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Designing of two-voltage power supply systems for 110 kV/medium voltage substations†

The paper tackles the problems of designing redundancy feeding lines for supplying medium voltage (MV) municipal power networks in the conditions of increased load of 110 kV/MV transformer stations. Designed feeding systems lie in direct MV connections between 110 kV/MV transformer stations. The 110 kV/MV transformers were planned to be replaced and MV switching stations modernized. A mathematical model with an objective function for minimizing the total capital cost of the planned network was worked out. A genetic algorithm was used for solving the optimization task. Exemplary calculations for two power networks, results of analyses and final conclusions close the paper.

1 Introduction

Electrical power networks cover high voltage (HV – 110 kV), medium voltage (MV) and low voltage (LV) networks and stations [2]. The 110 kV/MV transformer stations, the so-called Main Feeding Points (MFP) receive power in 110 kV networks. These stations are fed by electrical power line systems, extended between feeding points and HV node stations. The 110 kV/MV stations are usually equipped with two transformers feeding MV networks. MV switching stations in 110 kV/MV stations are made as frequently single- (SBB) or rarely double-busbar arrangements (DBB), divided in sections.

Medium voltage networks are closed (e.g., loop) or open (e.g., radially branched off) systems. Closed networks operate in open configurations, i.e. during breakdowns of the feeding system energy can be supplied to the receiving MV/LV

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stations through a new pathway obtained after changing the present configuration of network.

The operation of 110 kV/MV transformer stations should guarantee mutual reserving of the installed transformers, i.e. when one of the transformers is switched off (planned action or failure situation), the other (operating) transformer should overtake the full load of the station. This is guaranteed when the total load of the station does not exceed the rated power of the operating transformer and is possible in the case of slight exceeding the power value. Problems may occur with mutual reserving in the case of considerable increased load of 110 kV/MV transformers. The increased power demand may be admissible if an alternative feeding source is provided at the level of MV power distribution networks (change of configuration of the network, distributed generation), which is not always possible (open structures or limited transmission abilities of the elements making up the system), frequently requiring numerous and tedious connecting operations.

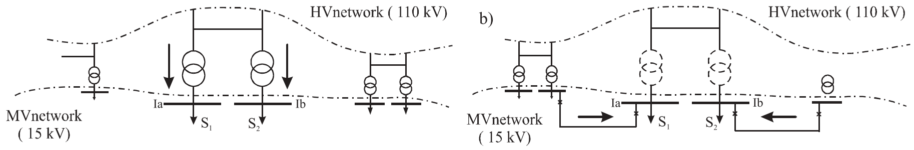

Figure 1. Pathways of feeding electrical energy customers in a MV network (15 kV), a) basic supply, b) redundancy supply.

The most feasible solution for the city areas is making use of the existing or making new MV lines directly connecting 110 kV/MV transformer stations (Fig. 1b). With suitable capacity, such connections safeguard power supplies to the switching station in failure situations of 110 kV/MV transformer stations (Fig. 1a) or 110 kV lines; they also eliminate redundancy problems for the MV switching network. The missing power is transmitted in the state of highest load, i.e. in the worst state of operation of the station.

2 Problem to be solved

The analysis is focused on a medium voltage electrical power network having a special structure, and playing the role of redundant feeding network for municipal MV distribution networks. The MV reserving feeding networks (MFP-to-MFP) consists of co-operating 110 kV/MV transformers and MV cable lines, directly connecting stations of the analyzed area with switching stations. The solution of the MV lines system in the analyzed situation may depend on the 110 kV system, therefore the presented problem can be viewed in terms of designing a two-voltage system.

The task lies in optimizing the structure of MV networks MFP-to-MFP at a selected time, without accounting for optimization of the MV distribution networks operation and predicting its development. A sum of capital costs of the reserving feeding systems, covering the cost of building the MV lines, replacement of 110 kV/MV transformers and modernization of MV switching stations (double-busbar instead of single-busbar arrangement) has been assumed as objective function. Owing to the fact that operation of MV reserving lines has been assumed to operate for relatively short time following the break-down during the year, the function of costs was limited to capital costs only. The power supply safety reasons have been accounted for in the assumed reliability criterion [6] – realization of power supplies without any limitation. The task to be solved is reduced to optimization of a function of several variables, function of discrete variables, in a limited domain of admissible solutions.

3 Mathematical model

3.1 Network representation

Mathematical model represents operation of electrical power systems that are most frequently encountered in practice. The remaining systems may be accounted for after the model has been modified or broadened. The analyzed electrical power network consisted of:

- HV networks (110 kV) – a real network system which does not undergo changes in optimization task,
- T – transformer station (110 kV/15 kV) – existing stations, for which the transformers can be replaced (higher rated power) and MV switching stations (double-busbar arrangements),
- MV networks (15 kV) – a network, for which designed MV redundancy feeding network can be distinguished.

The analyzed power network is represented by a network of the theory of graphs. A two-voltage network has been analyzed:

$$\Phi = \Phi^{HV} \cup \Phi^{MV} \cup \Phi^{T} = \langle X_{ahv}, X_{mv}, L_{hv}, L_{mv}, L_t, C_{hv}, C_{mv}, C_t \rangle \ , \qquad (1)$$

where: Φ^{HV} is a high voltage network, Φ^{MV} is a medium voltage network and all HV/MV transformer stations are represented by the symbol Φ^{T}. The sets X_{ahv}, X_{mv} are sets of nodes s and n, respectively, defined for the HV and MV networks. Sets of arcs L_{hv}, L_{mv} and functions of costs described on these arcs C_{hv}, C_{mv} are defined for these networks. The set X_{ahv} (set of all nodes of HV network) contains set X_{hv} of n nodes of HV network representing points where the 110 kV/MV transformers are connected. The nodes of arcs of the set L_t link the respective nodes of sets X_{hv}, X_{mv}. The cost functions described by C_t include costs of replacement of 110 kV/MV transformers C_T and modernization of MV switching stations C_r on arcs in the set L_t.

