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Effective approach to distributed optimal operation control in rural low voltage microgrids

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Abstract. The paper raises the issue of optimizing the control of the rural low voltage microgrids. Microgrids can operate in a synchronous mode with grids of distribution system operators and in an island mode. We can distinguish two control strategies in microgrids: one approach based on centralized control logic, which is usually used, and another on decentralized control logic. In this paper we decided to present the approach based on the distributed control, combining the efforts of the distributed cooperative control and modified Monte Carlo optimization method. Special attention has been paid to the impact of the order of processing particular devices' groups on results of optimization calculations. Moreover, different scenarios of behavior of the microgrid control system with respect to the communication loss have been also presented. The influence of the issue of continuity of communication between particular devices' groups on the possibility of carrying out the optimization process has been investigated. Additionally, characteristics of power loads and generation of electricity from small renewable energy sources appearing in rural areas have been described and the sensitivity of the optimization algorithm to the changes of demanded power values and changes of values of power generated by renewable energy sources has been studied. We analyzed different objective functions which can be used as an optimization goal both in synchronous and island operation modes of microgrid. We decided to intensively test our approach on a sample rural LV microgrid, which is typical in the countryside. The observed results of the tests have been presented and analyzed in detail. Generally, results achieved with the use of proposed distributed control are the same as with the use of centralized control. We think that the approach based on distributed control is promising for practical applications, because of its advantages.

Key words: microgrids, optimal operation, distributed control, rural areas.

1. Introduction

The topic of microgrids (MG), including low voltage (LV) ones, is an issue, which has intensively been studied for more than a dozen years. Microgrids are strictly connected to the development of distributed generation (DG), and are a component of the Smart Grid (SG) concept.

The topic of DG has already been widely described in the literature, similarly as the topic of SG. For example, paper [1] presents various technologies of DG for residential houses and for municipalities, as well as "energy plus" technologies for other buildings. In turn, paper [2] describes the issue of integration of distributed energy sources (DES) with the electric power grid via power electronic converters (PEC). Publication [3] is devoted to the detailed overview of the most important issues concerning the use of PEC in the context of Smart Grids.

The issue of MG has been also discussed thoroughly in the literature. In technical brochure [4], as well as in [5, 6] we can find a formal definition of microgrids. In these sources detailed characteristics of different kinds of MG have been presented. The concept of MG has been also presented in many other publications, for example in [7, 8].

Essential components of low voltage MG are: microsources (MS), electricity storage units (ES), electricity loads (controllable loads – CL and non-controllable loads – NCL), and LV network infrastructure.

Microgrids can operate in grid-connected (synchronous) mode with networks of distribution system operators (DSO), as well as in island mode. One of the most important challenges is proper setting of the operating points of MSs, ESs and CLs located within a microgrid. Different aspects of the issue of MG operation control has been already widely described in literature sources, e.g. in [7–11]. In turn, paper [12] presents an overview of the strategies of control, grid integration and energy management in MG. In referenced publications, different approaches for operation control have been presented. We can distinguish two control strategies: one approach based on centralized control logic and another on decentralized (distributed) control logic.

Usually, centralized control logic is used for operation control in microgrids. Such approach was presented for example in [13, 14]. In turn, publications [15–17] present distributed control logic for operation control in MG. It is worth noting, that paper [18] describes the issue of implementation of optimal operation control algorithms in low voltage microgrids.

Considering the topic of this paper, we will devote the further part of the literature review to distribution control logic. We can distinguish two distributed control strategies: competitive control and cooperative control.

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Cooperative control [19–21] concerns systems performing engineering tasks, which can be described with the use of the set of elements making their own decisions, having some limited possibilities with regard to data processing and making use of local information that is available. Together with communication connections between these elements, it allows for cooperation and making some efforts to reach common (collective) goals. Microgrids can also be treated as members of this class of systems.

Distribution of information imposes the application of distribution control and the performing of some necessary calculations by cooperating components. The technique that is worth to be mentioned in this particular case is the "consensus algorithm" formulated by Tsitsiklis [21]. Distributed control and necessity of performing calculations can be perceived as an obstacle when someone tries to implement predictive control in multi-agent system [21]. Multi-agent systems (MAS) [22–24] are composed of many interacting computer programs, called agents, whose aim it is to achieve some individual or collective goals. Agent is a computer application working autonomously within its environment.

Examples of concrete solutions in the range of distributed cooperative control in electric power grids have been presented, among others, in [25–30]. Some of these solutions concern distributed cooperative control with the use of multi-agent systems.

One of the essential issues concerning the microgrid is its autonomous operation. In this mode, active power balance between generated power and received power must be ensured. This problem was a subject of article [25]. This publication proposes the distributed control of microsources based on subgradient.

Algorithm of distributed control, whose goal is the regulation of output power level of big number photovoltaic systems (generators) located in distribution grid, has been described in work [26]. For that purpose, cooperative control method is used. In the proposed approach of distributed cooperative control, agents representing PV sources constitute groups, with communication within these groups. Also the communication between the groups of agents and higher level controller takes place.

In the publication [27] the issue of the secondary control in microgrid is considered. To implement the reliable secondary control for the microgrid distributed cooperative control, approach with the use of multi-agent systems can be applied. The secondary control encompassed both voltage and frequency regulation in the microgrid. Similar concept has been presented in [28], in which the method of the distributed cooperative control with the use of multi-agent systems was used for the secondary voltage control in microgrid.

Article [29] presents the method of decentralized control for distributed generation sources connected to the electric power network by the means of power electronic converters, controlling the level and frequency of output voltages and the level of generated power in synchronous mode of operation, in islanded mode as well as during synchronization.

The strategy of cooperative control of microsources and energy storage during the islanded mode of the microgrid operation has been presented, in turn, in [30]. The evaluation of the strategy has been made there by performing appropriate experimental research studies.

Some of the algorithms presented in mentioned publications are being formulated only theoretically and evaluated in a simplified manner. It seems there is still a need to study and evaluate control methods for MG operation, especially the ones based on the distribution control logic.

Publication [31] provides such methods and their evaluations for sample rural microgrids, whose topologies and assumptions of operation truly reflect the conditions which can be seen in practice. This paper was an extension of the previous concept research, carried out in the RIGRID (rural intelligent grid) project, which was described, among others, in [14, 18]. In article [31] the issue of the centralized as well as distributed control logic of MG operation has been considered. But the main attention has been given to the method based on the centralized MG operation control. Presented results of optimization calculations based on decentralized control logic should be treated as initial and approximate.

This paper is an extension of paper [31]. In this paper we decided to present the approach based on the distributed control logic for sample rural microgrid, utilizing the distributed cooperative control and modified Monte Carlo optimization method. We think that this approach is promising for practical applications, because of its advantages.

The optimization problem has been formulated in the paper with the assumption in mind, that all generating units together with the energy storage unit belong directly to (are under full control of) a single microgrid's operator and realize its aims. In this way it is possible to formulate the considered optimization problems as ones falling into the single-criterion optimization category. If it was assumed, that particular generating units and controllable loads have to realize aims of their owners (prosumers), then the considered optimization problem related to the maximization of profits should be formulated as a multi-criteria optimization one. A distributed control paradigm can be well-fitted for this aim as well, but in the current version of the optimization program our goal was different. The motivation of applying a distributed approach was rather to look for a way of reducing the complexity of the problem by introducing an algorithm, which is simple, easy to understand and implement and efficient at the same time, not to consider the problem of many separate entities with different goals.

We are able to apply our algorithm in practice, which is partially the result of our participation in one of the European research project dedicated to rural electric power grids. We decided to utilize a topology of a sample low voltage rural microgrid, which is typically seen in countryside conditions. For this sample microgrid, we intensively tested our approach. This paper presents selected observed results of the tests. The data returned by the proposed algorithm for different microgrid operation conditions was analyzed.

In this paper special attention has been paid to the impact of the order of processing particular devices' groups on results of optimization calculations. Moreover, the influence of the issue of continuity of communication between particular devices' groups on the possibility of carrying out the optimization process has been investigated. Additionally, the sensitivity of the optimization algorithm on the changes of demand power values and changes of values of power generated by renewable energy sources in particular nodes of MG has been studied. These changes can be caused by e.g. inaccuracy of ultra-short-term forecasting process of the mentioned magnitudes.

Similarly as in [31], we analyzed different objective functions which can be used as an optimization goal both in synchronous and island operation mode of MG.

The structure of the paper is presented below.

First, introduction to the analyzed problem has been presented and review of the selected publications concerning the subject of the paper has been done. Then, characteristics of power loads and generation of electricity from small renewable energy sources appearing in rural areas have been presented. Next, the description of the proposed microgrid control algorithm, including: problem formulation (objective functions, constraints) and algorithm of distributed control logic has been done. In the further part of the paper different scenarios of behavior of the microgrid control system with respect to the communication loss have been discussed. Then, case study including: description of the test microgrid, results of optimization calculations obtained with the use of algorithm of the distributed control logic, as well as the most important observations after having carried out experiments, has been presented. At the end of the paper summary and final conclusions have been made available.

2. Characteristics of power loads and generation of electricity from small renewable energy sources in rural areas

2.1. Introduction. The microgrids operated in rural areas are able to satisfy locally the energy demands of the consumers. In intended islanded operation the microgrids also allow for improvement of supply reliability of electricity for consumers who are connected to them [14].

Small wind turbine-generator sets, photovoltaic installations, power plants based on biomass and biogas, small hydro power plants, as well as small reciprocating engines with internal combustion (engine-generator sets) are usually used in microgrids in rural areas [1, 6, 8, 14, 18]. Amongst electrical energy storage units, battery storages are the most popular units in rural areas.

2.2. Characteristics of loads in rural areas. Farms are essential entities in rural areas. A farm is an arrangement of land and buildings with devices, whose task is to produce agricultural products. The demand for electricity is strongly dependent on the size of the farm and the type of agricultural production. Consumed electricity is used both for domestic purposes (like lighting or heating) and for conducting agricultural activities (like breeding or fruit-growing). According to the Polish Central Statistical Office data [32], rural households in Poland consumed 12101 GWh of electricity in 2017. Approximately only 15% of this energy consumption concerns agricultural production. Generally, the most electricity is consumed by farms which cool or dry harvested crops. The electricity consumption also depends on the weather and the type of fruit grown though. The consumption of electricity for living purposes is not subject to such significant changes. Electrical devices for agricultural purposes may work as single ones or in groups. Examples of single devices are a feed mixer or a grinding mill. Group devices are located in special buildings, such as a piggery, barn or cowshed. It is estimated that about 60% of electricity is used to drive machines for agricultural work [33].

Farm load profiles change to the rhythm of the activities performed. Some loads may occur at certain times, while others only when needed. Moreover, some devices like refrigerators or freezers are on continuously. Sample rural households load profiles are presented in Fig. 1. In presented profiles some characteristic features can be observed. The biggest demand for electricity occurs during the winter, while the lowest during the summer. Also the afternoon-evening peak in the summer usually occurs later than in other seasons.

