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MULTI-OBJECTIVE OPTIMIZATION OF TRANSMISSION LINES

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Introduction of new advanced electrical connections into a transmission grid reduces the capacity of existing overhead lines (OHLs). At the same time, designing & building of new OHLs and substations involves considerable technical, environmental and economical problems. The authors propose a concept of the multi-objective optimization for selection of transmission line routes, towers (their type, placement and geometry), of conductors, insulators, dampers, earthing and lightning protection systems, span lengths, etc.. The optimization is organized in five stages. At the first and second stages a search for optimum solutions is performed along with determination of the main impacting factors. The next two stages present a two-objective optimization based on Pareto's approach. At the last stage (exemplified by a case study), the probability of the restriction removal conditions is assessed, and preventive measures are identified. The presented approach uses a real line design and is intended for minimizing the total invested capital and maximizing the net present value. In the framework of this approach 20 alternatives have been elaborated, which can successfully be applied in the cases described in the paper.

Keywords*: design engineering, Pareto's optimization, power transmission, transmission lines.*

1. INTRODUCTION

Power systems (PSs) are among the most complex systems created by mankind. They include hundreds and thousands of components: boilers, turbines, generators, transformers, transmission lines (TLs), etc.. The functions of the components are interdependent: the processes going on in one part of a PS influence the functioning of its other elements. Such interdependence should be taken into account already at the stage of designing new energy facilities (e.g. TLs). The impact of a high- or superhigh- voltage TL on the remaining parts of a PS is significant; also, the changes in the system may substantially affect the transmission situation. The operating conditions are continuously varying in time – new customers and power plants appear, prices and power consumption are rising, and so on. Costly PS elements and components have sometimes a life cycle of several decades; this motivates the need to estimate conditions that may arise in rather a distant future. Obvious enough that these conditions cannot be predicted exactly; therefore, it is necessary to account for numerous impacting factors and circumstances. The random and uncertain nature of these factors makes it too complicated to formulate and solve the task of optimizing the design of expensive power objects (in particular, TLs).

Over the last decades a significant increase has been observed in the electric power flows caused by serious structural changes in a PS (competing energy markets, development of large-scale wind power farms, etc.) followed by a greater impact of technical and legislative restrictions on the allowable load current of the existing distribution and transmission network. Building new high-voltage OHLs not only requires considerable capital to be invested but also creates a significant impact on the environment.

Quite obvious is the necessity to minimize the invested capitals, increase the PS reliability, and decrease the impact on the environment at the designing, construction and operation of OHLs. To achieve these objectives, new advanced power transmission and OHL design technologies have been developed and implemented within the framework of Smart Grid [1]. For instance, high-temperature low-sag (HTLS) conductors are now available, which is one of the possible solutions for upgrading and improving the existing TLs [2, 3]. In this way, the replacement of traditional type conductors with HTLS type ones, the use of modern insulators [4], appropriate towers [5], earthing and lightning protection systems [6] and monitoring & control systems may offer technical and economic advantages such as long-term reliability, higher capacity, low sag tension, easy and quick design and installation, low reconstruction investments, etc.. For simplifying the OHL design, powerful software has been developed [7, 8].

The most widely used TL designing methods are based on the cost-effective analysis and maximization of the net present value (NPV) [9] or minimization of the capital costs involving impermissible restrictions. The approach aimed at finding the minimum cost of TL design is described in [10]. Development of the methods that explore the sensitivity of the required present value of revenue in order to achieve design performance at the least cost is presented in [11], while in [12] a study is reported concerning the line optimization techniques that can be applied to decide between the standard and the optimized TL designs. An OHL design method [13] taking into account the lightning impact offers the most suitable line insulation level, tower footing resistance, and average height of shielding wires. In [14] another method for this purpose is developed, with the main objective of minimizing the total annual cost of the line considering the relevant technical restrictions. As a rule, the OHL impact on the environment is significant, which causes complications at the selection of TL routes, since it is necessary to provide appropriate places both for human activities and for animals and birds [15]. The above-mentioned publications are based on the deterministic methodology.

In turn, a study relied upon the game theory criteria and the application of a stochastic approach for the network development is presented in [16].

In the general case, the optimization objective could be presented as shown in Fig. 1, where it is seen that the existing restrictions limit the allowable area for the search among optimum solutions.

