Optimization of Exchange of Electrical Energy between Microgrid and Electricity Utility Distribution Network

Mirosław Parol
Institute of Electrical Power Engineering
Warsaw University of Technology
Warsaw, Poland
miroslaw.parol@ien.pw.edu.pl

Tomasz Wójtowicz
Institute of Electrical Power Engineering
Warsaw University of Technology
Warsaw, Poland
tomasz.wojtowicz@ien.pw.edu.pl

***Abstract*—Microgrids are autonomous subsystems, in which generation units, energy storage units and power and electrical energy consumers appear. Microgrid can operate in synchronous mode with distribution network of electricity utility (electric power company), or in autonomous (islanded) mode. The problem of optimization of exchange of electrical energy between microgrid and distribution network of electricity utility has been described in the paper. The optimization problem has been formulated and its mathematical model has been presented. The objective function and set of constraints have been presented, as well as algorithm of solution based on evolutionary algorithms technique. The results of optimization calculations, obtained for exemplary low voltage microgrid, based on defined objective function, have been presented. By the end of the paper conclusions and remarks resulting with carried out optimization calculations have been presented.**

Keywords-component; distributed generation, microgrids, electricity utility, electricity trade, optimization, evolutionary algorithms

I. INTRODUCTION

Microgrid (MG) is the particular case of LV electric power distribution network with installed DG units. The concept of the microgrid has been presented in [1-3]. Different types of microsources, energy storage units, electricity and heat loads appear in microgrids. Setting the operating points of microsources (MS), energy storage units (ES) and controllable loads (CL) is one of essential problems. For this purpose it is necessary to develop proper control algorithms (strategies) [4-8]. The steady states analysis of microgrid operation has been presented in [9]. In [10, 11] optimization of operating points of microsources in order to minimize microgrid operation costs has been discussed in detail. In [10] another criteria – minimization of total active power losses in microgrid has been also presented. In turn the problem of exchange of electrical energy between microgrid and distribution network of electricity utility has been formulated in [11].

The problem solution of optimization of exchange of electrical energy based on evolutionary algorithms and obtained results of optimization process have been presented in the paper in detail.

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II. MICROGRIDS

During the synchronous operation mode of MG it is possible to exchange electrical energy between microgrid and network of electricity utility.

The most often used microsources are [1-3]: fuel cells, microturbines, small hydro units, small reciprocating engine generators, photovoltaic units, wind turbines, microturbines supplied with biogas. Among energy storage units we can distinguish: battery energy storages, super (ultra) capacitors and flywheels. Electrical loads can be divided into noncontrollable loads and controllable loads.

The structure of exemplary microgrid is presented in Fig. 1. This network is a modified microgrid structure given in [12]. In relation to original version, among others the number of microsources has been increased and their locations have been changed. There are three feeders in the considered microgrid. Five residential loads, one industrial load and eight commercial loads are supplied with MG. Each load is characterized by its own typical daily load characteristics (as it was defined in [12]) and given peak load. Three kinds of microsources are located within microgrid: fuel cells, microturbines supplied by gas and wind turbines. Presented here microgrid was a subject of the investigations described among others in [10, 11]. Data concerning microsources are presented in Table I.

III. OPTIMIZATION PROBLEM FORMULATION

The optimization problem can be defined as follows: determining values of active and reactive powers generated by microsources in optimization period in order to maximize profit from electrical energy sale. Values of powers generated by microsources in each 15-minutes interval of twenty-four hours time are the solution of the optimization problem. The influence of energy storages installed within microgrid and the possibility of using demand response control for controllable loads are not considered in the problem. The "ideal citizen" concept has been adopted in the task, in which consumers connected to microgrid buy electricity at the market prices.

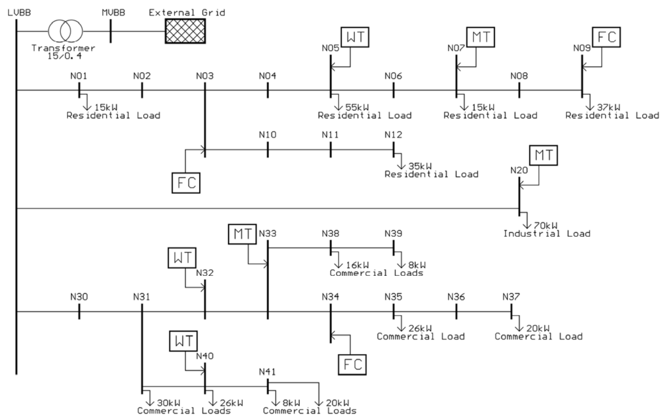

Figure 1. Structure of exemplary microgrid (WT – wind turbine, MT – microturbine, FC – fuel cell) [10, 11].

