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Optimal arrangement of sectionalizing switches in medium voltage distribution network

Abstract. *This paper presents a selection method of sectionalizing switches location in the medium voltage distribution network. Defined reserve network rate is an adopted location selection criterion. In the article an algorithm and computational example, illustrating application of the developed optimization algorithm were presented.*

Streszczenie*. W artykule przedstawia się metodę wyboru lokalizacji łączników sekcjonujących w sieci rozdzielczej średniego napięcia. Przyjętym kryterium wyboru miejsca lokalizacji jest zdefiniowany współczynnik rezerwowania sieci. W artykule przedstawiono algorytm oraz przykład obliczeniowy ilustrujący zastosowanie opracowanego algorytmu optymalizacyjnego.(****Optymalne rozmieszczenie łączników sekcjonujących w sieci rozdzielczej średniego napięcia****).*

Keywords: medium voltage distribution network, sectionalizing switches, evolutionary algorithm.
Słowa kluczowe: elektroenergetyczne sieci rozdzielcze średniego napięcia, łączniki sekcjonujące, algorytm ewolucyjny.

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Introduction

Medium voltage (MV) electric power distribution networks have opened or closed structures, in addition always work in opened configurations. In main line of MV networks usually are installed switches enabling, in case of breakdown, separation of damaged network fragment. With increase in the number of such sectionalizing switches a capital cost grows, but reliability of network work increases, and hence decreases cost of undelivered energy to customers. Selection of sectionalizing switches number as well as location is a complex combinatorial optimization task.

Selection problem of the sectionalizing switches location for many years is brought up during scientific conferences and in trade literature. To solve this problem both classical mathematical methods and algorithms based on the artificial intelligence are applicable.

Publication [1] shows the task solution of optimal switches location with analytical method, bringing analysis to simplified algebraic relations. In works [2], [3] and [4] heuristic algorithms were applied. In work [2] ant colony optimization algorithm was applied, however in the work [3] genetic algorithm. In the work [5] to solve the switches location problem a swarm algorithm was applied, assisted by genetic algorithm. Works [2] and [5] are widening the task of sectionalizing switches location for distribution networks with connected additional power sources.

Quoted literature constitutes only an example of applicability diverse solving tasks methods of the optimal sectionalizing switches location. Problem classified as combinatorial, often is solved by applying so-called artificial intelligence methods. This article presents one of these group method applications – an evolutionary algorithm.

Installation profitability of the sectionalizing switches

In the economic analysis of power network operation an important component are costs associated with non-delivery energy to customers, called the power supply unreliability. For companies providing services of electricity transmission and/or its distribution, costs for the power supply unreliability include [6]:

- penalties paid to customers for failure to comply customers quality service standards;
- lost income from transmission fees.

In the regulation [7] definite are acceptable durations of power failures. One-time unscheduled break cannot exceed 24 hours, and the sum of unscheduled time breaks within one year shouldn't exceed 48 hours (IV and V additive group). If the break time in power supply doesn't exceed permissible values, the cost of undelivered energy is equivalent to changeable component of the network rate and total undelivered energy quantity E_{u} to customer within one year. Undelivered energy, as a result of power line unreliability, it is possible approximately to appoint from the relation (1).

$$E_{\mathrm{u}} = q_0\, l\, E \quad (1)$$

where: q_0 – annual unavailability, l – line length [km], E – energy quantity provided to customers within one year [MWh].

Disruption in line work (e.g. short circuit) cause stimulation of the appropriate protection system and exclusion from the line work. If the feeder line is equipped with one switch installed in its beginning (in the feeder bay), the entire line is turned off and all customers supplied from it are deprived of power supply. In order to reduce interference effect (excluding customers), the line can be equipped with substantial amount of switches – sectionalizing switches. The number of n switches and their location should be as established that the total cost of these C_{s} switches didn't exceed the profit associated with reduction unreliability power supply cost ΔC_{ue} in the operating period (2).

