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Optimal operation control of low voltage microgrids in rural areas functioning on the basis of centralized control logic

***Abstract**. The paper presents a problem of optimal operation control of low voltage microgrids in rural areas, functioning on the basis of centralized logic control. In this work a short description of low voltage microgrid, with a special focus on the solutions typical for rural areas, will be carried out. Then the issue of the selection of optimal operating states of individual elements of microgrid will be described. In particular, the formulation of optimization criteria, together with the associated constraints will be given. In the next part of the paper an exemplary microgrid control algorithm will be presented. The developed algorithm will be based on the centralized control logic and PSO optimization algorithm. In the remaining part of the work the possible way of implementing the developed control algorithm will be described. In the final part of the paper a summary and conclusions will be presented.*

***Streszczenie.** W artykule przedstawiono problem optymalnego sterowania pracą mikrosieci niskiego napięcia na terenach wiejskich, funkcjonującej w oparciu o logikę sterowania scentralizowanego. W pracy zostanie dokonany krótki opis mikrosieci niskiego napięcia, ze zwróceniem szczególnej uwagi na rozwiązania typowe dla obszarów wiejskich. Następnie zostanie opisane zagadnienie wyboru optymalnych stanów pracy poszczególnych elementów mikrosieci. W szczególności zostaną przedstawione kryteria optymalizacyjne razem z towarzyszącymi im ograniczeniami. W następnej części artykułu zostanie zaprezentowany przykładowy algorytm sterowania mikrosiecią. Opracowany algorytm będzie oparty na logice sterowania scentralizowanego oraz metodzie PSO. W pozostałej części pracy zostanie opisany możliwy sposób implementacji komputerowej opracowanego algorytmu sterowania. W końcowej części artykułu zostanie przedstawione podsumowanie i wnioski. (**Optymalne sterowanie pracą mikrosieci niskiego napięcia na obszarach wiejskich funkcjonujących w oparciu o logikę sterowania scentralizowanego**).*

Keywords: low voltage microgrid; optimal operation control; PSO algorithm; rural areas; centralized control logic.
Słowa kluczowe: mikrosieć niskiego napięcia, optymalne sterowanie pracą, algorytm PSO, obszary wiejskie, logika sterowania scentralizowanego.

Introduction

Low voltage microgrid is the autonomous power generation and distribution micro-system [1], in which there are sources of electricity and heat (microsources – MS), electricity storage units (ES) and heat storage unites (HS), controllers (power electronics converters), heat recovery devices, as well as electricity loads and heat loads. Among electricity storage units we can distinguish: battery energy storages, super (ultra) capacitors and flywheels. Electricity loads can be divided into non-controllable loads (NCL) and controllable loads (CL). Most of MSs, ESs and CLs are integrated with microgrids via the specialized power electronics interfaces. The concept of the microgrid has been presented in many literature sources, among others in [1-6].

These micro-systems can operate in synchronous (parallel) mode with distribution grids of electricity utilities, as well as in island mode. In both modes, setting the operating points of MSs, ESs and CLs is one of essential problems of control. To solve this problem it is necessary to develop proper control algorithms (strategies) [7-11]. In island mode of microgrid operation it is necessary to ensure a balance between generated and consumed electricity within this micro-system. These issues have been described e.g. in [12]. In [5, 13] optimization of operating points of microsources in order to minimize microgrid operation costs has been discussed in detail. In [13] another criteria – minimization of total active power losses in microgrid has been also presented. In turn the problem of exchange of electricity between microgrid and distribution grid of electricity utility has been formulated and solved in [5, 6, 14].

The optimization task, optimum control algorithm and general considerations concerning implementation of control algorithm have been presented in the paper in detail.

Description of Low Voltage Microgrids in Rural Areas

Very good characteristics of different kinds of microgrids has been presented in [15]. In case of AC microgrids one can distinguish the ones, which are physically connected to the grid of distribution system operator (DSO) and the ones, which are separated from the grid of DSO. Taking into consideration the range of possible applications of microgrids, their ownership structure and types of loads supplied by them, we can distinguish [15]: utility microgrids (directly connected to the public grid of DSO), industrial microgrids (working in industrial conditions), commercial microgrids (located in public utility buildings) and remote microgrids (functioning away from the public grid of DSO).

