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Energy management in a microgrid using a multiagent system

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Chapter 1

Introduction

The renewable energy sources developed rapidly over recent years. Production of the energy by many of them is, however, very volatile. This is one reason why the idea of dispersing the sources, within the power grid, is believed to be economically profitable. It is essentially connected with the prosumer concept [34], that is an entity that not only purchases energy, but can also produce and export it to the power grid. With such configuration there appears need for new, efficient, and reliable management systems.

Traditional energy management systems with centralized structure fail to provide well-suited solution to recent distribution generation concepts. This is caused mainly by the traditional system assumption of unidirectional flow of energy, 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 [27]. A microgrid can be treated as an aggregated prosumer, which consumes or produces energy. Prosumer-like networks are 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).

Efficiency of these subnetworks depends mainly on the power balancing systems. As generators are dispersed in the grid, the idea of a decentralized management system arises as a natural solution. Recently, decentralization of decisions in computer networks is realized more and more often by multi-agent systems [28]. This paradigm is also applied in the energy management system considered in this paper. Agents are associated with devices, like power sources, loads, and energy storages. They have their own knowledge and individual goals defined. 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.

The developed multi-agent system aims to balance the differences in short time intervals. Agent-based Power Balancing System for the Microgrids follows the idea given in [20, 21]. The deviations are caused by unpredictable level of dispersed, renewable sources of energy, and by variations of the actual demand.

An auction is a well-suited solution to solve the problem with decentralized, autonomous parties that tend to realize only its 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 Power Balancing System for the Microgrids, the bargaining of the unbalanced energy is performed to minimize differences between actual energy production and consumption. As short reaction time as possible is looked for to suppress imbalance, and to lower the costs borne by devices owner. Thus, a quick auction type has been chosen, viz. the reverse one-side auction. The goal of the paper is to discuss application of this auction algorithm and to present results of its implementation in a simulated microgrid.

Chapter 3

Intelligent distributed system for flexible management

3.1 Introduction

Microgrids consist of a number of small, independent consumers, producers, prosumers and energy storage units. In this situation the normal mechanisms for energy distribution may be not sufficient and not optimal. Energy Management Systems (EMS) are being implemented to manage sources, loads and energy storage devices to balance the power and minimize operational costs of the grid. Thus, EMS ([11]) have much bigger responsibility than Energy Information Systems (EIS) that are oriented only toward monitoring the state of the network, gathering data about devices and storing them for later analysis.

The current approaches to energy management involve shifting loads in time to move consumption of energy toward off-peak hours, and fitting generation to the load. Shifting and scheduling load tasks were described by many researchers, for example in [2, 8, 23, 30]. The idea is to counteract the periodic change of the consumed energy by shifting load as much as possible toward the off-peak periods of the day and night. For example, a computer system can inform about the best time of switching on a washing machine or an air conditioning device, limited by user needs and preferences. When energy storage units are present, an EMS task is also to use the stored energy when the price of the energy is high and charge the units when it is low.

Controllable energy sources, like gas microturbines, are extremely helpful in optimization of the generation side. Controllable generators can be not only switched on or off when necessary, but also make it possible to control the generation in a continuous way.

An architecture of an EMS system may assume centralized planning and managing of the power. This allows in principle for exact optimization of the costs, but participants have to agree to conform to the decisions of the system and also send to the system information about electricity consumption plan and details of the installed facilities. It raises trust problems. Problems may be also caused when grid structure changes quite often and/or when frequent rapid changes of the production and consumption of energy occur in the microgrid.

Decentralized EMS (DEMS) reach, perhaps suboptimal, solutions by negotiating the production\consumption plans of each device in the grid. This type of agreements can be reached by using a market based schemes and multilateral negotiations. Very often an auction algorithm is used for negotiations, as an often used mechanism of distributed decision making.

3.2 Scope of the system

The aim of the paper is to present a DEMS based on the multi-agent paradigm and to test operation of this DEMS in a simulated research and education center. The objective of the system is to optimize the operating costs of electric energy consumed, taking into consideration also its ecological impact. Energy management system is expected to assure constant supply for all devices and maximize the utilization of its own green energy sources as wind turbines and photovoltaic panels. The system performs it by planning and forecasting production and consumption levels, trading energy on the energy market and balancing on-line small variations of the power in the grid. It also considers physical limitations of the microgrid and maintains good power quality factors (voltage deviations) in the process.