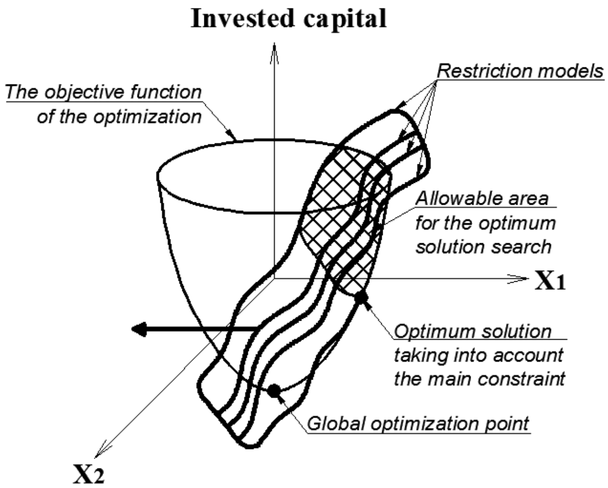

Fig. 1. A graphic representation of the optimization objective.

This paper deals with an OHL design method which is also partially based on the stochastic approach and game theory criteria to be applied for making the final decision. For this purpose the following five steps are taken:

1. Based on analysis of the development plans of a region, scenarios implying rise in the load are elaborated, and the corrections to be introduced into the requirements for the OHL transmission capacities are estimated.
2. Using the relevant software with appropriate database, a number of competitive structural variants and OHL parameters are selected. The most impacting restriction is defined.
3. Evaluation of the capital costs and expected NPV of all the variants – both when the restrictions are observed and in the case if one of them is violated.
4. The whole variety of the competitive decisions is constructed. The plane of capital costs and the parameter that characterizes the restriction are used.
5. Assessment is performed for the probability of the conditions that allow for removal of restriction and its consequences and for the relevant preventive measures.

The last two steps are explained below in a case study.

2. THEORY

Theoretical formulation of the optimization task for designing a power transmission line

In order to formulate the tasks of TL designing with account for the influence of random and uncertain factors we will make the following assumptions:

- The company which is the owner of OHL strives to minimize the invested capital I_C and increase its revenues R_{ti} (the net cash flow, i.e. the cash inflow-outflow, for each year t_i of the planning period $T=m\cdot t_i$).

- Revenues R_{ti} and invested capital I_c of the company depends on the multi-structure Σ_j and parameters Π_j of the OHL chosen by this company. The structures Σ_j are described as those of discrete variables (the number of wires per phase, the height and parameters of standard towers, the cross-section of the conductor, its mechanical and electrical parameters, etc.). Each structure of the type presents alternative A_j (j=1, …, N). The parameters Π_j are described by a set of continuous variables (the span lengths, coordinates for the construction of towers, etc.).
- Freedom in choosing the structures and parameters of the company is limited.
- S_j is the set of all permissible structures and parameters for the OHL and $s_j = \{\Sigma_j , \Pi_j\}$ is the chosen combination of the structure and parameters, $s_j \ni S_j$. The frontier confining the space of permissible structures is determined by inequalities that describe the technical and legislative factors and regulations.
- OHL functions under the influence of ambient environment are characterized by a set of random and uncertain parameters X_{ti} (load current in a power line, ambient temperature, wind speed, humidity, etc.). In the general case, parameters X_{ti} vary with time. In our case these parameters are assumed to be constant for each year t_i.

Due to the influence of random and uncertain factors, the revenues are also uncertain: in this case the approach involving different scenarios in combination with probabilistic variables can be used for solving the task of planning. The uncertain information will always be modelled by a number of scenarios. For each scenario SC_n (n=1, …, k) we can state that revenues R_{tij} are probabilistic values, i.e.:

$$R_{tijn} = R_{tijn}\left(s_j, X_{tijn}\right). \tag{1}$$

Suppose that the following distribution functions:

$$F_{tijn} = F_{tijn}(R_{tijn}\left(s_j, X_{tijn}\right) \middle| SC_n, A_j) \tag{2}$$

may be assigned to each combination of scenario SC_n and alternative A_j.