The HV network system is known and is not designed. The relations between arcs and nodes of a graph of the initial MV network are described by a matrix **B**. This is a square matrix and its magnitude corresponds to the population of the set X_{mv}.

$$\begin{aligned} \mathbf{B} &= [b_{kl}]\ ; \quad k,\ l = 1,\, 2,\, \ldots,\, n; \\ b_{kl} &= \begin{cases} 1, & \text{if nodes } k, l \text{ are connected with an arc oriented to } l, \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \tag{2}$$

The initial feeder line network is a basis for making an optimal network of MV feeder lines. Matrix δ describing the MV network arcs is introduced:

$$\begin{aligned} \delta &= [\delta_{kl}]\ ; \quad k, l = 1,\, 2,\, \ldots,\, n; \\ \delta_{kl} &= \begin{cases} 1, & \text{if node } k \text{ reserves } l, \\ 0, & \text{if arc } l_{kl} \text{ does not exist.} \end{cases} \end{aligned} \tag{3}$$

3.2 Reserving variants

Two reserving variants have been assumed for a 110 kV/MV transformer station involving MFP-to-MFP redundancy lines. The first variant, determining the basic reserving level stems from the risk of a situation when mutual reserving transformers of a 110 kV/MV station is not possible – the disturbance situation of the station lies in switching off one of the transformers ("partial" reserving variant). Having assumed that in the failure situation one of the transformers was switched off, then the station would be reserved by two lines (archs of the graph) of redundant feeding lines (Figs. 2b and 2e). The operating transformer may "overtake" the consumers devoid of power supplies. However, this is possible when the load of the switched off transformer is lower than the reserve of the operating transformer. Otherwise, the transformer may feed only part of the customers. The remaining customers will be fed by a transformer from a different

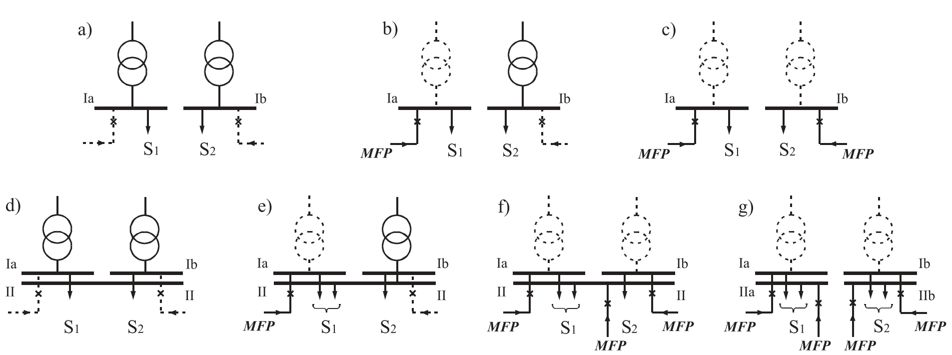

Figure 2. Analyzed states of operation of 110 kV/MV transformer station with MV redundancy lines: a), d) regular operation; b, e) ”partial” reserving; c), f), g) ”full” reserving (continuous line – active elements, broken line – switched off elements).

station through the redundancy MV lines. Such a situation is possible when the redundancy station has a double-busbar switching station (Fig. 2e). In the case of a single-busbar switching station every redundancy line overtakes full load of the switched off transformer (Fig. 2b). In the second variant, determining the increased redundancy level, results from the risk of a situation when both transformers are switched off concurrently (Figs. 2c, 2f and 2g). The redundancy MV lines MFP-to-MFP provide supplies from other stations, overtaking full load of the station (”full” reserving). At the same time the ”partial” reserving requirements are met. In this variant, the station can be reserved by two, three or four redundancy lines, and their number depends on the number of busbar systems in the MV switching station (single-busbar redundancy system is a solution consisting of two reserving lines only).

In each variant, the reserving MV line directly determines the 110kV/MV transformer station. For increasing the capacity of reserving MV lines, in each reserving variant they can be composed of a number of single power cables connected in parallel.

For a 110 kV/MV transformer station equipped with two transformers of load S_{Tj} and S_{Tl} the minimal capacity of MV lines S_{pij} and S_{pkl} is defined in the following way

1. Complete redundancy of station – both transformers are reserved by:

    - two redundant feeding lines (Fig. 2c):

$$S_{p\,ij} = S_{P\,j} \quad \text{and} \quad S_{p\,kl} = S_{P\,l}\ , \quad i,\, k \in \{1,\, 2, \ldots,\, n\}\ , \qquad (4)$$

where S_{Pj} defines redundancy load of j-th transformer of rated power S_{nTj} and S_{Pl} defines redundancy load of l-th transformer of rated power S_{nTl};

- three or four redundant feeding lines (required a MV double-busbar arrangement of transformer station (Figs. 2f and 2g):

$$S_{p\,ij} = S_{p\,kl} = \max\left\{\frac{S_{P\,j} + S_{P\,l}}{3}\,, \frac{S_{P\,j}}{2}\,, \frac{S_{P\,l}}{2}\right\}\,, \quad i,\, k \in \{1,\, 2, \ldots,\, n\}\ ; \tag{5}$$

$$S_{p\,ij} = S_{p\,kl} = \max\left\{\frac{S_{P\,j} + S_{P\,l}}{4}\,, \frac{S_{P\,j}}{2}\,, \frac{S_{P\,l}}{2}\right\}\,, \quad i,\, k \in \{1,\, 2, \ldots,\, n\}\ . \tag{6}$$

In compliance with the assumption of complete redundancy, the first component of the dependences (5) and (6), defines the division of the total power into three or four equal parts (three, four redundand feeding lines). The remaining two components enable redundancy if a single transformer is switched off. In this case, when a double-busbar arrangement of MV switching station is used, two redundant feeding lines provide the supplies.

