Solving Company Cooperation Tasks in the Construction of Power Transmission Lines

Igor Moshkin
Riga Technical University
Riga, Latvia
igors.moskins@gmail.com

Jevgenijs Kucajevs
Riga Technical University
Riga, Latvia
jevgenijs.kucajevs@rtu.lv

***Abstract*— The article is dedicated to tasks related to rational cooperation of supply and distribution network companies in the designing and construction of power transmission lines at market conditions. Specifically, the individual and cooperative approaches in decision-making for individual market participants are considered. To substantiate the rationality of the decisions and to show the additional gain in case of cooperation between the companies, avoided cost method and cooperative game theory methods are used. The article considers solution alternatives in case of a collision of interests between the companies of the high-voltage network and those of the low and medium voltage networks; the selected alternatives are compared and the possible gain of the participants in case of various models of behavior is analysed. The proposed strategies and calculation examples are based on an ongoing high-voltage power transmission line reconstruction project in a real European country.**

Keywords*— electrical engineering, power transmission, power transmission lines, power distribution, avoided costs, cooperation, optimization of decision-making

I. Introduction

Power transmission lines (PTLs) have an important role in modern-day power engineering. They ensure output of power from large power plants and serve as the linking element in a country's united power system.

Designing of power transmission lines is an integral part of the designing of power supply as a whole. Correct selection of PTL elements lies at the base of long-term and safe operation of the lines and, consequently, reliable and standard-compliant power supply to consumers. Designs of this kind represent a multistage process, which requires from the design body not only technical skills but also basic knowledge of legal and economic standards: land use regulations, regulations regarding land alienation, organisation of tenders, etc. Since recently, particular attention is being paid to the safety of people and the impact of electromagnetic radiation on human health; therefore, a modern PTL design has to comply with the strictest requirements regarding electromagnetic radiation. With respect to radio noise or electromagnetic interference, power lines are usually considered in two classes: (1) lines below 70 kV and (2) lines above 110 kV [1]. Over the recent years, transmission network planning has been strongly influenced by the electricity market conditions, the changes in the economic environment and the regulation models, climate and weather issues, integration and utilization of new technologies, random events, etc. [2].

Considering the development of the free electricity market, we assume that the power distribution and transmission systems are separated. Nowadays, according to the functions performed, supply and distribution networks are distinguished between. Currently, the free market conditions more and more frequently lead to the emergence of various companies in each sector, which compete between themselves and strive to win consumers. Along with the continuous development of technologies and the annual increase in electricity consumption, networks are developing and expanding, which inevitably leads to a collision between the interests of various companies and to a need to address tasks jointly.

Also, we examined the possibilities of demolishing small privately owned structures and subsequently building new ones, in those cases when such reconstruction is less expensive than the changing of the configuration of the 110/330 kV PTL under design.

Also, we analysed individual cases with combined crossings, where more than one crossings of low and medium voltage PTLs as well as roads and private structures were encountered in one land plot. In this case, it became necessary to solve several route reconstruction tasks at once, with the participation of all the interested parties.

The authors of the article also considered opportunities of making coalitions in the projects of reconstruction of power transmission lines where several high-voltage companies were involved. These companies would solve the problem of planning joint two-chained power transmission lines with sharing the expenses for planning, construction and exploitation. In one of the examples [3] the authors were reviewed the case were three companies were involved. In the given example, it is assumed that there are three independent companies two of them are engaged in the creation of power transmission lines and third company is interested in implementing optical communication line. The one of power transmission companies is engaged in the creation of a 110 kV transmission line and the other in the creation of a 330 kV

ISBN 978-1-5386-3917-7.

transmission line. The alternatives that are advantageous for each company have to be chosen as the decision. It is also necessary to show the costs of the project and the potential benefit for each company in the case of an individual approach, implementing the whole project separately, and check if it is possible to form different variants of coalition. Then there is the task of analyzing the outlook for forming coalitions with other companies. The example is based on a real Latvian project; however, today the system for dividing the power supply including transmission lines is somewhat different. All power transmission above 110kV belongs to one company. Therefore all the revenue of the project in the case of combining 110kV and 330kV transmission lines is the profit of mentioned company. The cooperative game approach is typical for other countries of Europe and the Russian Federation where the issue of cooperation is more topical because of the potential profit for each company [3].