$$n \cdot C_{\mathrm{s}} < \Delta C_{\mathrm{ue}}(n) \quad (2)$$

Specified in the regulation [7] acceptable time breaks include disturbed situations of various network components, which have an impact on the continuity power supply for final customers. These are e.g. medium voltage (MV) lines, low voltage (LV) lines, MV/LV transformers. Acceptable annual unplanned time breaks determination for e.g. MV power lines, requires failure knowledge of all network elements creating supply system. Data such as the number of damage per year for individual network elements as well as breakdown duration are collected by distribution operators system. If damage intensity of SN overhead line is λ = 8 1/100km/year, and the average interferences duration t = 3.8 h (data according to statistics of the distribution operator system), so the average total break time for this line type about 100 km length is 30.4 h.

Analyses points [8] that time values of unscheduled break, set based on statistical data collected by distribution operator system, usually don't exceed acceptable time breaks. If the break time in power supply doesn't exceed permissible values, the sum of discounted annual undelivered energy costs, in established analysis period, it is possible to set from the relation (3).

$$C_{\mathrm{ue}} = \sum_{t=1}^{N} \left(E\left(1+\alpha\right)^{t-1} \cdot c_{\mathrm{v}} \cdot q_{\mathrm{s}} \cdot \left(1+p\right)^{-t} \right) \tag{3}$$

where: t – year, for which calculations are conducted; α – relative annual network load increment; p – interest rate (discount rate); q_s – annual unavailability (line with installed switches); c_v – changeable network rate component [PLN/MWh]; N – analysis period.

Penalties paid to customers for failure to comply customers quality service standards (so-called discounts) are calculated when time breaks in the power supply exceeds permissible values. In case of emergency breaks exceeding permissible values, the sum of discounted annual undelivered energy costs for N year period is set from the relation (4).

$$C_{\mathrm{ue}} = \sum_{t=1}^{N} \left(E\left(1+\alpha\right)^{t-1} \left(q_{\mathrm{s}} - q_{\mathrm{lim}}\right) \cdot c_{\mathrm{b}} \cdot c_{\mathrm{E}} \cdot \left(1+p\right)^{-t} \right) + \sum_{t=1}^{N} \left(E\left(1+\alpha\right)^{t-1} \cdot c_{\mathrm{v}} \cdot q_{\mathrm{s}} \cdot \left(1+p\right)^{-t} \right) \tag{4}$$

where: q_{lim} – border annual unavailability appointed based on the acceptable emergency time break in the year; c_b – multi of energy price (discount entitled to the customer); c_E – average energy price [PLN/MWh].

Appointment, from the relation (2) of optimal switches number (providing value maximization: $\Delta C_{ue}(n) - n \cdot C_s$) is a complex task. Cost change of the unreliability power supply after inserting sectionalizing switches is dependent from places of their installation. In situation where relation (2) isn't fulfilled (lack of grounds for sectionalizing switches installation), switches can be installed in order to improve continuity parameters of the supplying customers and network operating conditions. In the present article exactly such a case is considered.

Problem formulation of the optimization task

In Figure 1 presented a distribution network model with installed sectionalizing switches a and b dividing circuit to section X, Y and Z. Respectively arranged switches allow to reduce number of excluded customers (undelivered energy). In case of disruption in the section Y, switches a and b allow on reliable X and Z section work. Section Y is turned off (opening switches a and b), but section X and Z are supplied appropriately from the station A and B (after switching at the point of permanent network division). Number of excluded customers (section) is conditional on the possibility to reserve line. In the opened structure network, sections located further from the power source, also will be deprived of power supply. In case of circuit power exclusively from the station A, sections Y and Z will be excluded. Therefore, network structures can have an impact on the location selection to install sectionalizing switches.

