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Power System Expansion Planning - State of the Problem

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Abstract

The paper gives an overview of the latest results in the development of the development of the methodology for expansion planning of electric power industry, electric power systems and companies in the market environment. The prerequisites of the market methodology are analyzed. The market approaches in generation and transmission networks are presented. The main principles of the holistic power system expansion planning are given. The conclusion of the paper suggests same generalization in this important area.

Keywords: Power system; Generation; Transmission; Expansion; Planning market approaches

Introduction

Expansion planning in electric power industry is a multi-stage process, where the decisions made at the previous stages are specified at each subsequent stage. The complexity of this process is explained by the need to consider many important factors and the uncertainty about the future development of the energy sector. Under the conditions of liberalized relationships in electric power industry, the process of analyzing and making decisions on its development involves many participants (stakeholders) that have different interests. These are electric power companies, consumers, investors, public organizations, federal and regional authorities. Today, the coordination of interests of stakeholders and the formation of mechanisms for ensuring the development process become the main objectives of expansion planning of electric power systems and companies.

In the past, many years of experience in planning the development of electric power industry under the planned economy in the USSR made it possible to form a comprehensive methodology for planning the expansion and placement of generating capacities, and the development of transmission electric network. This methodology was based on a system approach to the considered complex problem and included the hierarchy of interrelated problems in terms of territory, time, and function. An analogous methodology in the USA was called the integrated resource planning.

At present, the methodology of power industry expansion planning is undergoing radical transformation from centralized planning into a new paradigm of the multilateral process for justifying the decisions and creating the mechanisms for their implementation under the conditions of uncertainty, multicriteriality, and multiplicity of different interests. This transformation is characteristic of all the countries experiencing energy liberalization and deregulation. The formation of a new methodology has only started. The principles and methods for expansion planning in electric power industry in the market environment [1-6] are being developed with due consideration of general methodological developments [7-10]. Certain problems and methods of generation [1,6,11-13] and electrical network [6,14-16] expansion planning in the market environment are being studied with particular attention paid to game approaches [1,11,14]. The mechanisms for providing investment in electric power facilities and effective development of electric power industry, electric power systems and companies are being considered in terms of increased risks [2,17-19].

Liberalization and deregulation processes in electric power industry were activated in the 1970s and 1980s. The main stimuli for this activation were the powerful arguments for the inefficiency of electric power industry as a public sector of the economy, its occasional inability to ensure stable rates of economic growth, anonymity of property, state protectionism, etc. The ideas of liberalism, monetarism, deregulation of the economy (including the electric power industry), privatization of state property, freedom from state intervention in trade and other economic activities became quite popular. Thus, it was not by accident that radical and liberal reforms were often accompanied by a considerable relaxation of state control aimed at fast activation of self-regulatory market mechanisms, which were supposed to stimulate economic growth and restructuring of electric power industry [20].

This approach was mainly based on the theoretical conclusions of the classical school of economics that the market balance is achieved owing to the law of demand and supply by means of flexible market pricing under the conditions of perfect competition; prices reflect individual preferences and fluctuations according to the changes in demand and supply; resources are distributed according to the relative price level in the market, and if this level depends on fluctuations in demand and supply, the absolute price level is determined by the amount of money; when the balance is disturbed, the system strives to restore it, that is why any attempts to interfere in the operation of market mechanisms can only aggravate the situation.

In the 1980s and early 1990s many countries recognized that it was reasonable to use the market mechanisms in their electric power industry and had some euphoria over the almighty “invisible hand” of the market. There was an opinion concerning the problems of electric power industry development that the market mechanisms would give the necessary economic signals for the expansion of both generating capacities and electric networks. In Russia, such ideas were especially popular in the early and mid-1990s. A failure to recognize the significance of the problems of electric power industry development in the economically developed countries was explained by the fact that the intensive energy saving virtually stopped electricity consumption growth; at the same time large backups were formed at generating facilities and in the electric network; as a result, the problems of power shortage and electric network constraints did not manifest themselves for a long time, and surplus power made it possible to create competitive electricity markets. During this period, Russia experienced a considerable decrease in electricity consumption, which led to a significant rise in the amount of unloaded generating capacities.