2. Partial redundancy – loading of an individual transformer is overtaken by the respective redundant feeding line:

   - for a MV single-busbar arrangement of transformer station (redundant feeding lines overtake full transformers' load; Fig. 2b):

$$S_{p\,ij} = S_{P\,j} \quad \text{and} \quad S_{p\,kl} = S_{P\,l}\ , \quad i,\, k \in \{1,\, 2, \ldots,\, n\}\ ; \tag{7}$$

   - for a MV double-busbar arrangement of transformer station (redundant feeding line overtakes part of transformer's load – the remaining power is overtaken by another working transformer; Fig. 2e). In the case of a practical realization of the system, the transformer station can be reserved with the use of only one high capacity line (assumed in the calculation example):

$$S_{p\,ij} = S_{P\,j} - (S_{nTl} - S_{Tl}) \text{ and } S_{p\,kl} = S_{P\,l} - (S_{nTj} - S_{Tj})\ , \quad i,\, k \in \{1,\, 2, \ldots,\, n\}\ . \tag{8}$$

3.3 Objective function

On the assumption that 110 kV network does not undergo designing, the function of cost of arch of HV network C_{hv} is not determined (is equal to 0) and is not accounted in the objective function.

The optimal solution is determined by a series of values of variables δ_{kl}, $\delta_o^{(r)}$ and $\delta_j^{(T)} = f\left(\delta_{kl},\ \delta_o^{(r)}\right)$, for which the objective function:

$$C\left(\delta\right) = \sum_{k=1}^{n}\sum_{l=1}^{n} C_{mv\,kl}\left(\delta_{kl}\right) + \sum_{j=1}^{n} C_{T\,j}\left(\delta_j^{(T)}\right) + \sum_{o=1}^{n/2} C_{r\,o}\left(\delta_o^{(r)}\right) \tag{9}$$

assumes the lowest value, and the Kirchhoff law is met in each solution of power flow, admissible value of voltage drop in MV lines is not exceeded, and the technical limitations related with:

- the number of redundancy MV lines (depending on the assumed variant of redundancy (partial, complete) and the selected solution of the MV switching station (SBB, DBB),
- admissible load of MV lines,
- admissible level of short-circuit power on MV busbars,
- maximum load of transformers.

The optimum system of MV lines MFP-to-MFP is determined by matrix δ. The cost of the line is a function of its length and capacity S_p. The cost function of arc $l_{jk} \in L_{mv}$ of MV network C_{mv} is defined by the cost of making the MV line between nodes (transformers) j, k:

$$C_{mv\,jk} = c_{mv\,jk} \cdot dl_{jk} \cdot \delta_{jk}, \tag{10}$$

where: $c_{mv\,jk}$ is unit capital cost of making a connection between nodes j, k; $c_{mv\,jk} = f\left(S_{p\,jk}\right)$ and dl_{jk} denotes length of connection between nodes j, k.

The cost function C_t, Eq.(1), described on HV/MV line arcs covers the cost of replacing transformers C_T and the cost of modernization of the MV switching station C_r (to a double bus-system):

$$\begin{array}{l} C_{Tj} = c_{Tj} \cdot \delta_j^{(T)} \\ \delta_j^{(T)} = \left\{ \begin{array}{l} 0, if S_{Taw\,j} \leq S_{nT\,j}, \\ 1, if S_{Taw\,j} > S_{nT\,j}. \end{array} \right. \end{array} \tag{11}$$

$$
\begin{aligned}
&C_{ro} = c_{r\,o} \cdot \delta_o^{(r)}; \quad o = 1,\,2,\,\ldots,\,n/2;\\
&\delta_o^{(r)} = \begin{cases} 1, & \text{if DBB arrangement is planned,}\\ 0, & \text{otherwise.}\end{cases}
\end{aligned}
\tag{12}
$$

where:

S_{nTj} – rated power of j-th 110 kV/MV transformer,

c_{Tj} – capital cost of replacing a 110 kV/MV transformer; $c_{T\,j} = f\,(S_{Taw\,j})$,

c_{ro} – capital cost of modernization of o-th MV switching station.

The value of binary variable $\delta_j^{(T)}$ $(j = 1,\,2,\,\ldots,\,n)$ (decision about the replacement of j-th transformer) depends on the value of reserved power $S_{Taw\,j}$. The power $S_{Taw\,j}$ per redundancy transformer results from the designed system of MV lines. Its magnitude may be limited on the assumption that failure situation occurs simultaneously for 110 kV/MV transformers. The MV switching station (single- double-busbar arrangement) can be selected on the basis of the binary variable $\delta_o^{(r)}$ $(o = 1,\,2,\,\ldots,\,n/2)$.

4 Calculation method

4.1 Technique of solving the task

The optimization problem was solved with genetic algorithm [1,3]. The metaheuristic algorithm was selected for a number of reasons, i.e. combinatory character of the posed problem, computational complexity, difficulty with applying analytical approach and a great number of variables, discrete variables including.

4.2 Chromosome representation and fitness function

The solution of a task is written in a form that is “egible” to the genetic algorithm as a string. This is realized with the use of the binary coding method.

The string (chromosome) consists of two parts:

- the first (basic) one describes MV redundancy networks MFP-to-MFP,
- the other (auxiliary) one is related with the type of busbar arrangements in the MFP.