For given circumstances, we have five combinations of the entire project including power transmission and optical networks. To simplify the recording of all possible variants of designing and realizing the project we assume that company "A" manages power transmission lines 330kV, company "B" manages power transmission lines 110kV and respectively company "C" manages optical communication networks [3].

There were five possible ways of realizing the project. In the case of organizing a coalition of two or three companies it is necessary to distribute the additional revenue by using the Shapley value, which requires an agreement and approval of each company [3].

In case of cooperative behavior, the investments of the project reduced considerably. This means that the formation of any variant of coalition is rational and possible in terms of economy of investments. The most profitable is making a coalition of three companies and then it will be a task to divide an additional profit. Effective way to do it is using a Shapley value. We note that in the real project the revenue is the amount of tens of millions EUR [3].

The present article is dedicated to the solution of tasks related to rational cooperation of supply and distribution network enterprises in the designing and construction of power transmission lines at market conditions. Along with problems related to crossings of distribution networks, the authors have also addressed other problems related to crossings of roads as well as land property and small privately owned buildings. Also, a description is given of the possibility of using the avoided cost method and cooperative game theory methods [4] for solving the above problems.

II. The development plan of the transmission network of the Baltic region

An example which was taken as a basis for calculations in this article is an energy infrastructure project "Kurzeme Ring" involving the construction of a 330kV overhead line and reconstruction of existing 110kV transmission line in the western part of Latvia with a main purpose of increasing the throughput capacity in Kurzeme region, which was impossible up to now. It is a part of the larger NordBalt project, the implementation of which includes the interconnection installation Latvia – Estonia – Sweden with a view to improve power supply reliability in the Baltics [4,5].

The "Kurzeme Ring" construction is necessary mainly due to the fact that the present 110 kV transmission network does not ensure sufficient electricity supply reliability in Kurzeme region. This insufficiency was evidenced in 2005, when a large part of Kurzeme population was left without electricity as a result of the fierce storms. The Kurzeme Ring construction will reduce the possibility of accidents, at the same time increasing the operativeness of emergency repairs. The project implementation will raise electricity supply reliability to consumers in the whole Kurzeme region and its towns as well as ensure the potential of connecting new electrical installations of users [5].

III. Case Study

The authors examined a design for the reconstruction of a high-voltage power transmission line (PTL), within which a supply network company is planning to replace an existing single-circuit 110 kV PTL and to construct a new double-circuit 330/110 kV PTL in parallel to the axis of the first line.

The designing of a PTL is a demanding and labour-consuming process, which includes development of all the required engineering and design documentation as well as calculation and compilation of a number of other documents that are necessary for building the supports and performing the electric installation works.

Since, in order to ensure power supply reliability, during the construction it is necessary to provide for emergency energisation of the PTL under reconstruction, the axis of the new PTL is located at some distance from the first one. The peculiarities of the landscape, the density of buildings in the suburbs as well as the large number of crossings and utilities make it impossible to position the route of the new 330/110 kV PTL at a strictly unchanging distance from the axis of the existing 110 kV PTL; therefore, already at the designing stage, the new route diverges from the existing one, which leads to the emergence of new utility crossings.

One of the problems in the designing process is posed by aboveground utilities, which require adherence to special standards and clearances, both vertical (from the conductors) and horizontal (from the supports).

One of such crossings is examined by the authors of this article, namely, crossings with the medium-voltage and low-voltage PTLs. In this case, we see interaction between the supply and distribution network companies. Within the examined example, there are not only new crossings but also special attention is needed for the existing crossings that are to change due changes in PTL voltage and dimensions.

Since the axis of the line under design is to be shifted in relation to the existing one, in some sections the supports of the low-voltage lines are situated under the conductors of the 330/110 kV PTL under design. Here, it is often impossible to maintain the clearance from the low-voltage support to the lower conductors of the PTL under design, especially in the middle of the span, where the sag reaches its maximum values.