If the distribution function is known, the expected value of a year's t_i revenues for each SC_n and A_j combination can be determined by the equation with Lebesgue-Stieltjes' integral [17]:

$$E\left[R(s,\mathrm{X})\right] = \underset{\Omega}{\int ... \int} R(s,\mathrm{X}) dF(R(s,\mathrm{X})), \tag{3}$$

where Ω is the integration area limited by the space of random parameters X. The frontier of the space for allowable parameters and structures S_j is determined by the following inequality:

$$FR\left(s_j, X\right) > 0. \tag{4}$$

Knowing the expected revenue values we can derive the equation for determination of the net present value as the main optimization criterion:

$$NPV = -I_C + \sum_{i=1}^{m} \frac{E(R)}{(1+I)t_i}, \tag{5}$$

where I_C is the investment capital, which is a function of s_j.

The optimum planning task can thus be presented as

$$s^*_{jn} = \arg\max\left(-I_C + \sum_{i=1}^{m} \frac{E(R)}{(1+I)t_i} \right), \tag{6}$$

where arg is "the argument for" the subject of maximization; I is the discount rate.

Solving Eq. (6) will give the system's structures and parameters s^*_{jn} that maximize NPV for the planning period T for all selected scenarios SC_n and alternatives A_j. For each SC_n-A_j combination the NPV estimate can be found. In the NPV maximization process, an extended space s^*_{jn} is added in order to determine the alternatives and parameters approaching the frontier of the allowable space that can be stored beyond its limits. These parameters (R_i) will be reviewed as additional criteria in the optimization. Having obtained the NPV and R_i values for all combinations of scenarios and alternatives, we can formulate the relevant matrix (see Table 1). After that, it remains to choose the best alternative. In the given set of alternatives there are even solutions that lead to removal of the most influential restrictions.

Each of the columns in Table 1 may contain a Pareto's set; if there are restriction indices R_i, consider the second optimization criteria (note that in the general case such indices can be numerous).

Table 1

The expected NPV values and restriction indices R_i

Alternatives	**Scenario 1**	**…**	**Scenario k**
A_1	NPV_{11}|| R_{11}	…	NPV_{1k}|| R_{1k}
…….	…….	…	…….
A_N	NPV_{N1}|| R_{N1}	…	NPV_{Nn}|| R_{Nk}

The final decision-making based on the decision set (Table 1) is, in the general case, a complex task; for its solution several methods are proposed (see [18]). As shown below, particular tasks of the type could be substantially simplified.

Selection of scenarios and alternatives

The need in construction of a new transmission line can be revealed based on the forecasts of economic development for a certain geographic region. If new or increased loads are expected and the existing network cannot meet any more the demand for electricity, the decision on construction of a new TL can be made. Under uncertainties, various scenarios should be considered – e.g. concerning the load increase. After the PS development scenarios have been selected, different alternatives are examined with the purpose of choosing the optimization parameters S.

The following parameters can be subjected to optimization: the nominal voltage of TL; the mechanical and electrical characteristics of the conductor (its diameter, cross-section, the coefficient of linear expansion, the modulus of elasticity, the allowable temperature); the load current; linear loads, destructive loads; the type of conductors and their number per phase; the type of tower, its geometry, height, the allowable wind, weight and clearance spans; the type of insulators and dampers; the lightning wire type, the earthing and lightning protection systems; the optimum line route.

Thus, to achieve the best technical and economical solution of the TL design, a large number of optimization variables should be taken into account. As mentioned previously, any OHL is under the influence of ambient environment (described by set X_{ti} of random and uncertain parameters). The parameters affecting the OHL operation are: climatic conditions (ambient temperature, wind speed and direction, solar radiation, air humidity, ice thickness, etc.); the TL capacity in a future PS; the forecasted electricity consumption; expansion of the existing interconnection systems; environmental impact.

The task of estimating the revenues at a large number of scenarios and alternatives (combinations included), choosing among numerous optimization variables is therefore very complicated. To simplify it, another task – that of filtering less competitive variants – is formulated and solved by disregarding obviously expensive or unreliable ones. Until recently, this task was solved based on experience, with various guidance documents issued. In the last decades, powerful software tools are used [7, 8], which give the opportunity to form a significantly smaller initial set of competitive alternatives. Then the estimation should be performed for the effectiveness and appropriateness of each alternative in each scenario with account of the technical and legislative restrictions.

