow rate is variable throughout the day. The only variable which can be controlled is speed of the water. A more regulatable type of hydro power plant is a reservoir hydro which is commonly used for the purposes of covering peak and half-peak parts of a load diagram.

An operation of pumped storage power plants is based on the principle of having upper and lower reservoirs. The water is moving between them, in productive state it generates power and in consumption state it consumes power. Pumped storage power plants provide energy storage opportunity along with load regulation possibilities as well as peak shaving due to its fast response time.

Hydro power plants can be controlled by an energy management system (EMS). The automatic control of small hydropower plant includes turbine and generator control, voltage and water flow regulation, maintaining the voltage and the frequency of the generator power and monitoring by local stations for multi-plant management.

One of the power control technique is based on using a dump load to control and regulate active power. The dump load is basically an artificial load that reduces the power level by cooling the water in case if there is more energy produced than it is needed for the grid. Using this technique means that part of the energy produced will be lost. To prevent loss of energy it can be stored in an accumulation unit. Accumulated energy will then be used, for example, to accelerate energy supply at the beginning of energy supply cycle.

From the point of view of decentralized generation, pumped hydro power plants are largely utilized for the purposes of balancing supply and demand. [13] Since pumped hydro power plants can generate large amount of power within seconds it has the capability to balance load. This means during the high demand, when PV or wind power plant are not able to generate electricity, pumped storage hydro has accumulated energy and can sell it to the grid.

4.4 Biomass control methods

One of the types of installation for biomass processing which can be implemented in small scale houses is a cogeneration unit, which is used for production of useful heat and for generating electricity simultaneously. Micro cogeneration units are used to generate electricity and heat for residential buildings or small facilities.

Cogeneration boiler control technology is the following: the amount of heat produced can be regulated by controlling intake of oxidizer, usually fresh air into a boiler. If natural gas or biogas for CHP production will be used, those kind of cogeneration units can be controlled by regulation of gas supply.

5 INTRODUCING ENERGY MARKET PARTICIPANTS: LDS, AGGREGATORS, ENERGY TRADERS

Since the Energy Directive (96/92/EC of the European parliament and of the council of 19th of December 1996 concerning common rules for the internal market in electricity) was introduced, the entire European energy market system has changed. Liberalization of the retail electricity market has led to considerable changes in the whole energy system operation. New energy distribution, generation and retailing companies started to appear.

The following chapters explains and describes the main features and working principles of energy market participants, such as: local distribution companies, aggregators and electrical energy traders (licensed electricity retailing companies). In this chapter, and the following sections in this chapter, the term "customer" will be understood any as end-user or consumer of electrical energy, such as households, social and industrial buildings on a small scale.

5.1 LDS - the Local Distribution System

LDS is a locally restricted electrical distribution grid, which is connected to one of the global distribution system (GDS). Nowadays in the Czech Republic there are three GDS companies, which are PRE, ČEZ group and E.ON. The main difference between GDS and LDS is that the latter is not directly connected to the global transmission system, but it is connected to regional transmission system or to another LDS, to which LDS is attached by delivery points. The local distribution system is operated by licensed LDS operators, which can be a person or a company which holds the license on distribution electricity within a defined territory. Licensed LDS operators distribute electricity to the end consumers (small industrial, residential, commercial, medical and educational buildings and facilities) within a defined territory. The LDS operator is also responsible for safe and reliable operation of the LDS. It does so through its technical dispatching and its operational and development services. An LDC is always responsible for maintaining distributions wires, power meters and ensuring that electricity is delivered to infrastructure that the LDS serves.

According to the no. 458/2000 coll., on business conditions and public administration in the energy sectors and on amendment to other laws ("The Energy Act"), *"Business activities in* *the energy sectors in the territory of the Czech Republic may only be pursued by individuals or legal entities on the basis of government authorization in the form of a license granted by the Energy Regulatory Office."* [14] An operator of LDS needs to obtain a license on electricity distribution to be an energy market participant. After obtaining a license, LDS operators should carry out their activities based on §25 of "The Energy Act" about their rights and responsibilities.

It is important to mention the fact that according to ENACO, which is a Czech energy consulting company, it is reasonable to operate LDS in areas where more consumers are connected to the GDS via a single connection point and they share one distribution infrastructure. [15] An example of such infrastructures can be industrial and commercial areas, administrative and apartment complexes, shopping malls, etc.

5.1.1 LDS companies in Brno, Czech Republic

According to the Energy Regulatory Office there are 17 license holders for energy distribution within the territory of Brno, Czech Republic. [16] Based on website research, the author of the thesis found that 5 power companies offer services, which are similar to LDS activities, see Table 3.