The considered research and education center is designed to develop technologies and techniques in the renewable energy area. It consists of five buildings [26, 37]:

- Laboratory of Solar Techniques,

- Laboratory of MicroCHP and Ecological Boilers · Laboratory of Wind Power Engineering,
- Laboratory of Energy Consumption Rationalization,
- Laboratory of Power Industry Safety Engineering (located in two buildings).

The size of the whole complex exceeds 9 000 square meters. It is connected to the external 15/0,4 kV distribution network by a power transformer. The buildings contain conference rooms, laboratories, offices, hotel rooms, social facilities, a restaurant, a coffee corner, etc. It carries out specialized experiments in the area of producing and consuming energy, but also holds conferences, trainings, etc.

Due to its research, educational, conference, and hotel functions the center has a number of facilities that have different profiles of power demand. The complex is equipped with its own power sources, but they cannot fully cover all power needs of the center, particularly during its intensive activity. Thus, the EMS looks for decreasing energy that have to be bought by possible best management of produced energy.

Some of the events can be planned or can be foreseen, for example the dates of the conference, the number of people inhabiting the hotel rooms, etc. An average value of needed energy for these events can be estimated. Knowing an average, typical load profile for a given day of the year and the energy used in the planned events provides us with a better estimation of the expected load. On the other hand, other activities, like using electric kettles or coffee machines, microwaves, charging car batteries or laptops, are hardly predictable. Some of these non-planned events take considerable power, though for a rather short time. But if a number of such cases happen at once, they may create a noticeable change in the power used, as compared to the assumed profile. This requires an energy management system to act and control accordingly the devices in the grid. Actions of the system should be possibly unnoticeable for users and should not limit their activities.

3.3 General architecture

The structure of the simulated system consists of two layers: the physical and the logic ones, consisting of multiple modules, as presented in Fig. 3.1.

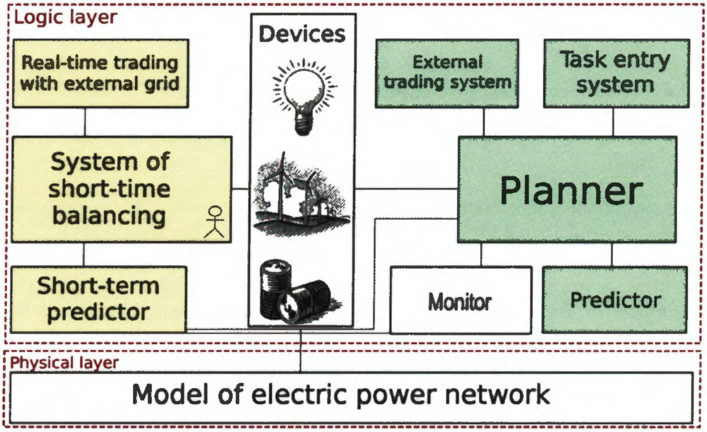

Figure 3.1: Diagram of main components of the system.

The modules contain power flow calculating program, device models (such as a model of the electric grid, models of the physical devices), a short time balancing system, a scheduler for the planned task and a module for trading energy on the external grid market. The whole system is monitored and managed from a single interface.

The basic part of the physical layer is the simulated model of the electric grid, which is responsible for electric energy flow calculation. It can be defined how many load nodes are considered, and what types of the devices are connected to the grid. Also parameters of the devices and their way of working are recorded there. The model computes the power flow in the network and reports any violation of the grid physical constraints. For the simulation purpose, the data to this layer are fed from the Planner module and from the short-time power balancing multi-agent system, which are parts of EMS.

Power Flow Calculator simulates the operation of the electrical network in microgrid and calculates the load flow in the considered microgrid. Program was developed by the team from Warsaw Technical University, led by prof. Parol. Detailed description of the program has been presented in [26] by its authors. The program is an integral part of the simulated system. It includes the electric part and the heat part. It allows for load flow calculations either for the currently considered configuration of the whole internal electric power network or for the electric installations in particular buildings of the microgrid. It has been implemented in the Java programming language.

The electric part of the model includes the data of internal electric network and installation elements; the data on the structure of the electric networks and installations; the data on the considered electric energy sources (the gas microturbine, the reciprocating engine, the photovoltaic panels, the water micro power plant, the wind microturbines); the data on the analyzed electrical energy storages (the battery energy storage, the set of the flywheels); the electric power loads data; the sun and wind generation data, which include the insolation (irradiance) and the wind velocity.