The experience of market transformations in electric power industry in most of the countries showed that the initial excessive optimism about the efficiency of purely market forces in the operation and, particularly, expansion of electric power systems proved unjustified. Extremely liberal models of electricity market organization and functioning were set aside and the role of “soft” regulation of these markets by implementing the appropriate government policy was recognized. In essence, the specialists acknowledge now that the most rational method for efficient operation and expansion of electric power systems is a combination of market mechanisms and state regulation. It is worth emphasizing that the determination of such a rational combination is not an easy task and its performance is country-specific because of specific features of economy and electric power industry, conditions of their operation and development.

Moreover, by the late 1990s, the backup generating capacities had started to decrease considerably in many countries, since it turned out to be unprofitable for the generating companies to maintain extra capacities. The electricity market functioning revealed the limitations on the transfer capability of the electric network often at the points, where such limitations had not manifested themselves before (the so-called congestion problem). All this triggered the research into the methods of expansion planning of generating capacities, and particularly electric networks, on a new market basis.

The above mentioned new paradigm of a multilateral process of making decisions and creating the mechanisms for their implementation under the conditions of uncertainty, multicriteriality, and multiplicity of interests is topical and has to be comprehensively studied disregarding the future organization structure of the electric power industry, principles of electricity market functioning, state control in electric power industry, etc. Regardless of these “internal” conditions, the electric power industry will develop in a liberalized market environment characterized by uncertain conditions of development, a great number of stakeholders with different interests and a lot of decision-making criteria.

Below, the paper presents a systematic analysis of the latest developments in the expansion planning of electric power industry, electric power systems and companies in the market environment. The main principles of the so-called holistic power system expansion planning are given. The analysis finishes with some generalizations.

Modern Models and Methods

Currently the mathematical models and methods for expansion planning of electric power industry, electric power systems and companies develop in the following conventional directions:

- Transformation of methodological principles;
- Generation expansion planning;
- Electric network expansion planning;
- Joint generation and transmission expansion planning

Transformation of methodological principles

As regards the transformation of methodological principles of expansion planning in electric power industry, electric power systems and companies, one of the main postulates is to recognize that it is very important to consider the corresponding problems as multi-criteria problems. A lot of attempts have been made to use a convolution of several criteria by measuring them in monetary terms, for instance, "costs + losses caused by insufficient reliability" [21,22], "costs + economic assessment of environmental impact of the electricity generation" [23].

The notion of the so-called social welfare is used, i.e. a corresponding integrated criterion that takes into account the criteria of all the stakeholders: network company, generating and supply companies, and consumers. In some cases, the criterion of social welfare is written as a sum of criteria of individual parties without any weighting coefficients [24]. A more careful approach consists in independent assessment and expert comparison of criteria of the stakeholders without the formal procedures [25] or by means of constructing Pareto curves “costs – reliability” [26] or "costs – revenue" [27]. The method of concessions is also used [28]. Consideration is given to the approaches based on multi-criteria utility function [29-31] (the authors of [29] suggest a formal procedure for the determination of weighting coefficients in a multi-criteria utility function) and game approaches [1,11,14,32-34].

Another important aspect of modern approaches to the planning of electric power industry, electric power systems and power companies under the conditions of liberalization and deregulation is connected to greatly increasing uncertainty of the expansion planning factors and a growing number of factors forming this uncertainty, as compared to the conditions of the centralized electric power industry. In terms of methodology, there is a short-term uncertainty and a long-term uncertainty. The short-term uncertainty (for instance, fluctuations in electricity prices in prospect as against the forecast, load variations at system nodes as against the forecast, etc.) is represented as random and modeled, for example, by the Monte-Carlo method [13,22,35-37]. The long-term uncertainty is represented by scenarios (for instance, the scenarios of electricity consumption, fuel or equipment prices, etc.) [26,31,38]. The fuzzy sets and fuzzy logic are used [35,39,40]. In many cases, uncertainty is associated with risk [5,29,41].