The main restrictions in the optimization

In the search for the best OHL alternatives we should take into account several restrictions: thermal (allowable conductor temperature, load current), mechanical (conductor sag, mechanical tension), electrical (insulation levels) and environmental (climatic conditions, electromagnetic field impact) [19]. In designing an OHL it is necessary to estimate the adjusted maximum capacity (the allowable load current), the earth clearance as well as the clearance to the crossed objects, and the distributions of electric and magnetic fields. Since a large number of optimization parameters are discrete, it can be argued that for solving the optimization task formulated in Eq. (6) it is necessary to perform the investment calculations for all possible combinations of parameters s_j corresponding to the area that meets $s_j \ni S_j$ restrictions.

Generally, if one of the restrictions is not met, the alternative is not taken into account in the optimization task and is rejected. However, in this study the alternatives are considered in which such restrictions are removed: for this, new technical possibilities (e.g. Smart Grid), different monitoring systems as well as the high-temperature low-sag (HTLS) conductors could be applied. Thus, the proposed approach allows some restrictions to be removed (after the relevant probability estimation).

The most significant restrictions are described below.

A. Thermal Restrictions

Commonly, thermal restrictions are defined by the OHL load current and physical characteristics of the conductor (the most important being the permissible conductor temperature). To check the fulfilment of the restriction conditions, the IEEC 1507 thermal rating method [20] is mostly applied, according to which the heating-cooling balance equation of the conductor is used along with numerous parameters that characterize the climatic conditions.

B. Mechanical Restrictions

Basically, the mechanical restrictions relate to the conductor sag, the "clearing distance" to the earth and to the crossed objects: roads, waterways, railways, other (low-voltage, medium-voltage, high-voltage) TLs or telecommunication lines and buildings.

For systematic calculation of the conductors in the TL under design the SAPR LEP 2011 software was used. This program was also employed for siting the towers according to the terrain profile obtained by laser scanning.

C Environmental Restrictions

To estimate the environmental impact, first of all the electrical and magnetic fields should be identified. These depend on the TL voltage & current, the height of conductors above the earth and their configuration.

All calculations of the electric and magnetic fields are to be done using appropriate software (e.g. as described in [21]).

Calculation of revenues and net present value (NPV)

The NPV calculation is a very difficult and time-consuming task due to the following:

- The price of OHL elements that should be taken into account is usually defined empirically at negotiations with the stakeholders (the compensation for the land under the OHL route, the cost of towers and conductors, the conditions for credits, etc.).
- Lack of commonly recognized methods concerning revenues to be expected [22] at the OHL construction calculation.

Thus, at the construction of a new TL we pursue the following main purposes: to connect new generation and resource areas to the network (with integration of renewable, fossil, hydro- and nuclear resources); to improve the reliability of a grid based on economic and congestion reasons; to realize its risk management by providing access to additional generation sources; to increase efficiency by reducing the line losses; to minimize the energy cost by providing access to diverse generation sources; to make wholesale markets more competitive and effective [23].

In this study, we suppose that the additional income of a transmission network is distributed uniformly among the existing network and newly built objects; thus the annual income will be:

$$R_{inc} = \left(\frac{I_l}{I_s}\right)\frac{C_{aug}}{2}, \tag{7}$$

$$C_{aug} = \beta\left(\alpha_1 E_{an} + \alpha_2 E_{antr}\right), \tag{8}$$

where I_S is the annual investment in a transmission network; I_l is the investment in the OHL construction; E_{an} is the annual growth in power consumption; E_{antr} is the annual transit energy; α_1 and α_2 are coefficients of power consumption growth; β is the energy cost rate.

3. RESULTS AND DISCUSSION

The use of the described methodology for TL design optimization could be exemplified by a real project to be implemented in Latvia.

In the Baltic region (Latvia, Lithuania, Estonia, the west coast of Russia, and Belarus) the designing and construction of a number of major power plants (a nuclear power plant included) are now underway. A number of projects (including submarine cables and overhead lines) have already been implemented or will be initiated in the near future for connection with the power systems of Scandinavia and Poland. As a result of analyzing the operating conditions of PSs, new lines are to be built (a fragmentary diagram in Fig. 2 shows but a minor part of the whole interconnected PS). The electrodynamical model that was used for calculation of static and dynamic operating conditions of the Latvian PS could be applied in majority of Baltic countries for selection of the maximum permissible current in a particular TL.