Two different types of sources are specified in the program (model), [26]. Some of the sources can not be controlled (the wind microturbine, the photovoltaic panels). Thus, when carrying out load flow calculations, the program provides appropriate values of the generated active power for them using simulated models of their activities. All other sources are treated as the controlled ones. Then, the user is responsible to define (set) the proper values of the generated active power for them. In our case the powers are set by EMS. Electric energy storages can operate in either the charging (taking energy from the network) or the discharging (turning back energy to the network) mode. Before starting the load flow calculations, it is necessary to define the voltage in the balance (slack) node, the operation points of the electric energy distributed sources and also the operation modes and points of electric energy storages.

The program allows for computations both in the synchronous and the island modes. In the island mode the research and education center network is supplied only by its own sources and does not take energy from the external network of the electricity utility. In this mode, the role of the balancing (slack) node is played by the reciprocating engine. The input data include the branches data, the nodes data, the sources (generators) data. The results of the load flow calculations include the nodes, the branches, and the power balancing. The electric current and voltage violated constraints are written down into a disk file. Some results of a simulated load flow calculations in the synchronous and the island mode of the considered microgrid have been presented in [26, 37].

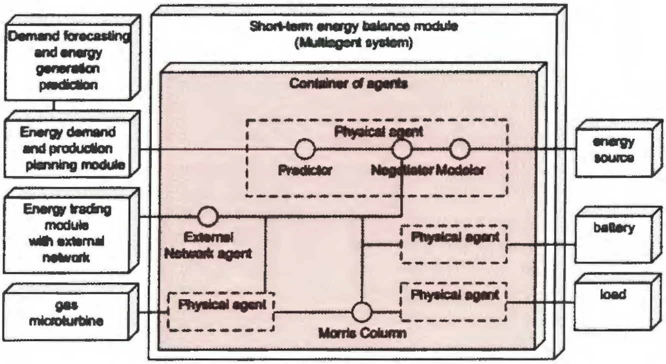

Figure 3.2: An outline of multi-agent system for short-time power balancing.

Events that are planned to happen are characterized by the amount of electric power consumed or produced. These events might be of different types, as for example performing a research laboratory experiment, switching off a device for maintenance, organizing a conference or any other meeting, etc. Also average day load profiles, aggregating all loads that are too small to be inserted separately, are treated as tasks. Examples may be a total power of using kettles, microwaves, lights, charging laptops, etc. The hotel reception system reports the number of hotel guests, which is also used to plan the schedule of giving meals (cooking facilities consume a significant amount of energy, especially during some periods in the day). The event description includes information about its shiftability, and particularly if it is possible to postpone the task for some time and for how long. An important information for the scheduler is also if operation of some devices can be interrupted and restarted during their work.

3.3.1 Models of devices

The models of the devices in the simulated microgrid are divided into three groups: energy sources, energy storage units, energy consumption units (loads). The energy sources comprise [26, 37]:

- Wind turbines – they produce electricity by converting the power of the wind that moves the blades of a windmill. The wind turbine operates within a defined range of wind speeds. The amount of the produced energy depends on the wind speed, the size of the blades and the efficiency of the windmill.

- Photovoltaic panels – they produce electricity by converting the power of the solar radiation to electricity. The power produced depends on the size of the panel (its area), efficiency of the process and intensity of the solar radiation. An important element is also the temperature, as the efficiency of the panel decreases with increase of the temperature. Thus, the same panel usually produces more electricity in early spring than during hot summer days.

- A reciprocating engine – this category includes a combustion engine (a Diesel, a spark-ignition engine) or a gas engine. Although it is not a really ecological friendly power source, in an island mode it is very reliable and may play a role of a balancing node.

- A gas microturbine – the natural gas is considered the most "green" power source acquired out of all fossil fuels. It is also fairly cheap. This solution is even more interesting when the biogas is used. It is assumed here that the gas or the biogas is bought on the market and the accessibility of the fuel is unlimited.

- A hydropower plant – the center is placed near a small river with a small hydropower plant constructed on it. Its production abilities depend on accumulation of water in the water reservoir. In wet seasons the hydropower plant can work with its maximal power, but in situation of a drought the water supply has to be carefully controlled.

To make the power balancing easier, energy storage units are considered, as follows [26, 37]:

- Batteries – gel accumulators have efficiency of about 88%, but the charging and discharging power is limited. Batteries are suitable for keeping power for a long time, can be charged and discharged frequently and the density of the stored energy is high.