Microgrids connected to the network of DSO allow for big-scale integration of distributed energy sources (DES) and cogeneration sources (generating both electricity and heat) in distribution grids. They are able to satisfy locally the energy demands of the consumers and at the same time they make it possible to provide system services. In microgrids of this type the following kinds of microsources are usually used [15]: small hydro power plants, small wind turbine-generator sets, photovoltaic panels, power plants based on biomass and biogas, gas microturbines. Such microgrids can be located in rural areas. During the operation in synchronous mode they can offer system services, such as: providing reactive power and regulation of voltage levels in network nodes, as well as management of limitations concerning branches capacities in medium voltage networks of DSO. In turn, intended islanded operation has an impact on improvement of supply reliability of consumers that are connected to the microgrids.

They can be also used as self-standing systems aiming to supply with electricity the buildings and housing communities (for instance countrysides) situated away from publicly available grids (belonging to DSO) [15]. In remote microgrids the following kinds of microsources are most often to be seen: small hydro power plants, small wind turbine-generator sets, photovoltaic panels, gas (biogas) microturbines. In microgrids of such a type, microsources have to be chosen properly, so that the microgrid could be able to cover the total power demand, both in normal and fault conditions, which requires to ensure the appropriate level of generated power reserves.

Taking into account the control strategy, two types of low voltage microgrids can be distinguished: microgrids containing the central controller of microgrid (CCM) and microgrids without the central controller, relying their functioning on the concept of distributed control. Local controllers (microsources controllers - MSC, energy storages controllers - ESC, controllable loads controllers - CLC) cooperating with the central controller (CCM), because of the functionality they provide, are of a big importance in the process of controlling the microgrid operation. They allow for among others controlling power flows (active and reactive ones) in microgrid branches and regulation of nodal voltages levels. The levels of control signals (base operating points) are determined and transmitted to local controllers by the central controller.

In centralized control three hierarchical levels can be defined, which is shown in Fig. 1. On the highest hierarchical level DSO is placed, which is necessary if at least two microgrids are connected to distribution grid. On the same level Market Operator (MO) is defined, which is responsible for realization of operations concerning electricity market. Both these subjects represent electricity utility (EU). CCM constitutes the second hierarchical level. This controller is element which connects EU with microgrid and plays different roles. Particularly, it coordinates operation of local controllers (LCs). On the lowest hierarchical level local controllers are placed. These controllers are connected with MSs, ESs and CLs. Each LC is characterized by determined level of intelligence. In case of centralized control, operating points of LC are determined by CCM. Controllable loads controllers have to realize commands of CCM, which concern management of demand side or load shedding.

In case of centralized control, CCM performs the task of optimization of exchange level of electricity between microgrid and DSO grid. It is obtained through defining by CCM proper operating points for microsources, energy storage units and controllable loads, which are installed within microgrid [4, 7, 8].

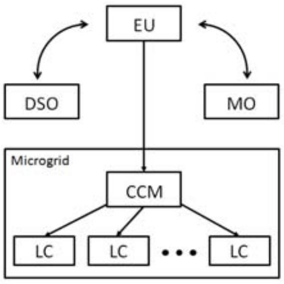

Fig. 1. Scheme of microgrid operation control (EU – electricity utility, MO – market operator); elaborated on the basis of [4, 7, 8, 14].

Optimal Operation Control of Low Voltage Microgrids in Rural Areas

General assumptions

Optimal operation control of low voltage microgrid is based on the given optimal structure of LV microgrid. The input data to optimal operation control algorithm should include the number, placement and type of microsources, energy storages and power receiving devices and arrangement of connections between microgrid nodes (number, type and topology of LV power lines).