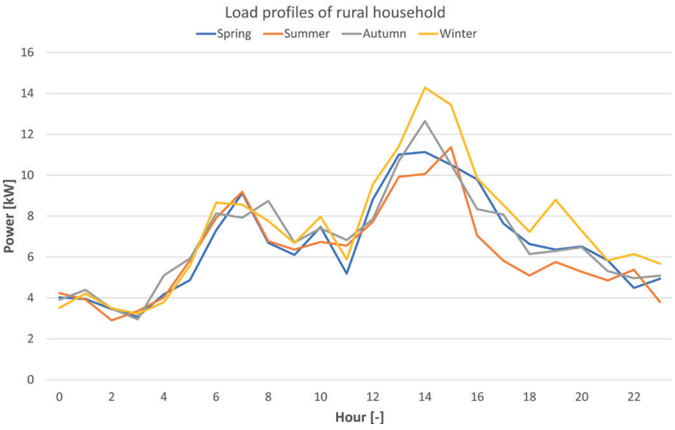


Fig. 1. Load profiles of rural household; elaborated on the basis of [34]

Agricultural room load profiles change to the rhythm of routine operations. Fig. 2 presents cowshed load profile. The increase in demand for power in the morning and afternoon is associated with the process of milking cattle.

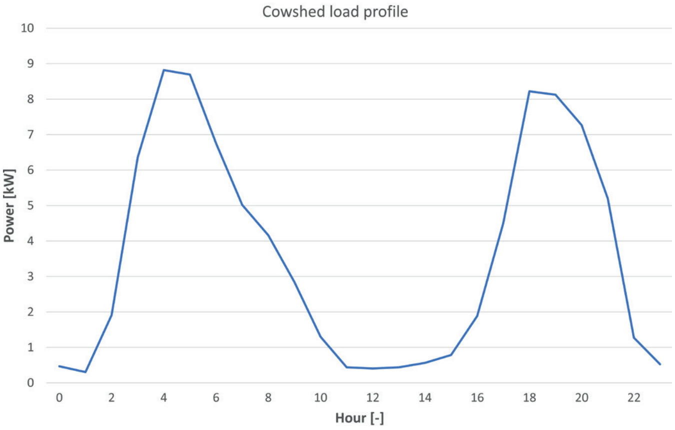


Fig. 2. Cowshed load profile; elaborated on the basis of [35]

There may also be small shops or service points in the countryside. Their load profiles are usually similar to rural households profiles as shown in Fig. 3.

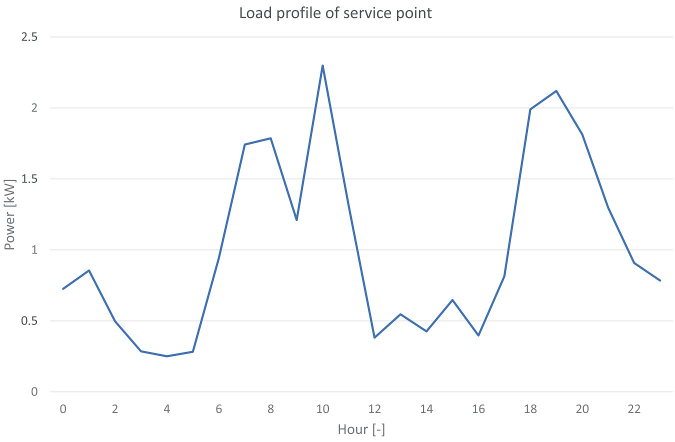


Fig. 3. Load profile of small service point in rural area; elaborated on the basis of [36]

Knowledge of farm load profiles can be helpful in changing the seller of electricity or in the selection of renewable energy sources. These types of energy sources in a farm can be used to cover the energy needs of living in households, as well as for the needs of agricultural production. Photovoltaic (in short – PV) installations and small wind turbines are the most popular renewable energy sources.

2.3. Characteristics of photovoltaic installations and small wind turbine-generator sets in rural areas. Each photovoltaic installation consists of a PV module, an energy receiver and auxiliary devices. An example place for PV installation can be the roof surface of the piggery or barn. As a result, arable land is not used. Solar installation generation profiles in June and January are presented in Fig. 4. Generation peaks can be observed at 12:00–13:00 in winter and 11:00–14:00 in summer. Electricity is generated mainly during the day, which predisposes the photovoltaic installation to cover part of the farm's demand at that time. The presented generation profile is typical for Polish conditions.

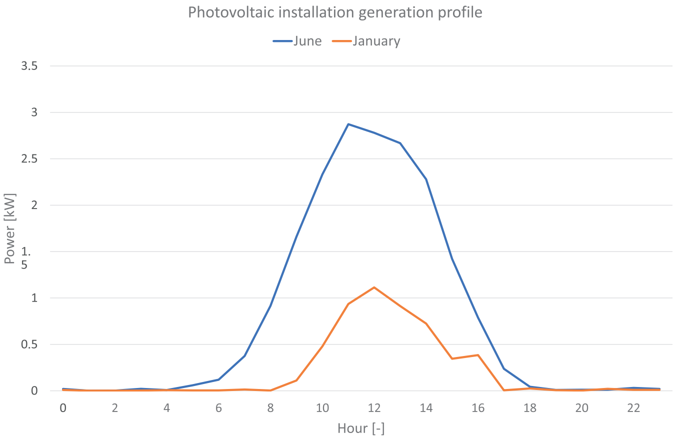


Fig. 4. Generation profiles of 5 kW PV installation during June and January; elaborated on the basis of [37]

The farm load profiles with a PV installation are expected to flatten during the hours of the largest generation. If some part of the energy available during peak hours is not used, it can be transferred to the distribution network. Photovoltaic installation can usually power processes which do not require large amounts of electricity, such as irrigation, poultry lighting or supplying small appliances for commercial services.

Unlike a photovoltaic installation, a small wind turbine-generator set can generate electricity continuously. In agriculture, small wind turbine-generator sets with rated power from 5 kW to 20 kW are usually used. They can be connected to the distribution network or work in a separate network as well. In contrast to photovoltaic installation, small wind turbine-generator sets have lower investment outlays. Also it will not occupy space for planting plants or grazing animals.

Small wind turbine generation profiles in June and January are presented in Fig. 5. The presented generation profile is typical for Polish conditions.

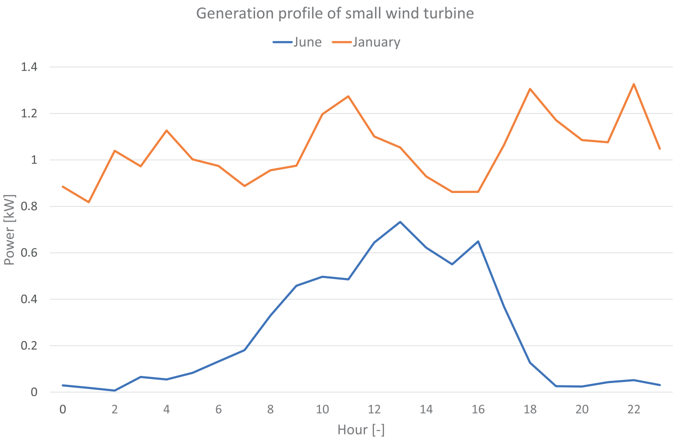


Fig. 5. Generation profiles of 5 kW small wind installation during June and January; elaborated on the basis of [37]

Analysis of the profile presented in Fig. 5 shows that in winter the turbine-generator set is able to generate noticeably more electricity than in summer. An important aspect is the place of turbine installation. The proximity of buildings or forests may cause slowdown in wind speed, whereas the occurrence of hills – acceleration. Disadvantages of using small wind turbines in the countryside are significant fluctuations in generated power and small wind resources at low altitudes.

Analysing the presented load profiles, it can be concluded that any type of building in a rural area can successfully use renewable energy sources to cover part of its demand. One of the key requirements is the knowledge of a typical load profile. This knowledge is also necessary for the proper selection of an energy storage device due to the lack of continuity of generation by PV installation. Farm load profiles should be adjusted so that as many agricultural processes as possible are carried out during the hours of the highest generation from renewable sources. The use of PV installation can significantly affect the load profile of a given building. The sudden decline in the PV generation

(Fig. 4) coincides with the occurrence of the afternoon-evening peak (Fig. 1, 2, and 3). As a result, there is a possibility of changing the shape of that peak to a larger and steeper one than when there is not a PV installation. Partial coverage of demand by renewable energy sources can reduce the cost of purchasing electricity and ensures supply during rural distribution network failures.

It is worth considering the use of hybrid systems to simultaneously obtain electricity from solar radiation and wind energy. This will be especially important for farms with increased electricity consumption in the morning and afternoon when the generation from photovoltaic system in not large.

3. Optimization problem formulation

The distributed algorithm for determination of the set of (sub)optimal operating points for all the devices composing a microgrid, which has been presented in the further part of the paper, is based on several assumptions. In the current section we are going to present all the most important ones.

Firstly, we assume that the algorithm takes advantage of the cooperative control approach [29]. In this hierarchical scheme of both organization and coordination of distributed entities, different units (in our case devices composing a microgrid) form groups managed by some group controllers, which are responsible for controlling the behavior of the groups. In a case of our microgrid we will have 4 different groups of similar devices: controllable loads (CL), controllable microsources (CM), non-controllable microsources (NCM) and energy storages (ES). Each group controller is responsible for exchanging information with other group controllers, making appropriate calculations and on their basis, for making decisions on the proper choice of the operating points for all the devices belonging to the group it is in charge of. In our version of the cooperative control approach each device also has its own local controller responsible for communication with the group controller, listening to its orders and applying the demanded operating point on the device. Apart from group controllers and local controllers there exists also a single master controller (MC) responsible for monitoring the state of different network components (lines, transformers, switchgears and so on) and informing group controllers about all failures and incidents within the network, as well as about the mode of the microgrid operation.

Secondly, for each device an operating point can be set. We understand the operating point as a pair of active power P and reactive power Q values which can be applied on the device. In a case of different types of devices we have different levels of flexibility when choosing the operating points. In a case of all energy storages, controllable loads and controllable microsources we can choose any operating point we want from the available – individual for each i-th device – range of regulation possibilities spanning from $P_{\mathrm{min},\,i}$ to $P_{\mathrm{max},\,i}$ and from $Q_{\mathrm{min},\,i}$ to $Q_{\mathrm{max},\,i}$. For all non-controllable microsources (renewable energy sources) the choice is discrete. We can turn the i-th device on and then it will work with the operating point $(P_{current,\,i};\, Q_{current,\,i})$ determined mostly by the current weather conditions and the individual technical characteristics of the device. We can also turn it off and apply on the device the operating point $(0;\, 0)$. We have also decided that all devices should work with some individually chosen, fixed for them, constant values of power factors $(\tan(\varphi))$, which will not be changed during the whole optimization process. This way we only need to choose the level of generated or consumed active power for each device – the level of reactive power will be automatically determined. Such an assumption does not seem to be a big limitation – it is a common practice to keep the power factor of the device unchanged for a given short time interval. However, it will simplify our optimization process significantly, by turning our optimization problem into one-dimensional one (only the levels of active powers need to be chosen).