- Flywheels their efficiency is very high, reaching 93,5%. The electric energy is transformed to the kinetic energy of the flywheel that can turn with the speed up to 60 000 rpm. This is a very fast reacting device that can even survive short-time overcharge (up to 150% for 1 minute). Flywheel cannot keep energy for a very long time, which makes it unsuitable for using in the same way as batteries. That is why flywheel is considered as the device that is automatically balancing the power and just reports the covered imbalance to the system.

Along with the sources and storage units of energy, the third group of the active elements in the center are consumers of electricity, such as refrigerators, computers, lights, air conditioner, special devices for experiments, etc. Considering every single device or socket in the building as a separate power consuming device would be unpractical, because it would require equipping each device with an energy meter or even a power electronic converter. Such technology is available, but it would be exceptionally expensive to install it in all small devices. In this simulation, it is assumed that the power is measured in nodes of the electric installation which gather several consuming units, for example sockets in few rooms, or the chain of corridor lights.

All receiving points have day load profiles assigned. In the project 26 of such load profiles were defined, for example external lighting, air conditioning, heat pomp power supply, preparation of the food. They are used for general testing of the parts of the system, to achieve high quality of testing the consumption simulator was developed, it is described in section 4.3.

All of the loads are divided into two groups: the ones that have to be powered in any conditions and the ones that can be switched off under power deficit. If the connection to the external grid is cut, the center switches to the island mode. Then the reciprocating engine is switched on and less important circuits are disabled, to keep the core of the electrical system in operation. When the connection to the external grid is restored, the system automatically returns to the normal (synchronous) operation mode.

3.3.2 Planner

The Planner module analizes the list of submitted tasks and suggests better time for realizing them taking into account limitations defined by the user. Some tasks require negotiations before the execution time has been fixed. For example, when a conference is planned, the system checks if the suggested dates do not collide with other events, in terms of resources used, or with some energy-consuming experiment, and may suggest postponing it for few days. The Planner takes into account the expected load provided by the Predictor on the basis of historical data, the profiles of usual power production and consumption, the prices and availability of electric energy, and evaluates the cost to realize the task at the proposed time. The Planner constructs a schedule using heuristic algorithms, which allow for a compromise to be made. The schedule is only suboptimal but it guarantees to provide a result within a specified time. The schedules are repeated in half an hour time. The schedule includes not only the list of tasks that are executed at certain time point, but also the operating level of all controllable devices in the system. Having such information, it is possible to compute the total surplus or deficit of power in every time period by comparing the planned consumption of power to the expected amount of production.

The total inner production of energy cannot be known exactly because of, to some extend random production by renewable energy sources, as wind turbines and photovoltaic panels. To balance the power in the center, the energy bought from the external network is used. It is assumed that the external network can send unlimited power[1]. Trading with external network is realized by the user, supported by the External Trading module, that knows the load profiles and the schedule. The module prepares required amounts and times of delivery of electric energy and suggests deals. Better energy prices are possible to be negotiated on the electric energy market, if the amount and time of buying the deficit energy is known in advance. Advanced planning of the lacking energy helps in diminishing the cost of its buying. If the connection to the external system is deactivated, the center system switches to the island mode, and all plans are invalidated.

The Planner operates in a long time scale, usually few days ahead of the planned events, although it updates the plans every half an our, if necessary. It considers historical data from a number of previous years and daily con-

[1]The power is actually limited by the transmission ability of the transformer. It is, however, assumed that this limit is never achieved.

sumed and produced energy, gathers information about the events that may last from a part of an hour to days (such as conferences or experiments).

3.3.3 Short-time Power Balancing System

Organization of the system

Agent is an abstraction of a unit that has certain amount of independence and distinguishes itself from the environment. As was mentioned before, multi-agent technology is very suitable for modeling electricity-connected issues, as was widely described in [18] and [19].

A concept of an agent is used in this project to describe the participant in the microgrid, that is the energy producer or the energy consumer. It is also applied to programmable agents, that are autonomously working programs.

The planning system can schedule certain tasks and predict the average load level, but it is impossible and not welcome to schedule small human activities as making coffee or using microwaves. Renewable energy sources like wind turbines and photovoltaic panels depend not only on general weather conditions but also on local meteorological situation of the wind gusts and on cloudiness of the sky in the area.

