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Balancing electric power in a microgrid via programmable agents auctions[*]

by
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Abstract: The paper presents an application of an auction algorithm in a multi-agent computer system for managing the unbalanced energy in a microgrid. The main goal of the system is to control and minimize the deviations of the current energy demand from the actual energy production, using an auction algorithm. Distributed generation is assumed in the microgrid, with renewable power sources. The energy storages and the controllable power sources improve the system operation. The differences between the actual demand and produced energy are caused by unpredictable level of electric power generation by uncontrolled sources, like wind turbines or solar panels, and/or randomness of power utilization. The system will tend to balance out these differences on-line in short time intervals (less than one minute) to follow-up varying levels of local power generation and loads.

Keywords: multi-agent system, micro-grid management, short-term imbalance reduction

1. Introduction

The renewable energy sources develop rapidly over recent years. Production of energy by many of them is, however, very volatile. This is one reason why the idea of dispersing the sources, mainly renewable ones, within the power grid is believed to be economically profitable. It is essentially connected with the prosumer concept (Vogt, 2010), 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 the 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

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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, a need for a new management systems appears (Ramchurn et al., 2012). 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 (Rogers et al., 2012). 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 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 energy. This forms a distributed energy management system.

Control and minimization of the deviations of the current energy demand from the long-time plan is one of main issues of the here presented Agent-based Power Balancing System for the Microgrids, which follows the idea given in Nahorski et al. (2011). The developed multi-agent system aims to balance out the differences in short time intervals. The deviations are caused by unpredictable level of dispersed, renewable sources of energy, and by variations in the actual demand.

An auction is a well-suited solution to solve the problem with decentralized, autonomous parties that tend to realize only their own goals. As in the actual trading, particular entities can reach sub-optimal allocation of goods in a competitive environment, even without the assumption of 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. The possibly short reaction time is sought to suppress imbalance and to lower the costs borne by device 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.

2. Related work

Power grids are on the brink of revolution: the current infrastructure becomes insufficient, there are strong incentives to close highly emitting coal power plants and the prices of energy are increasing. This trend is well known and has been forecasted for many years. Marnay and Venkataramanan (2006) present the history of development of electrical grid in US and define reasons why the connected, centralized power macrogrids might become insufficient in the future. They point out the inability to keep up with the increasing demand of modernisation and expansion of the grid, the problems of centralized planning, the inefficiency of the energy market and the reliability issues (like system failures and vulnerability to terrorist attacks). On the other hand there are benefits from introducing microgrids and microsources to the existing infrastructure. The main ones are: gains from using combined heat and power (CHP) plants, the ability of small sources to cope with heterogeneous power quality and reliability (PQR), and the easiness to adopt new technologies by small prosumers. Benefits of microgrids and distributed micro networks are also discussed in Borbely-Bartis and Awerbuch (2003).

However, as pointed out for example in Vogt et al. (2010), due to dynamic generation and demand of electric power and need to obtain the power balance, the prosumer power grids require application of more complex control systems than simple regulation used at present.

Management of power distribution in grids develops rapidly. The recent concept of supplying the loads in the distribution grids differs from the previously used structures, in which the distribution grid is supplied from the high voltage power grid. In the previous structures flow of energy is unidirectional, from the sources to the loads that are located in the leaves of the power grid tree structure. Dispersed power generation causes the flows to become bidirectional. There appears a concept of energy subnets, in which energy is both produced and consumed. Thus, the new concept of smart-grids, that are subgrids with bidirectional power and information flows, is currently being considered.

For majority of power generators existing in the subgrids, like wind turbines or solar panels, the level of produced power depends strongly on meteorological conditions. They have no automatic mechanisms to self-adapt energy level production to existing demand, such as are used in large power stations. Thus, the level of energy produced in dispersed generation microgrids is to a large extent random. Moreover, due to relatively small number of loads and generators in a microgrid, there is no so strong averaging as in large grids, and the energy consumption is characterized by high volatility. This fact significantly hinders forecasting of demand for power consumption. Both these factors put considerable requirements on the management system to balance power flows in prosumer sub-grids.

This is particularly acute in the island operating mode. But also prosumer grids connected to a distribution network gain from power balancing. The reason is that the prosumer grid operator loses on two-way trading of energy with the distribution network operator. He/she pays more for the delivered energy than gains from that sold out.

In order to manage power in small grids, it is often necessary to apply energy management systems (EMS). These systems often comprise control subsystems, oriented on optimization of the grid operating costs, cooperation with the distribution grid operator, and securing reliability of energy supply. Other goals of these systems can be load balancing, load reduction, acquiring additional supply of the energy in the peak, or increasing the load during the off-peak periods (Abbey and Joos, 2005; Palma-Behnke et al., 2011; Tsikalakis and Hatziargyriou, 2011; Westermann and John, 2007).