The horizontal distance between the supports of two lines of different voltages changes as well. In some cases, the above-indicated changes lead to non-compliance of clearances with the valid construction standards and regulations. PTLs are designed for periods of 40 to 50 years, hence it often happens that the standards themselves change during the operation of the lines. Even the existing lines, if they were being built today, would not meet part of today's standards, since the standards gradually become stricter due to efforts to achieve safety and diminish risks in the maintenance and operation of PTLs.

In the case of crossings of this kind, it is necessary to either reconstruct the 20 kV PTL or change the route of the 330 kV line. Due to differences in the costs of designing, assembly and materials, in most cases it becomes inefficient to lengthen the 330 kV PTL. Therefore, reconstruction of the 20 kV PTLs is done. Here, the interests of two companies are affected, which has been mentioned before.

In the design, there are sufficiently many cases of this kind, in which medium-voltage and low-voltage PTLs are crossed, even in the case of long PTLs or densely settled areas. In the example examined in our article, in a 30-kilometre section of the line route, there are 24 such crossings with medium-voltage and low-voltage PTLs, for which new reconstruction designs need to be developed. The authors have singled out one of such places, conducted calculations and analysed various solution alternatives for individual crossings. Also, the avoided costs (which were mentioned at the beginning) have been shown for the selected solution alternative. The avoided costs method gives a clear idea about the expected gain, yet it does not offer any information as to the distribution of the profit among the participants. Hence, the authors also examined the cooperative game theory method and profit distribution according to the Shapley value.

In case of cooperative behavior, there is a problem of revenue distribution between the members of the coalitions. The simple approach would be to give to each player his contribution c_i:

$$c_i = R\left(S \cup \{i\}\right) - R(S) \tag{1}$$

where $R(S)$ is the revenue of the coalition S, $R\left(S \cup \{i\}\right)$ is the revenue of the coalition S with participation of the actor i.

However, such an approach is not anonymous, i.e. ordering of the players makes difference in the amount they are rewarded.

In game theory, a Shapley value describes one approach for the fair allocation of gains avoiding the mentioned drawback. Fair allocation ensured by selecting uniformly a random ordering and rewarding each player the expected marginal cost in ordering. Since players can form $n!$ possible random orderings, the probability of set S being ranked exactly before player i is [6]:

$$\frac{|S|!\left(n-1-|S|\right)!}{n!} \tag{2}$$

Thus the additional amount that the player i gets is:

$$\phi_i = \sum_{i \notin S \subseteq N} \frac{|S|!\left(n-1-|S|\right)!}{n!}\left(R\left(S \cup \{i\}\right) - R(S)\right) \tag{3}$$

Further, the obtained profit is distributed among the participants of the coalitions by the Shapley value (3) [6].

In the examined section, due to the small angle of crossing between the 330/110 kV PTL and the 20 kV PTL as well as due to the peculiarities of support location in this section, it was impossible to conduct reconstruction of the line, which would enable relocation of the supports of the 20 kV PTL. This is related to the peculiarities of the locality and to the fact that the supports would turn out to be located in additional forested land plots, which leads to additional cutting of forest and an additional need for approvals from landowners. Hence, the most efficient solution in this case was to lay a section of the 20 kV line as a cable under the ground in the place of the route crossing, along with the installation of two transition supports from the overhead line to the cable line and vice versa.

IV. Calculations and Analysis of Results

To safeguard the interests of real-life companies, the calculations were conducted by using averaged cost indicators from the implementation of reconstruction projects of 20 kV and 110/330 kV routes; also, the probable course of action of the involved parties was selected.

In the examined example, it is assumed that the high-voltage PTL company agrees to meet the expenses of the designing works, assembly and materials for replacing the 20 kV PTL section in the land plot directly affected by their 330/110 kV project. However, at a distance of three spans after the examined place, there is a transformer substation. Due to this, laying a small portion of the 20 kV PTL as a cable line is not rational. Hence, it can be assumed that in one of the