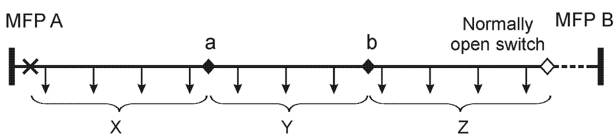

Fig.1. Distribution network model with installed sectionalizing switches

In solved task an optimal sectionalizing switches locations are seek. In order to compare conditions of certainty line work with a different number, arranged in many switches locations, shall be amended the reserve line rate ρ. Reserve line rate, constituting the objective function of optimization task, is determined as follows:

$$\max \rightarrow \quad \rho = \frac{S - S_{\mathrm{r}}}{S} \tag{5}$$

where:

$$S_{\mathrm{r}} = \frac{\sum_{i=1}^{\mathrm{s}} S_i \left(q_{\mathrm{ol}} \sum_{j=1}^{\mathrm{m}_i} l_{\mathrm{ol}ij} + q_{\mathrm{cl}} \sum_{j=1}^{\mathrm{n}_i} l_{\mathrm{cl}ij} \right)}{\sum_{i=1}^{\mathrm{s}} \left(q_{\mathrm{ol}} \sum_{j=1}^{\mathrm{m}_i} l_{\mathrm{ol}ij} + q_{\mathrm{cl}} \sum_{j=1}^{\mathrm{n}_i} l_{\mathrm{cl}ij} \right)} \tag{6}$$

where: s – number of section in the network, S – total network load [kVA], S_i – total load of i section and other sections if in i damage causes power deprivation [kVA], q_{ol}, q_{cl} – annual unavailability of the overhead line and underground power cable, l_{olij}, l_{clij} – lengths of j overhead line and underground cable sections in i section [km].

If the network isn't equipped with sectionalizing switches, reserve rate (5) assumes 0 values. If the network is a feeder line without lateral branches with possibility to reserve (double-sided power supply) and in every feeder line point, on its beginning and the end a switch is installed, the reserve rate amounts 1. In such a case, none line damage won't cause exclusion any of customers (omitting needed shutdowns for effecting switching). Real power networks are usually more extended and sometimes deprived of possibility to supply from other transformer station (such as in e.g. on Figure 1 – reserve power supply from B station). Determined installment locations of set switches number in a given network will be optimal if the reserve line rate ρ will accept maximum value. Annual unreliability of distribution power line with installed sectionalizing switches it is possible in such case to express the relation (7).

$$q_{\mathrm{s}} = q\left(1-\rho\right) \tag{7}$$

where: q – annual unreliability of distribution power line.

Solution task method

Described optimization problem, due to the need for switches location selection from extensive set of possible variants, is a discreet, combinatorial task. Along with the increase in power distribution network extensiveness, a number of possible sectionalizing switch locations and combination of their arrangement increases. In the optimization task this means an increase in variables number. The most beneficial switches locations it is possible to obtain by applying, in the case of rather small networks, the complete review method. For larger networks applicability of such a technique is limited due to longer computation time. Substantial solutions number and computation time growing with the task scope support to consider many simplifying assumptions (e.g. omitting switches location in lateral branches). However, such assumptions may cause omission of the most beneficial sectionalizing switches localization. In case of large networks, in which the localization of at least three switches is assumed, other optimization methods can be successfully applied. Algorithms of so-called artificial intelligence are an example of such methods e.g. evolutionary or genetic algorithm [9], [10]. Evolutionary or genetic algorithms perform searching a solution space for an optimal or near-to-optimal solution to a problem. The evolutionary algorithm is characterized by an easiness of adaptation to solved problem (particularly combinatorial) and computer implementation simplicity.

Evolutionary algorithm operates on the entire solutions task groups, called populations [9], [10]. Algorithm operation principle consists on providing next solutions (obtained in an iterative cycle), elements (features) previously obtained solution (individuals). Only best adapted individuals have a chance to survive like longest and pass to its numerous offspring features. This provides a directed computational process towards desirable results – solutions about the considerable objective function value. The general evolutionary algorithm diagram is presented in Figure 2.