Particularly interesting are EMS systems designed for distributed energy management (Ramchurn et al., 2012; Rogers et al., 2012). The approach of treating consumers and producers as agents is gaining popularity. McArthur et al. (2007a, 2007b) present the advantages of using multiagent approach for power engineering, and propose a systematization of notions related to multi-agent systems applications in the energy following earlier propositions of simple EMS presented in previously published papers (Abbey and Joos, 2005; Lagorse et al., 2009; Ricalde et al., 2011). It is also suggested (Vogt et al., 2010) that the multi-agent systems may be a promising solution of this problem. Other publications, like Kwak et al. (2012) and Schaerf et al. (1995), propose to use agent systems in load control, either to balance lack of sufficient energy supply or to save the use of energy. The paper by Ricalde et al. (2011) describes a concept of a multi-agent system application for a public facility, powered from the distribution grid, with installed distributed generators. The system comprises agents representing dispersed generators, storages, and loads of the energy. The goal of the system is to ensure power balance, and minimization of the cost of the purchased energy from the distribution grid. Lagorse et al. (2009) provide more details of the multi-agent system structure. The agents apply fuzzy logic algorithms to regulate the generators, storages, and loads. All the above mentioned systems are, however, either simple simulated systems or conceptual systems in an early stage of designing. Moreover, as definitions of agents in a multi-agent systems are quite general, many of the described systems use agents in an actually centralized control.

A simple management system for microgrids, in which a multi-agent system is used, is presented in Kouluri and Pandey (2011). The system is simulated using the Matlab/Simulink environment. Although the title suggests that the described system might be a decentralized one, it is actually a hierarchical system with centralized control. There are three kinds of agents in the system: the control agent, the energy resource agents, and the load agents. Decisions concerning management of energy in the microgrid are taken centrally by the control agent, which detects emergency conditions and sends messages to the energy resource agents and/or to the load agents to connect/disconnect them or to change their working point. The device (energy resource or load) agents receive the messages from the control agents and report to it the state of the device. Their decisions are confined only to supervision of the local device. Thus, management of energy in the system is actually centralized.

Contrary to it, in our solution all agents actively participate in balancing the power in the microgrid, and form a real decentralized decision system. Both generation and load device agents volunteer to take part in balancing the power in the grid, if only they are able to do this. An agent notifies other agents, if it detects or predicts change of supply/load of its device. All agents whose device can balance the change submit their proposals, and the best of them is chosen by the calling agent, according to prescribed rules. This has two important consequences. The decentralized system is more reliable, more tolerant to management system breakdowns. Moreover, it may quicker resolve the imbalance situation when many quick changes overburden the central control agent. To the best knowledge of the present authors there is no general agent-based system for managing energy in a microgrid with such decentralized functionality.

There are also some ideas of using the multi-agent approach in trading electric energy on markets. Kaleta et al. (2009) proposes the multi-agent system to trade on the wholesale electricity market. The solution considers centralized balancing system, with independent, selfish agents, concerned about their interests. A particular solution for solving the problem of exchange of energy is proposed by Dimeas and Hatziargyriou (2005), who use an auction in the distribution grid among microgrids, including those with the dispersed generations. Each generator willing to sell energy, declares the price for every consumer. The price can differ for different consumers. The resulting auction price, that is used to link the generators and loads, is not the transaction price in the strict sense. The auction is there only a method for linking the pairs, in order to maximize the overall accepted offer prices. This solution differs considerably from a free trade among agents.

Linnenberg et al. (2011) present an idea of nested grids and markets connected with them. Each market is used for balancing energy in the connected grid and unbalanced energy from the lower lever grid. Requests for selling or buying energy is submitted by the prosumer agents to the agent called marketplace. It matches the appropriate agents and sets the prices. Unmatched requests are directed for solving to the higher level market. Although in this proposal the market is partially decentralized, it is not a full decentralization, as solutions for each market are found centrally.

The solution presented in this paper could be possibly considered for the spot market. The main difference is that the trading agents have to be involved in bargaining and/or bidding, with possible negotiations of the selling/buying prices, which is missing in our solution, as a common owner of all devices is assumed. Although the algorithm for finding a partner device for balancing the power gap in our solution is patterned on a simple reverse one-side sealed auction (tender), only generalized costs are used in choosing the best option. Thus, whenever the notion *auction* is used in the sequel, this particular method of choosing a partner device co-operating in closing the gap in power balancing is meant.

3. Agent-based power balancing system

As mentioned above, the management system presented in this paper uses the multi-agent technology. Each generation unit, including renewable dispersed sources, traditional generators, groups of possibly aggregated loads, and energy storing devices, is represented by a corresponding group of autonomic software components. These components interact with each other in order to reduce imbalance. According to the agent-based programing paradigm (Shoham, 1993), these software components can be treated as autonomous agents. Individual goals have been defined for agents. In order to meet them, the agents interact. The goals are modeled by different roles of agents, while the common aim is to ensure suitable working conditions for particular loads, and to pay less for the lacking unbalanced energy, which is much more expensive than the contracted one. With the above assumptions, the system satisfies the multi-agent system requirements (Shoham and Leyton-Brown, 2009). The overall goal of the system considered is to ensure security of supply and to reduce the energy imbalance in the grid.

