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Development planning algorithms of 110 kV/MV substations

Abstract: *This paper presents a mathematical model for the development of the distribution transformer substation 110 kV/MV. Discusses optimization algorithms to solve multi-step task in determining the development strategy of the 110 kV/MV substation in period T. Presents developed a computer program and an example calculation for the study of the development of the 110 kV/MV substation operating in urban areas.*

Streszczenie: *W artykule przedstawia się model matematyczny rozwoju stacji transformatorowo-rozdzielczej 110 kV/SN. Omawia się algorytmy rozwiązywania zadania optymalizacji wieloetapowej przy wyznaczaniu strategii rozwoju stacji 110 kV/SN w okresie T. Przedstawia się opracowany program komputerowy oraz przykład obliczeniowy dotyczący badania rozwoju stacji 110 kV/SN pracującej w warunkach miejskich.* ***(Algorytmy rozwiązywania zadania optymalizacji wieloetapowe przy badaniu rozwoju stacji 110 kV/SN)****.*

Key words: transformer substation, multi-stage optimization, development analysis
Słowa kluczowe: stacje transformatorowo-rozdzielcze 110 kV/SN, optymalizacja wieloetapowa, badanie rozwoju

Introduction

The place where electricity passes through on its way from where it is produced to where it is used is called high voltage transformer substation. It operates on high voltage of 110 kV and middle voltage (MV) of 15 kV. Substations play a key role in electrical systems because they combine transmission networks with distribution networks so that significantly affect their configuration, and work of the entire network. In view of the growing demand for electricity, an important aspect of planning the development of distribution networks is the analysis of algorithms for optimization multi-stage substation development.

Building new substations is often hampered due to urban sprawl. Expansion of existing substations, in particular, the replacement of transformers for higher capacity units is one solution to the above problem. Application of multi-stage optimization algorithms is of great importance. This allows you to achieve the required power demand for distribution systems in an optimal manner.

Mathematical model of optimal development of high voltage substation

Substation structure in year t is defined by $a(t)=a(v,i,j)$ where i, j means the individual working capacity of transformers [4]. There are many types of transformers that can significantly vary parameters in spite of the same power rating, instead of the type of transformer is given its power. The number of structures is a combination of the two-element of the available power capacity of transformers. For reasons of reliability and operational, transformers capacity requires not differ much from each other. In practice, we found only substations where the capacities of transformers vary by a maximum of one place in a set of power transformers. The set of structures is expressed as follows using pairs of the rated power of transformers [5]: *(0, 16), (16, 16), (16, 20), (20, 20), (20, 25), (25, 25), (25, 31,5), (31,5, 31,5), (32, 32), (32, 40), (40, 40), (40, 63), (63, 63), (63, 80), (80, 80).* Acceptable structures are numbered in ascending order by using a transformer rated power and further structure is determined using the number of $a(t)$ which clearly defines the rated power and other parameters of the structure. Decision variable is the vector components of the following form:

$$[t_1, a_1(t), t_1, a_2(t), ...] \quad (1)$$

where: t_i – moment of i transformer replacement, $a_i(t)$ – number of substation structure after i replacement.

In the reporting model it assumes that the structure of the station is changed only at the end of next year and in the course of a year is constant. This assumption stems from the use in the calculation of the cost of the annual maximum load station. This means that the time t is an integer. It is the best solution for the proposed algorithms.

$$d_t = a(1), a(2), ..., a(T) \quad (2)$$

where: d_t - selected substation development strategy, $a(t)$ – the number of substations structure in year t, T – optimization period.

Function is a transformation of a stochastic process $S_0(t)$.

$$K(T) = K[S_0(t), d_t] \quad (3)$$

where: $S_0(t)$ – annual substation peak load.

In substation optimization problem expression $K(T)$ is the sum of the discounted per year zero annual costs.

$$K(T) = \sum_{t=1}^{T} \frac{1}{(1+p)^t} K_{rs}(t, d_t) \quad (4)$$

Currently in research of the development of power stations most common criterion method for assessing the quality of solutions is method of annual costs. This method is the most suitable due to the optimization of multi-step and economic reproduction substation components. Most of investment decisions shall be based on an analysis of costs. The annual cost of substation is calculated from equation (7), (8) and (9).

The problem of searching for the optimal substation development strategy lies in the fact that the period T should determine the optimal strategy for the development of the substation, i.e. the sequence of structures in various stages of that minimalize objective function. When programming a deterministic function of the sum of the costs will be discounted during the T while in programming stochastic expected value of risk function: maximum probability, minimum variance, etc.

