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Analysis of sectionalizing switch placement in medium voltage distribution networks in the aspect of improving the continuity of power supply

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Abstract. The paper addresses the problem of placement of sectionalizing switches in medium voltage distribution networks. Proper placement of sectionalizing switches is one of the elements leading to higher power networks reliability. The methods of optimal allocation of such switches in a MV distribution network are presented in the paper. SAIDI was used as a criterion for the sectionalizing switches placement. For selecting optimum placements, three methods were used: brute force method, evolutionary algorithm and heuristic algorithm. The calculations were performed for a real MV network.

Key words: reliability of distribution networks, sectionalizing switches, SAIDI.

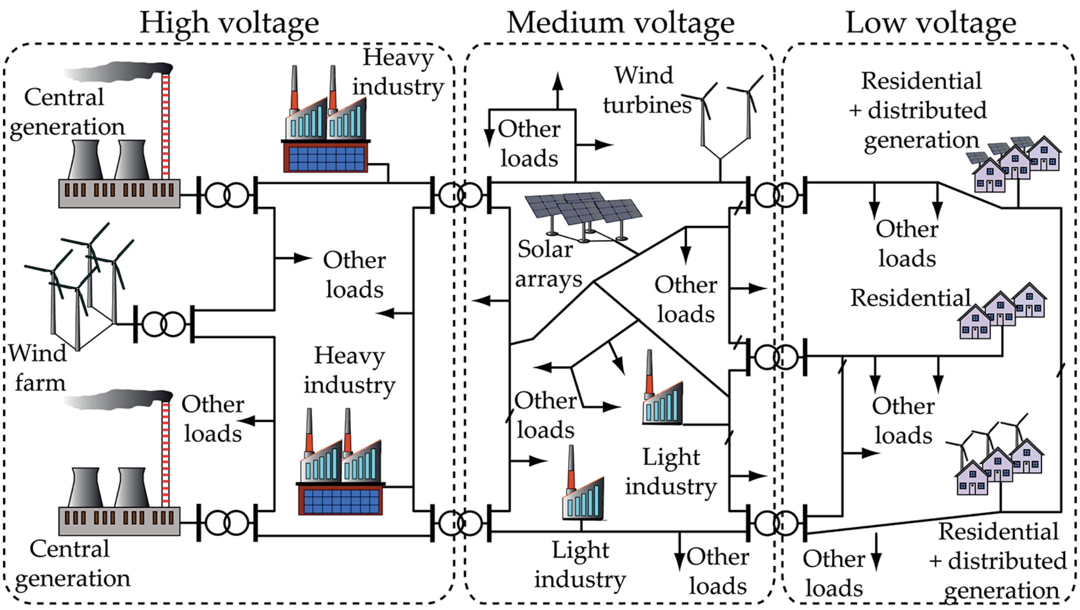

Fig. 1. Structure of a modern power grid

1. Introduction

The constant technological development observed in many aspects of human activity allows for introducing new solutions, also in electrical power networks. Presently the intelligent solutions help optimize the management of power systems. Soon, independent systems based on artificial intelligence will be worked out to substitute humans in monitoring and controlling electrical power networks.

A simplified structure of a Smart Grid power system is presented in Fig. 1. The modern networks will cooperate with new generation and customer types on many levels. Their increasing number creates new problems to be solved as far as reliability and safety of the network are concerned. This especially applies to MV distribution networks. The certainty of operation of these networks is important due to the increasing number of distributed energy sources favoring the improvement of broadly

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understood power quality. It is not only the continuity of electricity supplies awaiting unlimited and uninterrupted access to electrical energy, but also readiness of the power network to provide services to a new type of consumer, i.e. prosumer (producer and consumer) [1].

High reliability of supplies depends on three aspects of network operation. The first of them is the reliability of its particular elements and resistivity to environmental impacts. The second one is connected with the time in which the failed elements are detected and fixed. The last element is the continuity of supplies in the time the disturbance is being fixed. The structure of the network should be designed so as to provide the customers with energy using alternative supply systems, presently also with the use of distributed energy sources [2–4].