TABLE I. TECHNICAL AND ECONOMIC PARAMETERS OF MICROSOURCES; BASED ON [11]

Node name	**Rated power**	**Investment costs**	**Life cycle costs**	**Fixed costs**
-	***kW***	***PLN***	***PLN***	***PLN/h***
Wind turbines				
N05	50	152700	8128	0.9279
N32, N40	10	30500	1626	0.1856
Microturbines				
N07, N33	30	70500	4373	0.4992
N20	60	141000	8747	0.9985
Fuel cells				
N03, N09, N34	10	70500	3963	0.4524

Attention: PLN is Polish currency; PLN ≈ 0.24 EUR.

The objective function in considered task can be formulated as follows [11]:

$$\max\left\{ Z_D = \sum_{t=1}^{96} Z_{D,t} \right\} \tag{1}$$

$$Z_{D,t} = 0{,}25\left(c_{s,t}\left(\sum_{i\in MS} P_{g,i,t} - P_{\Delta,t} \right) - \sum_{i\in MS} c_{p,i,t} P_{g,i,t} \right) \tag{2}$$

in case of export of electrical energy from microgrid to electricity utility, or

$$Z_{D,t} = 0{,}25\left(\begin{array}{l} \dfrac{c_{s,t}+c_{p,t}}{2} P_{l,t} + \\ -\left(c_{p,t}\left(P_{l,t} + P_{\Delta,t} - \sum_{i\in MS} P_{g,i,t} \right) + \sum_{i\in MS} c_{p,i,t} P_{g,i,t} \right) \end{array} \right) \tag{3}$$

in case of import of electrical energy from electricity utility to microgrid,

where: $Z_{D,t}$ – the profit from energy sale in *t*-th time interval, $c_{s,t}$ – energy sale price at the market in *t*-th time interval, $P_{g,i,t}$ – 15-minutes average active power generated by *i*-th microsource in *t*-th time interval, $P_{\Delta,t}$ – power losses within microgrid in *t*-th time interval, $c_{p,i,t}$ – energy purchase price from *i*-th microsource in *t*-th time interval, $c_{p,t}$ – energy purchase price at the market in *t*-th time interval, $P_{l,t}$ – 15-minutes average power received within microgrid in *t*-th time interval, *MS* – set of microsources in microgrid.

The following constraints should be considered in all specified time intervals:

- Power flows in particular components of microgrid must not exceed the current-carrying capacity of that components,

$$\left| S_j\left(\mathbf{\Delta_{g,t}}\right) \right| \le c_j, \quad \forall j = 1,2,\ldots,m \tag{4}$$

- Voltage levels in all nodes of microgrid should be kept within permissible values,

$$U_i^{\min} \le U_i\left(\mathbf{\Delta_{g,t}}\right) \le U_i^{\max}, \quad \forall i \in \left(MS \cup L\right) \tag{5}$$

- Active and reactive powers generated in each microsource should be kept within permissible values,

$$P_{g,i}^{\min} \le P_{g,i,t} \le P_{g,i}^{\max}, \quad \forall i \in MS \tag{6}$$

$$Q_{g,i}^{\min} \le Q_{g,i,t} \le Q_{g,i}^{\max}, \quad \forall i \in MS \tag{7}$$