In the case of power transformer substations load increase makes it necessary to its development and above all replacing transformers into units with higher power rating. Since both of replacing transformers and the operation of the substation are related to specific costs particularly dependent on the choice of the transformers becomes necessary to plan the optimum moment of replacing transformers and the selection of newly installed unit so as to have satisfied the necessary technical limitations and a maximum reduced costs associated with the operation and development of the network. In practice, operating transformers have been withdrawn from the substation or replaced with larger units are typically installed in others. The task is to find the optimal substation development policy (expansion) in period T taking into account the load in each year. It is recommended to use periods $T=5\text{-}10$ years in order to avoid errors resulting from the adoption of shorter times. Taking longer time varies with time counteracts the discount rate and the uncertainty in determining the anticipated load increase.

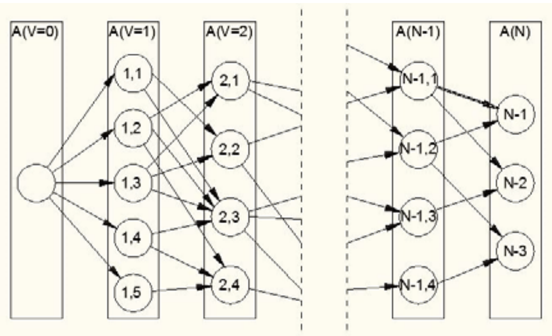

Fig.1. Development graph [4]

The development of the 110 kV/MV substation is a process which presents itself as a network-oriented. Such a network is characterized by layered structure, the number of layers equal N_w. In addition, each node is connected to the inner layer arc (branch) with at least one previous layer node and at least one node to the next layer. Each layer arc $[s_i(n),\ s_j(n+1)]$, where $s_i(n),\ s_j(n+1)$ are the united network weight with a sense of evaluation of the quality of the transition from a state of $s_i(n)$ to $s_j(n+1)$. In this case it is the arc length. The length of this corresponds to the cost of replacement of the transformer or both transformers in the development process. Each transition from a layer n to the layer $n+1$ is characterized by a function (local indicator) of quality:

$$\mathrm{f} = F_s[s(n), s(n+1), n] \tag{5}$$

Algorithm for optimizing the development of the power substation with deterministic load

The symbol C_i^j means an event that in year j was installed i structure of transformers. In the graph (fig.1.) the set of nodes of the graph $X=\{C_i^j\}$, composed of all the permitted structures of transformers during the forecast T. The initial arcs of this graph are $(p,\ C_i^1)$ connecting acceptable structures in the first year of period and the final arcs $(p,\ C_i^T)$ which combine acceptable structure in the last year of considered period T. Furthermore arcs $(C^j,\ C^{j+1})$ describes the possible development of the substation in any j year. If we have a $C_i^j=C_k^{j+1}$ it means no replacement in j year. And in the case of replacement of the transformer is described as $C_i^1 \neq C_k^{j+1}$. In such a graph ways $d(p,k)$ connecting starting point p with ending point k are decisions $d(.)$, taking into account the technical conditions $d(.) \in D \cap D_T$. Arc length $d_t(.)$ with assigned a positive number allows you to receive the structure $S=(X, Ł, d_t)$ called network. One of the many programming tasks is to seek network minimum way, such as $d_0(p,k)$ connecting the nodes (p,k):

$$d\left[d_0\left(p,k\right)\right] = \min_{a(p,k)\in G} d\left[d_0\left(p,k\right)\right] \tag{6}$$

The minimum length of the road is equal to the minimum cost of the development of a substation structure. The minimum path sets the optimum solution development tasks station for deterministic load with assumption of load limit.

The effectiveness of algorithms

The problem of optimizing the development of substation is a very complex process. It depends on a number of factors. The results of a given algorithm with such a large amount of input data cannot be regarded as reliable results. However, they may give a lot of valuable information about the problem, it will help to make optimal from a given decision criterion. The main factor influencing the efficiency of presented optimization algorithms is a forecast load of power transformer substations. The choice of the appropriate method greatly increases the efficiency of the calculations performed by an algorithm which translates to a large extent on the quality and accuracy of the results. After analyzing the optimization algorithms and consideration of examples of calculation and literature of this subject should be stated that the most effective in determining the optimal strategy for the development of the power transformer substation is algorithm for back. Advantages of this algorithm are revealed mainly by analyzing a large number of graph nodes which makes it very convenient in the study of the substation development. Substation elements such as substation building, MV switchgear, HV switchgear must be built at the beginning or in the first stage of the existence of the estate or area of the city and should be enough for at least 20 years. Accordingly, the process of development testing starts from the end. The use of this technique allows a major reduction of the number of respondents strategy which results in a significant reduction of the computation time.

It cannot be determined which of the algorithms is the best. Selection of the correct method and proper criterion depends mainly on the type of optimization task. In deciding it is not enough to use only one of them. Optimal solution requires consideration of various criteria and their careful interpretation. The final decision should be based on the selection of one from among the several proposed options.