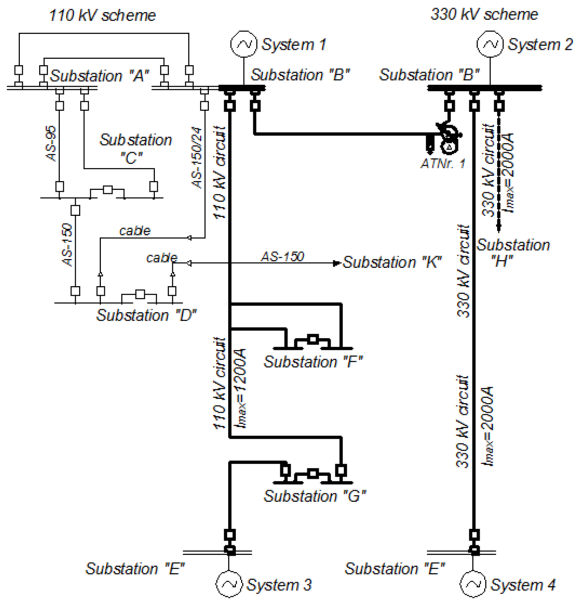

Fig. 2. A fragment of PS diagram including 330 kV and 110 kV lines under design.

The power system's analysis for the regional development scenarios has resulted in the following alternatives for a new transmission line (see Fig. 3):

- 110 kV TL with the maximum current of 1200 A (optimistic scenario 1) or 800 A (pessimistic scenario).
- 330 kV TL with a maximum current of 2000 A (optimistic scenario 2) or 1500 A (pessimistic scenario).

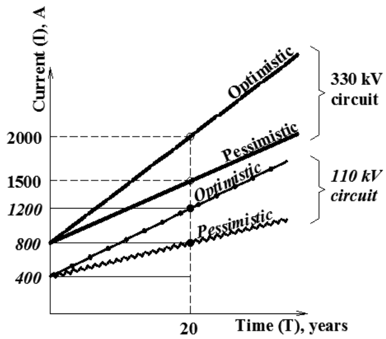

Fig. 3. The optimistic and pessimistic scenarios of the TL capacity for 330 kV and 110 kV lines

Currently, a 118 km long OHL is being designed for climatic conditions of a region near the Baltic Sea. The relevant parameters are:

- Wind pressure: 650 Pa.
- Ice thickness: 10 mm.
- Minimum temperature: –35°C.
- Maximum temperature: +35°C.
- Average operating temperature: +5°C.

For this new OHL the task of structural and parametrical optimization was formulated. After searching for the optimum solutions using the software for OHL design, twenty alternatives were selected, with different combinations of towers and conductors (see Table 2).

To simplify the task, at the first stage instead of the NPV maximization according to Sect. 2 the invested capital minimization has been performed, with both options compared.

For the comparison three main conductor types were chosen:

a) The traditional type conductor – the aluminium conductor steel reinforced (ACSR), consisting of a steel core and aluminium strands [24].
b) The HTLS type conductor – the aluminium conductor composite core (ACCC), consisting of a hybrid carbon and glass fibre core, with trapezoid-shaped aluminium strands and a steel core [3].
c) The HTLS type conductor – the aluminium conductor composite reinforced (ACCR), relying only on aluminium-based materials, where the core strands are composed of wires from aluminium oxide fibres embedded in high-purity aluminium [25].

Based on the experience in construction of PSs power lines with the mentioned voltage and on discussion with the manufacturers, two tower types were accepted. This was done in compliance with two general technical solutions for the TL design. First, using standard towers (the height to the lower conductor is to be 20 m) with a combination of different conductor types. Second, the same solution but with a difference in the use of higher towers (with the height to the lower conductor of 22 m). The height of towers, span lengths, clearing distances of the conductors to the earth or the crossed objects determine the electric and magnetic field parameters which must ensure the least impact on the environment. The results of simplified estimation (Fig. 4) allowed for a simple verification of the restrictions in different alternatives.