As it has been noticed in Nahorski et al. (2011), for the sake of the system design it is worth dividing the devices into two groups. The first group consists of devices that can control the level of produced or consumed energy, provided that appropriate technical constraints are met. The second group cannot control it, as the level of consumption or production depends on meteorological or hydrological conditions, or finally on unpredictable human behavior. Note that each group can contain both generators and loads. The first group is called **controllable**, and contains reciprocating engines, thermal units, micro cogeneration units, and hydro turbines. Also some loads, that are able to control its demand, like smart refrigerators, smart washing machines, smart cars, etc., can be included in this group. The second group is called **uncontrollable**, and includes majority of loads, excluding those, which are able to control their demand and also cooperate with the balancing system, and majority of renewable sources, mostly wind turbines and solar units. We assume that **active** agents represent controllable devices, while **passive** agents represent uncontrollable devices. Energy storage devices can be either active or passive.

The Agent-based Power Balancing System is a multiagent system composed of few main components. The diagram of the components is presented in Fig. 1. The centre of the whole system is a database where the required configuration of devices and their features is defined. Whole communication with the database as well as basic data structures and definition of the production/consumption units are placed in the MicroGrid Structures component. Agents simulating operation of the devices are placed in the MicroGrid Environment Simulator component. An example of such an agent is a set of photovoltaic panels that produce energy when the weather simulator reports that there is sufficient sunlight. Agents dealing with changes of energy and responsible for balancing of the power, are placed in the MicroGrid Balancer component. The Launcher is the component responsible only for initialisation of the system: it reads from the database what kind and how many of the devices shall be simulated and launches appropriate agents from the Balancer and Environment Simulator components.

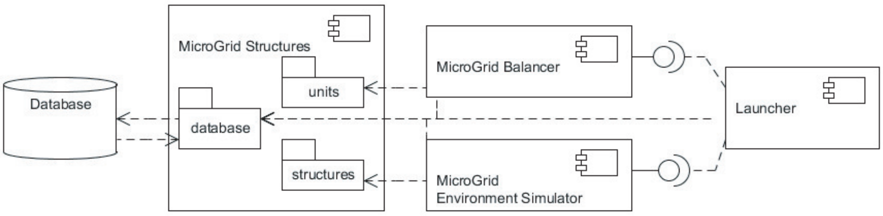

Figure 1. Diagram of main components of the system.

The Agent-based Power Balancing System for the Microgrids is implemented using the JADE 4.0 framework (Bellifemine et al., 2007), the Java 1.6 language, and the PostgreSQL 9.1.1 database.

Agents of the MicroGrid Environment Simulator contain both definitions and implementations of each type of the device simulated in the system, as well as meteorological conditions and time-dependent simulators. This module is still in development, as proper characteristics of consumers and producers need statistical data of real energy usage, which are not yet ready.

Within the MicroGrid Balancer component nine main agent roles are designed and implemented:

- active and passive **modelers** that model the physical behaviour of the devices in a power generation or consumption states; the modeler communicates with an agent from Environment Simulator to receive a current status of the device;
- active and passive **predictors** that provide short-term forecasts of demand or energy production taking into account a forecast of meteorological conditions;
- active and passive **negotiators** that negotiate the delivery or dispatch of the energy;
- the **Morris Column** agents, whose goals are to provide distributed public repository task, where particular agents are able to report information, as well as seek it;
- the **external grid agent** that deals with trade with the external grid;
- the **monitor** agent, whose goal is to monitor the state of particular agents, detect unexpected imbalance conditions, and start appropriate actions after having detected them.

The modeler, the predictor and the negotiator are called physical agents and their implementation differs depending on whether they are representing controllable ('passive') or uncontrollable ('active') devices.

The main goal of the system, that is - balancing the power, is realised by the Balancer component, through a constant dialogue between active and passive agents.

'Passive' agents, representing controllable devices, provide the information on their current regulatory capacities, which determine their abilities to provide or receive a given amount of energy. A passive modeler agent periodically reports information about regulatory capabilities of the device. The regulatory capabilities can be considered as permissible increase or decrease of produced or consumed energy from the working point of the device. The working point can be positive (when the device generates energy), zero, or negative (e.g. if the energy storage unit is charged, or if the device consumes the energy).

'Active' agents, representing uncontrollable devices, verify their state. When they detect a change, which can cause an imbalance of the power in the grid, they submit to the associated negotiation agent the request to seek a device able to compensate the imbalance. Looking for the change, the active modeler compares the actual working point with the planned one, and with the contracted energy. It receives a short-time forecast from the predictor agent, and on the basis of a mathematical model of the device determines its working point in the future, with a predetermined (short-time) horizon. Both active and passive predictor agents provide short-time forecasts on the basis of the weather forecast, time of the day, day of the week, and the season, as appropriate for the device considered. As a result, it may be concluded that the device entered, or may shortly enter the imbalance state.