- Quantities of interchanged powers between microgrid and electricity utilities determined in concluded sale/purchase contracts must not be changed,

$$P_{s,t} \le P_{s,t}^{arbit}; \quad t \in J_s \tag{8}$$

$$P_{p,t} \le P_{p,t}^{arbit}; \quad t \in J_p \tag{9}$$

- Requirements concerning turning-off microsources in specified time intervals should be satisfied

$$P_{g,i,t} = 0; \quad i \in J_{off,t} \tag{10}$$

$$Q_{g,i,t} = 0; \quad i \in J_{off,t} \tag{11}$$

where: $\mathbf{\Delta_{g,t}}$ – vector representing active and reactive powers generated by microsources in *t*-th time interval, $Q_{g,i,t}$ – 15-minutes average reactive power generated by *i*-th microsource in *t*-th time interval, $P_{g,i}^{\min}$ – minimum active power generated by *i*-th microsource, $P_{g,i}^{\max}$ – maximum active power generated by *i*-th microsource, $Q_{g,i}^{\min}$ – minimum reactive power generated by *i*-th microsource, $Q_{g,i}^{\max}$ – maximum reactive power generated by *i*-th microsource, $\left|S_j\left(\mathbf{\Delta_{g,t}}\right)\right|$ – module of maximum apparent power flow in j – th arc in microgrid, c_j – power-carrying capacity of *j* – th arc in microgrid, $U_i\left(\mathbf{\Delta_{g,t}}\right)$ – voltage in i – th node of microgrid, $U_i^{\min}$ – lower permissible limit of voltage level in i – th node, $U_i^{\max}$ – higher permissible limit of voltage level in i – th node, $P_{s,t}^{arbit}$ – arbitrary maximum value (threshold) of power which is sold to electricity utility network in *t*-th time interval, $P_{p,t}^{arbit}$ – arbitrary maximum value (threshold) of power which is purchased from electricity utility network in *t*-th time interval, J_s – set of indexes of time intervals in which arbitrary value of sold power is fixed, J_z – set of indexes of time intervals in which arbitrary value of purchased power is fixed, $J_{off,t}$ – set of indexes of microsources turned-off in *t*-th time interval, *L* – set of receiving nodes in microgrid, *m* – number of branches (arcs) in microgrid.

Four penalty functions have been formulated in the task:

- Ψ_I – penalty function in case if "current" constraints are violated

$$\Psi_I=\begin{cases}1-\text{if none of "current" constraints is violated}\\ k^I\prod_{i=1}^{n^I}\left(\dfrac{I_{B,i}}{I_{z,i}}\right)^2-\text{if "current" constraints are violated}\end{cases}\tag{12}$$

- Ψ_U – penalty function in case if "voltage" constraints in microgrid are violated

$$\Psi_U=\begin{cases}1-\text{if none of "voltage" constraints is violated}\\ \prod_{i=1}^{n_{\min}^U}\left(\dfrac{U_i^{\min}}{U_i}\right)^2\prod_{j=1}^{n_{\max}^U}\left(\dfrac{U_j}{U_j^{\max}}\right)^2-\text{if "voltage" constraints are violated}\end{cases}\tag{13}$$

- Ψ_{E1} – penalty function in case if quantities of powers delivered from microgrid to electricity utility are greater than ones determined in sale/purchase contract

$$\Psi_{E1}=\begin{cases}1-\text{if none of "export" constraints is violated}\\ \left(1+\dfrac{P_{s,t}-P_{s,t}^{arbit}}{P_{s,t}^{arbit}}\right)^2,\text{if } P_{s,t}^{arbit}>0 \text{ and } P_{s,t}>P_{s,t}^{arbit}\end{cases}\tag{14}$$

- Ψ_{E2} – penalty function in case if quantities of powers delivered from electricity utility to microgrid are greater than ones determined in sale/purchase contract

$$\Psi_{E2}=\begin{cases}1-\text{if none of "import" constraints is violated}\\ \left(1+\dfrac{P_{p,t}-P_{p,t}^{arbit}}{P_{p,t}^{arbit}}\right)^2,\text{if } P_{p,t}^{arbit}>0 \text{ and } P_{p,t}>P_{p,t}^{arbit}\end{cases}\tag{15}$$

where: n^I – the number of branches in microgrids with exceeded their current-carrying capacity, k^I – factor of proportionality in penalty function, $I_{B,i}$ – calculating (operational) current in *i*-th branch in microgrid, $I_{z,i}$ – current-carrying capacity of *i*-th branch, U_i – voltage in *i*-th node of microgrid, $n_{\min}^U$ – the number of nodes in microgrids with exceeded lower permissible voltage limit, $n_{\max}^U$ – the number of nodes in microgrids with exceeded higher permissible voltage limit.