Table 3 Distribution energy license holders in Brno, which do LDS activities and are focused on customers.

Company name	Services	Website
KRÁLOVOPOLSKÁ, a.s.	Power distributor (and trader) only within the defined industrial complex territory of the former Královopolská engineering plants.	http://www.kralovopolska.cz/en/products-and-services/power-engineering
ENERGZET, a.s.	Energy trading and distribution	http://www.energzet.cz/distribuce-elektriny/
ERDING, a.s.	Generation and supply of electricity, running distribution networks, i.e. transformer stations and HV distribution systems, including the purchase and sale of electric energy.	http://www.erding.cz/cs/produkty-a-sluzby/energeticke-sluzby/vyroba-distribuce-a-obchod-s-elektrinou/

L.D.ENERGY, s.r.o.	Construction and operation of LDS for residential and industrial areas. Currently operates 20 LDSs in Moravia region in the Czech Rep.	http://www.ldenergy.cz/o-nas.html
KOMTERM Morava, s.r.o.	Generation, distribution and selling electricity to final customers.	http://www.komterm.cz/produkty-a-sluzby

5.1.2 LDS working principle

Power-supply transformer disconnects LDS area from GDS. Power-supply transformer is connected on the side of high voltages while electricity consumers are connected on the side of low voltages.

Electricity from the utility grid is transmitted to the LDC by high-voltage transmission lines and go through a number of transformers. Subsequently LDC provide distribution of electricity to the consumers through distribution wires. At this step, the voltage is stepped down by LDC and low-voltage power is provided to end-consumers. An example of GDS and LDS with SUNSYS PCS² between them is shown on the figure below. SUNSYS PCS² is a power conversion system and storage from 33 kW to MW, offered by the company Socomec. [17]

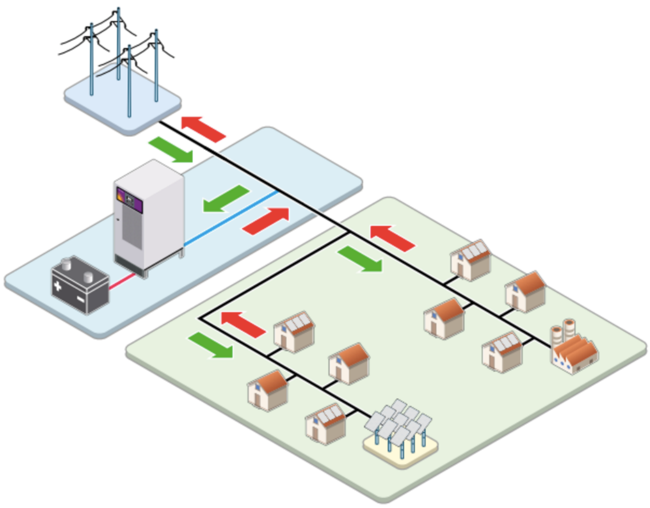

Figure 5 An example of GDS and LDS with SUNSYS PCS² between them. (Taken from: www.socomec.com).

5.1.3 Advantages and drawbacks of LDS

For the end- electricity consumers, LDSs have more advantages than drawbacks. For instance, lower electrical energy costs in comparison to the GDSs due to reducing transmission costs because of high local energy generation. Consumers do not pay more for the electricity in the case that there is no generated electricity in the LDS and the operator needs to buy electricity from the grid of from other generating points.

Another advantage for both consumers and GDS is the possibility to operate both in on-grid and off-grid operational modes. When a system operates in off-grid mode, it means that power failures, blackouts or outages on the utility grid do not affect off-grid systems. The off-grid operation has its own disadvantages such as: storage systems for off-grid are expensive and should be replaced every 10 years and in case there is not sufficient energy production, it is possible to run out of electrical energy, because of that LDS systems usually operates on-grid and use off-grid mode when a local generators produce sufficient amount of energy.

5.2 Aggregators

The aim of this chapter is to describe the concept of operation of only independent aggregators. This chapter will not consider electrical market participants who act as aggregators and at the same time do another activity.

With the rise of renewable electrical energy generation in Europe, it became necessary to develop advanced control technologies to control its stochastic character. Aggregators, in particular, entered the energy market in order to control energy demand in peak times to bring value to consumers and in order to secure energy supply, since renewables are not as flexible as conventional fossil fuel power plants.

5.2.1 Defining aggregators

Aggregators started to appear in Europe after liberalization of retail energy market, but still this concept is relatively new even for the most economically and politically developed countries. Worldwide the role of aggregators is debated. The aim of this chapter is to shed the light on this concept.