When the state of imbalance is detected, the active modeler requests the active negotiator to reduce it. The process of imbalance reduction using the auction algorithm is described in more details in Section 4. A passive modeler agent also checks the current working point, and publishes its regulatory capabilities at the Morris Column agents. Moreover, it obtains the forecast from the passive predictor, and publishes the future working points.

A Morris Column agent acts as a public repository. It provides the possibility to publish, look for, remove, and update information about the actual and predicted regulation capabilities of passive agents. To make the system resilient against the crash of the single Morris Column agent, with the one central repository, the information can be distributed among multiple Morris Column agents. Spatially separated multiple Morris Column agents should be particularly considered in large systems. In such a case, the modeler agents can submit or seek information in the closest one.

The external grid agent trades with the distribution network operator. It is active only when the microgrid is connected to an external distribution network.

4. Auction algorithm for energy balancing

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

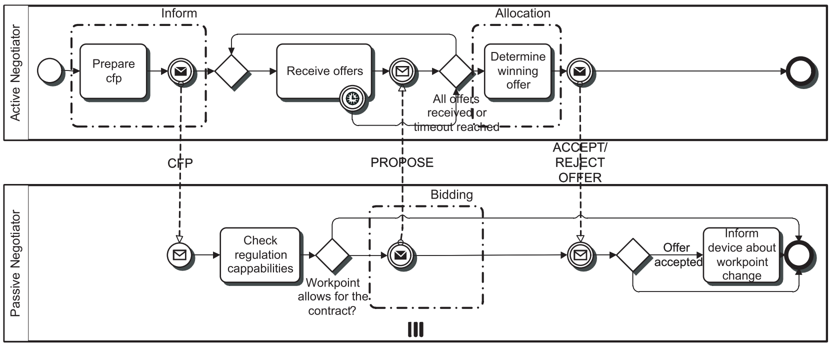

Figure 2. Single auction process presented on the BPMN collaboration diagram.

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, with the main focus 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 an 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 mutual interference. Thus, to act swiftly, simple auction algorithms are advisable. The negotiation technique described in this paper is a 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 exists no single, centralized entity that supervises it. Actually, ad-hoc auctions are executed, operated by the active negotiators.

In Fig. 2 a single auction process is presented. BPMN 2.0 notation (Allweyer, 2009) is used due to its convenience and transparency. It provides not only the flow of communicates, as in the UML or AUML (Bernhard et al., 2001), 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 workpoint 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, if the imbalance is negative, indicating 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 appliances, able to control 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 an 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 demands. 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 update 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 current and predicted imbalance reduction processes at the same time. Passive negotiator in turn, tries to manage its regulatory capabilities to avoid the situation, when it allocates in all concurrently going auction processes more energy than it has available. 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.

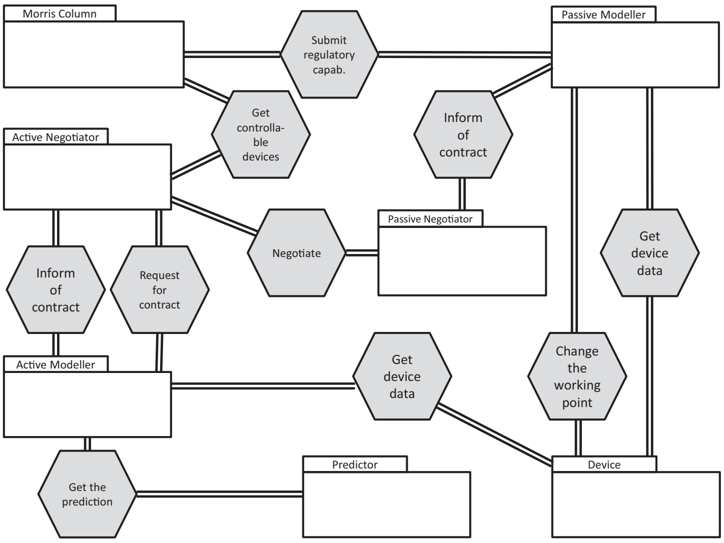

Figure 3. BPMN 2.0 conversation diagram in the Agent-Based Power Balancing System. Hexagons represent particular conversations, double lines represent involvement of the agents in the conversation

5. Communication diagrams

For the auction algorithm to work properly, each agent should be able to communicate with one another. The system does not assume a central entity, nor central repository, to manage the communication process. Particular agents communicate with each other, according to the proposed schema. There are eight different conversations in the schema, each of them focuses on the specified topic. In Fig. 3 an overview of possible communications performed by agents is sketched. Sequences of particular conversations are presented on the choreography diagrams, thus they give us more details about the flow of the messages.