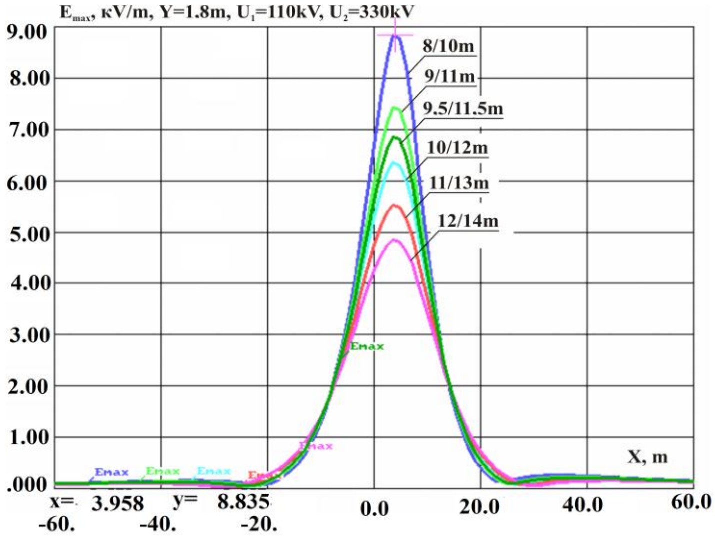

Fig. 4. Electric field distribution (E_{max}) at 1.8 m above earth in the cross-section of a 330/110 kV line for the minimum clearing distances of the 330/110 kV conductors: 8/10 m, 9/11 m, 9.5/11.5 m, 10/12 m, 11/13 m and 12/14 m.

The following combinations of alternatives were selected:

a) A1 and A10; A11 and A20 – the traditional type conductors for both 110 kV and 330 kV TLs;

b) A6 … A9; A16 … A19 – the HTLS conductors for both 110 kV and 330 kV TLs;

c) A2 … A5; A12 … A15 – the traditional type conductors in combination with HTLS conductors for 110 kV and 330 kV TLs.

Figure 5 shows the results of optimum solution for the two-objective optimization based on the Pareto approach [26], where I_C (p.u.) is the invested capital and E (kV/m) is the strength of the electrical field. As a result, the competitive alternatives are A6, A7, A9, A10, A15, A17, A19 and A20.

Table 2

Invested capital for the examined alternatives

Alternative	**Invested capital (I_C), p.u.**	**Alternative**	**Invested capital (I_C), p.u.**
	Optimistic scenario 1		***Pessimistic scenario 2***
A1	5.22	A11	4.85
A2	5.23	A12	4.86
A3	5.23	A13	4.86
A4	4.70	A14	4.37
A5	4.69	A15	4.36
A6	4.95	A16	4.60
A7	4.53	A17	4.21
A8	4.95	A18	4.60
A9	4.41	A19	4.10
A10	4.30	A20	3.93

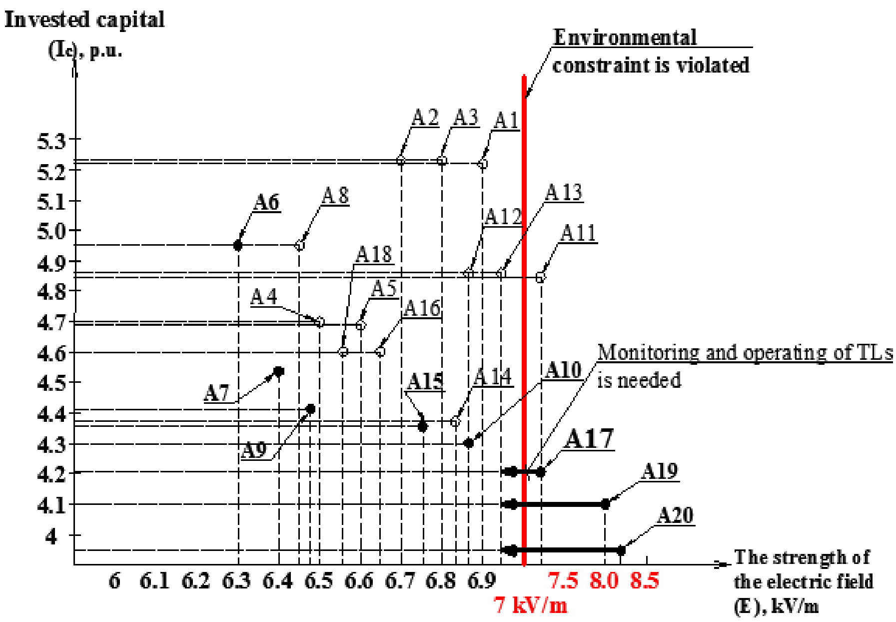

Fig. 5. Pareto's set for the alternatives.