In the first part of the string, every bit represents a single MV connection (Fig. 3). The bit number corresponds to the number of elements equal of matrix **B** equal to 1. Bits can assume values 1 or 0, which corresponds to the existence

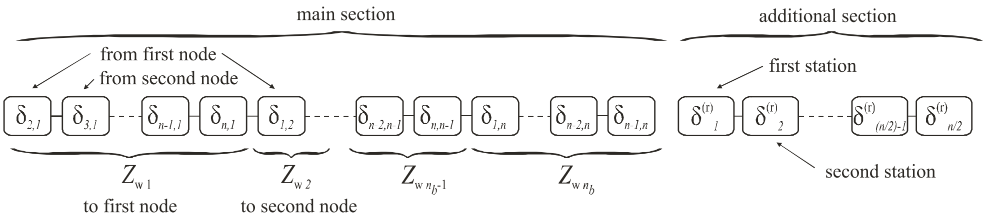

Figure 3. Chromosome: basic part - description of MV lines connections; auxiliary part – types of HV/MV transformer stations.

or lack of specific MV connection. Bits of the basic part of the string are divided into sets Z_w. Each such set covers genes representing redundancy lines of one of the nodes in the MV network. Depending on the assumed transformer redundancy method, and so the number of redundant feeding lines, genes equal to 1 may occur at one or two positions in each of the sets Z_w. The remaining genes of the set assume a value equal to 0.

Another, auxiliary part of the chromosome (Fig. 3) stores information about the type of the MV busbar arrangements. The gene equal to 1 at a suitable position of the string necessitates using medium voltage double-busbar arrangement in a definite 110 kV/MV transformer station.

The auxiliary variable of the string is active (does not undergo evolution mechanisms) if the partial redundancy variant (it is assumed that in a failure situation only one transformer station is cut off) is assumed for a suitable 110 kV/MV transformer station. The auxiliary variable of the string may remain inactive (does not undergo the evolution mechanism), if there was assumed a complete redundancy variant through the designed MV connection (it is assumed that in a failure situation both or only one transformer of a given station are cut off) for a suitable 110 kV/MV transformer station. At such an assumption, the value of an inactive variable is established on the basis of the number of connections of the main part of the string. Therefore, if a given MV transformer station covers three or four redundant feeding lines, the respective part of auxiliary chromosome will be equal to 1.

Fitness of the i-th individual is determined from the relation:

$$F_i(\delta) = c_p \cdot C_{\max}(\delta) - \left[C_i^p(\delta) + C_i^{HV}(\delta)\right] \tag{13}$$

where:
c_p – constant ($c_p > 1$);

$C_{max}(\delta)$ – highest cost of solution obtained for a given generation;

$C_i^p(\delta)$ – cost of solution represented by i-th individual, accounting for the feasible penalty for overloads. The component $C_i^p(\delta)$ of the adjustment function is determined from Eq. (9). The value of the component for non-admissible solutions (observed excess of transformers' rated power), is increased to lower the competitiveness as compared to the admissible solutions. The magnitude of growth of the function by the penalty element accounts for the exceeded rated power of the transformers;

$C_i^{HV}(\delta)$ – penalty function accounting for the 110 kV network system. The component $C_i^{HV}(\delta)$ is determined in the analysis of a system of HV lines. Determining this function requires determining the so-called critical sets (failure cuts [4,5]) for each analyzed node of MV network. The critical set is made of such elements of a HV feeding system, whose simultaneous closing results in the lack of supply in a given MV node. One- and double element critical sets are determined. The costs of solutions lying in MV MFP-to-MFP connecting nodes of the MV network, for which the same critical sets occur. The penalty function is higher the higher is the number of critical sets in common.

4.3 Genetic operators

Their initial population (specified in number) is random. Each selected individual meets the imposed assumptions regarding the required number of arcs – every set Z_w of an individual contains one or two genes equal to 1.

A method based on a remainder stochastic sampling with replacement mechanism was used [1]. The selection stage covers two sub-stages. The first one lies in selecting the fittest individuals, providing them a place in the newly created population. The second stage lies in leaving the remaining places in line with the roulette wheel method. A single-point crossover was applied, limiting the places of string division. The set of admissible crossover points determines the division places of sets Z_w. The determining of exchange points facilitates generation of a new population of individuals representing admissible network configurations.

Mutation of an individual lies in a change of the value of one (introduction or removal of connection) or two genes (change of connection) of set Z_w in the basic part or an individual gene of additional part of the chromosome (single- or double-busbar arrangement of transformer station).

5 Selected calculations results

The following assumptions were made in the presented calculation examples:

- in the regular state o operation of the station, both transformers are switched on,
- parallel operation of both transformers on common 15 kV busbars parallel is not admissible,
- transformers cannot operate with rated power overloads.

5.1 Characteristic of test networks and task parameters

A series of calculations for two test electrical power networks were made in view of their practical applicability.

Network A: A fragment of an electrical power distribution network owned by one of the South Poland Distribution Companies was analyzed. The 110 kV distribution network is fed in three points. The power is received by 6 110 kV/15 kV transformer stations (Tab. 1) distributed in an area of ca. 70 km^2.

Table 1. Rated powers (S_{nT}) and loads (S_T) of transformers.

MFP	1		2		3		4		5		6	
S_{nT} [MVA]	16	16	16	16	25	16	16	16	25	25	25	25
S_T [MVA]	14.1	11.8	13	6.4	12.7	8.8	8.2	1.7	14.9	17.9	10.7	16

The analysis of network A lied in designing a MV reserving feeding system MFP-to-MFP for four calculation simulations differing in the assumptions:

A-I partial reserving, does not account for the influence of the 110 kV network system;

A-II partial reserving, accounts for the influence of the 110 kV network system;

A-III full reserving, accounts for the influence of the 110 kV network system;

A-IV partial and full reserving, accounts for the influence of the 110 kV network system, (the 110 kV line was switched off – open system 110 kV network was obtained for some stations – for these stations the full reserving variant was assumed).