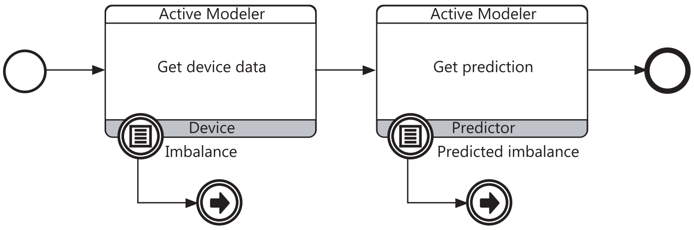

Figure 4. Main choreography diagram for the active modeler agent

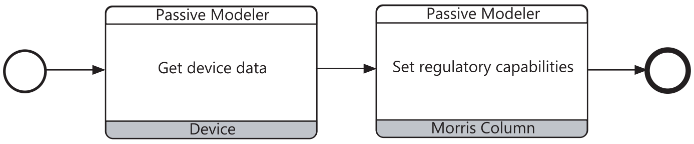

Figure 5. Main choreography diagram for the passive modeler agent

Active modeler's goal is to model the physical behavior of the represented device, considering the external impacts, due to weather or hydrological conditions, or human activity (see Fig. 4). Therefore, it retrieves the information of the current working point from the device, and compares it with the modeled working point. If the modeled and actual working points differ, the modeler reports the imbalance state to the associated negotiator. Moreover, the modeler tries to anticipate future imbalances, using the short-time predictions received from the predictor agent. When it detects a future imbalance, it reports it to the negotiator, together with its time of occurrence. The process of retrieving the data from the device and predictor agent is repeated periodically . The particular imbalance reports are submitted independently, and the negotiator agent can run those processes concurrently. Moreover, the imbalance detection is modeled as the intermediate interrupting condition event, as each imbalance state causes an appropriate call for starting a process of imbalance reduction.

The passive modeler activities are also performed periodically. As the passive modeler works with the controllable devices, it retrieves the current working point from the device, calculates its regulatory capabilities, and reports the data to the Morris Column agent (see Fig. 5). The regulatory capability consists in the admissible increase or decrease in energy production. To calculate them, the passive modeler uses a model of the device and the data retrieved. The data are received from the Morris Column agent (see Fig. 6, the 'Get controllable devices' activity), and the associated passive modeler retrieves accurate information on the working point during the negotiation (see Fig. 3, 'Check regulation capabilities' activity). They are subsequently used in the negotiations.

Another activity of the passive modeler is initiated by the passive negotiator, after having concluded a contract (see Fig. 6). The contract specifies appropriate change in the production (or consumption) of energy. As the device associated with the passive agent is controllable, the modeler requests from the device to execute the appropriate change of the working point.

The main process that occurs in the system is the negotiation process (see Fig. 6). At the same time, there can be a number of negotiations performed concurrently, and all processes must be mutually isolated. The active modeler agent initiates the negotiation process, after having noticed an imbalance. The request for concluding a contract is sent to the associated active negotiator. Next, the active negotiator obtains the list of potential devices, which can possibly compensate the detected shortage or surplus of energy. Afterwards, the

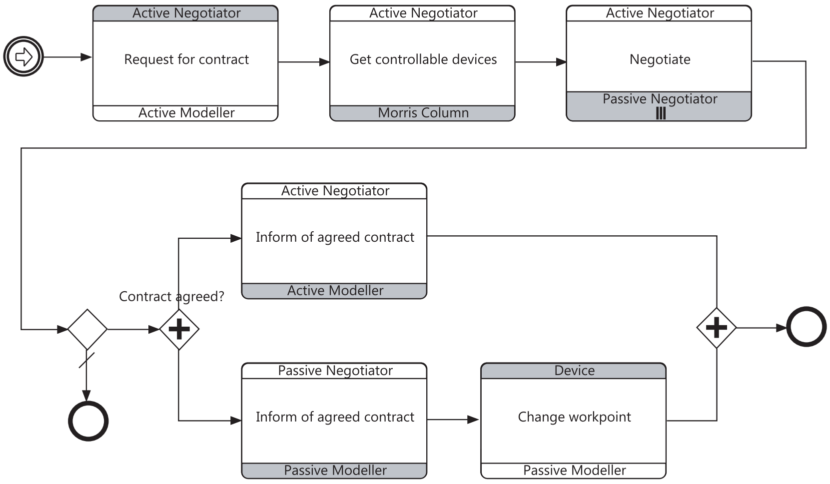

Figure 6. Negotiation choreography diagram.

active negotiator starts the main negotiation process with all passive negotiators from the list, associated with the controllable or energy storage devices (the negotiation process is described in more details in Section 4, and depicted in the collaboration diagram presented in Fig. 2). The negotiation can terminate successfully (i.e. with the contract agreed, which is equivalent to imbalance compensation), or not (i.e. when there is not enough energy to deliver, or there is lack of sufficient additional load to use the energy).