Thirdly, we take into account that the microgrid should be able to work in two different operation modes – synchronous one and island one. We are going to consider 7 different objective (criterion) functions (CF) [14, 18, 31]: (1)/(2) minimization/maximization of the amount of energy imported from/exported to the network of the distribution system operator, (3) minimization of active power losses, (4)/(5) maximization/minimization of the amount of energy generated from renewable/non-renewable energy sources, (6) minimization of costs related to the operation of the microgrid, (7) maximization of profits resulting from the operation of the microgrid. Two of them: (3) and (7) will be analyzed in much more detail in the paper. The mathematical formulation of them is presented below [14, 31].

1. Minimization of active power losses in the microgrid (CF3). The objective function has the following form:

$$F_{obj} = \min(\Delta P), \tag{1}$$

where F_{obj} is the objective function and ΔP is the sum of all active power losses in the microgrid.

2. Maximization of all profits related to the operation of the microgrid (CF7). The objective function has the following form:

$$F_{obj} = \max(PR_{opMG}), \tag{2}$$

$$PR_{opMG} = A_{tot} \cdot p_s - C_{opMG}\,, \tag{3}$$

where: PR_{opMG} are the profits related to the operation of the microgrid, p_s is a price, per unit, of the energy sold to the clients, including also the DSO power grid, A_{tot} is the sum of energy sold, C_{opMG} are the costs related to the operation of the microgrid within the optimization period.

Last but not least, we assume that the final solution being the result of our optimization process needs to be a feasible one – it cannot violate any of the optimization constraints. The feasibility of solutions is checked with the use of Newton-Raphson method of calculating power flows. The set of the following optimization constraints should be met: (a) the long-term current-carrying capacities of all lines cannot be exceeded, (b) the rated powers of all transformers should not be exceeded, (c) nodal voltages for all nodes should be within permissible limits, (d) levels of energy stored in energy storages should be within the permissible ranges of values. In the publications [8, 31] detailed forms of the constraints are given. If the candidate solution does not violate any of these constraints it is treated as a feasible one and can compete with other ones to become a (sub)optimal solution returned by the decentralized algorithm.

4. Description of proposed microgrid distributed control logic algorithm

The general idea of the proposed approach of decentralized determination of operating points in a microgrid is based on a quite simple heuristic algorithm belonging to the family of Monte Carlo methods. At the same time we also want to take advantage of the cooperative control approach, in case of which each group of devices (in our case: energy storages, non-controllable microsources, controllable microsources and controllable loads) will be managed by a group controller, which is responsible for calculating and setting the operating points of all devices belonging to the group. In our approach we want each group controller to sum all power generation or power consumption capabilities of the devices which it is in charge of and to generate a set of candidate solutions which cover uniformly the range of power generation or power consumption capabilities of the group treated as a whole. Within this process only active powers need to be taken into account – because the values of power factors are fixed for all devices, reactive powers will always be determined automatically. Each group controller cares only about the devices composing its own group – it treats devices belonging to other groups as the ones, for which the operating points have been already optimized and set by other group controllers. All group controllers perform such computations one-by-one, in a synchronized or a non-synchronized manner. Synchronization is not necessary. However, taking into account that the whole approach is an iterative one – many invocations of the algorithm on all group controllers are needed to obtain the (sub)optimal solution, it can speed up the whole optimization process. After some number of algorithm iterations on all group controllers a balance point should be achieved and the (sub)optimal solution should be found.

The details on how a single group controller creates its candidate solutions set is illustrated in Fig. 6. Let us assume the group of devices consists of N devices. First it sorts them according to their power generation/power consumption capabilities. Then it divides the whole group into K separate subgroups. After that, $(K \times L) + 2$ candidate solutions are generated, L for each subgroup. The numbers K and L should be chosen arbitrarily, independently of the value of the parameter N. Subgroups are processed in order, one-by-one, beginning from the subgroups containing the devices with the biggest capabilities and ending with the subgroups containing the "smallest" devices. When generating L candidate solutions for the subgroup with index k, all devices belonging to the subgroups with indices lower than k must work with their full power generation/power consumption capabilities, while all devices belonging to the subgroups with indices greater than k must be turned off. Devices belonging to the subgroup k work with a fraction of their full potential. In case of each of L candidate solutions we generate operating points for these devices in a totally random way. At the end of the candidate solutions generation procedure we also add two special solutions to the whole candidate set – the one where all devices belonging to the group are turned on and work with their full potential and the one where all devices are turned off. After the generation part, all $(K \times L) + 2$ solutions need to be evaluated. Different objective functions are possible. We propose 7 different functions. The feasibility of candidate solutions is checked by power flow calculations procedure performed with the use of Newton-Raphson method. The best candidate solution is chosen as the (sub)optimal one for the group. The operating points are then applied on the physical devices composing the group.

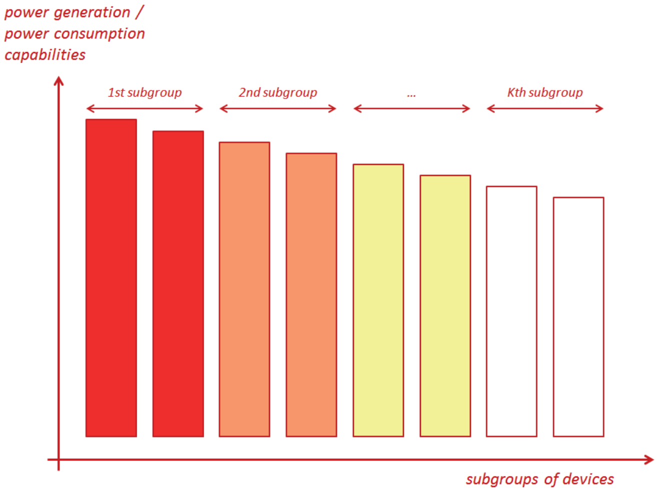


Fig. 6. An illustration of the generation of candidate solutions set in case of a single group controller

The last question to consider is how often to invoke the optimization algorithm on a single group controller. We have already said that the same algorithm needs to be executed on each of the group controllers. The invocations on different group controllers do not need to be synchronized (of course they can be, but it is not required).

Many iterations consisting of single algorithm invocations for all group controllers (one invocation per group controller) are needed to achieve the balance point, when the final solution proposed by all group controllers will be one and the same (group controllers will somehow agree on the final solution). How many iterations will be needed to achieve this point and find the (sub)optimal solution? How often to invoke the algorithm on a single group controller? In the Fig. 7 three possible approaches are presented. Let's assume that the length of the optimization period is fixed and set to M minutes. We call the approach presented in the upper part of Fig. 7 the "initial-phase" approach. In case of this approach, at the beginning of each optimization period a fixed number of iterations is scheduled. We seek for the best possible solution in terms of its quality (objective function value) in each iteration. In case of two other approaches the optimization process is being conducted during the whole optimization period. We invoke the

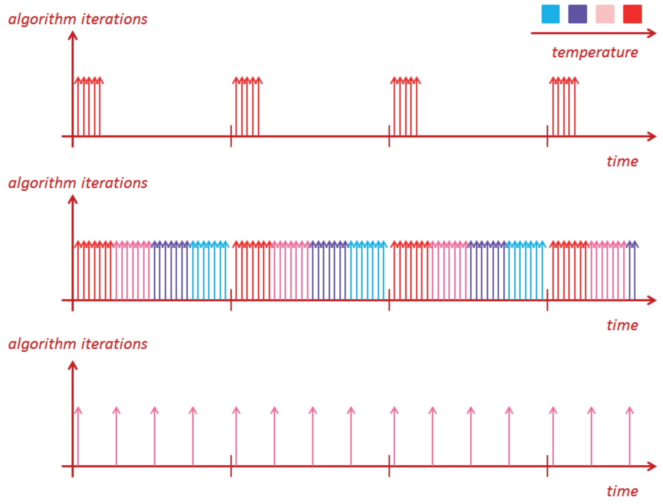


Fig. 7. An illustration of how often the optimization algorithm can be invoked on a single group controller. Top: initial-phase approach, middle: continuous-dense approach, bottom: continuous-sparse approach

optimization algorithm continuously at regular intervals. However, changing operating points all the time, turning the devices on and then after a while turning them off and then turning them on once again is not what we look for. We would rather like to calculate some set of (sub)optimal operating points at the beginning of the optimization period and then listen for some changes in the microgrid operational conditions (changing load demands, changing solar and wind generation capabilities) and be able to react to them. That is why instead of only looking at the value of the objective function, we can calculate some combined score which takes into account both the objective function value and the distance between the currently applied solution and the newly proposed ones. At the beginning of the optimization period the objective function value component is of a greater importance, while at the end the distance component should be much more significant. This pattern resembles the behavior known from the simulated annealing algorithm, with the relative importance of components playing the role of the temperature. The "continuous-dense" approach (presented in the middle part of Fig. 7) is the exact realization of the scheme described above. However, this approach can quickly become a "computation-heavy" one. An acceptable compromise can be a "continuous-sparse" approach (presented in the lower part of Fig. 7) – computations are performed during the whole optimization period, but the intervals between them are much longer. At the same time, we still calculate the score based on two separate components. In this approach, the temperature is stable and has the same value during the whole optimization period.

5. Scenarios of behavior of the microgrid control system in case of the communication loss

This section presents different scenarios of behavior of the microgrid control system (MCS) with respect to the communication failure. Details are presented in Fig. 8. It shows features of MC, MGCs, LCs and interrelations between them.

The proposed algorithm is based on two independent communication channels. The primary channel is used to control and gather information from LCs. The secondary channel is used to transmit data measured by independent grid analyzers. This approach ensures MCS may operate with full observability in case of the communication fault of a channel.

We may distinguish the following classes of the main group controllers:

- controllable generation units (CGU),
- controllable loads (CL),
- energy storage units (ESU),
- uncontrollable generation units (uCGU),
- uncontrollable loads (uCL),
- circuit breakers (CB).

Circuit breakers can be opened or closed remotely. Uncontrollable loads and generation units can be switched on or off, but generally under normal conditions, they follow their demand or generation profiles. Typical uncontrollable generation units are photovoltaic panels and wind turbine-generator sets.