Network B: The test network assumed for the analyses does not represent the real electrical power network. The network does not much differ from the practical realizations, but differs with the distribution of transformer stations and idealized level of transformers' loads. Power is supplied to 5 110 kV/MV transformer stations, distributed symmetrically in a circle of radius r.

The investigations of the test network B covered designing MV lines MFP-to-MFP, accounting for the influence of the size of the power network area:

B-I partial reserving of all 110 kV/15 kV transformer stations,

B-II full reserving of all 110 kV/15 kV transformer stations.

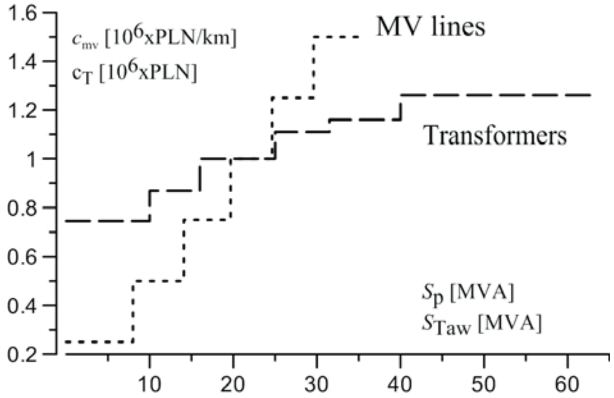

Figure 4. Cost of replacement of 110 kV/SN transformer c_T in a function of reserved power S_{Taw} and cost of building a MV line MFP-to-MFP, c_{mv} in a function of transmitted power S_p.

The level of capital cost of the transformers and cable line (240 mm^2) in the function of transmitted power (Fig. 4) was assumed in the calculations. The assumed unit cost of modernization of the MV switching station in all transformer stations was of PLN $2{\cdot}10^6$.

The scope of influence of mechanisms representing evolution processes on the course of calculations was established through an individual selection of the following parameters for each group of tasks:

- crossover probability: 0.8;
- mutation probability: 0.02–0.035;
- number of population: 50–70;
- number of generations: 1000–3000.

5.2 Switching network A — selected results

It has been assumed that in a failure situation (transformer is switched off) the customers cannot be reserved in the MV network by reconfiguration of MV power distribution network. The power load is overtaken by another transformer (belonging to the same or other station) – a reserving transformer. The reserving transformer may provide reserves for a number of customer groups. However, owing to the little probability that many transformers are switched off simultaneously, the reserving ability is limited to the summaric power of two biggest groups of customers. The rated power of the transformers was reduced to 40 MVA because of the increasing level of short-circuit power in the MV network.

The capital costs of the best solutions (best fitting) obtained for the specific simulation variants are presented in Fig. 5. The following elements of cost were analyzed:

- 15 kV lines – total cost of realization of 15 kV cable lines,
- 15 kV switchgears – total cost of modernization of 15 kV switching stations,
- 110 kV/15 kV transformers – total cost of installing the new 110 kV/15 kV transformers.

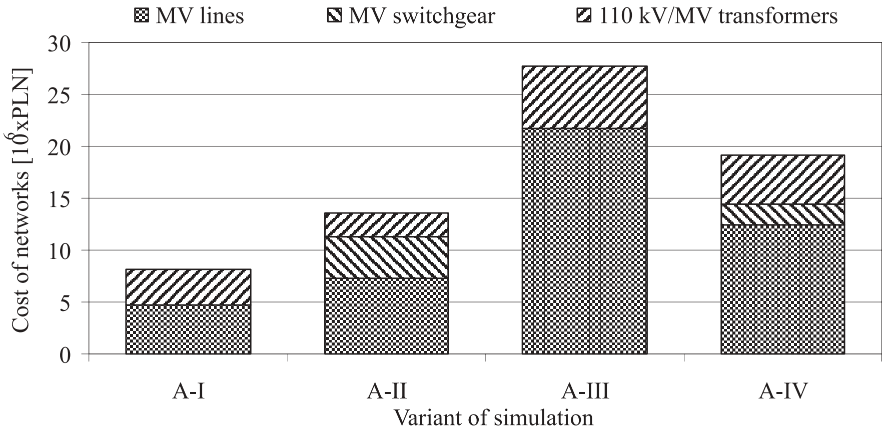

Figure 5. Components of function of cost of optimum solutions for various simulation variants.

Different solutions of a system of MV reserving networks were obtained for each simulation (Fig. 6), therefore various values of objective function and reliability of feeding of the analyzed nodes (Fig. 7).

The variety of solutions stems out of the assumed level of reserving of the specific stations (partial or full) and the decision about accounting for the 110 kV network (introduction of penalty functions for MV lines).