If the microgrid is connected to the external higher level grid, the external grid agent becomes active. Its goal is to trade with the external distribution network operator, and provide the surplus or shortage compensation when the grid devices cannot do it. When the external grid agent works properly, each negotiation process terminates successfully. When the grid works in the island operation mode, then the external grid agent is not active, and the success of every negotiation process depends on the inner devices.

If the negotiation has been finished successfully, both active negotiator and passive negotiator, which agreed on the contract, inform of this the associated modelers. Moreover, the passive modeler additionally requests to appropriately change its device working point.

6. Test cases analysis

Two sets of tests were made, one to check the agent system for balancing energy and another to check if the adopted technology and methodology are capable of coping with fast changes of power levels in the grid. Demand and production dependent upon weather conditions is modeled in this study by a simple random generator. For example, the wind turbine receives a varying wind power level, in which some random aspects occur. Also the loads start with an initial demand and at each time interval a random amount is added or subtracted. We focus on developing methodology and simulated artificial data provide more controlled environment, where different cases can be examined.

The methodology was first tested on the Intel(R) Core(TM) i5 3.20 GHz computer with 8 GB of RAM memory. All agents, as well as querying the database, were executed on a single machine.

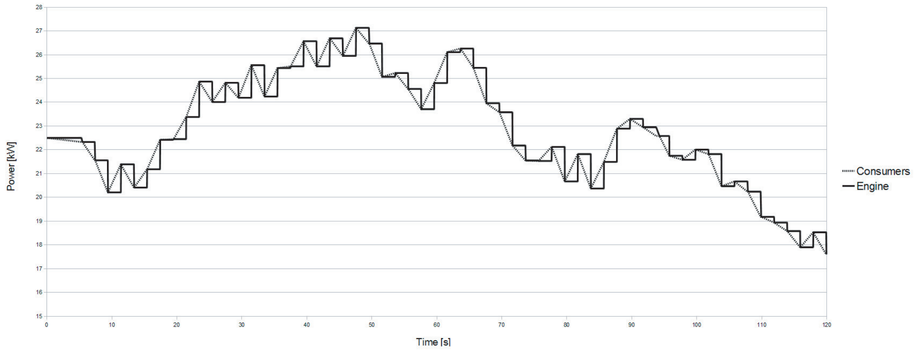

Figure 7. Test case with two working units: consumer and controllable source

The first test case is simplified in order to present the way the energy is balanced. There is only one aggregated consumer and one controllable unit source called engine. As shown in Fig. 7, energy is balanced shortly after the state of imbalance has been discovered.

Adding the battery to the previous test case showed clearly the purpose of using storage units. This test case is presented in Fig. 8. The battery reacts fast and can balance small fluctuations of energy. When energy is changing in more trend-like behaviour, the engine changes its working point in order to track it.

In Fig. 9 the aggregation of the energy used by the battery and the loads are compared with that produced by the controllable source (engine). It can be seen that power is generally balanced, but some small imbalances in time are visible. These imbalances are caused by the negotiating process. Each device is reporting its status with different delay. When the power of all the devices is gathered, small, short imbalances are visible, even though every change of power is eventually balanced.

The next test case was done by adding a wind turbine to the set of devices. The wind turbine introduces high volatility of energy generated in the system. Power production and consumption of each device is presented in Fig. 10. The system manages to cover all imbalances, but as it can be seen in Fig. 11, the fluctuations of power become more visible.

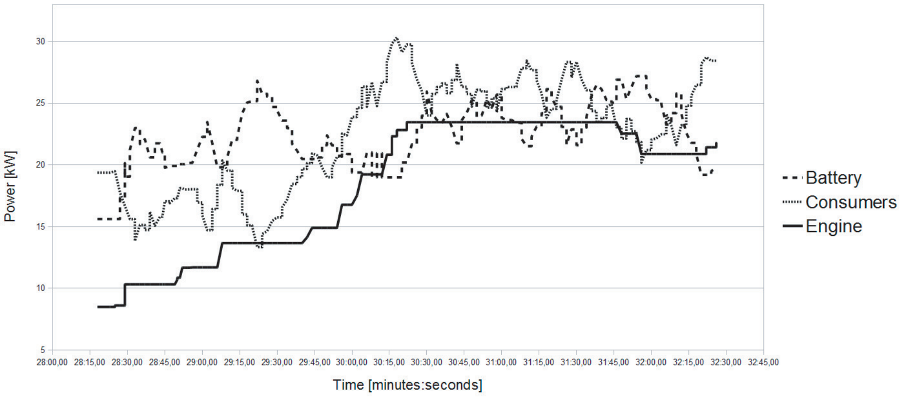

Figure 8. The energy produced in the test case with 3 devices: controllable source (engine), consumer and battery