Currently there are no official legislations or laws in the EU, which regulate aggregators activities, conditions for licenses, rights, responsibilities, etc. However, there is the so-called „The Winter Package", which is a proposal from the European Commission, whch is comprised of a summary of eight legislative proposals in the field of electrical energy that creates European Energy targets by 2030. The winter package is currently undergoing negotiations across the member states of the European Union. In the case that The Winter Package will be approved by the European legislation and will be properly transposed into national law, it can be expected that completely new entrants will appear in the electricity market (for example aggregators). One of the main goals of the winter package is to reduce CO_2 emissions by 40% by 2030 and to achieve that the share of renewable electricity in electricity generation will be equal to 27%. However, the main objective is the decentralization of electricity generation. [18]

To maximize comprehension, the key terminology related to aggregators activity should be explained. First concept is so-called: "demand response", sometimes also called "peak hours" or "conservation events" all of the above represents one event. Demand response (DR) can be defined as activities or programs made by aggregators aimed to reduce the customers' demand for electricity or to inform consumers about peak times. By DR we understand a change in the consumption of electricity by consumers in response to electricity prices changes during the day or when electricity supply reliability is at risk. Another important term is "flexibility" it is defined as customer's ability to quickly change his consumption.

This thesis adopts a definition of aggregator from the report which studies the role of the aggregators in Finland, *"an aggregator is a company who acts as an intermediary between electricity end-users and DER owners and the power system participants who wish to serve these end-users or exploit the services provided by these DERs."* [19]

In the report made for the Great Britain electricity market, the role of an aggregator is specified as follows: *"Aggregators specialize in coordinating or aggregating demand response from individual consumers."* [20] From two definitions stated above, it can be said that an aggregator is a company which provides demand services through cooperation with end energy users and other energy market participants.

5.2.2 The role of aggregators

In the current liberalized regime, Europe needs energy flexibility due to increasing intermittent renewable energy. Aggregators can be the best solution to provide flexibility. Flexibility can be provided by the following aggregators activities: one of them is collaboration with individual energy consumers (end-users) and aggregation of the demand response (DR) they provide. A second aggregators activity is to work with network operators and providers of flexibility. This is done to provide data about current energy flexibility to the system operator (SO) or to the distribution network operators (DNOs). [20] Aggregators activity does not involve energy supply or distribution. But in some cases, an aggregator can have the license of energy supplier, or aggregator can be at the same time an energy trader, however, the aim of aggregator is to act in the interest of the energy customer and be independent.

Now let us consider the contribution and benefits for energy market participants, which they have from aggregators activity (or equivalently saying from demand response providers, as aggregators are sometimes called). First of all, an aggregator allows consumers to participate in the energy market by informing them about their consumption flexibility value. It is beneficial for consumers to have business relationships with an aggregator to be able to control demand response (their energy consumption). Demand response control can be performed manually, for example in the peak hours when energy prices are high by turning on and off some household's appliances which require manual control, i.e. washing machine, clothes dryer, conditioning system, etc. Control can be also performed automatically using off-peak meters or smart meters.

According to the research report paper written by Ikäheimo [19] the main reason why aggregators started to appear in energy market was to meet two requirements: work with customers demand response, change consumption behavior when it is required and bring data to the wholesale market particularly to distribution companies, energy suppliers, network operators and electricity traders to secure energy supply. The overall purpose is to secure energy supply and allow consumers to reduce expenses on electricity by taking part in energy market.

To be successful in the energy market, the aggregator should be able to find customers which can provide DR and promote and inform customers about the possibilities to operate with their DR. After the aggregator finds customers it needs to install control and measurement equipment and offer rewards for the customers to encourage them to provide demand response. [19]

5.2.3 Aggregators classification

Aggregators can be divided according to the cooperation with different energy market participants. Some aggregators focus on providing DR only to the consumers, whereas others focus on offering services to both consumers and small generators. [20]

Aggregators can also be classified according to their status on energy market and their established relationship with customers (end users). The aggregator can be an independent company which has no "energy" relationships with customer. On the other hand, an existing retail company can act as an aggregator and its advantage will be having a connection to the energy market and its existing customers. The disadvantage of that combination will be, as said in [19], for energy traders being an aggregator it is not a way to produce load response but a way to limit their price risk for them.

5.2.4 Aggregators in Europe and worldwide

Aggregation business is only starting to develop worldwide. Aggregators can be found in the USA, Australia and some of them in the European market. From the table below, it can be stated that there is small amount of companies in Europe who have a license to perform an aggregator's activities. While in the USA, for instance, there is much more aggregators which have entered the energy market.