Considering the above remarks, building an autonomous intelligent system for monitoring and controlling power networks will be fully justified after prior assessment of its reliability and reconfigurability provided by optimal placement of operating elements of the control system, i.e. sectionalizing switches [5].

Advanced control systems rely on properly distributed working elements of intelligent systems. The number and placement of sectionalizing switches (SSP) affects the rate at which the network disturbances are eliminated and consequences mitigated. This problem has a linear and discrete combinatorics task, which can be solved by various methods, for example: the mixed integer linear programming method [6–8], tree-structure based algorithms [9], fuzzy multicriteria method [10], tabu search [11], ant colony algorithm [12, 13], genetic algorithm [14–16], swarm algorithm [17–19]. Objective function, independently of the method used to solve this task, may be based on the economic criterion [6, 8, 11–13, 15, 18–21] or reliability indices like: AENS, ENS [6, 8, 9, 22–24], SAIFI or SAIDI [6, 8, 9, 25] and reserve factor [25, 26].

The methods of sectionalizing switches placement (SSP) in a medium voltage distribution network are presented in the paper. The brute force method, evolutionary algorithm and heuristic algorithm were adopted into calculation. SAIDI was used as a criterion for solving this problem.

The paper is organized as follows. The task of optimized location of sectionalizing switches and algorithms have been described in Section 2. In Section 3 the description of a 15 kV model power network is followed by calculation results and their discussion. Concluding remarks are presented in Section 4.

2. Sectionalizing switches placement

2.1. Idea. A distribution network is presented in Fig. 2. The switches divide the network into sections and sections may contain subsections. In case of failure in section 2, feeding of section 1 can be restored only after the switch at the beginning of section 2 is opened. If the power line can be supplied on the other end, a part of the customers (section 3) can be supplied energy prior to the removal of the major cause of disturbance in the network (after opening the switch at the beginning of section 3 and closing a normally open switch in tie point).

The reliability parameters of the network (e.g. SAIDI) improve with the increasing number of installed switches and also their proper placement within the network.

2.2. Solving methods. The applicability of three methods of searching for optimal placement of switches has been analyzed in this paper: brute force method, evolutionary algorithm and heuristic algorithm.

The brute force method ensures that the optimal solution (best possible) is obtained. The results obtained by using this method allow to assess the quality of the results achieved by the other methods. The advantage of the other methods is obtaining a solution in shorter calculation time for large-size problems (do not guarantee the optimal solution – best possible).

The idea of the evolutionary algorithm is the implementation procedures (randomized) representing evolutionary mechanisms taking place in natural environment. Methods based on such algorithm are simple to implement and effective in solving many optimization problems.

The idea of the heuristic algorithm is a set of defined rules and guidelines which lead to a solution in short calculation time. Methods based on such algorithm are less complex and offer comparable quality solutions.

- **Brute force method**

Brute force method lies in determining values of the objective function successively for all possible placements of sec-

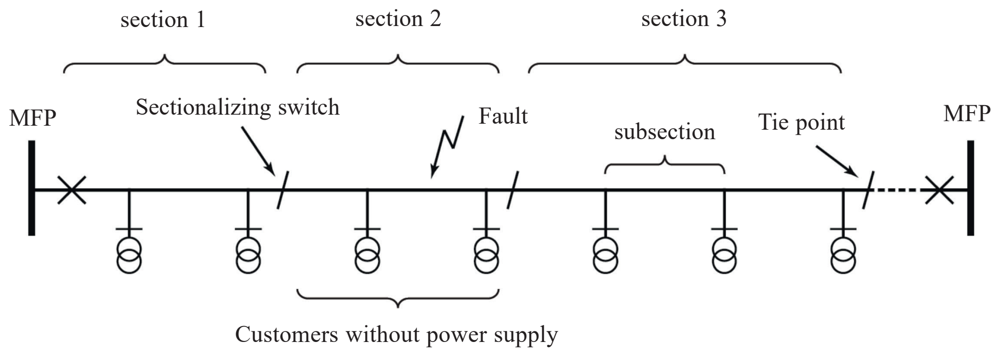

Fig. 2. Concept of SSP in a distribution network with sectionalizing switches and alternative supply (MFP – main feeding point)

tionalizing switches. In this way the best solution, i.e. global optimum can be found. This is an inefficient method because of the long computation time. Besides it can be used for small tasks, i.e. small networks (ten or so nodes) and a small number of switches (1÷3 switches).