The objective function with penalty functions can be defined as follows:

$$\max\left\{\sum_{t=1}^{96}\frac{Z_{D,t}}{\Psi_{p,t}}\right\}\tag{16}$$

where $\Psi_{p,t}$ is equivalent penalty function value whereas constraints are violated.

$$\Psi_{p,t}=\Psi_I\cdot\Psi_U\cdot\Psi_{E1}\tag{17}$$

in case of export the electrical energy from microgrid to electricity utility, or

$$\Psi_{p,t}=\Psi_I\cdot\Psi_U\cdot\Psi_{E2}\tag{18}$$

in case of import the electrical energy from electricity utility to microgrid.

Economic data used in considered optimization task are as follows:

- Components and coefficients of cost functions for particular kinds of microsources

Swing bus:

- fixed costs: 0.0168 PLN/kWh,
- variable costs (import): 0.4516 PLN/kWh,

- price for export: 0.2358 PLN/kWh.

Coefficients of 6-order polynomial describing variable costs for fuel cells: 0.335282; 1.893743; 8.273483; 18.662776; 23.113357; 14.830915; 3.853503.

Coefficients of 2-order polynomial describing variable costs for microturbines: 0.671402; 0.719551; 0.353492.

Variable costs for wind turbines: 0.0 PLN/kWh,

- Energy purchase prices from network of electricity utility and energy sale prices by microgid in all time intervals of twenty-four hours time; these prices are presented in Table II.

TABLE II. DATA CONCERNING ELECTRICAL ENERGY TRADE IN PARTICULAR TIME INTERVALS OF TWENTY-FOUR HOURS TIME

Consecutive hour in day and night	Energy sale price	Energy purchase price	Arbitrary power of sale	Arbitrary power of purchase
-	*PLN/kWh*	*PLN/kWh*	*kW*	*kW*
1	0.4476	0.4255	130	300
2	0.4596	0.3849	130	300
3	0.4596	0.3744	130	300
4	0.4861	0.3743	130	300
5	0.4886	0.3790	130	300
6	0.4729	0.4024	130	300
7	0.4273	0.4893	200	300
8	0.3820	0.4941	200	200
9	0.3612	0.5355	200	200
10	0.3428	0.5549	200	200
11	0.3279	0.5634	200	200
12	0.3153	0.5780	200	200
13	0.3100	0.5765	200	200
14	0.3088	0.5723	200	200
15	0.3119	0.5451	200	200
16	0.3232	0.5228	200	200
17	0.3443	0.5115	200	200
18	0.3742	0.5185	200	200
19	0.4015	0.5229	100	200
20	0.4080	0.5290	100	200
21	0.4130	0.5299	130	300
22	0.4113	0.5077	130	300
23	0.4113	0.5371	130	300
24	0.4181	0.4824	130	300

IV. SOLUTION OF THE PROBLEM BASED ON EVOLUTIONARY ALGORITHMS

To determine the vector $\mathbf{\Delta_{g,t}}$ in each t-th time interval of day and night, in the described optimization problem, the problem oriented evolutionary algorithm is used.

Each r-th individual $\mathbf{v}_r$ in population (representing vector $\mathbf{\Delta_{g,t}}$) is encoded in the following way

$$\mathbf{v}_r = \mathbf{\Delta_{g,t}} = P_{g,1,t} P_{g,2,t} \dots P_{g,MS_{contr},t}, Q_{g,1,t} Q_{g,2,t} \dots Q_{g,MS_{contr},t} \quad (19)$$

where MS_{contr} – set of microsources based on nonrenewable energy carriers, which take part in optimization process.

Initial population consists of the set of individuals. Each component of the individual (vector $\mathbf{\Delta_{g,t}}$) is determined by a value randomly chosen from the permissible range $\left\langle P_{g,i}^{\min}, P_{g,i}^{\max} \right\rangle$ or $\left\langle Q_{g,i}^{\min}, Q_{g,i}^{\max} \right\rangle$ - see inequality (6) and (7).