Table 4 Main existing aggregators worldwide. Based on data taken from research report [19]

Country	**Company name**	**Main activities in aggregation**
UK	Flextricity, Gas de France ESS	Demand and generation aggregation
USA	Comverge, EnerNOC, CPower, Energy Connect, Energy Curtailment Specialists, North America Power Partners	Demand response, energy management services, strategic energy asset management, selling DR to TSOs and utilities
Germany	Evonik New Energies	Decentralized energy supply, generation aggregation to TSOs
Australia and New Zealand	Energy Response	Demand response, selling DR to different types of market and programs
Netherlands	Anode	Balancing responsible party

5.2.5 Future of aggregators

From the legal point of view, the future of aggregators (and other new energy market participants) is highly depending on legislation which will be approved by EU countries based on The Winter Package, which was mentioned in the beginning on the section. From the point of view of contribution to the energy market, aggregator activities can significantly strengthen alternating renewable sources in the energy market, „*complement demand flexibility and decrease the reliance on renewable energy support schemes.*" Aggregators are expected to play an increasingly important role in the future. [21]

5.3 Electricity traders - licensed electricity trading companies

An electricity trader is one of the main electricity market participants among energy generators companies, the transmission system operators, distribution system operators, the market operator and end customers.

According to the act no. 458/2000 coll., on business conditions and public administration in the energy sectors and on amendment to other laws ("The Energy Act"), electricity trader is *"any individual or legal entity buying electricity for resale, such an individual or legal entity being a holder of an electricity trading license."* [14]

From the citation of law stated above it can be said that electricity traders can transmit or distribute purchased energy for resale, depending on the contract. According to the Section 30 1a, b of the act no. 458/2000 coll., Electricity trader can buy electricity in the territory of the Czech Republic and from other countries from electricity generation license holders and electricity trading license holders and sell it to other electricity market participants or to other countries. [14] In the case of unauthorized electricity consumption, an electricity trader is allowed to stop or interrupt supply of electrical energy to end customers.
At the same time, an electricity trader can be holder of several licenses, for instance, electricity trader license and transmission operator license. The same company can be at the same time an electricity generator, a trader or a retailer.

5.3.1 Electricity trader's working principle

Possibility to store electrical energy in large amounts and over the long term is the key aspect which influences the electricity market. Mainly for that reason the energy traders started to appear. The energy market participants are able to operate with electricity by purchasing it from different sources (from other traders, customers, transmission and distribution operators or directly from electricity generators) and by selling electricity to the customers or other energy traders.

Despite of openness of the energy market in Europe, all energy market participants should still work together as a single entity, as the one mechanism. According to The Energy Act, electricity trader should receive data from the electricity market operator, which is necessary for the settlement of electricity supplies to end customers. [14]

5.3.2 Electricity Traders - Advantages and drawbacks

The main disadvantage for the energy trader is the possibility of facing a situation when an energy trader will have at its disposal less power than the actual power consumption. In that situation, the trader faces a deviation that increases expenses.

When the situation of deviation occurs, the trader is still able to eliminate deviation by measurement and optimization. A trader is able to immediately react to deviation and buy or sell electricity on the market. However, there is always a risk for a trader of losing profits by buying expensive electricity.

One of the advantages for electrical energy consumers is the possibility to choose the energy trader according to their needs and requirements. There are various traders in the area of the Czech Republic. According to the data taken from Czech Energy Regulatory Office (ERU), there are 388 certified energy traders in Czech Republic, 34 are currently operating in Brno (as of 31.12.17) [16]

6 DECENTRALIZED SOURCES COMMUNICATION STANDARDS

Communication between individual energy sources of LDS is crucial for proper system operation. Standards and technologies as well as DER interconnection which are currently used for communication will be introduced in this chapter.

Distribution system's operation rules or (PPDS from Czech "Pravidla provozování distribučních soustav") is a main official document in the Czech Republic which establishes requirements for communication process. According to the PPDS, every communication protocol should meet the requirements which are written in the document. However, legislation of the communication infrastructure is not strictly specified, there are only general rules without specific information.

Unlike conventional power grid, LDS communication standards use two-way communication, which involves coordination between the generated and consumed energy. Communication infrastructure help power plants to quickly react on load changing, distributed generation monitoring and control, demand response, control of power generation, monitor, protect and optimize generation, transmission, distribution and consumption.