- **Evolutionary algorithm**

In this algorithm each solution is represented by a code series called chromosome. Evolutionary algorithm operates on groups of solutions of a task, i.e. populations [27]. The first set of solutions is randomly generated. This set, called primary population, consists of solutions which are usually far from optimal. The successive, basic part of the algorithm cyclically realizes procedures representing evolutionary mechanisms taking place in natural environment, like: selection (the best chromosomes are multiplicated), crossover (exchange fragments of chromosomes, which are randomly paired) and mutation (random replacement of chromosome elements) [21, 26].

Code (chromosome) consists of a number of positions with ascribed numbers. The number of positions of the code corresponds with the given maximal number of sectionalizing switches. The value of an element of each position is identified with one of admissible placements of the switch in the network.

- **Simple heuristic algorithm**

The switches placement algorithm consists of the following steps:

STEP 1: determining the main feeder line and number of switches to be installed NL.

STEP 2: division of the main feeder line into NL+1 sections, where the size of each section is based on nearly the same number of customers or randomly determined in case of multiple repetitions of the algorithm (number of iterations is the assumed parameter of an algorithm) – initial placement of switches and objective function calculation.

STEP 3: random determination of a sequence of switches, the location of which will be verified.

STEP 4: establishing two new placements of the switch (ordered as in STEP 3) – the successive possible placement towards main feeding point (MFP) and in the opposite direction (however not further than other switch).

STEP 5: determining objective function values for new switch placements and selecting the most advantageous one as compared to the original one. The improvement of the objective function values signifies a new position of the switch, otherwise – the switch is relocated to its original site.

STEP 6: if the placement of all switches has not been verified (ordered as in STEP 3), go back to STEP 4 or to STEP 3 until procedure (STEP 3÷STEP 6) is repeated (the number of cycles is the assumed parameter of an algorithm).

STEP 7: end of the algorithm – the placement of the switches are optimal.

2.3. Objective function. SAIDI was used as a criterion for solving SSP problem – a solution with the lowest SAIDI value is required. SAIDI is an index of an average system duration of outages in the supply of electricity expressed in minutes per customer per year [28]. This is a sum of the interruption duration multiplied by the number of customers exposed to the effects of the interruption during the year, divided by the number of customers connected to the network (1):

$$\mathrm{SAIDI} = \sum_{k=1}^{NK} U_k N_k \Big/ \sum_{k=1}^{NK} N_k \tag{1}$$

where: NK – number of power delivery points, N_k – number of customers in k-th power delivery point, U_k – annual duration of unscheduled interruptions in k-th point.

SAIDI is one of the basic reliability indices used by the Distribution System Operator (DSO). The DSO calculates SAIDI for long (duration exceeding 3 minutes and not exceeding 12 hours) and very long outages (duration exceeding 12 hours and not exceeding 24 hours). This index is calculated and published by DSO on the basis of registered power interruption incidents.

3. Results and Discussions

The analysis was conducted for a distribution network of nominal voltage 15 kV. The analyzed fragment of the network covers six lines fed by 110/15 kV transformer station. The data about the network are listed in Table 1.

Table 1
Basic data of lines in the analyzed distribution network

Line	Length (km)		Peak load of line (kW)	Number of customers
	Feeder line / Lateral branches	Overhead line / cable lines		
A	6.35/1.72	5.05/3.01	1156.6	238
B	7.15/24.36	25.46/6.05	3320.7	808
C	13.42/16.69	28.10/2.02	2996.7	870
D	6.78/3.36	4.93/5.21	1297.0	377
E	22.45/36.59	51.10/7.93	3222.5	994
F	9.50/20.76	24.60/5.66	2205.9	534

The outline of the main pathway of the network is shown in Fig. 3. This is a typical open distribution network. Numerous points of division were determined, thanks to which the lines could be reserved in the case of broken continuity of deliveries from the main feeding point. The reserve feeding improves the reliability of operation and so increases profits from the sectionalizing switch.