The resulting values of the optimization criteria are summarized in Table 3 (for further consideration only competitive alternatives are left). Analysis of the table reveals the following:

1. At the use of the "classical" problem – namely, NPV maximization complying with all the restrictions – alternative A10 should be chosen. The final decision will be taken using one of the criteria from [19].
2. If violation of the restriction is allowed, alternative A17 or A19 should be chosen.

Table 3

Expected NPV and restriction indices R_i

Alternative	Optimistic scenario 1	Pessimistic scenario 2
	NPV_{11}//R_{11}	NPV_{11}//R_{11}
A10	4.7 // 6.9	5.4 / 5.0
A17	6.2 // 7.1	5.33 / 5.6
A19	6.7 // 8.0	5.7 / 7.3

The risks of emergence of the conditions leading to operational changes (and, therefore, to additional economic losses) were estimated from the viewpoint of making the final decision. Violation of restrictions on the electrical field strength for the considered example under the Latvian climate can arise at the maximum air temperature of +35°C and the maximum load current. The combination of these two conditions is hardly probable: for alternative A10 it is 0.01, while for alternative A17 – only 0.000001 (both probabilities are estimated considering the optimistic scenario). After taking into account the above-mentioned probabilities, alternative A17 was chosen as the final decision for practical implementation; besides, to satisfy the relevant legislative conditions for the electric field, permanent monitoring and operating of TLs is needed.

4. CONCLUSIONS

The latest tendencies in the development of power systems – deregulation of the electricity market, introduction of new technologies and increase in the distributed and renewable generation – considerably affect the process of transmission network planning. The proposed approach is expected to facilitate decision making that would result in reduced invested capital as well as improved reliability of energy supply and power quality.

Utilization of multi-criteria optimization partially based on the stochastic approach ensures the possibility to consider even the alternatives with restriction violations; after some additional measures taken, these alternatives can be the most cost-effective solution.

The OHL design method, which is partially based on the stochastic approach and game theory criteria, can satisfactorily be used for the final decision making. For maximizing the NPV complying with all the restrictions, one of the 20 elaborated alternatives – namely, that of using the traditional type conductors for both 110 kV and 330 kV TLs (A10) – is to be chosen; the final decision is made using one of the main technical, mechanical and environmental criteria examined above. In the case when restriction violation is allowed after several preventing actions (e.g. permanent monitoring and operating of the examined line model), it is expedient to choose alternative A17 or A19. The final decision is based on the probability of occurrence of a selected variant when the least probable alternative is to be chosen (namely, A17).

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ELEKTROPĀRVADES LĪNIJAS DAUDZKRITERIĀLĀ OPTIMIZĀCIJA

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K o p s a v i l k u m s

Elektropārvades tīklam rodas nepieciešamība pēc jauniem elektriskajiem pieslēgumiem, kas noved pie esošo gaisvadu līniju jaudas nepietiekamības. Viens no iespējamajiem pastāvošās problēmas risinājumiem ir jaunu gaisvadu līniju un apakšstacijas būvniecība. Gaisvadu līniju projektēšana ir saistīta ar ievērojamām tehniskām, vides un ekonomiskām problēmām. Darbā aprakstīta elektropārvades līnijas optimālās trases izvēles daudzkritēriju optimizācijas koncepcija, ieskaitot balstu tipa, balstu izvietojuma koordināšu, balstu ģeometrijas, vadu tipu un parametru, izolatoru tipu, vibroslāpētāju tipu, zibensaizsardzības un zemēšanas sistēmu, kā arī laidumu garumu izvēles optimizāciju. Optimizācijas uzdevums tiek organizēts piecos posmos. Pirmajā un otrajā posmā tiek meklēta optimālo risinājumu kopa, kā arī noteikti galvenie ietekmējošie faktori. Nākamie divi posmi atspoguļo divkritēriju optimizāciju, izmantojot Pareto pieeju. Pēdējā posmā, kas ilustrēts ar situācijas piemēru, tiek novērtēta ierobežojumu pārkāpumu nosacījumu rašanās varbūtība. Tiek identificēts cēlonis un tā novēršanas metodes. Atspoguļotā pieeja ir balstīta uz reālas līnijas projektēšanas piemēra ar galveno mērķi – mazināt kopējo ieguldīto kapitālu un palielināt pašreizējo neto vērtību. Iegūtie rezultāti aplūkoti šajā darbā.

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