These small variabilities are impossible to avoid and the EMS has to cope with them. This is the task of the Agent-based Power Balancing System that reacts within a second to unexpected changes in power demand or power generation. The events in the system are not synchronized, so the power demand and generation fluctuate. However, it is necessary to wait with measuring the values of these changes until the established state has been reached. The minimal frequency of measuring the power for some of the devices (as for example the wind turbine) is one minute.

As mentioned earlier, all devices were divided to three groups: controllable, uncontrollable and energy storages. Controllable devices are the ones that can adjust their operating points to produce a determined power at the time, or consume certain power at the time. Such devices are, for example, a reciprocating engine, a gas microturbine, an intelligent fridge, an air conditioner, a battery energy storage, a flywheel, etc. Devices like wind turbines, computers, light bulbs are impossible to control, so, from the point of view of the system, they are uncontrollable devices. Battery energy storages can be set either to the charge or the discharge mode, so they are controllable devices, but they have been also designed with a mechanism, that at some point changes their operating mode to charging, to avoid the deep discharge state.

An outline of the power balancing system is presented in Fig. 3.2. The agent associated with a device (the physical agent) consists of up to three blocks that have different functions in the system. The Predictor anticipates the operating point of the device. For this, it needs sometimes forecasts of weather conditions, like in the renewable energy sources case. For other devices, the Predictor is much more simplified, or not needed at all. The Modeler analyses the situation of the device; detects changes of the operating point, checks its regulatory capabilities, determines the cost of producing the energy, sends the appropriate data to the Negotiator for starting the trading process, and orders a controllable device to change the operating point as a result of the trading. The Negotiator deals with other agents to compensate a detected change in the produced or consumed power in order to secure the balance of the power in the grid. The blocks of the physical agents were designed to simplify the computing within an agent and make it simpler to program for parallel computations. Their implementation differs depending on whether an agent represents controllable (a 'passive' one) or uncontrollable (an 'active' one) device. Passive devices are the ones that represent controllable sources. Other devices are active, with exception of the battery energy storage that is represented by two agents: the passive one (that responds to the balancing request) and the active one (that is actively trying to maintain the state of charge on the safe level).

An important feature of the system is that the need for balancing is recognized by the device itself. It is the device that sends information about change in consumed or produced power. The modeler agent decides if the consumed or produced by the device power is constant. If it is not, the modeler detects the imbalance and takes an appropriate action. It sends a request to the Negotiator to arrange a deal. The Negotiator checks with whom he can communicate to find the compensating power, then it starts conversations by asking for available regulation capabilities. When the deal is set, the controllable sources adjust their operating point to reach the state of balance. There is no central planning and agents are unaware of the whole amount of energy in the system or the value of the total imbalance. Buying the energy from the external grid has the same mechanism as balancing with any other agent, the difference is in the price of energy. The price is set on the external market and may depend on the already made deals.

The communication protocols between the agents has been presented in [24].

Types of agents

Six main agent roles are designed and implemented in the Agent-based Power Balancing module:

- active and passive **predictors** that anticipate the device power demand or power production, taking into account the meteorological condition forecast, if necessary;
- **modelers** that communicate with the device to receive its current state and with the predictor to learn its anticipated value to prepare a decision of trading/no trading, which is sent to the negotiator; it also updates the operating point of the device when appropriate;
- active and passive **negotiators** that negotiate the delivery or dispatch of the energy;
- **Morris Column** agents, whose goal is to provide public repository, where agents are able to report information about their regulation abilities, as well as seek for it;
- the **external trading agent** which trades with the external grid; it actually consists of two agents, one that is responsible for drawing energy from the external grid in case of deficit and another one that is responsible for transmitting energy to the network in case of its overproduction in the research center; two agents are used to reflect the difference in prices for 1 kW of power between sending and receiving the energy;
- the **monitor** agent, whose goal is to monitor the state of the network and particular agents, detect unexpected imbalance couditions, unnoticed by other agents, and start actions in order to have them corrected;

Auction algorithm for energy balancing

The deals are made by sending balancing offers from the active to the passive agents of the devices. This is done to limit the number of messages sent in the system. When taking decisions on the choice of the compensating device, the agents consider the cost of balancing provided by the active agents. The negotiation method is a one-side, sealed bid auction. Traded commodity is a change in the amount of electric power, that device generates or consumes, expressed in kW.