The search for optimal operation state of LV microgrid will be based on accurate power regulation of operating controllable microsources and energy storage units, switching uncontrollable microsources off or allowing them to operate with natural level of generating power (according to current weather conditions), possible reduction of power of controllable loads. Developed control algorithm can be used for both synchronous and island operation modes of microgrid. During the optimization process a structure of LV microgrid will not be modified.

The process of controlling the operation of LV microgrid based on the strategy of centralized control logic requires that microgrid should be equipped with a central controller, located usually in MV/LV substation, and local controllers.

Central controller is used to collect all necessary data from local controllers and send them to external computation server, which is used to perform optimization calculations. When the optimization process is finished, central controller receive the results from computation server, and send individual settings to local controllers. The task of local controllers, after receiving a signal from central controller, is to adjust generation levels of controllable microsources, demand levels of controllable loads, to set operation points of energy storage units and to prepare input data for the central controller in the next time interval.

It should be also assumed that:

- all elements of microgrid are modelled as three-phase, balanced elements,
- during a optimization period (usually 15-minute interval) operation points of microsources, energy storage units and loads will not change,
- microgrid is equipped with at least one ES device with voltage source inverter and synchronous generator,
- synchronous generator is connected directly to LV microgrid.
-

Problem Formulation

The process of optimal control of LV microgrid can be considered with different criteria. At this paper seven independent single-criteria optimization tasks are formulated (the general form of objective functions are given below).

1) Minimization of the amount of energy imported from DSO power grid

$$F_{obj} = \min\left(A_{imp}\right) \tag{1}$$

$$A_{imp} = \begin{cases} 0 & \sum P_G \geq \left(\sum P_L + \Delta P\right) \\ \dfrac{\sum P_L + \Delta P - \sum P_G}{4} & \sum P_G < \left(\sum P_L + \Delta P\right) \end{cases} \tag{2}$$

where: A_{imp} – energy imported from DSO power grid, ΣP_L – sum of active power consumed by loads and energy storage units which operate as loads, ΔP – sum of active power losses, ΣP_G – sum of active power generated in microsources and energy storage units which operate as microsources.

2) Maximization of the amount of energy exported to DSO power grid

$$F_{obj} = \max\left(A_{\exp}\right) \tag{3}$$

$$A_{\exp} = \begin{cases} 0 & \sum P_G \leq \left(\sum P_L + \Delta P\right) \\ \dfrac{\sum P_G - \Delta P - \sum P_L}{4} & \sum P_G > \left(\sum P_L + \Delta P\right) \end{cases} \tag{4}$$

where A_{exp} – energy exported to DSO power grid.

3) Minimization of active power losses in microgrid

$$F_{obj} = \min\left(\Delta P\right) \tag{5}$$

4) Maximization of the amount of energy generated in MSs which use renewable primary energy resources

$$F_{obj}=\max\left(A_{MS,RES}\right) \tag{6}$$

$$A_{MS,RES}=\frac{\sum P_{MS,RES}}{4} \tag{7}$$

where: $A_{MS,RES}$ – energy generated in MSs which use renewable energy resources, $P_{MS,RES}$ – sum of active power generated in MSs which use renewable energy resources.

5) Minimization of the amount of energy generated in MSs which use non-renewable primary energy resources

$$F_{obj}=\min\left(A_{MS,nRES}\right) \tag{8}$$

$$A_{MS,nRES}=\frac{\sum P_{MS,nRES}}{4} \tag{9}$$

where: $A_{MS,nRES}$ – energy generated in MSs which use non-renewable energy resources, $P_{MS,nRES}$ – sum of active power generated in MSs which use non-renewable energy resources.