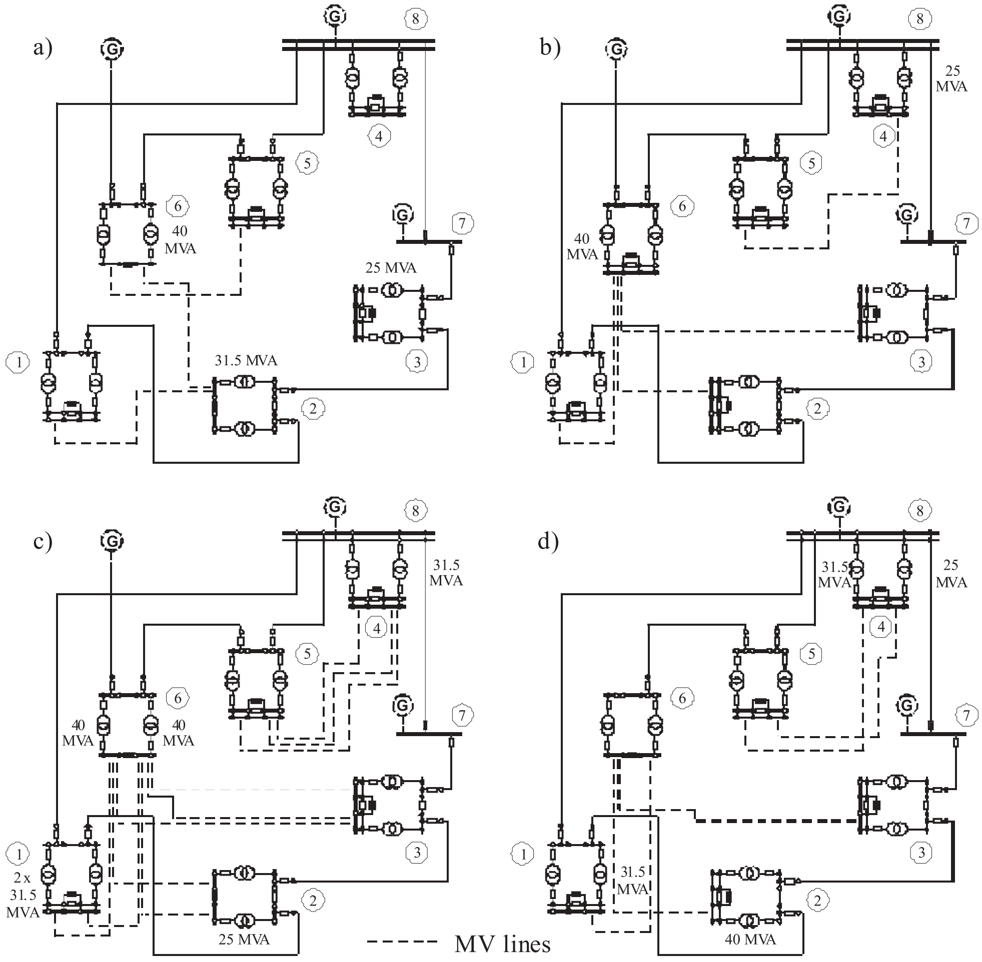

Figure 6. Practical realization of MV reserving lines in computation simulations (presented rated power of newly installed transformers): a) A-I, b) A-II, c) A-III, d) A-IV.

The following conclusions can be drawn from the results of simulations:

- accounting for the system of 110 kV lines (penalty functions) results in the increase of objective function of optimum solution. The differences in the obtained results are caused by the selection of usually longer MV lines between stations fed by various 110 kV line systems. The connecting feeding lines of the same 110 kV line system are imposed a "penalty" (by purposeful increasing the costs), as they provide feeding with these elements (110 kV lines) as in the case of basic feeding;

- selection of full reserving variant is connected with high capital costs. The expected difference in costs of optimum solutions (partial-full reserving) results from the transmission of higher power, selection of numerous lines (increase of line cost) and reserving higher power (increase of costs of the transformers).

Reliability analysis of feeding systems of MV nodes was made with the use of structural analysis method [4,5]. Indicators of feeding failure q for the state of an existing network and simulation variants A-I – A-IV are presented in Fig. 7. The reliability of feeding sources and 110 kV node stations was assumed in the analysis. The presented results were obtained for the highest transformer station load.

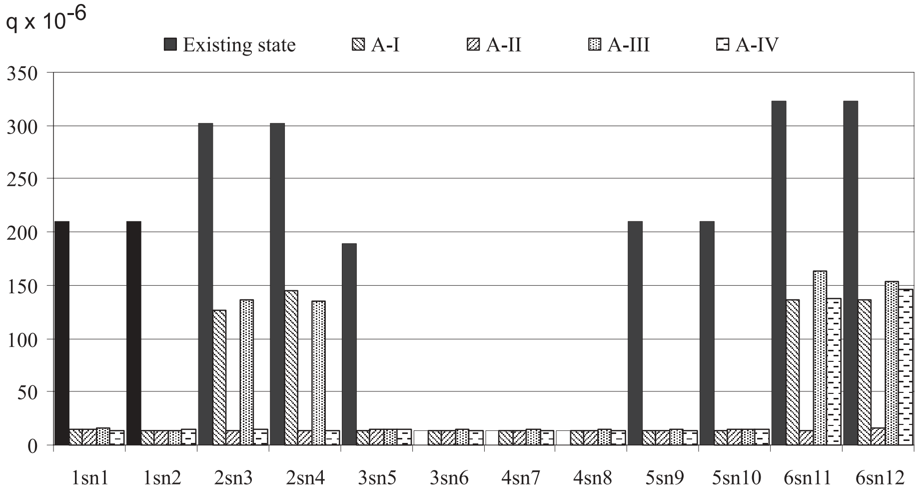

Figure 7. Indicators of feeding discontinuity in MV switchgear busbars (MFP).

The analysis of the presented values of feeding failure indices reveals that lowering the failure of feeding systems is possible through the MV reserving line (MFP-to-MFP) or/and use of switchgears with double-busbar (erroneous safety automation systems are not accounted for in the analysis). Moreover, the presented results show the influence of use of additional MV switchgear (incoming/outgoing feeder) units (for reserving MV lines).

Failure states or planned switching off situations of 110 kV lines increase the risk of breaks in power delivery. The state of open HV network (limited to a single 110 kV line system) is illustrated by the simulation A-IV. The existing state of 110 kV network, considered in variant A-IV, does not guarantee meeting the so-called n-1 criterion (break in supply is caused one of the elements is switched off) for transformer stations nos.: 5 and 6 in their entire load (open 110 kV line system) and stations nos.: 1, 2 and 3 for the highest load – one operating transformer does not provide reserving.