In the event of losing the continuity of communication between particular groups of devices and between individual devices within the group we can distinguish several cases:

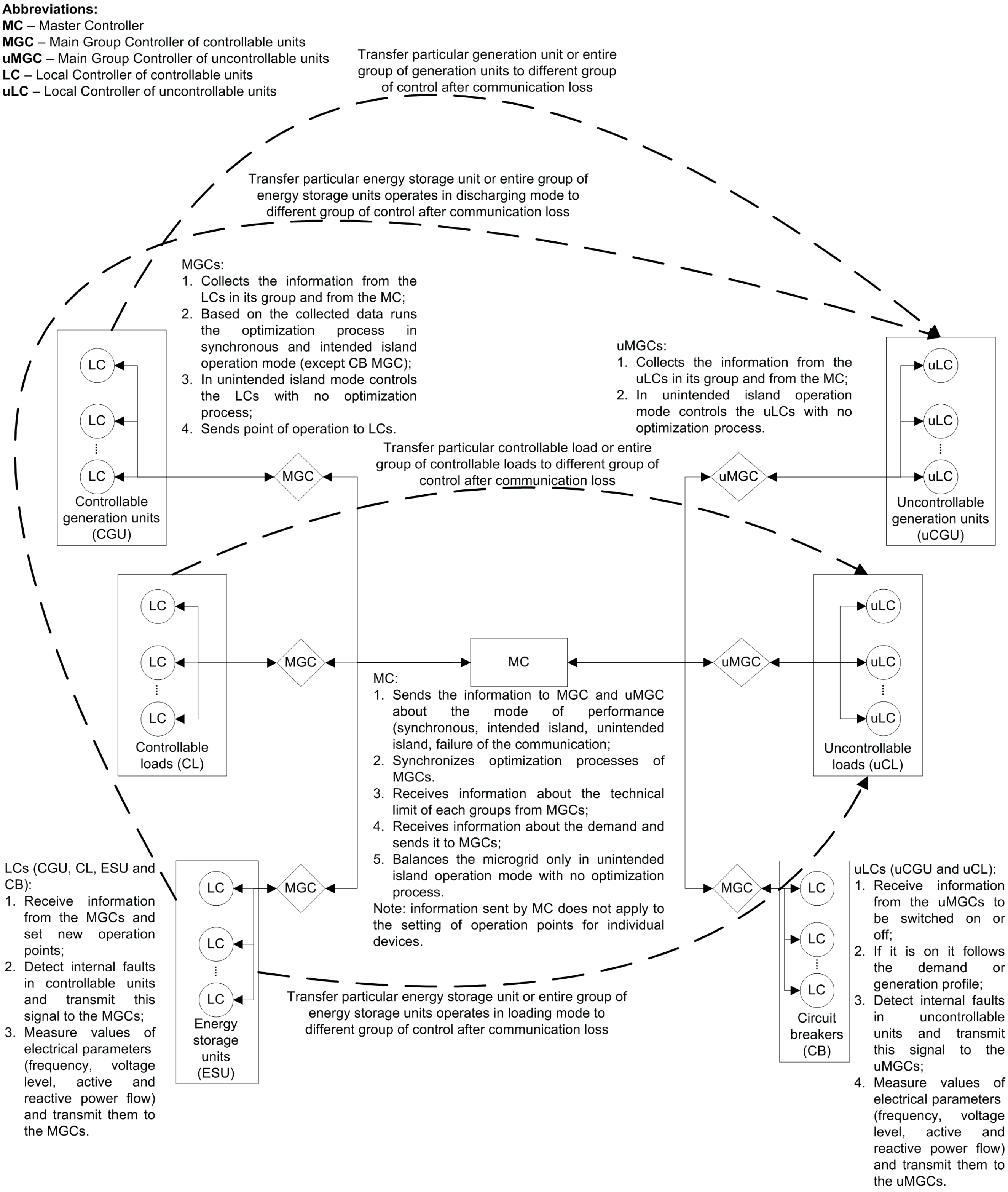
- uncontrollable LCs (uLCs),
- controllable LCs,
- uncontrollable MGCs (uMGCs),
- controllable MGCs,
- master controller – MC.

The loss of communication with uLCs and uMGCs changes the functioning of optimal control algorithm marginally. The only malfunction which happens during the communication failure is the disability of uLCs to be switched on/off remotely in the unintended island operation. Due to the fact that protection systems requirements (selectivity, sensitivity and timeous) are based on local parameters, the discussed case should not cause any problems during disturbances.

More complicated issues concerning communication losses occur when controllable LCs or MGCs are affected. The general rule of repair algorithms is a transfer of devices with broken communication to a different group of control. Details are presented in Table 1 and Fig. 8. When the controllable MGCs loses its communication with MC, repair algorithm is split into two different modes of operation. The first mode is activated when the duration of communication loss is shorter then optimization period. In this mode, MGC tries to optimize each LC in its group based on the last data received from MC. Otherwise, if the duration of communication loss is greater than optimization period a second mode of operation is activated – each LC in a group with failed MGC follows the transfer pattern given in Table 1 and Fig. 8.

Despite the lack of communication with selected objects, the optimization process can proceed. However, the objective function value may not be as accurate as in the case when the communication is fully operative.

Another failure, which may happen, is the loss of connection between all MGCs and MC. In such a case optimization



Abbreviations:
MC – Master Controller
MGC – Main Group Controller of controllable units
uMGC – Main Group Controller of uncontrollable units
LC – Local Controller of controllable units
uLC – Local Controller of uncontrollable units

Transfer particular generation unit or entire group of generation units to different group of control after communication loss

Transfer particular energy storage unit or entire group of energy storage units operates in discharging mode to different group of control after communication loss

MGCs:
1. Collects the information from the LCs in its group and from the MC;
2. Based on the collected data runs the optimization process in synchronous and intended island operation mode (except CB MGC);
3. In unintended island mode controls the LCs with no optimization process;
4. Sends point of operation to LCs.

uMGCs:
1. Collects the information from the uLCs in its group and from the MC;
2. In unintended island operation mode controls the uLCs with no optimization process.

Transfer particular controllable load or entire group of controllable loads to different group of control after communication loss

MC:
1. Sends the information to MGC and uMGC about the mode of performance (synchronous, intended island, unintended island, failure of the communication;
2. Synchronizes optimization processes of MGCs.
3. Receives information about the technical limit of each groups from MGCs;
4. Receives information about the demand and sends it to MGCs;
5. Balances the microgrid only in unintended island operation mode with no optimization process.

Note: information sent by MC does not apply to the setting of operation points for individual devices.

LCs (CGU, CL, ESU and CB):
1. Receive information from the MGCs and set new operation points;
2. Detect internal faults in controllable units and transmit this signal to the MGCs;
3. Measure values of electrical parameters (frequency, voltage level, active and reactive power flow) and transmit them to the MGCs.

Transfer particular energy storage unit or entire group of energy storage units operates in loading mode to different group of control after communication loss

uLCs (uCGU and uCL):
1. Receive information from the uMGCs to be switched on or off;
2. If it is on it follows the demand or generation profile;
3. Detect internal faults in uncontrollable units and transmit this signal to the uMGCs;
4. Measure values of electrical parameters (frequency, voltage level, active and reactive power flow) and transmit them to the uMGCs.

Fig. 8. Structure and functionalities of MCS

process could be less accurate. An unintentional island mode is impossible to last and an intentional island mode as well as a synchronous mode of operation may last. The accuracy of the optimization process (and possible balance) depends on the ramps demand and generation by uCGU.

To sum up, the cooperative control is more robust than the centralized one in case of communication faults. The proposed repair algorithms allow for the continuation of optimization process while different layers of control structure are affected.

Table 1
Transfer to different group of control after communication loss

Before the loss of communication	After the loss of communication
controllable generation units	uncontrollable generation units
controllable loads	uncontrollable loads
energy storage systems (charging)	uncontrollable loads
energy storage systems (discharging)	uncontrollable generation units

6. Case study

6.1. Description of a test microgrid. To evaluate the correctness and efficiency of the proposed approach some calculations have been made with the use of a sample test microgrid located in a typical countryside (see Fig. 9). The test microgrid has already been described in detail in the paper [31], where the main attention was given to methods based on the centralized control paradigm, and the current approach based on the decentralized control logic was discussed only very briefly. The test network consists of 22 non-controllable loads (farms with the total amount of demanded active power equal to 50.451 kW), 2 controllable loads (public utility buildings with the range of total demanded active power between 6.4 kW and 9.6 kW), one controllable microsource (with the active power generation capacity up to 49.0 kW), 7 non-controllable microsources making use of solar and wind energy (with the sum of the installed active power equal to 40.0 kW and the sum of active power generation capacities predicted for the time interval of making calculations equal to 17.413 kW) and one energy storage (with possible operating points between charging 20 kW of active power and discharging 20 kW of active power). All devices work with constant $\tan(\varphi)$ factors – in case of all non-controllable microsources and the energy storage the factor is equal to 0.0, while for other devices it takes some positive values (power factor $\tan(\varphi)$ equal to 0.395 for each load and power factor $\tan(\varphi)$ equal to 0.75 for controllable microsource). The optimization calculations were done for summer period (Wednesday, 12:00). We consider both the synchronous and island operation modes, as well as 7 different objective functions. The details on the specification of different objective functions and constraints have been already given in the paper [31].

6.2. Results of optimization calculations with the use of algorithm of distributed control logic. In the current discussion, we will focus on the minimization of active power losses and the maximization of profits (the difference between the sum of the revenues from selling the energy to customers and to the DSO network and the sum of costs related to generating the energy in microsources or purchasing the energy from the DSO network (also the distribution costs are included)). The feasibility of all the (sub)optimal solutions proposed by our distributed approach has been checked with the Newton-Raphson method for calculating power flows.

In Table 2 we can see the comparison of the objective function values obtained from the calculations based on both: the method based on the centralized control logic described in detail in [31] and the currently discussed decentralized algorithm. In case of the distributed algorithm the computations consisted of 10 iterations. In each iteration 4 group controllers have been invoked, always in the following order: controllable loads, controllable microsources, non-controllable microsources and energy storages. We assume, that the distributed algorithm works in its "initial-phase" variant, which is the simplest one, always seeking for the best quality solution. The starting point for the whole optimization process was the test microgrid with the controllable microsource working with the full power generation capacity, the energy storage working with the full power charging capacity, all controllable loads with their operating points in the middle of their possible power consumption ranges, half of the non-controllable microsources working with their full power generation potential and the other half of microsources turned off. We can see that for all the considered objective functions and operation modes the results are always almost exactly the same for both approaches being compared: the centralized algorithm and the distributed algorithm. Because the centralized

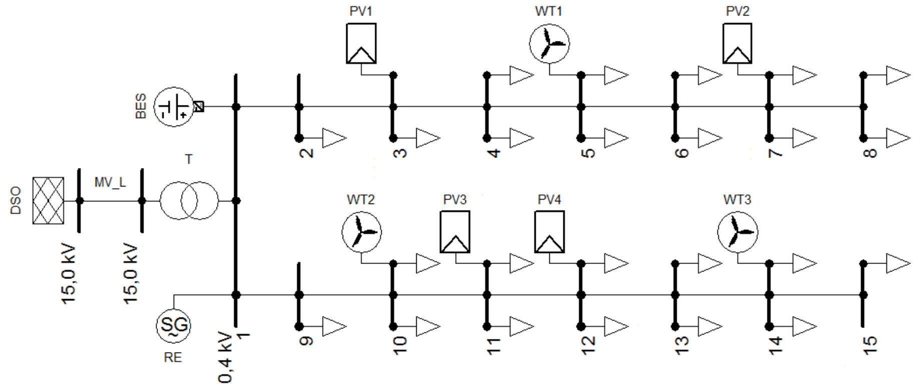


Fig. 9. Key diagram of the LV microgrid on a typical countryside (MV_L – MV overhead line, RE (SG) – reciprocating engine with internal combustion (engine-generator set), BES – battery energy storage, PV – photovoltaic panels, WT – wind turbine-generator set); elaborated on the basis of [31]

algorithm makes use of more sophisticated mechanisms, it is a more time-taking approach. It checks for a bigger number of possible solutions. We can then assume that the centralized algorithm is accurate. And since the results are the same, so is the distributed one. This way we can prove our distributed approach behaves in a proper way and yields correct results.