The whole communication process in LDS is based on three main types of networks: Home Area network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN). HAN is a type of network which is operated within a small area and allows all devices to communicate. All devices which consume energy and perform measurement can be connected to a HAN, such as smart meters, appliances, on-site power generation, From HAN the data can be transmitted to the NAN. NAN is a network which operates in area of hundreds of meters and use Wi-Fi or cellular technologies to transmit data. NAN receive the data from HAN and transmit it to the Local Data Centers (LDC). The last type of network is WAN which consist of several NANs, LDCs, generators, transmission and distribution. WAN works via Ethernet, WiMAX LTE, 3G and micro-wave technologies. [22]

There are global standards on communication, which were accepted by several electrical engineering organization, such as: Institute of Electrical and Electronics Engineers (IEEE) or International Electrotechnical Commission (IEC). The most common standards which can be used for LDC communication is shown in the table below.

Table 5 List of the most frequently used standards and technologies for communication in LDS based on IEEE article research [22] and IEC website [23]

Name of the standard	**Communication technology**
IEC 62351: Security	Cyber security of LDS
IEC 62056: Data exchange for meter reading, tariff and load control	Set of standards for electricity metering and data exchange
IEEE. 802.15.4 Low-Rate Wireless Personal Area Networks (LR-WPANs)	ZigBee
IEEE. 802.16 A Technical Overview of the WirelessMANTM Air Interface for Broadband Wireless Access	WiMAX
IEEE. 802.11 Standard for Information technology - Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications	WLAN

Communication protocols in general are the means which allow to exchange the data electronically via several networking technologies, such as: cable lines, fiber optic cable, cellular, satellite, microwave, WiMAX, power line carrier, broadband over power line, as well as short-range in-home technologies such as WiFi and ZigBee also Ethernet, LTE, PLC, WiMAX. [24]

The newly connected power plants to the distribution network (DN) must allow remote control circuit installation of the communication path between the electricity meter and the power plant.

7 LDS SIMULATION IN MATLAB SIMULINK

Matlab Simulink was chosen from the broad spectrum of simulation software due to various advantages, which it offers. The main advantage of this software is the possibility of quick and intuitive creation of mathematical model. There are default blocks, designed for the power engineering purposes, such as: transmission and distribution networks, in the latest updates Matlab offers a significant number of blocks designed to model the behavior of renewable resources. There is a mathematical model of a wind turbine, a PV panel, a model of an electrochemical energy accumulator and many others.

For the simulation we have chosen the simplified model of small-scaled microgrid offered by MATLAB database, see Figure 6. The original model is based on the American standards. We adjust the model to the European standards. Detailed description of all of the blocks in the model based on MATLAB support documentations is summarized according to the Matlab documentations [25].

All the used blocks are based on phasor simulation method. This method computes voltages and current as phasor. The modulation is based on changes in magnitude and phase of voltages and currents. It is not necessary to solve the differential equations resulting from the interaction between the individual R, L and C elements used in the circuit. The results from simulation based on the phasor solution are generated much faster. This method is enable us to simulate long time intervals for very large systems in relatively short time. For instance, for our system, which consists of a transmission and distribution network models, several consumption points, a renewable source and an accumulation unit, the simulation results for one day are obtained in several minutes.

Energy sources used in the model are the utility grid, roof mounted solar panel generation system and the accumulation unit. There are three loads (residential houses) in the model. The micro system does not depend entirely on the power grid, but has its own generation and storage means.