To provide reserving MV lines that would overtake the reserving function of MV network points (basic supply – 110 kV network, reserving – MV lines network MFP-to-MFP and 110 kV network), MV lines were designed on the assumption of "full" reserving level (MV reserving lines overtake the full load of the station). A system of 110 kV network was additionally accounted for in the optimization task by introducing the element of penalty function to the objective function. This guarantees that the reserving MV lines will not connect stations that are most liable to simultaneous switching off in break-down situations of the 110 kV network.

A solution for variant A-IV has been presented in Fig. 6d. The feeding systems of all transformer stations guarantee meeting the n-1 criterion [6]. The system of reserving MV lines provides the required level of safety of transformers operation and is comparable with the variant of closed 110 kV network's operation.

5.3 Description of network B

All stations are equipped with the same transformers ($S_{nT} = 16$ MVA) of the same load level ($S_T = 9$ MVA). The assumed load level disables mutual reserving of transformers in the stations. The same limitations were imposed as for network A. The aim of the analysis of such a network is analyzing the influence of the network extent (change of parameter r) on the obtained solutions of reserving MV lines MFP-to-MFP.

Calculation simulations were performed for the partial reserving variant (B-I) and full reserving variant of all stations (B-II), employing a dedicated genetic algorithm. The simulation B-I was made on a broadened variant, assuming various solutions of MV switchgear: a) MV switchgears with single-busbar in all stations, b) MV switchgears with single-busbar in three stations and MV switchgears with double-busbar in the remaining stations, and c) MV switchgears with double busbar in every station. The representation of the cost of the obtained solutions has been graphically presented in Fig. 8.

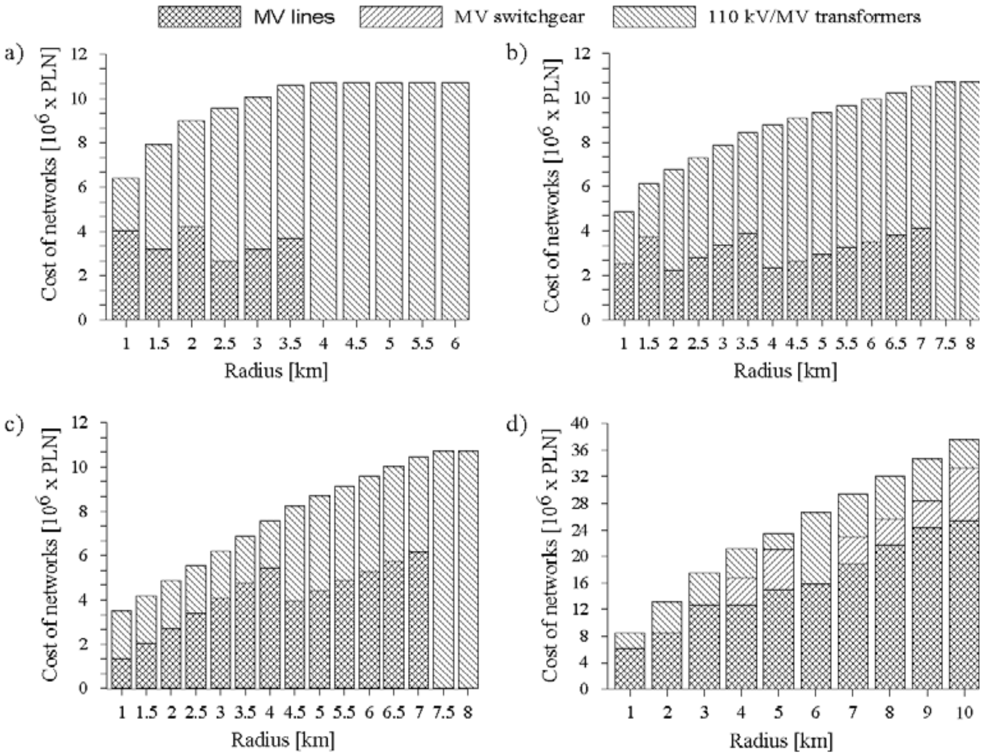

Figure 8. Cost of the best solution in the function of network range: a) for simulation B-I – MV switchgears with single-busbar in all stations, b) for simulation B-I – MV switchgears with double-busbar in two stations 1 and 3, c) for simulation B-I – MV switchgears with double-busbar in all stations, d) for simulation B-II – MV switchgears with single-busbar in all stations.

The introduction of redundancy supply systems is advantageous as it enables lowering the capital cost of actions aiming at providing power supplies without limitation. For higher r values a solution lying in replacement of all transformers into higher power units was selected. This is the only possible solution, on the assumption that no reserving lines will be introduced, the transformers cannot operate with overloads, and the MV distribution networks does not provide redundancy supply pathways. The obtained results reveal that the switchgears with double-busbar are not profitable in none of the obtained solutions (for a MV switchgear with single-busbar – simulation B-I). This observation, in turn, necessitated recalculations, on the assumption that MV switchgears with double-busbar are present in the network.

In all simulations B-I (a–c) the increased value of r led to a solution lying in replacement of all transformers in the network. The cost of the solution was PLN $10.7 \cdot 10^6$ and was attained for r values:

- > 3.5 km at switchgears with single-busbar in the network,
- > 7 km switchgears with double-busbar in the network.