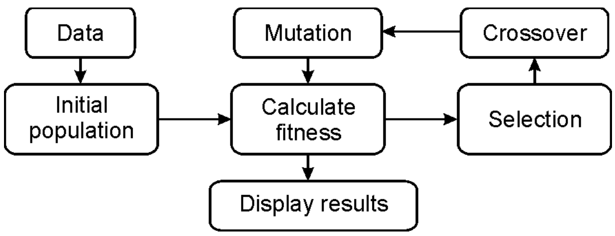

Fig.2. Flow diagram of the evolutionary algorithm

An evolutionary algorithm uses mechanisms inspired by biological evolution, such as selection, recombination and mutation. Evolutionary algorithm starts its operation from creating the so-called initial population. This population consists of randomly created individuals representing different, in generally non-optimal, set task solutions. Further algorithm actions consist in the cyclical evolution mechanisms realization, which are:

- selection – from current individuals populations are being chosen the best solutions and they are copied in a dependent rank on the fitness function value. In solved task used selection method based on a remainder stochastic sampling with replacement mechanism [9];
- crossing – individuals are randomly combined in pairs creating two new individuals. New population individuals receive, in different proportion, both parents' features. Such a combination of features gives the chance for creation even better adapted individuals;
- mutation – consists on current reproduction and crossing disruption process by giving selected individuals new features, not-appearing in individuals, from combination which arise. Process is carried out by change of randomly selected combination code element.

Individual fitness is determined based on their distinctive features. In algorithm these features are recorded in the form of combination code called also as chromosome. In presented optimization objective the combination code includes numerical values series. Position number within combination corresponds to the sectionalizing switches number. Element value of every position identifies one of acceptable network locations. Such a combination code structure in the appropriate way copies solutions to the presented problem. Quality of every solution (individual fitness) specifies an objective function value appointed based on the relation (5).

Described above evolutionary algorithm, adapted for the optimization arrangement sectionalizing switches needs, has been implemented using C++ programming language.

Computational example

Selected fragment of real distribution network is a network about closed structure, but working in the opened configuration. Simplified MV network diagram presented in Figure 3. Network, in the normal working layout, is supplied from one main feeding point (MFP). An alternative power supply (reserve) is possible of the entire circuit from other transformer station. It is conducted by closing down the switch in permanent network cut point (opened switch in the normal work state – Fig. 3) and turning off closed switch in the main feeding point.

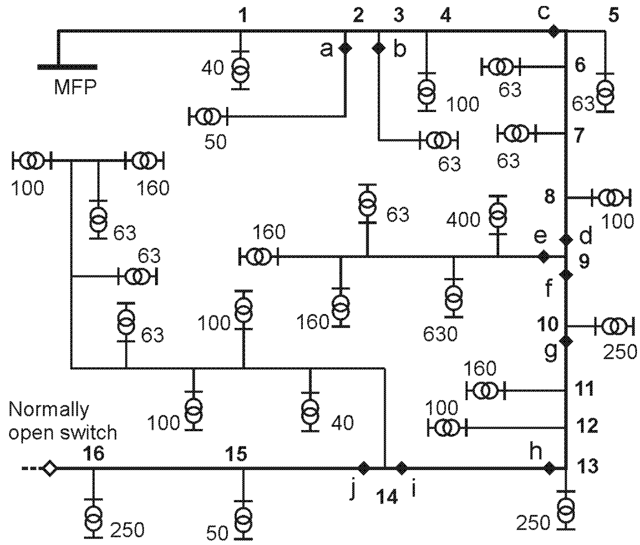

Fig.3. An example of MV distribution network

The analyzed MV circuit includes 27 MV/LV transformer stations. Installed in them transformers are units about powers 40 ÷ 630 kVA (transformers power ratings presented in Figure 3). In calculations assumed a steady load level of the transformer stations amounting 42.9 %. Described MV network includes exclusively overhead lines, which total length is 21.73 km (including branch length 10.89 km).

Calculations were carried out for two network work variants: network supplied one-sidedly and network supplied one-sidedly with the possibility of double-sided reserve (by closing switch in the cut point and supplying from other MV network circuit). In both variants all customers (MV/LV transformer stations), in the normal network working condition, are supplied from one main feeding point. In the network are planned to install 1 to 5 sectionalizing switches. In order to appoint the most beneficial switches locations a computer program was applied carrying calculations out by complete solutions review method (location 1 and 2 switches) and according to developed evolutionary algorithm (location 3 ÷ 5 switches).