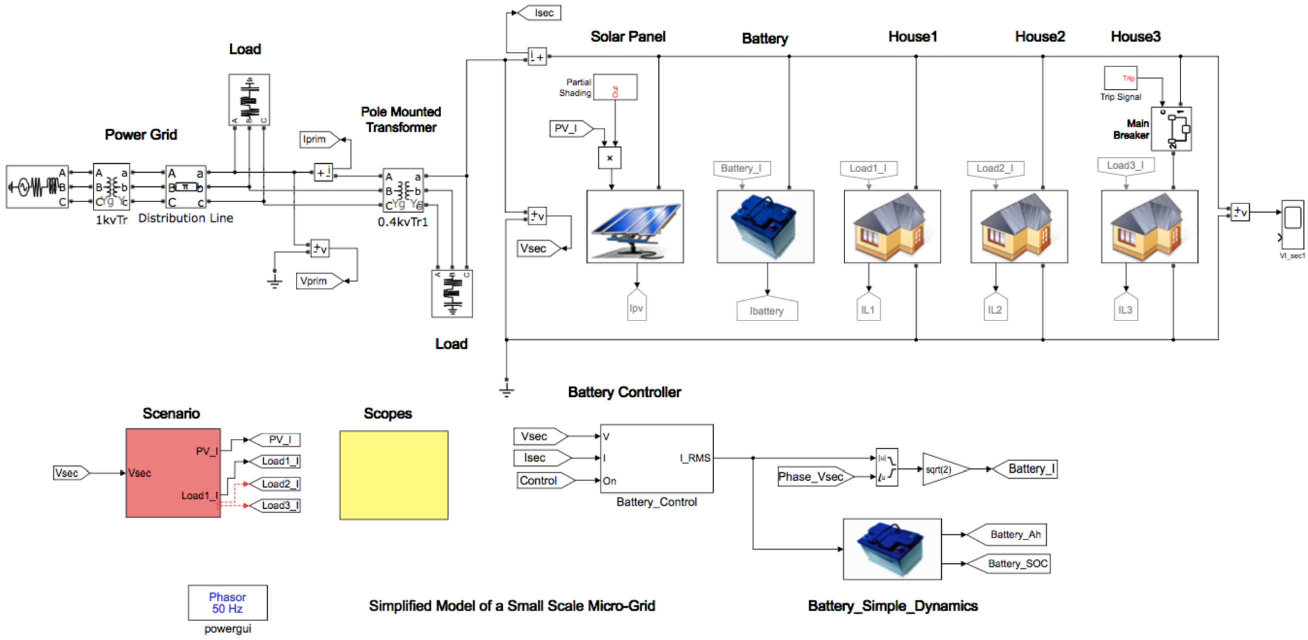

Figure 6. Simplified model of a small-scale microgrid based on the MATLAB Simulink model [26]

7.1 Description of the blocks in the model

First block in the model is the three-phase voltage source, which is operating at 50 Hz (power line frequency EU standards). The *Voltage Source* block simulates transmission network and maintains sinusoidal voltage of the specified magnitude. The transmission network (voltage source) transmits electricity at high voltages of 110 kV, this parameter is called Phase-To-Phase Voltage, which is a voltage between two lines. We can also select the connection type, by default it is selected that voltage source is connected in star to the grounded neutral phase (Yg).

The next block is connected in series with the Voltage Source and it is called *Three-Phase Transformer*. This transformer has two windings and consist of three single-phase transformers. In our case the transformer lowers voltage from 110 kV to 1000 V. In this block we can adjust nominal power and frequency, parameters of windings: phase to phase voltage (V1 and V2), resistance (R1, R2), inductance (L1, L2), types of the windings connections (in our case input winding is connected to the ground (Yg) and output is not grounded (Y)).

The next block is called *Three-Phase PI Section Line block*. It implements three-phase *distribution line* with parameters lumped in a PI section (parameters such as resistance, capacitance and inductance are not uniformly distributed along the lines but lumped in one point). This block simulates parameters of the three phase distribution cables. We can adjust frequency (in our case 50 Hz), positive- and zero-sequence resistances in Ω/km, inductances in H/km and capacitances in F/km. We can also adjust line length in km (in our case it is equal to 1 km).

There is a load going after distribution line block. It was decided that the *Three-Phase Series RLC Load* block will be used. The load should be connected at this point since the LDS is connected only to one phase of transformer (A phase), and other two (B and C) remains free. To create a balance, we connect the load to the two phases of transformer.

There are *current and voltage measurement* blocks which measure primary V and I (primary voltage is the input voltage of the transformer). The Current measurement block measures the instantaneous value of the current flowing through the distribution line. The output signal of the block is a signal that can be used by any Simulink-block. It is possible to specify the format of output signal (in our example it is set on Magnitude Angle, which output is the magnitude and angle of the measured current). The Voltage measurement block measures the instantaneous voltage between two electric nodes. Its output is also possible to select the format of the output signal, in our case it is also set on Magnitude Angle.

The next block is a substation distribution transformer and in MATLAB is called *Three-Phase Transformer*. Distribution transformers can step up or step down the voltage. In our case it steps down the voltage used in the distribution lines to the level used by the customer. In our case it lowers voltage from 1000 V to 400 V (supply voltage in Europe is usually equal to 400 V). We can specify nominal power and frequency and parameters of three windings. The load is connected to the two phases of the transformer's output to create a balance. The V and I measurement blocks are connected to the transformer's output and measures secondary voltage.

The LDS consist of residential houses, PV power station and accumulation unit. It is connected to the power grid via a *substation distribution transformer*.

The LDS contains 3 loads (residential houses), PV panel and an accumulation unit. The main block of the solar panel, battery and houses is the *Controlled Current Source*, which generates electrical current (AC or DC). It is possible to simulate consumption of residential buildings or generation from PV panel or battery. Positive current values represent consumption, while negative values represent generation.

The last block is the *Circuit Breaker* which opens and closes according to the external *Trip Signal* block which simulates fault and its duration.