The following fitness (evaluation) function form has been assumed

$$eval^p(\mathbf{v}_r) = \begin{cases} C_{\min} + \dfrac{Z_{D,t}(\mathbf{\Delta_{g,t}})}{\Psi_{p,t}(\mathbf{\Delta_{g,t}})}; & \text{if } C_{\min} + \dfrac{Z_{D,t}(\mathbf{\Delta_{g,t}})}{\Psi_{p,t}(\mathbf{\Delta_{g,t}})} \geq 0 \\ 0; & \text{if } C_{\min} + \dfrac{Z_{D,t}(\mathbf{\Delta_{g,t}})}{\Psi_{p,t}(\mathbf{\Delta_{g,t}})} < 0 \end{cases} \quad (20)$$

where: $\mathbf{v}_r$ – r-th individual in current population; $Z_{D,t}(\mathbf{\Delta_{g,t}})$ – the objective function value being profit from electrical energy sale in t-th time interval for r-th individual, determined from equation (2) or (3) respectively; $\Psi_{p,t}(\mathbf{\Delta_{g,t}})$ – the equivalent penalty function value connected with violation of constraints; $C_{\min}$ – constant estimated in initial population in the following way $C_{\min} = \left| \min \dfrac{Z_{D,t}(\mathbf{\Delta_{g,t}})}{\Psi_{p,t}(\mathbf{\Delta_{g,t}})} \right|$.

In presented approach the following assumption has been made

$$\begin{cases} \Psi_{p,t}(\mathbf{v}_r) = 1, & \text{if } \mathbf{v}_r \text{ is permissible solution} \\ \Psi_{p,t}(\mathbf{v}_r) > 1, & \text{in other case} \end{cases} \quad (21)$$

Finally, fitness function in each t-th time interval can be formulated as follows:

$$\max eval^p(\mathbf{\Delta_{g,t}}) \quad (22)$$

Three genetic operations are performed on the population of individuals: selection, crossover and mutation [13]. Selection is realized by the use of roulette wheel method. Elitist strategy is also possible to use. Evolutionary algorithm uses two problem oriented recombination operators: crossover and mutation. Linear scaling method is also used to prevent premature convergence of the evolutionary algorithm.

V. RESULTS OF OPTIMIZATION PROCESS

Results of the optimization process obtained with the use of evolutionary algorithm have been presented in Fig. 2-11.

Run of optimization process for one time interval (19.00 – 19.15), using determined set of values of genetic parameters, has been presented in Fig. 2 – 4. It can be noticed that evolutionary algorithm step-by-step improves obtained results and tends to find optimum solution. In Fig. 5 objective function value in particular (96) time intervals of twenty-four hours time has been shown. Profit from electrical energy sale has got big variation and is positive in all time intervals of day and night. The biggest value of the profit appears when active power generated by wind turbines is maximum.

Active and reactive power curves of exemplary microsources are presented in Fig. 6 – 11. It can be observed that active power generated by fuel cell (Fig. 6) and microturbine (Fig. 10) is changing considerably in twenty-four hours time. Average capacity factor for these microsources is equal to approximately 90%. Changes of reactive powers generated by the microsources are even bigger than active powers (Fig. 7 and 11). Variation of active and reactive power generated by wind turbines in twenty-four hours time (Fig. 8 and 9) results directly from assumptions made with regard to the way of operation of these microsources and wind velocity.

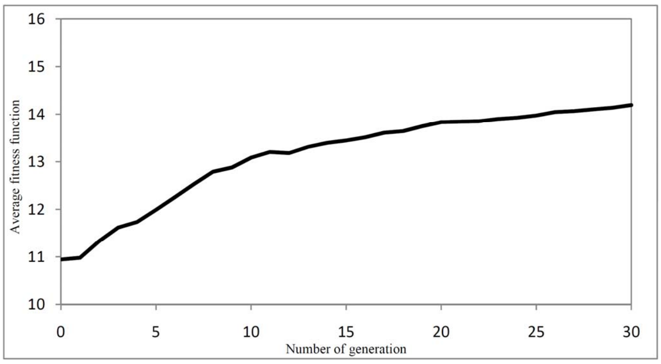

Figure 2. Values of average fitness function of individuals in population depending on number of generations for one defined time interval .

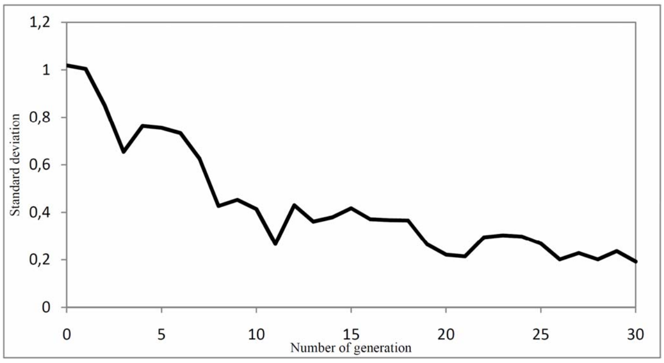

Figure 3. Values of standard deviation of individuals' fitness function in population depending on number of generations for one defined time interval.