To check the ability of the system to cope with time constraints, tests were made on few independent machines, each Intel(R) Core(TM) i5-3450, CPU@3.10 GHz, 8 GB RAM, with 64-bit Windows 7. The computers were connected by 1 Gb Ethernet network. In the first test the same number of units were used as in test case with four devices. Each device was placed on different machine, database and Morris Column agent were placed on a separate machine. The measurements of the balancing time are presented in Fig. 12. It is visible that the balancing takes less than 60 ms, except for the initial longer time (up to 800 ms) that was due to delays of agents registering their power regulation capabilities on Morris Column. It is assumed that the measurements of production/use of energy of devices are done once a minute and the energy should be balanced within this time (before the next orders are received). This test suggests that this period of time is sufficient. It is also obvious that the network does not jam the algorithm, as the messages are quite small and their exchange between agents is quick. Each set of agents (the device simulator and balancing agents) with their Java machines and JADE containers occupies on average 200 MB, so it neither exceeds the initial memory level set in Java Virtual Machine.

Next, an example with 19 devices was launched on 19 machines. A model of the device with its simulator and its agent were placed on a separate machine. The database and the Morris Column agents were running on another one. The loads were changing their consumption of energy randomly within specified limits. The goal was to check if there would be any problem with larger number of machines, causing, for example, delays in the network, or problems with concurrent accesses to the database. The test lasted 20 minutes. The system balanced energy and all agents behaved as expected. The balancing times are presented in Fig. 13. The states of imbalance lasted very shortly, on average 14

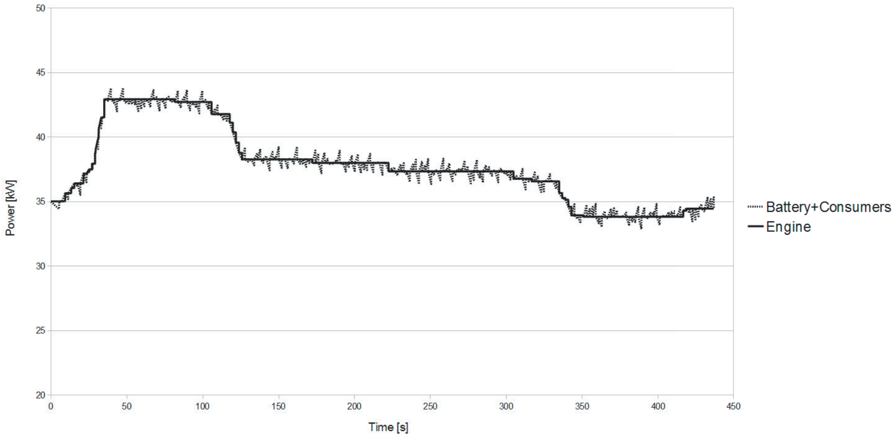

Figure 9. Aggregated power for supply and demand in system with controllable source, energy storage and consumer

ms, with the median of 13 ms.

Balancing can be done in time, which is short enough from the point of view of electric devices. Changes of device states are expected to be measured at intervals greater than 10 seconds. Combined with the fast response time of the system, this implies that the system has ample time to detect the imbalance and suppress it.

7. Conclusions

The simple auction algorithm applied in the Agent-based Power Balancing System to manage energy in a microgrid performs well. Moreover, in the simple cases considered it assured control of imbalances. The results presented show that the system performs well, with short imbalance compensation time intervals, even if up to twenty devices agents are considered to work on separate computers. As the system runs multiple auction processes, it is tempting to apply the multi-commodity market model (M^3) (Kaleta and Toczyłowski, 2012) to organize the notation. However, the impact of using the XML notation on prolongation of the communication time has to be checked.

Further development and examination of the Agent-based Power Balancing System is planned. Specifically, examination of the computation load due to dealing with the multiple, concurrent auction processes, initiated by different agents, has to be done for a more complicated network with more realistic number of a hundred of device agents.

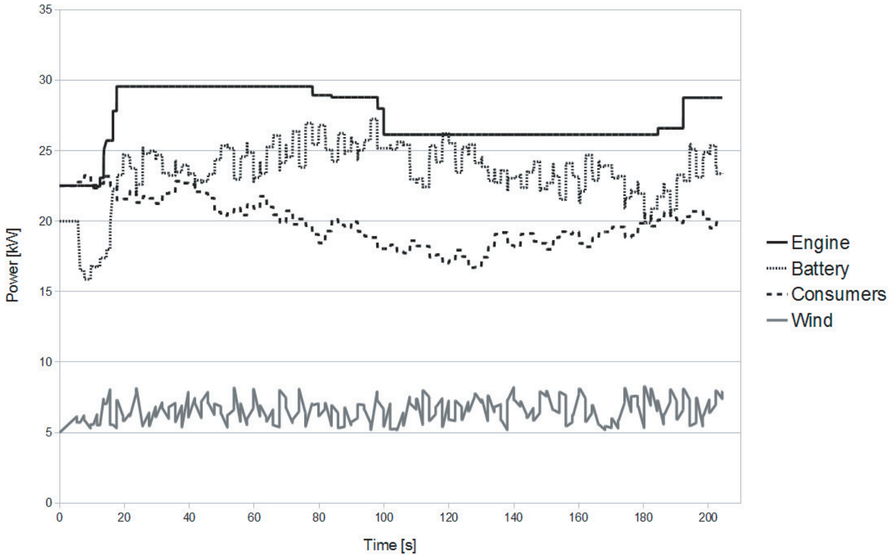

Figure 10. Energy produced by the controllable source (engine) and the wind turbine, power stored in the battery and power consumed in the test case with four devices