Battery controller is the name for a bunch of blocks, which modulates the control system which is responsible for activation of charging and discharging cycle. The working principle is based on two input values (voltage and current), which are converted into active and reactive power. Active power is then integrated, which is make it possible to control the battery. *Battery Simple Dynamics* block counts the amount of accumulated energy and state-of-charge. *Scope* block generates graphs depending on time based on the data, such as: PV power, secondary power, load power and battery power. Then the data graphs are shown on a display.

7.2 Input data

The input consumption and generation data for the simulations was obtained from the real systems installed in the South Moravian Region, Czech Republic. From the all measured data, we have chosen a sunny day in early April. Firstly, because the average irradiation intensity in April falling on 1 m^2 corresponds to the annual average level and secondly energy consumption in April is usually not affected by electric heating or cooling.

The model described above was used for the demonstration purposes. Some of the results from the simulation are described and shown on the graphs below. Generation and consumption data was taken from the real installation from 22^{nd} of April.
Initial conditions were the following:

- PV panel installed power is equal to 4 kWp,
- One consumption point (residential building) was used for simulation,
- Battery with capacity of 23 kWh, initial state of charge of the battery was 10 %

7.3 Simulation results

The first graph (see Fig. 7) shows power generation of PV power plant. On the y-axis is active power in Watts, on the x-axis is time in seconds. The simulation starts from 0 s, which corresponds to 12 PM. The graph shows the generated power for one day, we could recognize that the day was cloudy since there are many peaks on the graph, which means that solar irradiation was intermittent.

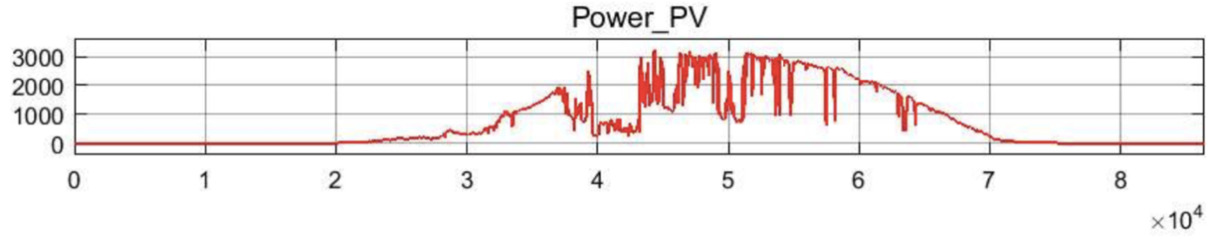

Figure 7. Power generated from PV power plant for one day

The next graph (see Fig. 8) demonstrates consumption and supply of electrical energy to the distribution grid. From 12 PM app. till 3 pm power was consumed from the grid, as can be seen from the fluctuation part of the curve. It was set that the battery was switched off during this time (no accumulation or supplying). Next, it is visible from the curve that app. at 11 AM was the first peak which can represent sudden rise in energy consumption. The energy from battery, PV and from grid was used for covering a sudden energy consumption. The second peak represents sudden rise in generation from PV power plant. The generated energy started to supply the grid.

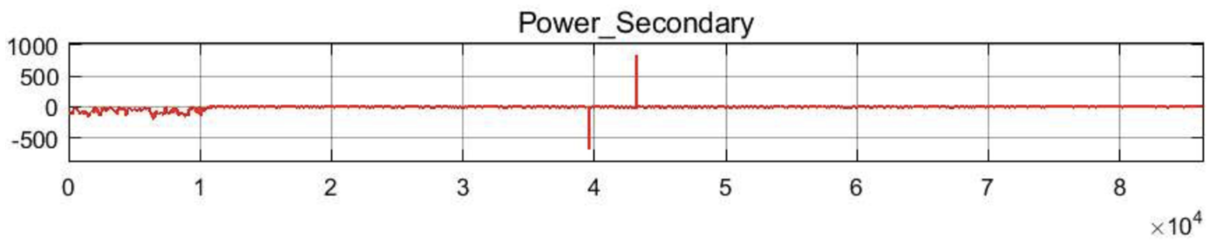

Figure 8. Consumption and supply of electrical energy to the distribution grid.

The power load graph represents residential building power consumption (see Fig. 9). It is visible that app. at 11 AM there was a large energy consumption. After that from 12 AM till 6 PM the energy consumption was higher.

Figure 9. Residential building power consumption.

The next graph demonstrates accumulated and consumed power on battery (see Fig. 10). Positive value means consumption and negative – accumulation. From 12 PM till 3 PM it was switched off. At 11 AM an accumulated energy was used for covering the peak. The rest the of curve represents that power was accumulated or consumed according to consumption and generation.