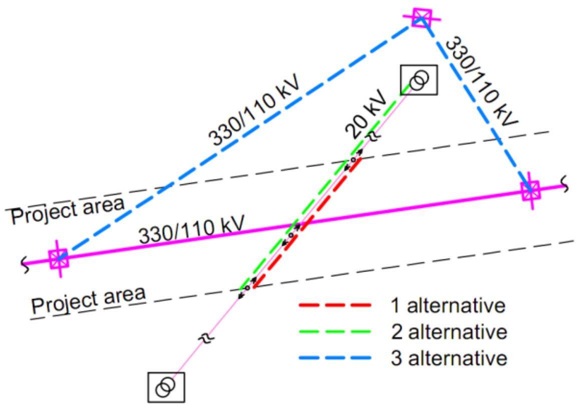

Fig. 1. Layout of PTL reconstruction design with solution alternatives

possible alternatives, the company that owns the distribution networks may decline to approve such a reconstruction project, since that would increase the operating costs and diminish the reliability of the line as a whole. In this situation, the company that owns the distribution networks approves the laying of part of the 20 kV line as a cable only on the condition that also the part up to the transformer substation will be replaced.

In such case, the high-voltage network company obtains two other solution alternatives: either to accept the conditions and lay as a cable line a larger portion than planned or to design a bypass of the 20 kV PTL to be crossed.

Figure 1 provides a basic layout of all the three solution alternatives for the examined PTL reconstruction project:

✓ Alternative 1 entails replacement of a portion of the 20 kV PTL only in the project area;

✓ Alternative 2 entails replacement of the portion of the 20 kV PTL in the project area and additionally up to the transformer substation

✓ Alternative 3 entails by passing the 20 kV PTL to be crossed

The authors have examined and calculated all the solution alternatives. Table 1 shows the results of these calculations.

TABLE I. CALCULATIONS FOR THE SELECTED ALTERNATIVES.

Alternative	Length of section, m	Cost, EUR	Excess cost compared to the cheapest alternative, EUR
1	80	4800	-
2	240	14400	9600
3	480	214800	113700

The above calculation results show the inefficiency of Alternative 3 due to the exceedingly high excess cost as compared with the other two alternatives. Since Alternative 1 is not approved due to the reasons mentioned above, the high-voltage network company will select Alternative 2, regardless of the excess cost of 9600 EUR.

Due to the development of modern technologies, the power transmission line design process is more dynamic nowadays. Specialised software, such as PLS-CADD [9], makes it possible to easily switch between various tentative alternatives of the design and to instantaneously receive cost calculations to select the optimum solution.

Currently, we see a tendency of gradually replacing medium and low-voltage PTLs with cable lines. This is due to both power supply reliability considerations and natural phenomena, such as snowstorms and strong wind. These events often cause serious damage and lead to power supply interruptions in entire regions, which naturally results in enormous financial loss. In many aspects, replacement of PTLs with cables is aided by the directives of local authorities. For example, in many European countries overhead lines of medium and low voltage are not permitted in large settlements and in cities.

In the examined example, the costs of laying the 20 kV as a cable within the section affected by the 110/330 kV PTL reconstruction project will be avoided costs for the distribution network company. For the actual example, these costs will amount to 23…25% of the cost of the whole section between the two 20 kV transformer substations.

V. ADDITIONAL INVESTIGATION DIRECTIONS

Along with problems related to crossings of medium and low voltage PTLs, the authors have also addressed other problems and peculiarities related to the designing process of the above-mentioned 110/330 kV PTL. Here, various alternatives of road crossings were examined, selecting the best reconstruction alternative: changing the road itself or moving the designed supports, thus increasing the overall number of supports and the PTL construction costs.

VI. CONCLUSIONS

In the designing of PTLs, it is necessary to address tasks related to the crossing of utilities, medium and low voltage distribution networks and roads as well as issues related to the crossing of private land plots. Here, several possible courses of action emerge for various market participants, from which the optimum solutions have to be chosen. Upon analyzing the obtained results, a preliminary conclusion can be made, namely: the development of technologies, the improvement of infrastructure as well as the market conditions bring about an uncertainty factor and create basis for the emergence of conditions at which part of companies may benefit at the expense of the development of other companies. In this way, a number of power companies arrive at avoided costs, which can often become a perceptible contribution as a percentage of current and new projects. To ensure fair distribution of the profit gained, it is proposed to use the Shapley value. Such an approach helps to take account of the costs and the interests of several companies participating in the project.

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