The switches placement was calculated on the basis of the brute force method, evolutionary algorithm and heuristic algorithm. SAIDI was used as a criterion for solving this problem. The calculations were performed with the author's

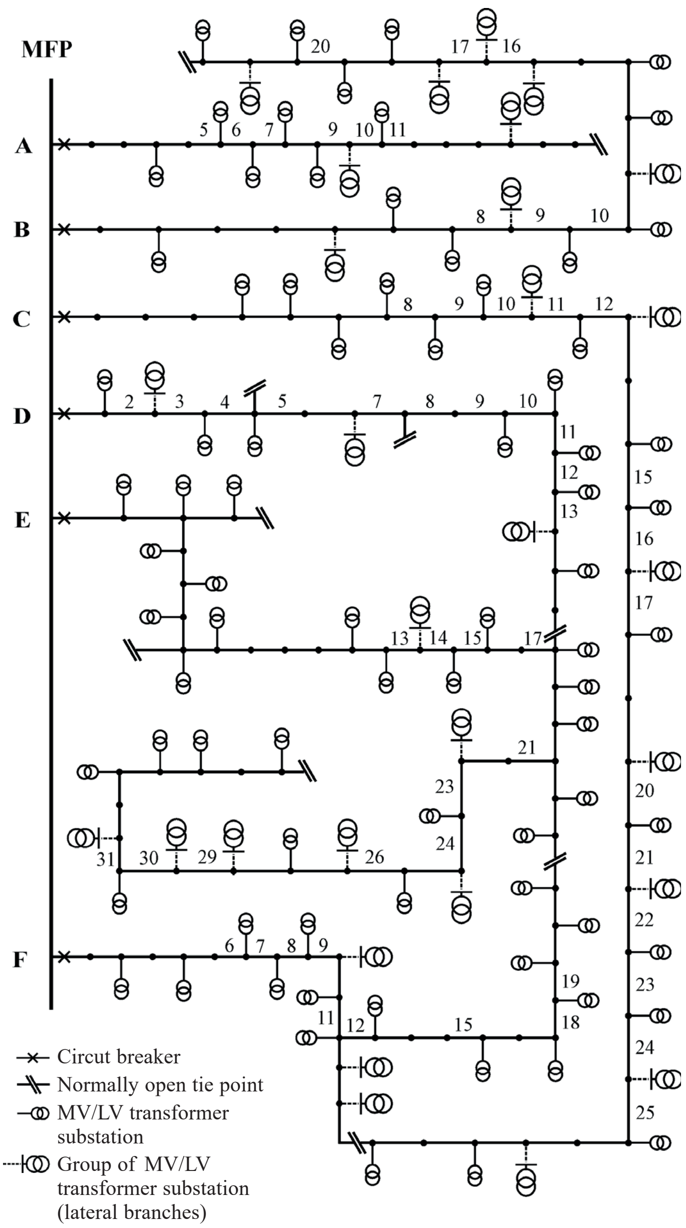

Fig. 3. Simplified schematic of 15 kV distribution network (no lateral branches shown)

computer program in C++ and PC 3.4 GHz, 16 GB RAM. In calculations based on the evolutionary algorithm the following was assumed: 20 populations, 3000 iterations (generations), probability of crossover 0.8, probability of mutation 0.04. In the calculations making use of heuristic algorithm there were assumed 300 iterations of a random solution and 5 cycles of iterative procedure.

The calculation experiment covers three groups of issues:

- determine the best, due to the SAIDI value (SAIDI minimization task), placement of sectionalizing switches in all lines of the network for their given number (1 to 4 switches in each line);
- calculate SAIDI for a sectionalizing switch placed in all successive subsections of the main line in line A;
- compare the computation time with described algorithms for placement of a given number of sectionalizing switches (1 to 7 switches) in line A.