6) Minimization of costs associated with the operation of microgrid

$$F_{obj}=\min\left(C_{OPMG}\right) \tag{10}$$

$$C_{OPMG}=\sum C_{f,T}+\sum C_{v,T} \tag{11}$$

$$\sum C_{f,T}=\sum C_{f,MS,T}+\sum C_{f,ES,T}+\sum C_{f,DSO,T} \tag{12}$$

$$\sum C_{v,T}=\sum C_{v,MS,T}+\sum C_{v,ES,T}+\sum C_{v,DSO,T} \tag{13}$$

where: C_{OPMG} – costs associated with the operation of microgrid, $\Sigma C_{f,T}$ – sum of fixed costs during optimization period, $\Sigma C_{f,MS,T}$ – sum of fixed costs associated with the operation of microsources during optimization period, $\Sigma C_{f,ES,T}$ – sum of fixed costs associated with the operation of energy storage units during optimization period, $\Sigma C_{f,DSO,T}$ – fixed costs associated with the possibility of exchange of electric energy between microgrid and DSO power grid, $\Sigma C_{v,T}$ – sum of variable costs during optimization period, $\Sigma C_{v,MS,T}$ – sum of variable costs associated with the operation of microsources during optimization period, $\Sigma C_{v,ES,T}$ – sum of variable costs associated with the operation of energy storage units during optimization period, $\Sigma C_{v,DSO,T}$ – variable costs associated with the possibility of exchange of electric energy between microgrid and DSO power grid.

7) Maximization of profits associated with the operation of microgrid

$$F_{obj}=\max\left(PR_{OPMG}\right) \tag{14}$$

$$PR_{OPMG}=A_{\exp}\cdot p_s-C_{OPMG} \tag{15}$$

where: PR_{OPMG} – profits associated with operation of microgrid, p_s – price, per unit, of energy sold to DSO.

Microgrid optimal operation control algorithm must be accompanied by the fulfillment of the requirements contained in the set of constraints. This set includes the following restrictions [4]:

- long-term current carrying capacity of LV power lines,
- rated power of MV/LV transformer,
- permissible nodal voltage levels,
- rated power of microsources and energy storage devices,
- permissible level of energy stored in energy storage devices.
-

Exemplary Operation Control Algorithm (Scenario)

Formulated optimization tasks will be solved by microgrid optimal control algorithm, based on a PSO optimization algorithm.

The first step performed by the proposed control algorithm is to determine the current operating state of a microgrid. In the next steps, algorithm examines whether one of the following situations happened:

- microgrid is already in island operation mode,
- microgrid is supposed to operate in island mode (intended island operation),
- there is a fault in DSO power grid,
- there is a fault in microgrid.

If none of the mentioned situations occurs, algorithm will optimize microgrid operating states according to user selected criteria for synchronous operation mode.

If it is supposed to switch the microgrid into island mode (intended island operation), algorithm will block Loss of Mains functions in protective devices, start reciprocating engine (synchronous generator), set it as a reference source and disconnect microgrid from DSO power grid. Once this procedure is finished, algorithm will optimize microgrid operating states according to user selected criteria for island operation mode.

If, during synchronous operation of microgrid with DSO power grid, a fault in DSO power grid occurs, microgrid will switch into unintended island mode operation. In this case islanding procedure is different. First of all energy storage unit with voltage source inverter is set as a temporary reference source and microgrid is disconnected from DSO power grid. Next a synchronous generator is started. If synchronous generator is fully operational, it is set as a reference source instead of energy storage unit.

In unintended island mode operation, control algorithm will analyse if it is possible to balance microgrid by changing operation states of ES devices, controllable microsources and loads. If it is necessary, some elements of microgrid could be switched off or on (critical loads must remain operative). If it is not possible to balance the microgrid, central controller will switch off all elements of microgrid. During the period of blackout control algorithm will analyse current conditions, wait for appropriate moment of power restoration and if it is possible, restore the microgrid.

If microgrid is already in island operation mode (intended or unintended) control algorithm examines if microgrid is supposed to operate in synchronous mode. Resynchronization of microgrid with DSO power grid is possible only when there is no fault in DSO power grid or in microgrid. During resynchronisation procedure microgrid will be connected to DSO power grid, Loss of Mains functions in protective devices will be unblocked and synchronous generator will be switched off. After that procedure control algorithm will optimize microgrid operating states according to user selected criteria for synchronous operation mode.