Two kinds of costs are defined, one for 'balancing up' and another for 'balancing down'. The cost of 'balancing up' is used when the device has to compensate increased consumption of the energy. The balancing down is used in situation when the device reacts to decrease in the energy consumed or to increase of the energy produced in the system. For some devices these costs are equal, while for another differ.

The object of the auction is the actual or predicted lack or excess of energy. Note, however, that time cannot be neglected in negotiations. Each imbalance is characterized by its size, and by the moment of time, when the imbalance is detected or predicted. Thus, the multi-commodity auction is performed, where the main focus is placed on the real-time auctions, with different times of realization.

The market entities structure is simple, as the particular devices correspond to particular negotiating agents. To obtain the list of possible bidders, an auctioneer queries a Morris Column agent about devices, whose regulation capabilities can satisfy the lack or excess of energy.

The main negotiation process begins, when an agent (the active modeler agent) detects imbalance due to the change of energy supplied or consumed by its device, either actual or predicted. Note, that each new negotiation process runs concurrently to the already existing ones. Moreover, particular negotiation processes are isolated. Each imbalance causes an appropriate auction algorithm execution, whose goal is to eliminate, or at least minimize the imbalance. It is of advantage if the auction process is immediate, to get fast imbalance reduction. Multiple instances of negotiation take place at the same time, so it is important to ensure that every individual negotiation is processed reliably, without interfering each other. Thus, to act swiftly, simple auction algorithms are advisable. The negotiation technique described in this paper is chosen to be an one-side, reverse, sealed bid auction (the tender). An auctioneer can sell the excess of energy, or purchase it when it is lacking. Each active negotiator can initiate the auction, thus there exits no single, centralized entity that supervises it. Actually, ad-hoc auctions are executed, operated by the active negotiators.

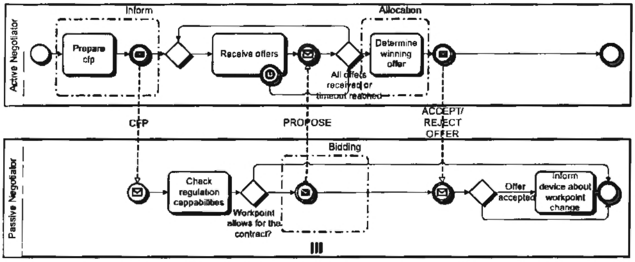

Figure 3.3: Single auction process presented on the BPMN collaboration diagram.

In Fig. 3.3 a single auction process is presented. BPMN 2.0 notation [4] is used due to its convenience and transparency. It provides not only the flow of communicates, as in the UML or AUML [5], but also the inner processes of particular agents and their decisions, associated with sending or receiving respective communicates. The active negotiator initializes an auction by sending the Call For Proposal (CFP) communicate to the passive negotiators that have been preselected as suitable entities for imbalance reduction. The active negotiator, which initiated the auction, waits for the offers for a specified time (e.g. 100 ms). For a passive negotiator, the auction process begins at the moment of obtaining the CFP message. In this way we model the situation, where each new CFP communicate received causes a new concurrent auction process. The passive negotiator checks, if its actual operation point and its production bounds allow for imbalance reduction. If the imbalance is positive, i.e. the device represented by the auctioneer produces energy in excess, the device willing to use the energy should increase its use by the imbalance value (to the accuracy of grid losses). Similarly, it the imbalance is negative, i.e. it causes the lack of energy, the device willing to close the energy gap should produce more or consume less. Note, that the devices reducing the imbalance need not be only generators, but may be also energy storages or controllable loads (e.g. smart refrigerator, smart car, or smart washing machine, which are able to control the demand).

If an agent determines that it is able to deal with the imbalance, it submits an offer (in the PROPOSE communicate) to the active negotiator, and waits for an answer. When the active negotiator collects all offers, or if the timeout is reached, it switches to the allocation phase, in which it decides which offer to choose. The decision is based on the allocation rule. In the system, the allocation rule is the sealed-bid auction allocation rule, that is the most profitable offer is chosen. When no offer is submitted, it means that the active negotiators cannot deal with the imbalance. However, if the exchange with an active external power grid is possible, such situation cannot occur, as the external grid agent should always respond to the propositions. When the offers are allocated, and the 'winning one' is chosen, the active negotiator sends to each of the session passive negotiators either the communicate ACCEPT_PROPOSAL when the agent has submitted winning offer, or REJECT_PROPOSAL otherwise. When the passive negotiator obtains ACCEPT_PROPOSAL message, it informs its modeler agent and device agent to change the working point. At the same time, the active negotiator informs its device modeler agent on satisfying the demand, in order to actualize its saved working point.