Computer program for the development of the power substations

A computer program "ROZWOJ PM" [6] is written in the programming language C++. The application uses the optimization method based on Dijkstra's algorithm. Given a graph with highlighted vertices (fig. 2). A graph is built for 9 possible substation transformer configurations: *(16, 16), (16, 25), (25, 25), (25, 40), (40, 40), (40, 63), (63, 63), (63, 80), (80, 80)*. Time of calculations $T=5$ years. In this case, the graph has 45 numbered nodes. Arrows show the direction of the development of the substation. In this case an initial configuration is fulfilled by two 16 MVA power transformers. In second and fourth year substation change its configuration by replacing both transformers with 25 MVA unit.

The algorithm finds the distance from the source or substation status in the year 0 to all other vertices. Each transition is assigned an appropriate cost of the transition. The costs of transition is the sum of the costs associated with the replacement of the power transformer. The algorithm is modified so as to look only for the shortest (cheapest) paths to a single fixed vertex, interrupting the action when the handle to the tip. Dijkstra's algorithm finds in the graph all the shortest paths between the selected node and all the rest, by the way, calculating the cost of passing each of these paths. Data for the calculation are taken from input files in text format. The input parameters are: fixed costs, variable costs and load. In addition, defines the value of the discount rate used to calculate the discounted costs and parameter specifies transformers capacity. The example assumes a discount rate calculated at 8% and the load factor of the transformer at the level of 50%.

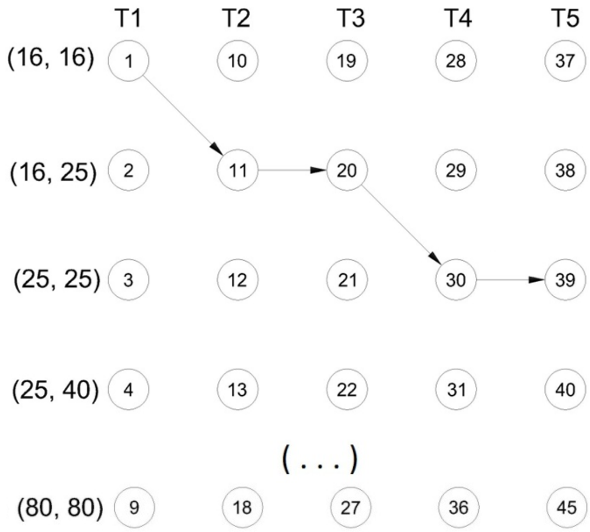

Fig.2. Example of development graph

Table 1. Load and the substation structure of the individual years [6]

Year	1	2	3	4	5
Load [MVA]	15	16,55	18,81	21,33	23,5
Structure	(16,16)	(16,25)	(16,25)	(25,25)	(25,25)

The calculation example is resolved in both classical method and using computer program. Assuming a typical technical solutions of power station and their costs were received following results of the development strategies cost (table 2, 3, 4). Fixed costs in individual years are expressed by the formula:

(7) $K_{ST} = K_b p_b + K_R p_{Rs} + K_{t1}(t) p_t + K_{t2}(t) p_t + K_w p_t$

where: K_b - the cost of the substation building, p_b - the rate of depreciation on the fixed costs for the substation building, K_R - the fixed cost of the MV switchgears, p_{RS} - the rate of depreciation for the MV switchgear, K_W - the cost of 110 kV switchgear, p_t - the rate of depreciation on the fixed costs for the substations, $K_{t1}(t)$ - the investment cost of the first transformer 110 kV/MV on stage *t*, $K_{t2}(t)$ - the investment cost of the second transformer 110 kV/MV on stage *t*,

Table 2. Fixed costs of the substation in tys. zl

Year	K_b	p_b	K_R	p_{RS}	K_W	p_t	K_{t1}	K_{t2}	K_{ST}
1	3200	0,11	1685	0,12	5010	0,2	850	850	1896,20
2							850	990	1924,20
3							850	990	1924,20
4							990	990	1952,20
5							990	990	1952,20

The annual variable substation costs in *t* stage consist of the costs of the loss of power and energy in the power transformer. It shall be calculated from the formula:

(8) $$K'_{ZT}(t) = \left[\frac{S(t)}{S_{n1}(t)}\right]^2 (\Delta P_{01} + k_e \Delta Q_{01}) k_{\Delta P01} + (\Delta P_{j1} + k_e \Delta Q_{j1}) k_{\Delta Pj1}$$