Table 2
The comparison of the results of optimization calculations for test microgrid in summer obtained with the use of centralized control logic and distributed control logic; based partially on [31]

Criterion function no.	Centralized control logic		Distributed control logic	
	Summer, Wednesday, 12:00		Summer, Wednesday, 12:00	
	Synchronous mode	Island mode	Synchronous mode	Island mode
1	0.000	–	0.000	–
2	7.087	–	7.087	–
3	0.764	0.776	0.764	0.776
4	4.353	4.353	4.353	4.353
5	0.000	5.054	0.000	5.054
6	4.613	5.450	4.613	5.451
7	2.787	1.940	2.787	1.940

In Table 3 we can see which operating points have been chosen by different group controllers for different objective functions and different operation modes. In a case of active power losses, to minimize them, the main motivation is to reduce the amount of energy transmitted over the different network branches and as a result to reduce the amount of energy consumed by all loads – that is why all controllable loads work always with their minimum operating points. Also, local energy sources are promoted over the DSO network – that is why all non-controllable microsources are turned on. In case of the island mode of operation we cannot make use of energy delivered by the DSO network anymore, so the usage of the controllable microsource and the energy storage is more prominent. In case of the maximization of profits the main motivation is to use cheaper sources of energy first – that is why all non-controllable microsources and the energy storage work with their full active power generation capabilities. In case of the synchronous mode of operation, the energy purchased from the DSO is cheaper than the one generated by the reciprocating engine (controllable microsource), so the import of the energy from the DSO network takes place. In case of the island operation mode we do not have this option. Also, in case of synchronous work with the DSO network, increasing the amount of energy purchased from the DSO to deliver this energy to the controllable loads is often profitable, but only to a point. After that point the additional profits will be lower than the costs resulting from the bigger level of active power losses.

In Fig. 10, 11 we can see how the objective function values changed over all optimization process iterations, when the chosen objective function was the minimization of active power losses and the test microgrid worked synchronously with the DSO network. In Fig. 10 all group controllers have been presented separately. In Fig. 11 the whole optimization process is presented as a single curve. However, also the second curve for the island mode of operation has been presented. The similar curves for the maximization of profits have been presented in Fig. 12 and 13. We can see that the minimization of active power losses is a little harder objective function to optimize. Also, in case of both objective functions 3 or 4 iterations (12–16 of distributed algorithm invocations) is usually enough for group controllers to reach and agree on the (sub) optimal solution.

We can see in Fig. 14 to 17 and 18 to 21 how the specific group controllers worked over time – which operating points they chose – for both objective functions and the synchronous mode of operation. For minimization of active power losses all non-controllable sources were turned on in the first iteration. Similarly, the amount of energy delivered to the controllable loads was reduced to the absolute minimum at the start. Over time we also observed the decreasing usage of the controllable microsource and the gradual switch of the operation mode of the energy storage – from charging to the discharging. In the case of the maximization of profits, the group controllers decided to increase the usage of cheaper energy sources (non-controllable microsources and the energy storage) to the maximum at the start. However, setting the right operating points for other groups of devices was a little harder.

Table 3
Operating points chosen for groups by respective group controllers – the comparison for different objective functions and operation modes

Criterial function, operation mode	Controllable loads active power	Controllable microsources active power	Non-controllable microsources active power	Energy storages active power	Active power imported from the DSO network	Total active power losses	Objective function value
Active power losses, synchronous	6.400000	25.719077	17.413000	−10.866746	3.616462	0.764	0.764399
Active power losses, island	6.400000	26.076424	17.413000	−14.133197	0.000000	0.776	0.775676
Profits, synchronous	7.517190	0.000000	17.413000	−20.000000	21.639229	1.084	2.787106
Profits, island	6.400000	20.215482	17.413000	−20.000000	0.000000	0.782	1.939689

Notes: Negative sign (minus) in case of energy storage active power means that this unit is in discharging mode; active power values as well as active power losses values are given in [kW].

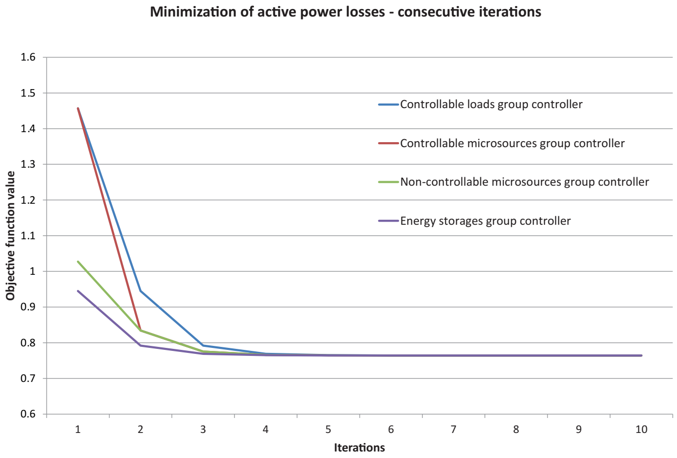


Fig. 10. The illustration of the process of optimizing the objective function value by different group controllers. All group controllers shown separately. Minimization of active power losses chosen as an objective function

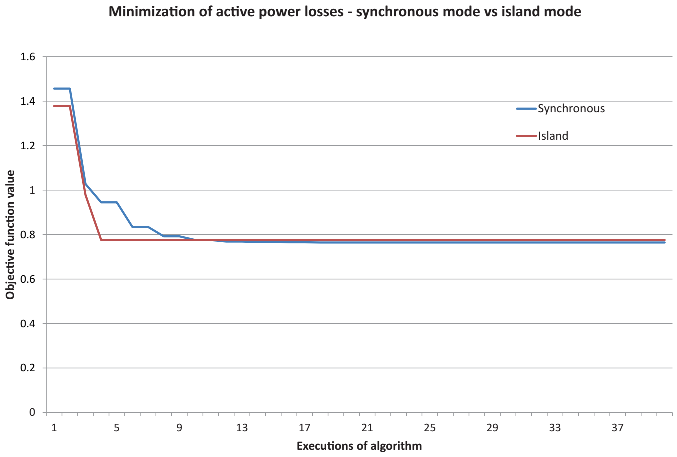


Fig. 11. The illustration of the process of optimizing the objective function value. The efforts of all group controllers shown together with a single curve. Minimization of active power losses chosen as an objective function. Two different operation modes considered: synchronous one and island one

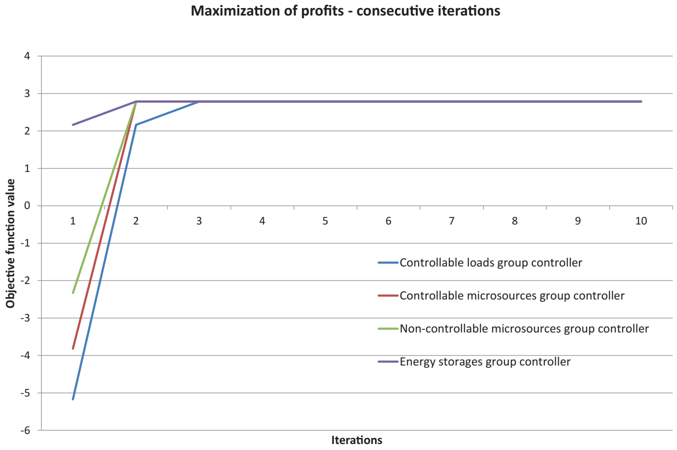


Fig. 12. The illustration of the process of optimizing the objective function value by different group controllers. All group controllers shown separately. Maximization of profits chosen as an objective function

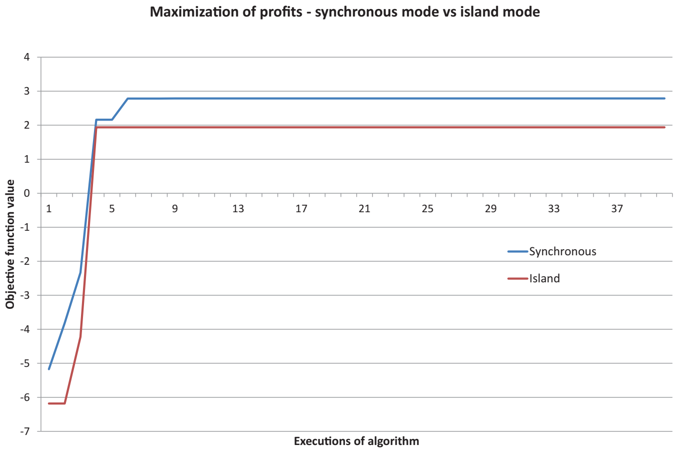


Fig. 13. The illustration of the process of optimizing the objective function value. The efforts of all group controllers shown together with a single curve. Maximization of profits chosen as an objective function. Two different operation modes considered: synchronous one and island one

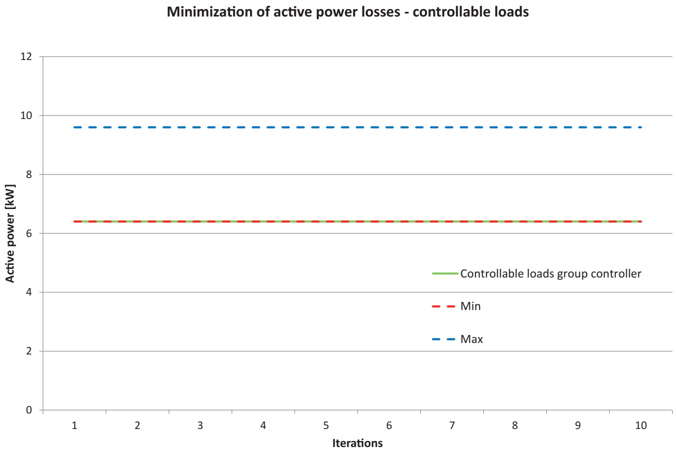


Fig. 14. The operating point chosen for the group of controllable loads by respective group controller. Minimization of active power losses chosen as an objective function

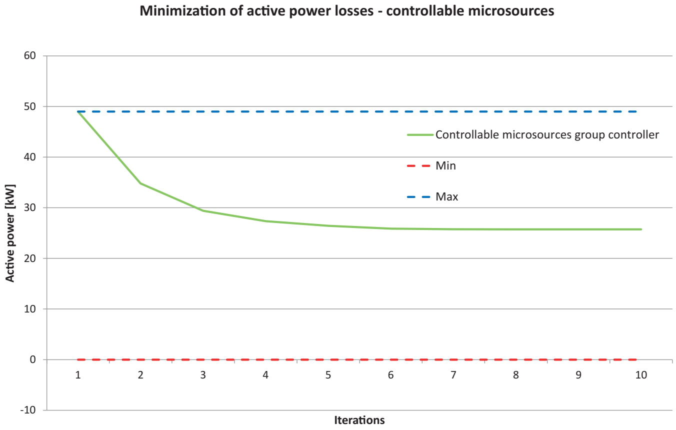


Fig. 15. The operating point chosen for the group of controllable microsources by respective group controller. Minimization of active power losses chosen as an objective function