In analysis assumed: N = 10 years, α = 1%, p = 8%, c_v = 86.56 PLN/MWh, E = 4818.73 MWh, power factor = 0.9. The following evolutionary algorithm parameters were established, and assumed: population of 20 individuals, 3000 iterations (generations), crossing probability 0.85, mutation probability 0.04. A complete review method was also applied to verify 3 switches location – received compliance of both methods results, what proves the correctness of selected algorithm parameters. Application of the complete review method for substantial switches amount, due to long computation time, is pointless. For example, for the three switches, the calculations took approximately 6 minutes using an evolutionary algorithm and about 90 minutes for a complete review (PC 2.5 GHz, 4GB RAM).

In Tables 1 and 2 optimization calculations results are presented. Optimal switches locations were described (location marking according to Figure 3) as well as set value of reserve network rates ρ.

Analyzing obtained results it is possible to state that distribution networks structure ensuring the possibility of multilateral power supply is beneficial. Reliability of power supply increases additionally with the installed number of sectionalizing switches. Substantial switches amount is recommended in particular for one-sidedly supplied networks. In double-sided supplied networks the switches number can be smaller at comparable rate value ρ.

Table 1. Calculations results of the sectionalizing switches location in the network without reserve

Switches locations	Reserve ratio ρ	EAUEC [PLN]
g	0,31979	337
f, h	0,38213	306
e, f, h	0,42979	282
a, e, f, h	0,46822	263
a, b, e, f, h	0,50572	245

Table 2. Calculations results of the sectionalizing switches location in the network with possibility to reserve at the point of permanent cutting-up

Switches locations	Reserve ratio ρ	EAUEC [PLN]
g	0,50709	244
d, h	0,71223	142
d, g, i	0,78419	107
d, g, i, j	0,82093	89
c, d, g, i, j	0,84840	75

In Tables 1 and 2 an equivalent annual undelivered energy costs (EAUEC) are presented. These values are calculated based on relation (3) and (4) dividing obtained results by the sum of discounting factors [6]. In considered example all results of annual undelivered energy costs were definite including the relations (3). The reason for this was low, with reference to permissible value [7], failure line rate. The biggest average breaks time was presented for not-reserved network equipped with one sectionalizing switch. It amounted 6.8 hours, while breaks time value for the network without switches was about 10 hours. This fact means that in such a case, the discount paid to customers for arises power supply breaks aren't included.

Assuming a remotely controlled switches cost amounting PLN 50000 (equivalent annual cost of installing a single switch is PLN 8701), analysis didn't showed the compliment with condition in any variant (2). In the presented example proves it a usefulness of formulating the objective function according to relation (5) – maximization rate ρ.

Summary

Cause disturbances in the power networks operation are most often short circuits resulting from mechanical damage (mainly overhead lines). A significant way to improve the power certainty is such an expansion network, which provides alternative power means for customers (closed structures). Medium voltage distribution networks should be equipped with the substantial sectionalizing switches amount. Their task, combined with the multilateral network supplying possibility, is an elimination of damaged line sections without any harmful effects for remaining customers in power supply continuity. The biggest advantages in this respect are automatic switches so-called reclosers, which have a possibility of automatic distinguishing sections affected by the breakdown.

This article presents selection method of the most beneficial installation switches location. The method is based on an evolutionary algorithm. Defined reserve network rate is an adopted location selection criterion.

Optimal switches arrangement in the network provides a reduction of undelivered energy to customers, and hence unreliability power supply costs. Medium voltage network operating efficiency is increased along with the switches installed number. Selection of their number may depend on cost change of unreliability power supply or funds amounts allocated for investments by the distribution operator network.

Future research will focus on the issue of location of sectionalizing switches in the MV distribution network with distributed generation sources.

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