Note, that every negotiator (passive or active) can take part in multiple auction processes simultaneously. Active negotiator can participate in both actual, and predicted imbalance reduction processes at the same time. Passive negotiator in turn, tries to manage its regulatory capabilities and avoid the situation, when it promises to cumulate an unacceptable amount of energy in the concurrent auction processes. Nevertheless, if such a situation happens, it starts a new auction process to close a gap.

The auction process presented above is very similar to the FIPA Contract Net Protocol (FIPA, 2012). However, as it was pointed above, the BPMN notation makes it possible to analyse the inner processes and message flows.

Costs

Some of the devices, like reciprocating engine, have fixed costs. The costs of others depend on the operating point of the device, as for example on the state of charge of the battery energy storage or the amount of water in the reservoir.

The cost of the water turbine actually does not depend on the amount of water used. However, it is modeled artificially as depending on the state of filling the reservoir, to avoid an excessive decrease of the water in the reservoir.

The costs of the battery energy storage unit and the flywheels depend on the state of their charge. The preferred state of the battery is the state of half charge. It gives the equal possibility of charging and discharging. The battery energy storage unit does not allow the total discharge or overcharge. In this case the device stops offering services in one direction. This happens when the state of charge is below 10% or over 90%.

Chapter 6

Conclusion

Impressive changes in electricity grid structures have been initiated by the emergence of new technologies, the new regulations to fight against the global warming, increasing demand for the secure supply of energy and rising prices of electricity. These changes gravitate toward development of renewable energy sources, prosumers and microgrids. Recent research results indicate that it is possible to create an energy self-sufficient community, that can be even selling surpluses of energy. The energy produced by renewable sources is, however, volatile, as it depends on changing meteorological conditions. Also the consumption of the energy in microgrids is proportionally much more volatile than in bigger grids. The problems caused by uncertain production and consumption can be overcome by using the computer based Energy Management Systems.

In this work, a modular distributed EMS is presented. The novelty of the solution presented is first of all in the complex treatment of the problem. It includes two modules dealing with balancing the power produced and consumed in the microgrid. One module solves in advance the task scheduling problem, in order to find a suboptimal way of shifting the loads to be possibly covered by the energy produced within the microgrid. The second module balances the power in the real time by activating both the generation and the load side of the microgrid. For this, it uses the multi-agent technology. Thus, both production and consumption of the energy in the grid self-adapt to the changing energy needs and supply. The reaction of the real-time system is accelerated by using short time forecasts of generation and demand of energy.

The main aim of the system is to optimize (generalized) costs of exploiting the electric energy in a Research and Education Center, which is simulated with a considerable high accuracy to allow for testing the EMS operation. As compared to the simple reduction of the energy bought, caused by straight exploitation of the renewable energy sources, application of the EMS provides savings due to making long-term deals with external power grid, which is cheaper in comparison to trading on the balancing (spot) market, and then possibly precisely following the contracted power trajectory, in spite of disturbances resulted from randomness in generation and demand of energy. In all decision making stages soft suboptimal algorithms are applied, as metaheuristic or multi-agent ones.

Although a Research and Educational Center is considered in the paper, the elaborated system and methodology is of a general character. Many solutions are opened and can be easily redefined. So, it can be applied as well for other grids.

To test the system the insolation, wind speed, water level and consumption simulators had to be designed and implemented. For weather data some specific requirements had to be met: data had to be adequate to the location of the microgrid and had to be calculated fast for long time (more than a year). For this purpose the Matched-Block Bootstrap was used. It is a fairly simple and fast method that generates data that have satisfying statistical properties.

Simulating power consumption proved to be more complex and much less researched problem than weather simulation. The most common method of describing the consumption are 24-hour or longer profiles, which is not enough for system that should balance continuous changes in power levels. Consumption simulator offers different, adjusted to the type of a device, ways of describing the behavior: profiles, probability profiles, rules and combination of rules with short profiles.

There are many aspects that were not yet studied in this work, like short term predictions, trading with external network, demand side management, island mode operation and many others. These are very interesting aspects of smart grids and very important ones. Up to now the research were blocked by lack of testing equipment and inaccessibility to existing smart grid installations.

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