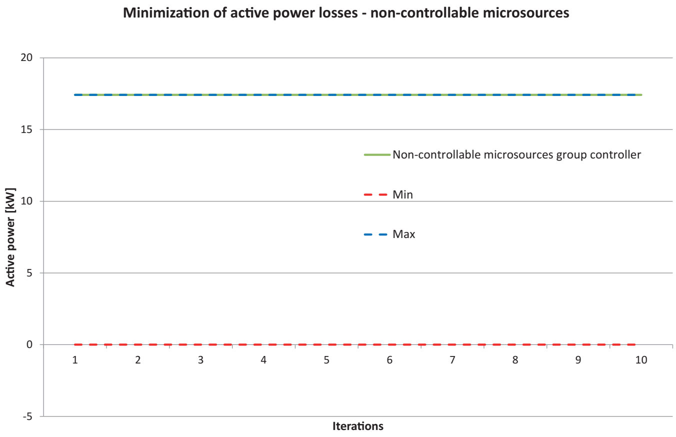


Fig. 16. The operating point chosen for the group of non-controllable microsources by respective group controller. Minimization of active power losses chosen as an objective function

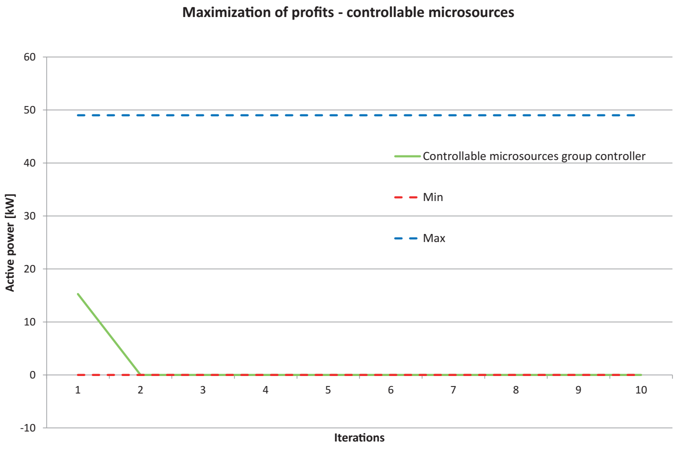


Fig. 19. The operating point chosen for the group of controllable microsources by respective group controller. Maximization of profits chosen as an objective function

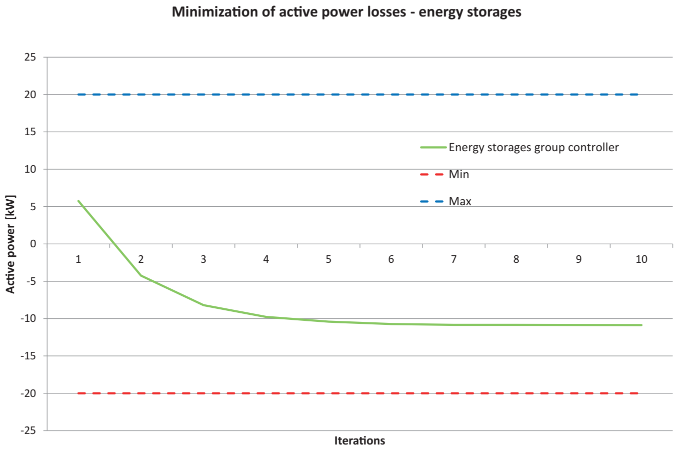


Fig. 17. The operating point chosen for the group of energy storages by respective group controller. Minimization of active power losses chosen as an objective function

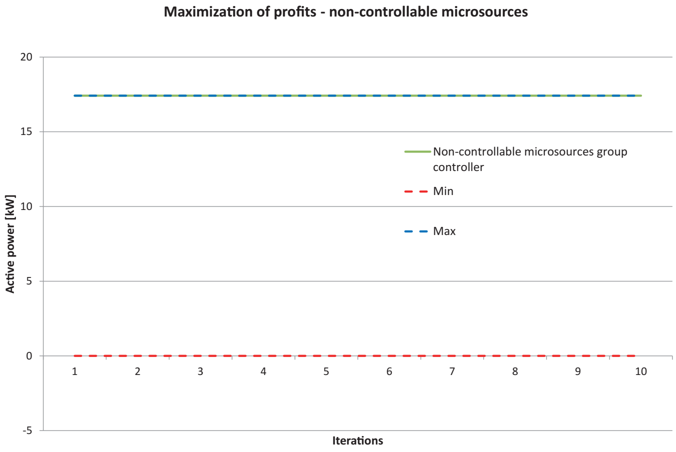


Fig. 20. The operating point chosen for the group of non-controllable microsources by respective group controller. Maximization of profits chosen as an objective function

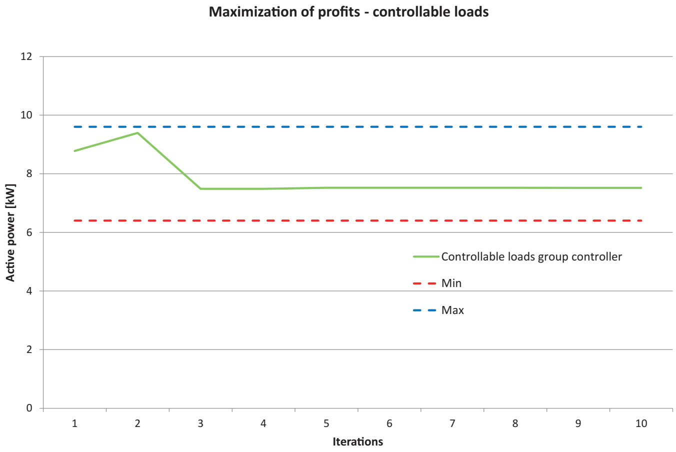


Fig. 18. The operating point chosen for the group of controllable loads by respective group controller. Maximization of profits chosen as an objective function

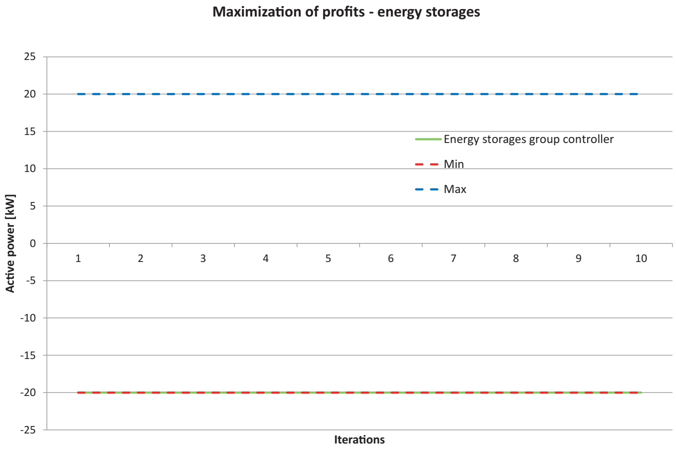


Fig. 21. The operating point chosen for the group of energy storages by respective group controller. Maximization of profits chosen as an objective function

We have also decided to study more advanced aspects of our decentralized approach. First, the impact of different group devices orderings (in which order the groups calculate their (sub)optimal operating points) on the speed of the optimization process has been analyzed. The results have been illustrated in Fig. 22 and 23. The most important finding is that no matter what the ordering is, the time of 3 or 4 iterations (12–16 of distributed algorithm invocations) is still enough to find the eventual solution. We can also see that the ordering in which the Energy Storages group comes first seems to be faster than the others, but we have too little evidence to treat is as a definite rule – some further research is necessary.

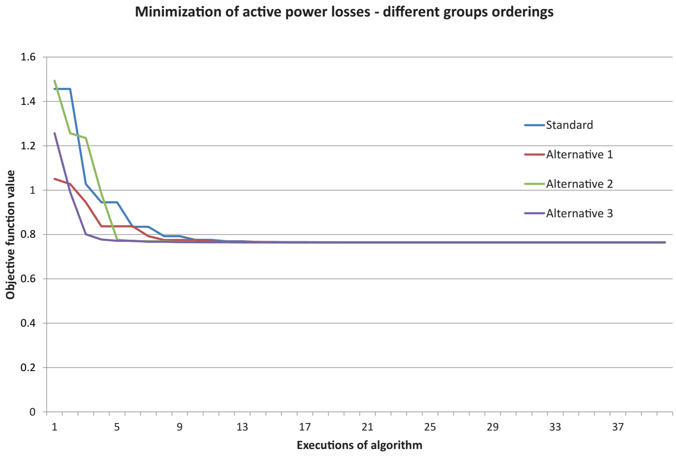


Fig. 22. The illustration of the process of optimizing the objective function value. The efforts of all group controllers shown together with a single curve. Minimization of active power losses chosen as an objective function. The comparison for different group orderings

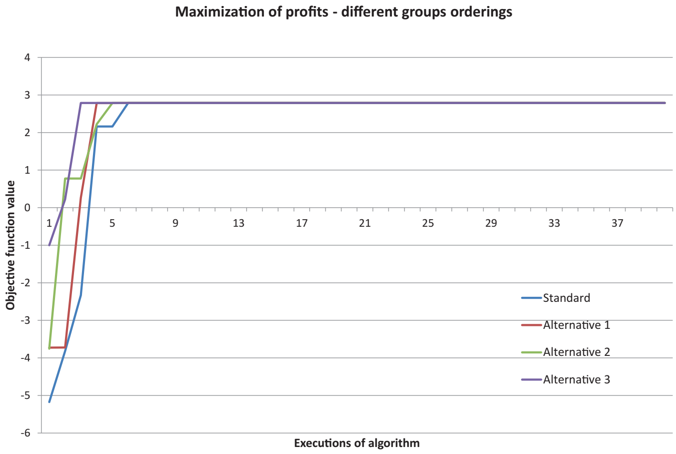


Fig. 23. The illustration of the process of optimizing the objective function value. The efforts of all group controllers shown together with a single curve. Maximization of profits chosen as an objective function. The comparison for different group orderings

Moreover, we also have investigated the scenario when one of the groups was losing the communication with all other groups and as a result was neither able to send nor to receive the information on the currently applied operating points. The results are displayed in Fig. 24 and 25. We have a common curve for all group controllers (40 consecutive algorithm invocations). The assumption is that the communication is lost during the iterations from 2 to 5. In the iteration no. 6 the communication is back and all group controllers can talk to each other without any problems. For both the minimization of active power losses and the maximization of profits we can observe some characteristic cycles for iterations from 2 to 5 (algorithm invocations from 5 to 20). Within such cycles all properly communicating with one another groups have their own single operating point (and the corresponding objective function value). The operating point (and the corresponding objective function value) of