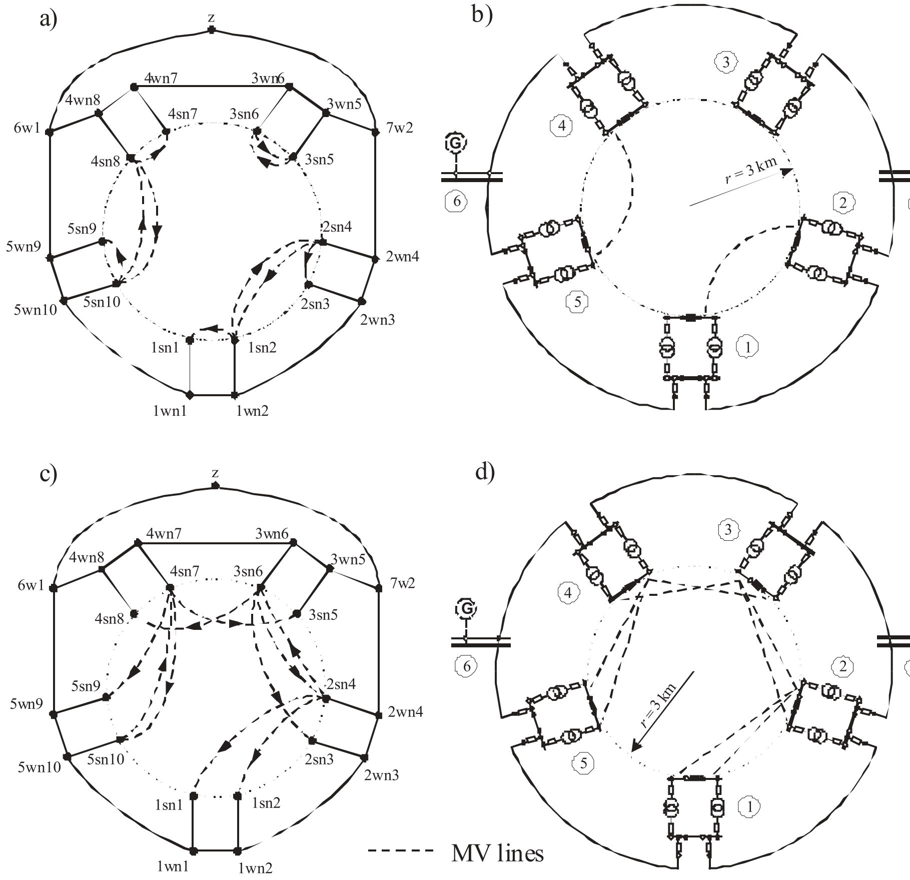

Figure 9. Calculation simulations for test network B ($r = 3$ km): a) network graph, and b) practical realization of MV lines in variant B-Ia, c) network graph, and d) practical realization of reserving MV lines in variant B-II.

The aim of simulation B-II was analyzing the reserving ability in network B, assuming the necessity of full reserving for each station. The cost of the obtained solutions, with their constituents, was presented in Fig. 8d. The obtained results prove the expected increase of the cost of lines with the coverage of the analyzed area (increase of radius r). The selected reserving solutions are presented in Fig. 9.

The analysis of simulation results of various busbar systems prompts the following conclusions:

- the reserving MV network MFP-to-MFP creates possibility of obtaining a cheaper way of developing feeding systems than replacement of all transformers,
- presence of a MV switchgear with double-busbar gives a possibility of cheaper solutions and enables using this option for reserving in larger networks with less concentrated transformer stations,
- higher number of switchgears with double-busbar provides higher share of lines in the total cost of the solution, with concurrent lowering of the share of the transformers replacement factor,
- few solutions accounting for necessity of using MV switchgears with double-busbar result from the high cost of MV switchgear modernization. It levels out the profit obtained from cheaper MV lines and smaller scale of new transformers installation.

6 Conclusions

1. Solution of a task oriented to designing optimum reserving feeding of 110 kV/MV transformer stations is possible with the use of techniques based on genetic algorithms.
2. The adjusting of evolution mechanisms (crossover, mutation) to solving tasks enables partial elimination of inadmissible solutions from the searched domain of solutions. It also makes it possible for the heuristic algorithm to be less sensitive to the generation of solutions of the so-called local optimum, the values of which assume a more distant value than the globally best one.
3. The obtained solution of MV reserving lines MFP-to-MFP are closely connected with unit capital costs of 110 kV/MV transformers, MV switchgears and MV power cables. The increase of any of the se elements (transformer, switchgear, cable) limits its applicability at the increase share of the remaining elements.

4. Accounting for the 110 kV networks in the calculation algorithm guarantees obtaining solutions, for which the MV reserving lines most frequently connect transformer stations fed by various 110 kV line systems.
5. The following conclusions were drawn for an example of a real and test electrical power network:
    (a) realization of MV reserving lines MFP-to-MFP provides the required level of reserving in highest load of the 110 kV/MV transformer stations – maintained n-1 criterion,
    (b) MV reserving network may provide the cheapest way of developing the network (reserving 110 kV/MV transformers) as compared to the replacement of the transformers,
    (c) when introducing reserving lines, the limited necessity of replacing transformers results from insufficient power reserves of the operating transformers.
6. The feeding failure indices considerably lower after introducing the described way of reserving, regardless the level of load level in the transformer stations of MFP.
7. After introducing MV reserving networks, the feeding discontinuity indices basically depend on the lack of reliability of the MV switchgear busbar systems.

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Projektowanie dwunapięciowych układów zasilania stacji transformatorowych 110 kV/SN

Streszczenie

Artykuł dotyczy problematyki projektowania układów zasilania rezerwowego dla punktów zasilania miejskich sieci średniego napięcia (SN) w warunkach zwiększonego poziomu obciążenia stacji transformatorowych 110 kV/SN. Projektowane układy zasilania polegają na budowie bezpośrednich połączeń średniego napięcia pomiędzy stacjami transformatorowymi 110 kV/SN. W omawianym zadaniu rozważana jest również wymiana transformatorów 110 kV/SN oraz modernizacja rozdzielni SN. W celu przeprowadzenia badań sporządzono model matematyczny wraz z funkcją celu minimalizującą całkowity koszt inwestycyjny projektowanej struktury sieci. Do rozwiązania zadania optymalizacji zastosowano algorytm genetyczny. W artykule przedstawiono przykłady obliczeniowe dla dwóch sieci elektroenergetycznych, wyniki badań oraz wnioski.