To determine the optimal placement of sectionalizing switches, a calculation model of the network should be worked out. In order to do so, the parameters of its elements which decide about the values of assumed objective function, should be identified. The length of the analyzed line subsections should be defined and classified to one or two types of line. The analysis was conducted for subsections of overhead lines with non-insulated conductors and cable line subsections without their detailed classification as far as the diameter and applied insulation are concerned. The literature reliability parameters of the line [29] are listed in Table 2. Information about the length of the sections and number of customers in particular nodes of the network creates bases for determining SAIDI (1).

Table 2
Reliability parameters of elements of 15 kV network

Element	**Frequency of faults (1/100 km year)**	**Average duration of a breakdown (h)**
overhead line	6.24	3.69
cable line	12.58	2.17

For determining SAIDI reference values an assumption was made that sectionalizing switches were not installed inside the network, but breakers at the beginning of each line. Such circuit breakers, as a line protection element, are typically installed in the MV substation in the main feeding point (MFP). The results obtained for networks without switches are listed in Table 3. The lack of sectionalizing switches inside the network is very disadvantageous. The disturbance of any element switches off the entire line. In this case no alternative supplying of the line (by closing the switch in the tie point) is possible (reclosing on short-circuit).

Table 3
SAIDI for particular lines without sectionalizing switches

SAIDI (min./customer/year)					
Line					
A	B	C	D	E	F
119.11	450.82	421.22	153.49	835.94	432.59

The optimized placement of switches was determined on the basis of assumed reserve feeding in the analyzed lines (closing switches in tie points) and distribution of one to four switches. Authors assumed that switches would be placed only in the main line of the feeder (Fig. 3).

Optimal placement of switches is based on the value of assumed objective function. In this paper the objective function is SAIDI. In this case, attempts are made to place the switches is such a way that the objective function has a minimum value for them. This placement of switches is an optimum solution of this task. The optimal solutions for analysis network, are presented in Table 4. The results show the expected conclusion – the more switches the lower the SAIDI value.

Table 4
SAIDI for particular lines with sectionalizing switches

Line	SAIDI (min./customer/year) and locations according to Fig. 3: [subsection no. b – beginning / e – end]			
	1 switch	2 switches	3 switches	4 switches
A	58.713 [7e]	24.600 [5e; 10b]	16.030 [5e; 8b; 10b]	12.741 [5e; 7b; 9e; 10b]
B	215.246 [10e]	158.061 [9b; 17e]	109.433 [8e; 9e; 17e]	90.8118 [8e; 9b; 16e; 20e]
C	202.603 [20e]	133.980 [15e; 24e]	101.284 [12e; 20e; 25b]	80.626 [11e; 17e; 22e; 25e]
D	74.956 [5b]	48.812 [3e; 7b]	31.532 [2e; 5b; 11e]	23.608 [2e; 4b; 7b; 12e]
E	381.998 [23b]	252.603 [21b; 29e]	188.783 [17e; 23b; 30e]	152.516 [14e; 21b; 26b; 31e]
F	216.607 [11e]	143.580 [9e; 12b]	109.561 [7b; 11e; 15e]	90.979 [7b; 11e; 12b; 18e]

The results show that for lines with already installed switches in optimal placement, the need to install an additional switch is related to re-solve the SPP. This means that determined best placements at *NL* switches may not correspond with optimal placements at *NL*+1 switches (Table 4). The presented results show the purposefulness of the use of sectionalizing switches. SAIDI can be reduced to up to 50% when one switch is installed (Fig. 4).