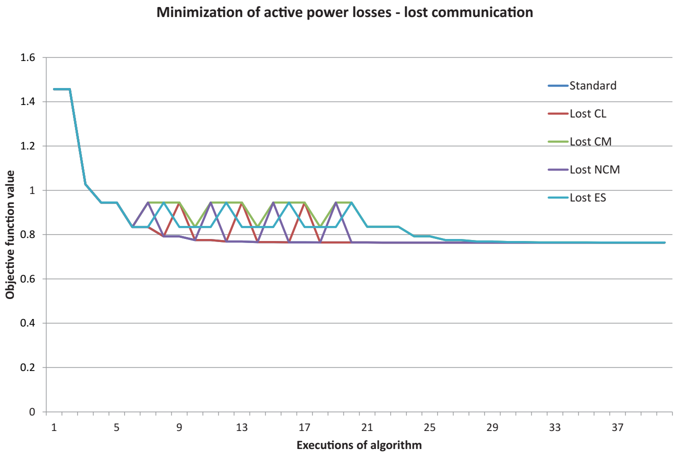


Fig. 24. The illustration of the process of optimizing the objective function value. The efforts of all group controllers shown together with a single curve. Minimization of active power losses chosen as an objective function. The comparison for different experiments, when different group controllers lose the communication with all other groups during the iterations from 2 to 5

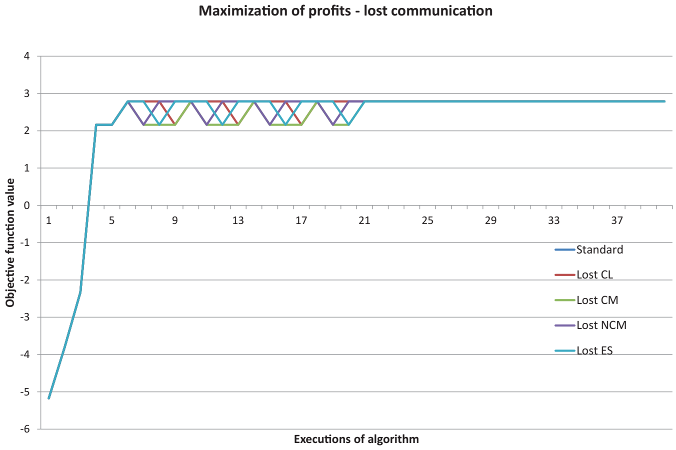


Fig. 25. The illustration of the process of optimizing the objective function value. The efforts of all group controllers shown together with a single curve. Maximization of profits chosen as an objective function. The comparison for different experiments, when different group controllers lose the communication with all other groups during the iterations from 2 to 5

the isolated group is different. What is interesting, none of these operating points is the one that is actually applied to the devices at that moment – no group has a full and true overview of what is happening in all devices within the network. What is more, we can see the optimization potential is locked during those cycles. When the communication is back this potential becomes unlocked and further improving of the objective function values is possible.

Last but not least, we have also decided to analyze the impact of the uncertainty of predictions of demanded active power levels of controllable and non-controllable loads and active power levels generated by non-controllable microsources. It is worth recalling that we have made an assumption that our test microgrid makes use of the "initial-phase" variant of the decentralized algorithm. It means all calculations are made only at the beginning of every 15-minute-long optimization period (this time interval is arbitrary and may be shorter if needed) and once applied they will not change during that period. It means when making the computations we do not know the true values of demanded active power levels and active power levels generated by photovoltaic power plants and wind turbine-generator sets. We need to rely on predictions and these, sometimes, are not very precise. That is why we have decided to check what will happen when we change all predicted values (for 24 loads and 7 non-controllable microsources) by at most 20% in a random way. We can observe the results in Tables 4 and 5. We can see that even if the predictions are a little bit different for single devices, the operating points chosen by group controllers remain more or less the same.

6.3. Results of optimization calculations proving the stability of the algorithm. In order to prove the reliability and stability of our algorithm we decided to make two additional experiments. Our intention here was to analyze the impact of some unexpected and accidental changes of the microgrid's work conditions on the functioning of our algorithm.

In the first experiment we analyze a situation when a short-circuit takes place in one of the lines of our sample microgrid (somewhere in the upper half – upper feeder of the microgrid). We assume here that during the experiment the microgrid operates in the island mode. As a result, the protection systems of the microgrid start to work and the whole upper half of the

Table 4
Operating points chosen for groups by respective group controllers for different sets of predictions of demanded active power for loads and weather conditions for non-controllable microsources; the minimization of active power losses chosen as an objective function

Active power losses	Non-controllable loads requested active power	Controllable loads min requested active power	Controllable loads max requested active power	Non-controllable microsources max active power	Controllable loads active power	Controllable microsources active power	Non-controllable microsources active power	Energy storages active power	Objective function value
Standard	50.450933	6.400000	9.600000	17.413000	6.400000	25.719077	17.413000	−10.866746	0.764399
Alternative 1	52.513632	6.157218	9.354789	18.884147	6.157218	26.386413	18.884147	−10.706908	0.805831
Alternative 2	52.203232	7.305418	9.759093	16.197076	7.305417	27.643244	16.197076	−12.426787	0.881627
Alternative 3	52.803455	6.691778	11.214232	17.048570	6.691778	27.376252	17.048570	−11.960431	0.842023

Table 5
Operating points chosen for groups by respective group controllers for different sets of predictions of demanded active power for loads and weather conditions for non-controllable microsources; the maximization of profts chosen as an objective function

Profits	Non-controllable loads requested active power	Controllable loads min requested active power	Controllable loads max requested active power	Non-controllable microsources max active power	Controllable loads active power	Controllable microsources active power	Non-controllable microsources active power	Energy storages active power	Objective function value
Standard	50.450933	6.400000	9.600000	17.413000	7.517190	0.000000	17.413000	−20.000000	2.787106
Alternative 1	52.513632	6.157218	9.354789	18.884147	8.694338	0.000000	18.884147	−20.000000	2.983249
Alternative 2	52.203232	7.305418	9.759093	16.197076	8.882640	0.000000	16.197076	−20.000000	2.648194
Alternative 3	52.803455	6.691778	11.214232	17.048570	8.483295	0.000000	17.048570	−20.000000	2.757713

sample microgrid becomes disconnected. We are particularly interested here in the situation when such a short-circuit event happens between the consecutive iterations of the optimization process making use of our distributed algorithm. If such a situation takes place before or after the start of the algorithm, there is nothing new in such a scenario. It is fully equivalent to performing optimization calculations for another microgrid of slightly different topology and different choice of devices. It is much more interesting to see how the algorithm behaves when such a serious change of topology takes place in the middle of our calculations (in our scenario the change starts after the 5. and before the 6. iteration of our algorithm and lasts up till the end of the calculations).

In Fig. 26, 27, 28, and 29 we can see how the value of the objective function changes both from the perspective of the whole microgrid and particular group controllers. We conducted separate experiments for both objective functions: the minimization of active power losses and the maximization of profits. In case of the minimization of active power losses we can see that after the short-circuit event the algorithm converges to some (sub)optimal solution which is better than the one before the incident. There is nothing surprising here – after half of the microgrid (upper feeder) becomes disconnected also a half of the loads cannot be supplied with electricity anymore (further we care only about the half of the grid – lower feeder in which no short-circuits happened), so the total amount of energy to be delivered is lower and the total sum of active power losses becomes lower as well. In case of the maximization of profits all the group controllers are also able to agree on some new common (sub)optimal solution after the short-circuit takes place. Here the new solution is worse, but it could be better as well – everything depends on the actual topology and the proportion of the lost generation capabilities from the renewable energy sources in comparison

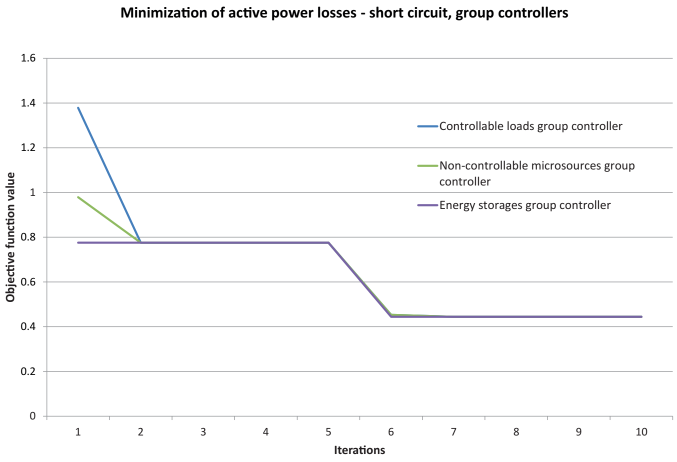


Fig. 26. The illustration of the process of optimizing the objective function value by different group controllers. All group controllers shown separately. Minimization of active power losses chosen as an objective function. The comparison for short-circuit in island mode

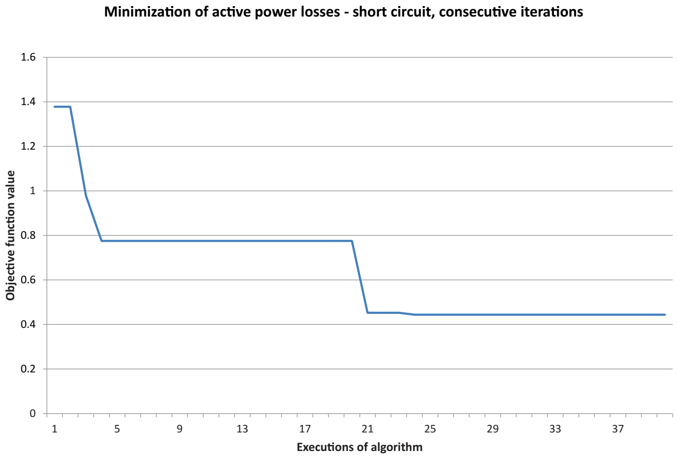


Fig. 27. The illustration of the process of optimizing the objective function value by different group controllers. The efforts of all group controllers shown together with a single curve. Minimization of active power losses chosen as an objective function. The case of short-circuit in island mode

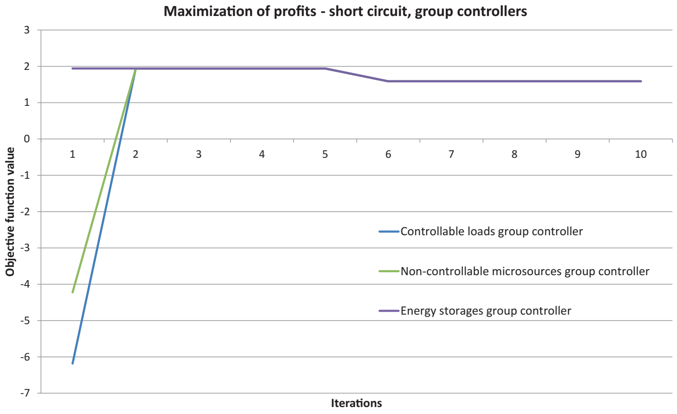


Fig. 28. The illustration of the process of optimizing the objective function value by different group controllers. All group controllers shown separately. Maximization of profits chosen as an objective function. The comparison for short-circuit in island mode