In case of internal fault in microgrid, control algorithm examines the possibility of a fault clearance. If the answer is positive, algorithm will isolate failed component and, if microgrid is connected to DSO power grid, execute unintended islanding procedure. If the answer is negative a blackout state occurs. During the period of blackout control algorithm will analyse current conditions, wait for appropriate moment for power restoration and if it is possible, restore the microgrid.

During its operation, control algorithm tests the connection between microgrid central controller and external computing server. If connection is lost, microgrid switches to emergency island operation mode. In this mode the following procedure is executed:

- all MSs and energy storage units, except reciprocating engine (synchronous generator) should switch off,
- control algorithm will analyse the possibility of covering the power demand only by synchronous generator,
- if synchronous generator is not able to cover the power demand control algorithm will reduce the power demand of controllable loads,
- if, after previous regulatory actions, it is not possible to cover the power demand, some uncontrollable loads will be switched off (all critical loads must remain operative),
- if, after previous regulatory actions, it is not possible to cover the power demand, control algorithm will switch off the synchronous generator.

During the period of blackout, control algorithm will test the connection between microgrid central controller and external computing server. If connection is restored, control algorithm will restore proper structure and configuration of microgrid.

Implementation of Control Algorithm

When analyzing all the possible variants of control algorithm implementation, we need to remember about some challenges that need to be faced. In particular, several following issues should be taken into consideration: real-time operation conditions, necessity of integration with other parts of control and management software, proper software architecture choice allowing for easy and effective code development and maintenance, dealing with optimization problem computational complexity, necessity of appropriate implementation of control algorithm components details and some other minor ones.

The fact that the control algorithm is supposed to operate in real-time conditions puts some specific additional requirements on the way it needs to be implemented. If it is assumed that the program has to return optimization results within some determined and fixed time interval, say 15 minutes, it is necessary to make sure that the solution is going to be delivered on time. In the worst and critical case, the obtained solution does not even have to be the optimal one - it is important for the whole control process to have access to any solution that is useful from the point of view of chosen optimization criteria. To reach this goal, the program should be implemented in a way making it possible to set the time limit for the total computation time. It can be achieved by making use of multi-threading. If the program iteratively search for the best possible solution and some intermediate results are stored in a dedicated table, the thread controlling the total computation time can kill the one responsible for performing calculations, access the results table that is shared by the threads and report the best so far obtained solution, when the time is up, even if the computations did not actually come to an end.

The control algorithm itself is useless if it cannot communicate with other software applications, which together constitute the whole system. Integration of all software modules can be organized in many ways [16]. To avoid any technological or platform dependencies between separate software units we can implement them as Web Services or RESTful Web Services - then any module can be implemented and launched on a different server and is able to communicate with others via HTTP protocol. However, within the code of modules there are still references to other ones in the form of procedure invocations. To achieve the effect of total separation between different units we can make use of so called message broker - message oriented middleware responsible for organizing the communication in such a way, that the involved parties may be not even aware of their coexistence. However, some effort needs to be put into the task of implementing the broker. Fortunately, it does not need to be done from scratch - we can base on some existing technologies, frameworks, protocols and libraries. As for data exchange between software applications, JSON or XML formats can be used. Also the solution involving usage of databases to share or exchange some data is possible.

The architecture that is proposed for the efficient implementation of control algorithm is shown in Fig. 2. It is composed of three separate parts. The first one is a module responsible for performing power flow calculations using Newton-Raphson method, described among others in [17]. The second one is an implementation of Particle Swarm Optimization algorithm, presented among others in [18], which main task is to find optimal solutions to any properly defined optimization problem. Both of them can be treated as black boxes. In accordance with the separation of concerns design principle they provide some functionality, at the same time encapsulating all the implementation details and hiding all the information behind well-defined set of programming interfaces. Such an approach allows for easy testing of a single module, which can be performed separately and with no involvement of other parts of the program. Such components of a general use, providing some services, in fact being unaware of a nature of the problem they help to solve, can be also easily reused in case of development of any other software tool. The last component is the one responsible for implementing the actual logic of the control algorithm. Depending on the current state, it asks PSO algorithm to perform appropriate optimization computations, at the same time providing through interfaces necessary information on how to construct initial solutions, evaluate them and check their feasibility. The last task related to checking constraints is also supported by power flow calculations module.