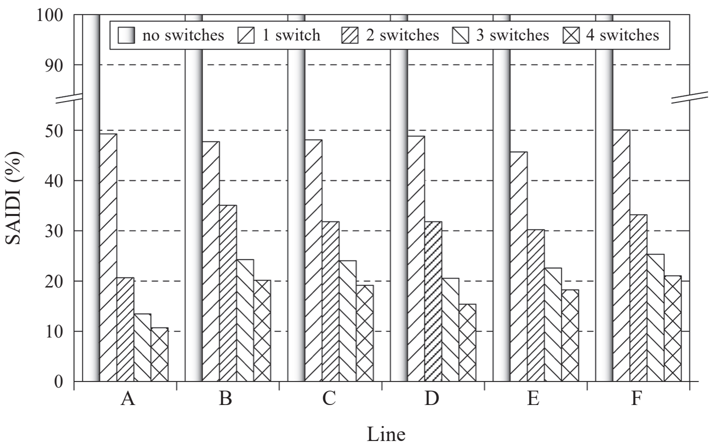

Fig. 4. Relative value of SAIDI for different number of sectionalizing switches

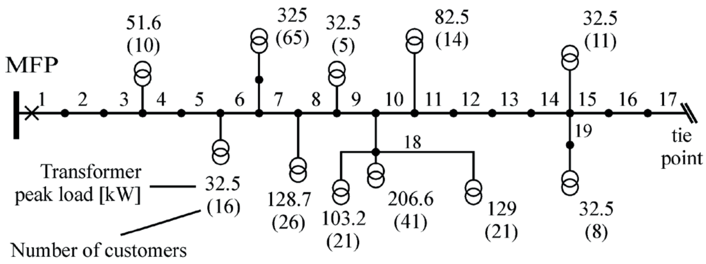

Fig. 5. Schematic of line A

The presented calculations do not include investment and maintenance costs. If the investment outlays are taken into account, it may result in a solution with a small number of switches and a smaller improvement of the reliability indices.

Thus, in practice, the number of switches will depend on the relations between capital cost of switches and profit, e.g. from limited cost of undelivered energy [21, 26, 28].

In order to present the effect of sectionalizing switches placement on the optimized objective function, calculations were based on the placement of a single switch in the successive subsections of line A of the analyzed network. A full picture of line A is given in Fig. 5.

The results of simulation of sectionalizing switches placement in each subsection of line A are presented in Fig. 6, count-

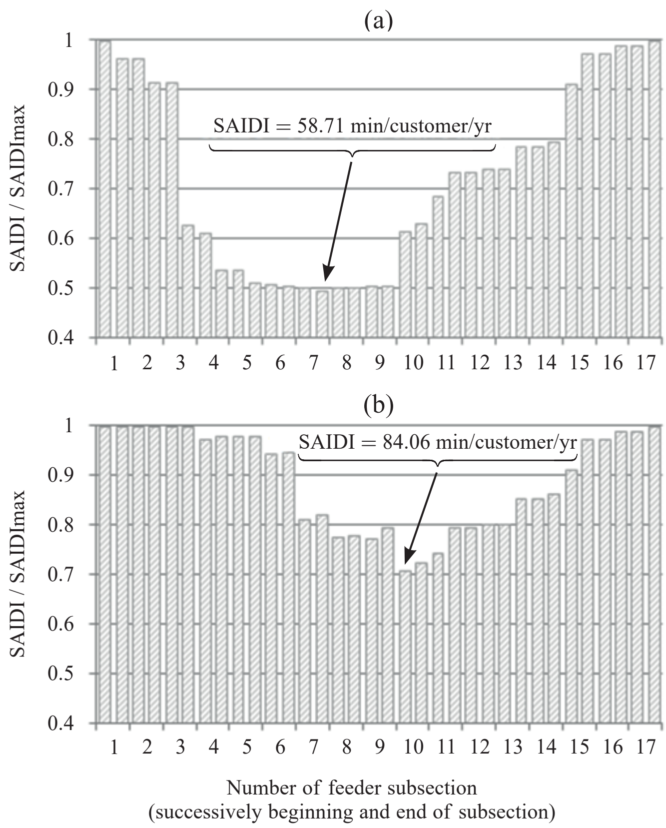

Fig. 6. SAIDI for the placement of an individual switch in successive subsections of the line A: a) possible supplying on the side of the tie point; b) no possibility of supplying on the side of the tie point

ing from the feeding station to the tie point. The results with and without alternative supply are presented in Fig. 6a and Fig. 6b, respectively.