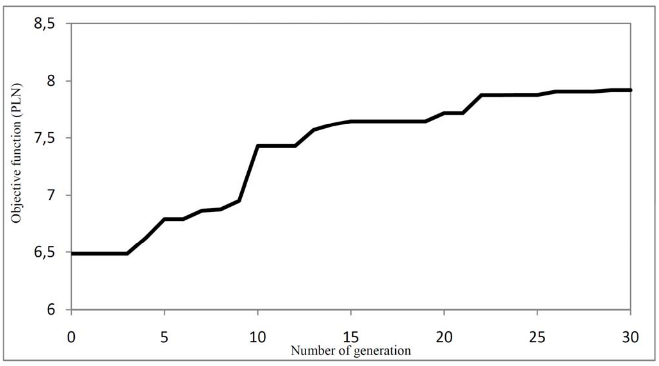

Figure 4. Values of objective function depending on number of generations for one defined time interval.

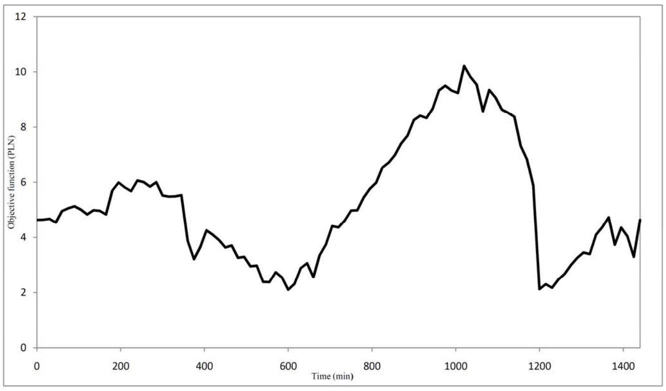

Figure 5. Values of objective function depending on time intervals of twenty-four hours time.

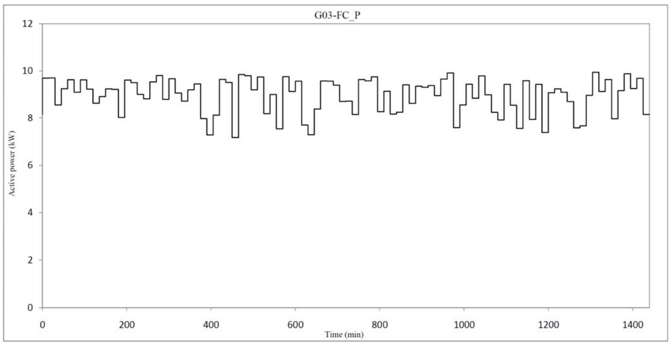

Figure 6. Active power curve of exemplary fuel cell in twenty-four hours time.

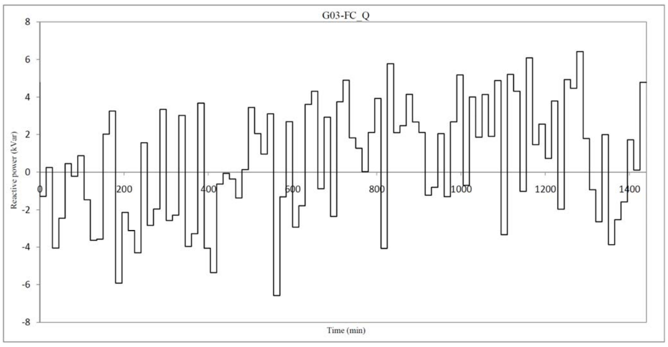

Figure 7. Reactive power curve of exemplary fuel cell in twenty-four hours time.