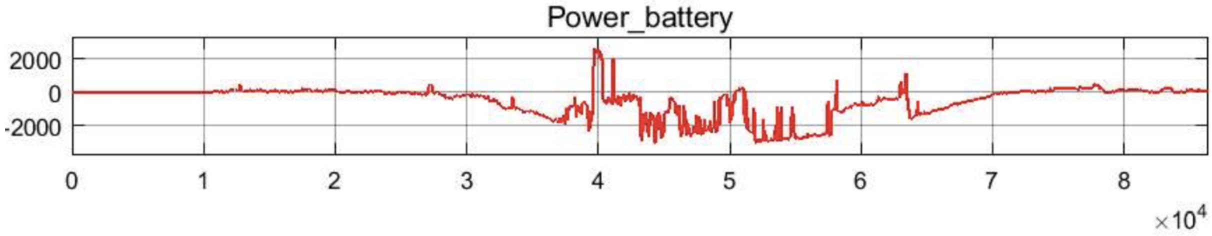

Figure 10. Accumulated and consumed power on battery

The last graph shows us state-of-charge of the battery in percent. (see Fig. 11). In the beginning of the day, the state of charge of the battery was 10 %. At the end of the day if was charged on app. 70 %.

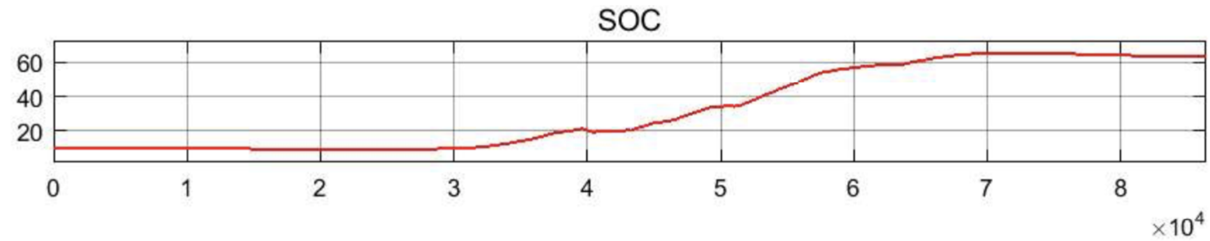

Figure 11. State-of-charge of the battery

The modified model in Simulink can be valuable when designing an accumulation system. Since it is difficult to determine an appropriate storage system capacity in large systems with several generation and consumption points. It is possible to easily change the storage capacity in the model and compare the results of several simulations under the same conditions. The obtained information can be a guide to determining the storage system parameters such as discharge depth and charging / discharging current. For long-term simulations, it is also possible to determine the number of cycles per year.

5 CONCLUSION

The next decade is likely to witness a considerable rise in use of distributed energy sources. Integration of decentralized renewable energy sources into the energy market system require emergence of new energy market participants as well as changes in controlling, transmission and distribution system. Furthermore, fluctuating energy generation (due to stochastic nature of renewable energy) can lead to overloads and grid control problems or can noticeably affects the quality of power supply. This is the reason why decentralized energy sources should be well-controlled either automatically via energy control systems or with human participations via demand response.

The aim of this bachelor's thesis was to examine decentralized energy generation and energy market participants, which started to appear in Europe after high penetration of small- scaled renewable energy power plants. The thesis is divided into four main parts, the first two chapters were focused on renewable energy sources that can be a part of decentralized system and basic control methods were introduced. After that energy market participants, such as energy traders, aggregators and local distribution systems were detailly explained from the operational, legal and economic point of view. The last part was practical and incudes working with the simulation model of local distribution system offered by Matlab Simulink software. The data for the modulation were provided by the thesis consultant based on the real household installation located in South Moravian Region, Czech Republic. The results of simulation showed us that given model can be helpful when selecting the appropriate type of accumulation unit.

6 LIST OF FIGURES

7 LIST OF TABLES

8 LIST OF ABBREVIATIONS

RE - Renewable energy

DER - Decentralized energy resource

DES - Decentralized energy systems

EU - European Union

DR - Demand response

DG - Distributed generation

CHP - Combined heat and power

EMS - Energy management system

RES - Renewable energy sources

DE - Decentralized energy

HAWT - Horizontal axis wind turbine

VAWT - Vertical axis wind turbine

SSH - Small-scale hydropower

MPPT - Maximum power point tracking

CSP - Concentrated solar power

PV - Photovoltaic

DFC - Digital flow controller

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