The possibility to reserve the line facilitates the optimal selection of switches placement. In the lack of alternative power supply the reliability indices significantly deteriorate and the switch has to be replaced (for SAIDI in subsection 7 to subsection 10 – Fig. 5).

Tables 5 and Table 6 contain results of optimal placement of switches based on SAIDI for line A with and without alternative supply. In this case switches could be placed not only in the main line (subsections 1÷17) but also in the lateral branches. The placement of switches in the branches is selected only for a bigger number of switches. The switches are allocated in the feeders at first. This justifies limiting the size of the task by the placement of the switches in the main line and possibly in larger lateral branches. Line A has so few lateral branches that switches were placed mainly in the main line. In line having numerous and long lateral branches, the switches will be placed in lateral branches more readily.

Table 5
Results of optimization calculations of sectionalizing switches for line A with alternative supply

No. of switches	**SAIDI (min./customer/year)**	**Location according to Fig. 3 no. of subsection b – beginning / e – end**
1	57.713	7e
2	24.599	5e; 10b
3	16.030	5e; 8b;10b
4	12.741	5e; 7b; 9e; 10b
5	9.870	5e; 7b; 9e; 10b; 19e

Table 6
Results of optimization calculations of sectionalizing switches for line A without alternative supply

No. of switches	**SAIDI (min./customer/year)**	**Location according to Fig. 3 no. of subsection b – beginning / e – end**
1	84.059	10b
2	77.110	7b; 10b
3	74.699	7b; 10b; 18b
4	72.737	7b; 10b; 11b; 18b
5	71.703	7b; 8b; 10b; 11b; 18b

To compare the efficiency of applied algorithms, calculations were made for the placement of 1 to 7 switches in line A. First, the brute force method was applied. The obtained results were taken as a reference for the remaining algorithms. The number of all placement combinations of switches and total time of program operation when using particular algorithms, are presented in Table 7. The efficiency was verified by comparing the obtained results, operation time of the program and time after which the optimal solution was generated.

Table 7
Number of possible solutions for sectionalizing switches in line A and time of program operation for particular algorithms

No. of switches	**No. of all solutions**	**Time of program operation (s)**		
		brute force algorithm	evolutionary algorithm	heuristic algorithm
1	32	0.03	65.792	1.145
2	496	0.66	73.048	10.713
3	4960	7.00	82.572	18.095
4	35960	61.93	96.668	24.886
5	201376	446.25	110.948	33.251
6	906192	2107.9	125.491	42.618
7	3365856	8946.91	137.078	49.694

Results obtained with the use of evolutionary and heuristic algorithms were congruent with the results for the brute force method, i.e. the global optimum was obtained. The comparison of working time of the program reveals that the brute force method is perfect for a small number of switches (1÷3 for line A). In the case of a bigger number of switches the evolutionary, especially the described heuristic algorithm, is more advantageous. It should be emphasized that the time of work of the evolutionary and heuristic algorithms strongly depends on the assumed parameters of calculation process. The correction of these parameters aiming at a shorter time of operation of the program may bring about a non-optimal solution, i.e. local optimum.

Comparing evolutionary and heuristic algorithms in terms of the time of obtaining optimal solutions, the advantage of the heuristic algorithm over the evolutionary algorithm can be observed. Time after which the optimal solutions are obtained depends on a number of important variables, the change of which may affect the results and the final conclusions. Among the variables influencing the calculation process are: the set of selected parameters of algorithms (e.g. number of population and iterations), specific character of the task (placement of switches in the feeder or in the whole network), size and parameters of the network (distribution of loads, fallibility of sections).

The structure of the analyzed network in combination with the given number of allocated switches determines the distribution of extremes of the objective functions in the space of feasible solutions of the task. The efficiency of the algorithms in view of the time of generating a global optimal solution was investigated by performing the calculation procedure 30 times (each time taking 300 iterations of a random solution and 5 cycles of procedure). The time values in which the optimal solution was obtained for a given number of sectionalizing switches with evolutionary and heuristic algorithms are presented in Fig. 7a and Fig. 7b, respectively.