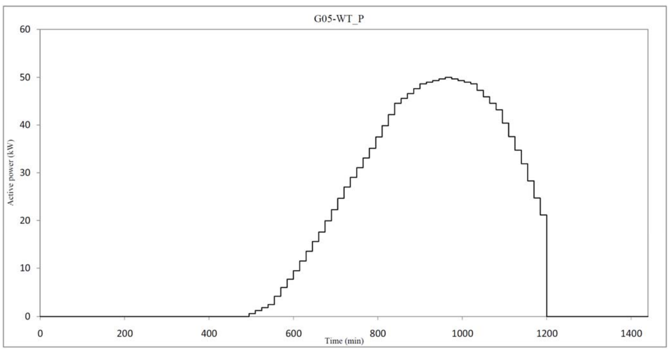

Figure 8. Active power curve of exemplary wind turbine in twenty-four hours time.

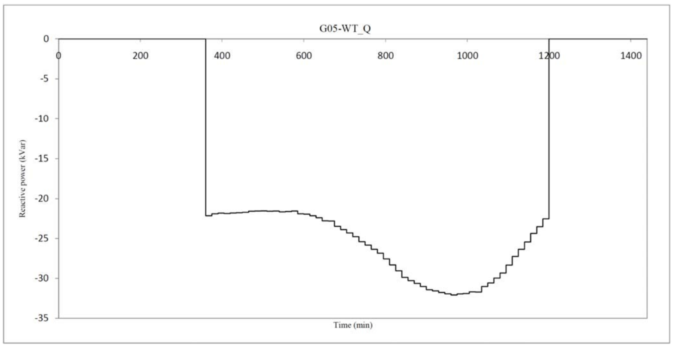

Figure 9. Reactive power curve of exemplary wind turbine in twenty-four hours time.

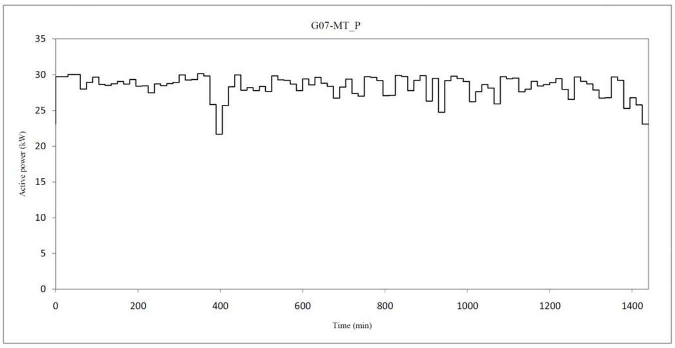

Figure 10. Active power curve of exemplary microturbine in twenty-four hours time.

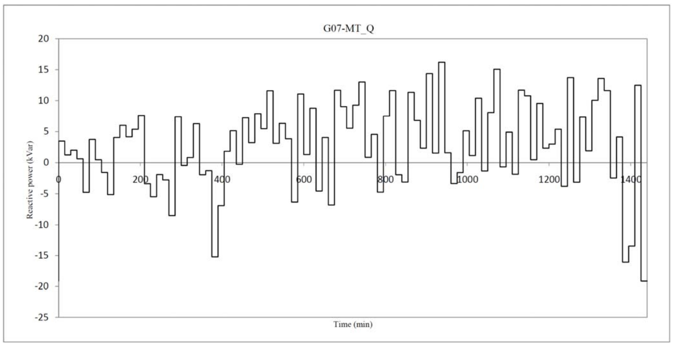

Figure 11. Reactive power curve of exemplary microturbine in twenty-four hours time.

VI. CONCLUSIONS

The main part of the paper concerns the problem of optimisation of exchange of electrical energy between microgrid and network of electricity utility. For the task the following issues has been discussed: problem formulation, objective function, constraints, penalty functions, objective function with penalty functions and economic data necessary for calculations.

In the last part the solution of the optimization problem has been given. Results of the optimization task obtained by the use of evolutionary algorithm have been shown and discussed. Achieved results show that considered optimization problem has got important economic and technical meaning.

Problem solution has been based on criteria of maximization of profit from sale of electrical energy. "Ideal citizen" concept has been adopted, in which consumers connected to microgrid buy electricity at the market prices.

Evolutionary algorithm turned out to be a good optimization tool, because it efficiently tended to find the best possible results. Optimization process was converged and always let to obtain still better results. Solution of optimization task for exemplary microgrid allows to make the statement that optimization process may be a source of increase of profit.

Scientific works concerning the issues presented in the paper should be continued. Further investigations should especially refer to the influence of energy storages installed within microgrid and the analysis of other types of microsources.

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