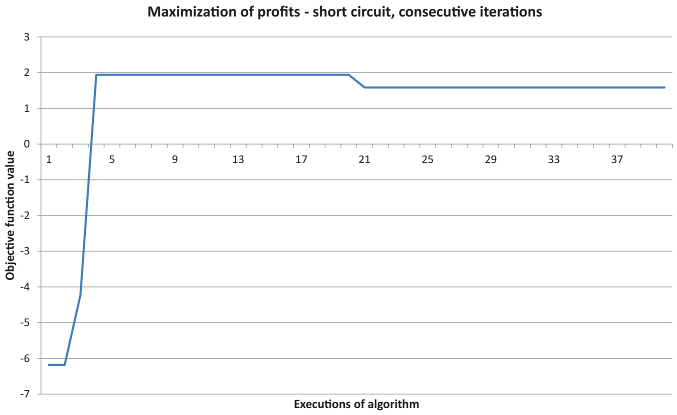


Fig. 29. The illustration of the process of optimizing the objective function value by different group controllers. The efforts of all group controllers shown together with a single curve. Maximization of profits chosen as an objective function. The case of short-circuit in island mode

to the total amount of energy that should be received by all the disconnected loads, but after the incident does not need to be delivered. We assume here, that such a random unpredictable event does not lead to any obligation of paying any penalties to the end consumers. When we take a look at the operating points chosen by particular group controllers (figures not present here because of the limited space) we can see that in case of both objective functions right from the start up till the end all the controllable loads work at their minimum consumption capabilities, while all the currently available non-controllable energy sources are turned on. In case of the minimization of active power losses it results from the fact that we need to minimize the amount of energy being conveyed and to promote the local generation of energy. In case of profits it results from the fact that the energy generated by the reciprocating engine is the most expensive one, so we need to decrease the total consumption of energy as much as possible and also try to make use of cheaper energy (from renewable energy sources) first. The missing part of the energy will be always provided by both the reciprocating engine and the energy storage. In case of the minimization of active power losses it does not matter which of the devices will produce the missing energy (only the distance between the generation and the consumption matters), while in case of the maximization of profits the energy storage is always prioritized (works at its maximum both before and after the incident) as the cheaper one.

The second experiment considers a situation when because of some random unpredictable situation we lose some big fraction of devices of the same type (loads or microsources). Here we analyze a scenario when during the execution of the distributed algorithm (more interesting dynamic scenario) clouds appear on the sky and all the photovoltaic panels stop to produce any energy (between the iterations no. 4 and no. 7 inclusively). In Figs. 30, 31, 32, and 33 we can see how the value of the objective function behaves. For both objective functions first we always find some (sub)optimal solution, then during the incident we switch to some other, always worse one and then we switch back to the original solution. The solution during the incident

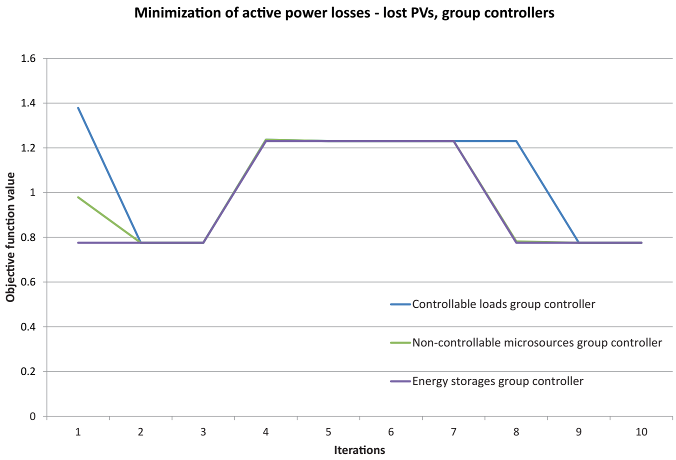


Fig. 30. The illustration of the process of optimizing the objective function value by different group controllers. All group controllers shown separately. Minimization of active power losses chosen as an objective function. The comparison for lost PVs in island mode

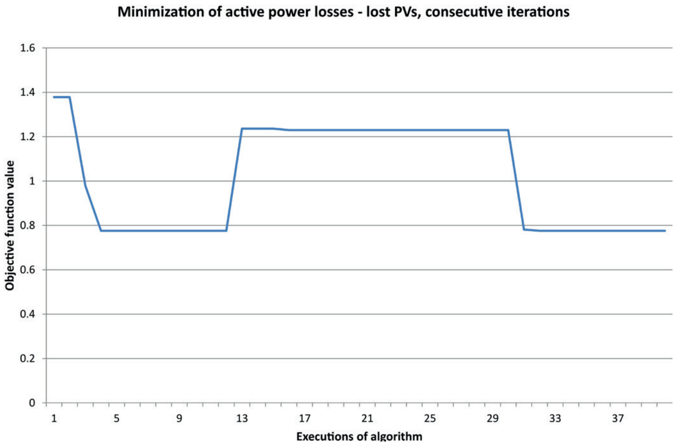


Fig. 31. The illustration of the process of optimizing the objective function value by different group controllers. The efforts of all group controllers shown together with a single curve. Minimization of active power losses chosen as an objective function. The case of lost PVs in island mode

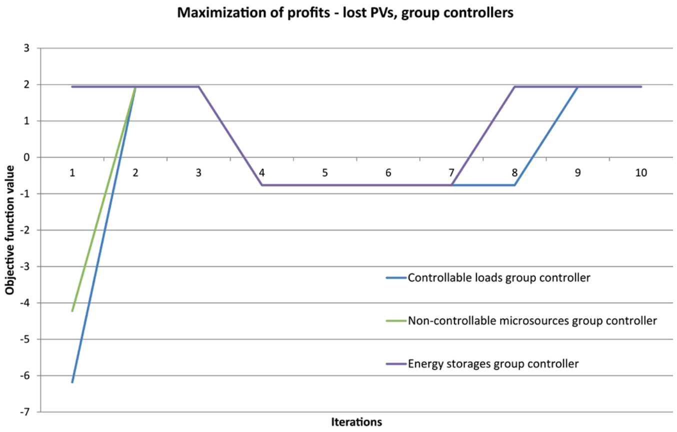


Fig. 32. The illustration of the process of optimizing the objective function value by different group controllers. All group controllers shown separately. Maximization of profits chosen as an objective function. The comparison for lost PVs in island mode

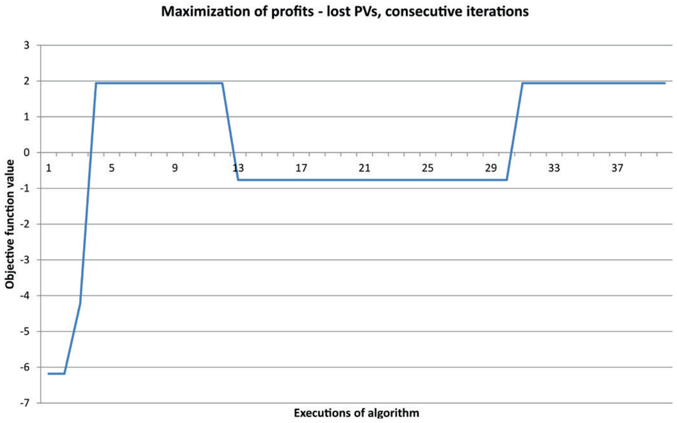


Fig. 33. The illustration of the process of optimizing the objective function value by different group controllers. The efforts of all group controllers shown together with a single curve. Maximization of profits chosen as an objective function. The case of lost PVs in island mode

is always worse because there is no possibility to make use of some cheap energy from the local microsources situated close to the places of the consumption. The analysis of the operating points chosen by particular group controllers (also not shown here for the sake of limited space) exposes generally the same behavior that could be observed in the previous experiment.

7. Summary and conclusion

In the paper we have presented a distributed method of determination of (sub)optimal operating points for devices composing a microgrid. The algorithm itself is rather not complicated – applied logic, similar to the ones known from Monte Carlo methods, is much simpler than in many other more sophisticated centralized approaches. The results obtained for our decentralized algorithm have been compared to the ones produced by a centralized method. We can see that in all cases the objective function values are exactly the same. We have analyzed the functioning of the decentralized algorithm in detail. Apart from the standard behavior we have tested different additional scenarios: a variant when the communication between group controllers is lost, a variant when the predictions of both the demands for active power and the solar and wind generation are not precise and a variant when the order in which group controllers execute the algorithm is chosen in a totally random way.

We have described and presented typical load and generation profiles and their characteristics. The knowledge of detailed daily profiles of all loads composing a microgrid together with daily profiles of wind and solar energy which is expected to be generated by different types of renewable energy sources which are possible to be installed can help to choose the right set of devices and design a microgrid in such a way, that its exploitation can be more effective and cheaper. If exact profiles are not known in advance, some typical profiles known from the literature can be used instead. The knowledge of load and generation profiles also helps in the task of predicting both the demands for active power and the generation capabilities of microsources for a specific future point in time. It is needed for many algorithms to work properly, especially when the set of operating points is being calculated in advance for a future optimization time period.

Having precise predictions on the total demanded active power and the active power which can be generated from the different renewable energy sources for sure helps in determination of the set of (sub)optimal operating points for every single existing microgrid. However, in case of our distributed algorithm we have proved that even if all predictions are not very precise and differ from the true (accurate) values by around 20%, the set of calculated operating points remains more or less the same. It shows that our algorithm is not very sensitive to the precision of the predictions.

Our studies on the potential loss of communication between the different group controllers show that establishing reliable communication between the entities is necessary to fully optimize the value of the chosen objective function. However, even without the possibility to exchange messages between one of the group controllers and all others, the process of optimizing the objective function value can still take place, at least to some point. When the communication is back, the distributed algorithm unlocks the optimization potential which could not be utilized during the communication loss period. Knowing the difference between the objective function values which can be achieved with and without the properly working communication network, the designer of the microgrid can choose if it is more beneficial to invest heavily in the reliable communication infrastructure or to accept that during some communication network failures the algorithm will choose a little worse set of operating points.

In our opinion, the cooperative control is more robust than the centralized one in case of communication faults. The proposed repair algorithms allow for the continuation of the optimization process while different layers of control structure are affected.

We have also showed that the choice of the order in which different group controllers make their calculations can be chosen randomly in case of our distributed algorithm. The final value of the objective function will still be more or less the same. However, in case of some orders the optimization process will be complete faster. Proper synchronization of executions of the algorithm on different entities can speed up the optimization process if time constraints are very strict.

Two additional, carried out experiments (the simulation of a short-circuit in one feeder of the test microgrid and the simulation of a loss of power generated by all photovoltaic panels in this microgrid) proved the reliability and stability of our algorithm.

In the future, a further research should be mostly focused on some further and more detailed investigation of the communication problems of different types.We have analyzed the situation of communication loss, but for example we have not taken into account the issue of communication delays (for example the situation when operating points from other group controllers are known, but always only from the previous iteration, not from the current one). Also, our current approach relies strongly on the assumption that the values of all power factors are constant, so the optimization problem becomes a one-dimensional one (only the optimization of active power is needed). The natural extension of our method will be partial or total giving up of this assumption and finding out how to generate candidate solutions with different and desirable values of reactive power in a smart way.

In our current approach we did not consider the problem of many separate entities (owners of generating units and energy storage units) with different goals. This issue can be an interesting subject of any further research related to the problem of optimization of microgrid operation in rural areas.

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