The results are presented in the form of Box-and-Whiskers plots, where the groups of numerical data are presented as quartiles. In this way the parameters defining the placement, scattering and shape of empirical distribution of the analyzed sample can be shown collectively. In many cases the analysis

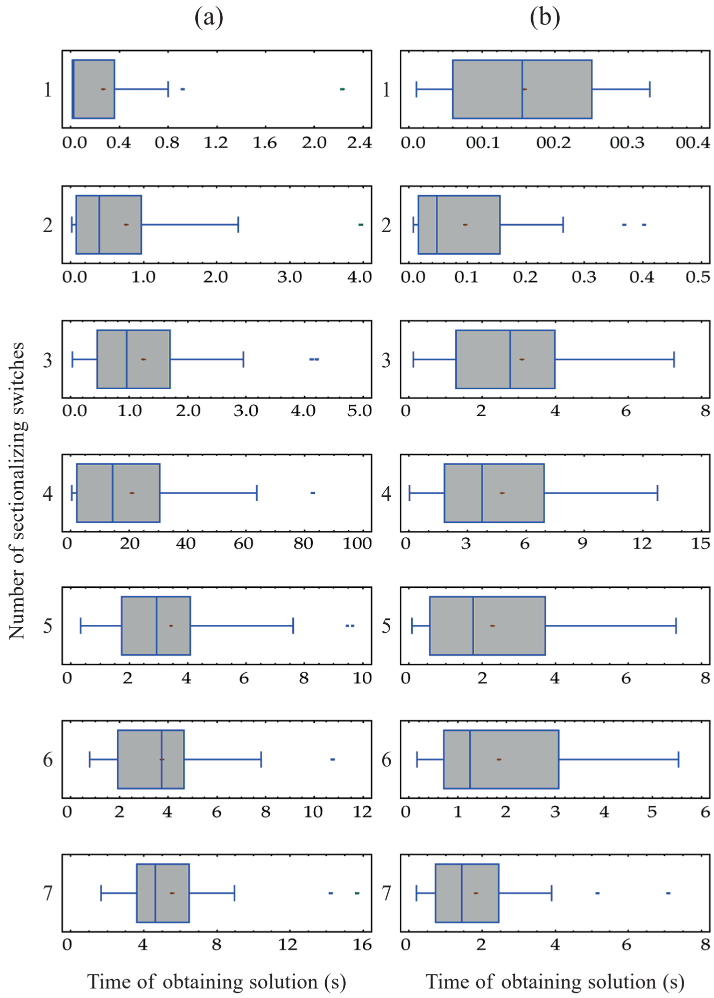

Fig. 7. Time in which optimum solution is obtained for the analyzed number of sectionalizing switches: a) evolutionary algorithm; b) heuristic algorithm

of time of obtaining optimal solutions showed to the advantage of the heuristic model. Attention should be paid to the fact that the placement of 4 sectionalizing switches in line A was connected with noticeable elongation of time in which optimal solution was obtained. This certainly stems from the closeness of the space of local optimum solutions having values close to global optimum.

SSP is not one of the problems that need to be solved in a very short time. The placements of the switches are in practice determined once for a long period of operation. However, in the literature we can find algorithms for this task which guarantee obtaining optimal solutions in a very short time [9].

4. Conclusions

The main element of the smart grids concept is monitoring of their conditions. At present these functions on MV level are basically limited to the main feeding points (in HV/MV stations). This hinders proper placement of sectionalizing switches of the advanced system controlling the MV distribution network. The implementation of autonomous control systems will be fully justified after expanding the measurement system in MV/LV stations compatible with the assumptions of smart metering technique.

The optimal selection of switches placement was based on three methods: brute force method, evolutionary algorithm and heuristic algorithm. The calculations were performed for a real MV power network.

Regardless the assumed localization criterion, the described evolutionary and heuristic algorithms can be successfully used in the described case. They provide optimal solutions in a relatively short time, especially as compared to the brute force method applied for extensive power networks.

Proper selection of sectionalizing switches in a MV distribution network is crucial for the improvement of the continuity of supplies and will allow for using the full potential created by intelligent control systems.

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