(9) $$K''_{ZT}(t) = \left[\frac{S(t)}{S_{n2}(t)}\right]^2 (\Delta P_{02} + k_e \Delta Q_{02}) k_{\Delta P02} + (\Delta P_{j2} + k_e \Delta Q_{j2}) k_{\Delta Pj2}$$

where: K'_{ZT} - the variable cost of the first transformer in stage *t* [tys. zł], K''_{ZT} - the variable cost of the second transformer in stage **t** [tys. zł], $S(t)$ - a load of transformers in stage *t* [tys. zł], $S_{n1}(t)$, $S_{n2}(t)$ - the rated capacity of the transformers in stage *t* [tys. zł], ΔP_{01}, ΔP_{02} - rated active power load losses in power transformers [kW], ΔP_{j1}, ΔP_{j2} - rated active power no-load losses in power transformers [kW], Q_{01}, Q_{02} - rated reactive power load losses in power transformers [kvar], Q_{j1}, Q_{j2} - rated reactive power no-load losses in power transformers [kvar], k_e - the energy equivalent of reactive power for transformer.

Table 3. Variable costs of the substation in tys. zł

Year	$S_n(t)$	$S(t)$	ΔP_0	ΔP_j	ΔQ_0	ΔQ_j	k_e	$k_{\Delta P0}$	$k_{\Delta pj}$	K_Z
1	16	7,5	150	27,5	2500	150	0,05	284,25	603,95	38,32
	16	7,5	150	27,5	2500	150				38,32
2	16	8,28	150	27,5	2500	150				35,88
	25	8,28	150	27,5	2500	150				35,88
3	16	9,41	150	27,5	2500	150				40,18
	25	9,41	150	27,5	2500	150				40,18
4	25	10,67	150	27,5	2500	150				35,37
	25	10,67	150	27,5	2500	150				35,37
5	25	11,75	150	27,5	2500	150				38,41
	25	11,75	150	27,5	2500	150				38,41

The total cost is the sum of the fixed and variable costs.

Table 4. Total cost of the substation in tys. zł [6]

	Years					Total [tys. zł]
	1	2	3	4	5	
K_T	1972,83	1995,95	2004,55	2022,93	2029,01	**10025,27**
K_d	1826,69	1711,21	1591,28	1486,91	1380,91	**7997**

All of this information with the algorithms used in the calculations are implemented in the computer program [6].

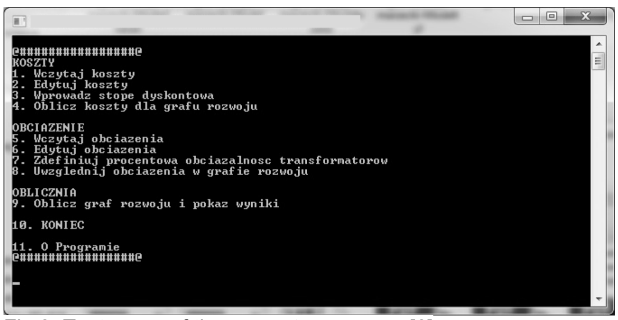

Fig.3. Text menu of the computer program [6]

Figure 3 shows the initial menu of a computer program. By performing operations batch files are load which contain costs, load and the discount rate-defined and maximum transformers load. The final step is to perform the calculations and display substation development graph.

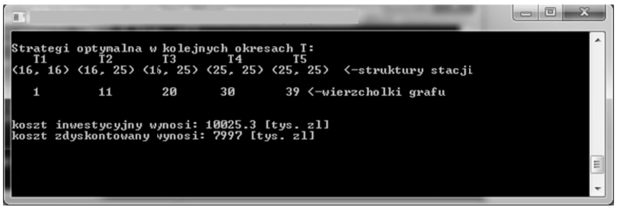

Fig.4. The results of the calculations [6]

Figure 4 shows the result of actions of which coincide with the results obtained using traditional methods. The main advantage of the use of computerized methods for the analysis of the development of the power substation is a considerable acceleration of calculations required for the various countries concerned. Using a computer program [6] we can significantly increase the quantity and diversity of data used to simulate and analyze the development of the power substations for periods longer than T = 5 years.

Summary

1. In distribution networks and power stations analysis to study further their development should be used multi-stage optimization methods. A very important element influencing the result and the quality of the calculations is the forecast power transformer loads.

2. Grid load forecasting simulation method plays an important role. It has many advantages over other methods. The accuracy of this estimate allows you to properly determine the concept of the development of the substation.

3. The most effective algorithm in determining the development strategy of the substation is back procedure algorithm. The advantages of this algorithm is the ability to apply it to the network of a large nodes number and the shortened calculations time in the case of the new power substation.

4. It cannot be determine which of described test algorithms of development of the substation is the best. Selection of the correct methods and the proper criteria depends mainly on the type of optimization tasks. When deciding it is not enough apply only one of them. Considering optimality solutions require different criteria and their careful interpretation. The final decision should rely on choosing one of several proposed options for the development of the power station.

5. The computer program has proven to be very useful for the analysis of the different variants of development of the power substation and significantly reduces the time associated with strategies in relation to traditional methods.

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