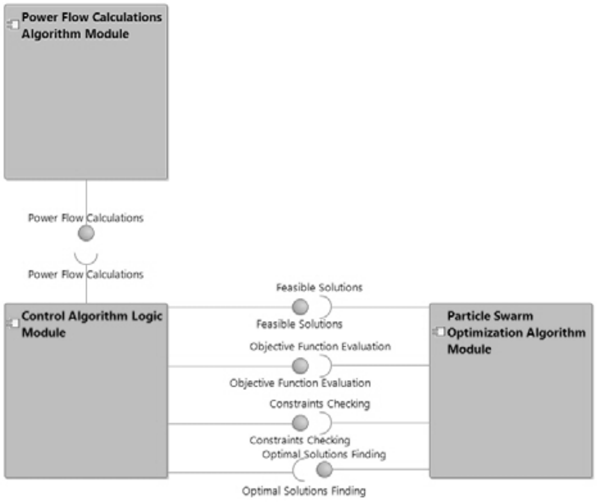

Fig. 2. Proposed architecture of the control algorithm program implementation.

When implementing the Particle Swarm Optimization algorithm module several decisions need to be made. Looking at the full definition of optimal control of microgrid problem formulation we can observe that the variables set is supposed to consist mostly of real and binary ones. We know exactly how to deal with such kind of variables. However, in case when some variables appeared to be integer ones, it would be not so obvious. Some possible solutions include taking advantage of binary representation of integer variables and using real variables, while interpreting them as integer ones, making use of floor and ceiling functions or operations of rounding to do so. Similarly, when the variables vector contains real and binary variables at the same time, special attention needs to be paid to the way some particular algorithm improvements are implemented. For example, if we want to employ spatial neighborhood structure in our PSO algorithm (the closest particles in the swarm in terms of their distance in Euclidean space become the neighbors of the given particle), we need to apply also some normalization procedures, so that all the dimensions (no matter if they are binary or real) are equally significant. Last but not least, it is important to decide if it is worth to incorporate some standard improvements into the basic PSO algorithm, having in mind that we have to deal with large computational complexity of analyzed optimization problems with multi-modal objective functions and time for performing calculations is strongly limited. Some of them, which aim to speed up the computation process, like selection, can be worth taking into consideration. Some others, requiring putting some additional computational effort, like breeding or spatial neighborhood structure, may appear to be too time-consuming.

Summary and Conclusions

Some selected issues concerning optimal operation control of LV microgrids in rural areas functioning on the basis of centralized control logic have been presented in the paper. First AC low voltage microgrid has been defined. Then short characteristics of different kinds of microgrids has been presented. In particular utility microgrids (directly connected to the grid of DSO) as well as remote microgrids (functioning away from the grid of DSO) have been described. Such microgrids can appear in rural areas. In further part of the paper some basic considerations concerning control strategy in LV microgrids have been presented. Special attention has been paid to centralized control mode and to hierarchical structure of the control system.

The proposed in this paper microgrid control algorithm allows for optimal management of microgrid operation according to the chosen optimization criterion. The algorithm allows at any time to change the optimization criterion. This change can be dictated by the current technical, social or economic conditions. In addition, the algorithm enables detecting faults in both microgrid and DSO power grid and responds to these faults to ensure reliable delivery of electricity, with appropriate quality parameters, to customers.

As for implementation issues we can see that our solution relies on some standard algorithms and software engineering approaches. However, because of the specific nature of the problem, including real-time operation conditions, necessity of efficient communication between several different entities and computational complexity, some effort has to be put to adapt these techniques, so that the solution can be truly effective.

Scientific works concerning the issues presented in the paper will be continued.

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