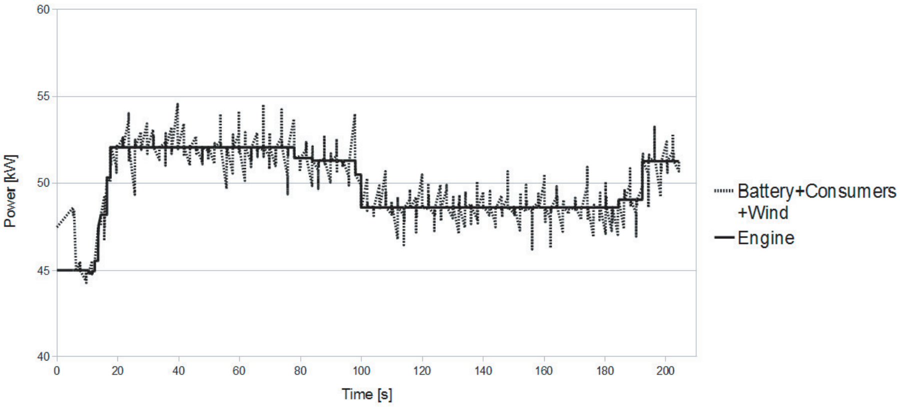

Figure 11. Aggregated power values for uncontrollable units with a battery and engine

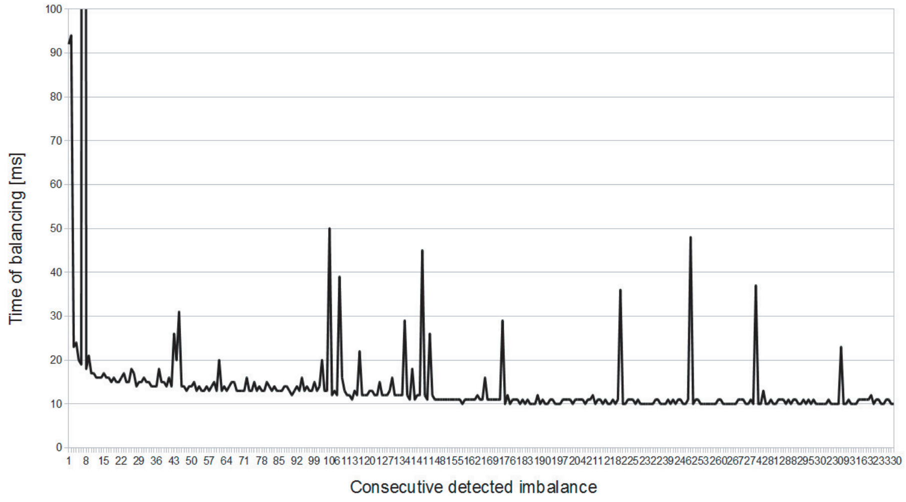

Figure 12. The times of imbalance reduction for the example with four devices launched on five computers

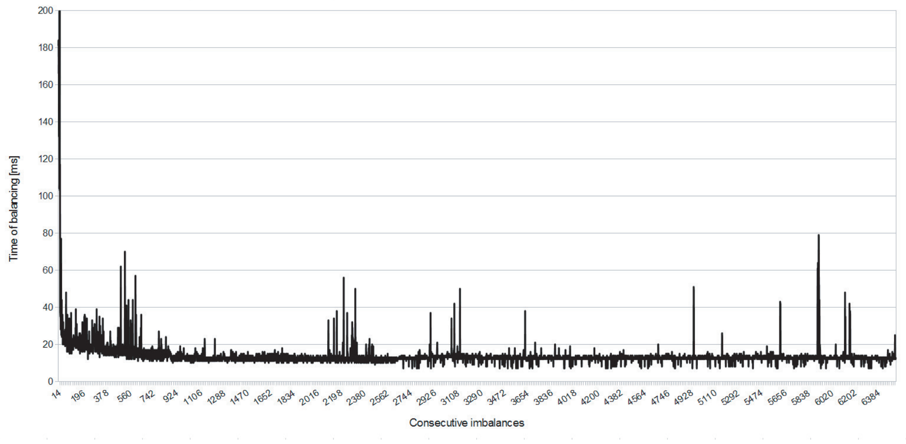

Figure 13. The times of imbalance reduction for the example with 19 devices launched on 20 machines (database was on a separate machine)

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