Considering the uncertainty of electric power industry development, it is recognized that the ideology of approaches to the expansion planning of electric power systems and companies should be transformed from optimization to forecast and simulation, and from planning to a development strategy [12,34]. As compared to the previous conditions, the sense and content of mathematical models used for forecasts and simulation expand since the technological models for electric power system expansion planning are supplemented with financial ones [3,42] and gain new functions including assessment of power supply reliability, consideration of demand-side management (DSM), and other capabilities [4,38,43,44]. The use of such powerful means as the geographic information systems is also considered [45].

Generation expansion planning

Some authors do not regard the generation expansion planning problem as pressing and assume that the market mechanisms should give the necessary economic signals to the investors to invest in the construction of new power plants. However, this viewpoint is supported by fewer and fewer researchers, since a deeper analysis and the existing practice show that the market is "shortsighted" and there is a need to foresee the corresponding mechanisms to improve the investment attractiveness of new power plants and reduce the financial risks to investors. To this end, a lot of different approaches are suggested, one of which is the so-called Stratum Electricity Market (SEM). According to this approach, the electricity market structure is considered hierarchically in time, including the spot (hourly), monthly, yearly and long-term markets. The long-term market makes it possible to arrange auctions and attract investment in the construction of power plants [46]. A similar idea was also formulated in [47]. Also, consideration is given to the capacity markets (in addition to electricity markets) that create long-term economic signals for investors for the expansion of power plants [48].

An important problem is the coordination of generation expansion, since every generating company and every independent investor that explore the possibility of investing in the construction of power plants, have their own interests, which should be reconciled taking into account the general system requirements. An independent system operator is considered as the coordinator [13,49,50], and social requirements (the main of which is the reliability of power supply to consumers) – as the system requirements to be checked by the operator. In other cases, the function of the generation expansion coordinator is performed by the state [47,51-53] (which is often identical to the previous case, where the system operator is the state property), and the problem can be viewed as a hierarchical game problem [52]. When the power plant expansion is regulated, the coordination can be performed by the companies. In this case, the problem is formulated as a cooperative game [1,54,55].

Some authors consider the state generation expansion planning as a means of protection against market risks [47,51,53]. In a more general case, it is most rational to combine market mechanisms of power plant expansion with the system of state and corporate generation expansion planning, which reduces investment risks. In this case a special fund is established to hedge independent investors against financial risks and construct power plants to avoid generating capacity shortage [47,56,57].

Transmission expansion planning

Since the functions performed by the electric network represent monopolistic activities, and are regulated by the state, the issues of electric network expansion planning are paid considerably more attention than the generation expansion planning. The main results can be formulated as follows [24,25,58-69]:

(a) Among the stakeholders interested in the expansion of the transmission electric network, the first to consider is the network company (in some cases, an integrated dispatching-network company, which includes a network company and a system operator), and then the generating companies, power supply companies, and consumers. The authorities (regulators) are not directly considered in the discussed plan as stakeholders. The investors are taken into account indirectly and in a simplified way – through the investment component of the expansion costs of the transmission electric network.

(b) The basis for the formation of criteria of the stakeholders can be represented by the following three cases:

- cost-based approach – consideration of the costs of electric network expansion, current electricity generation and transmission costs, consumer losses due to the electric network limitations and insufficient power supply reliability; in a number of cases, power supply reliability indices act as independent criteria [58,61,63,66,68]; market conditions are taken into account here only in a simplified way, for instance, as a thesis that the network should not limit free trade in electricity, and one of the criterion components considers minimum difference between the case of real network limitations and the above mentioned ideal case;
- market approach – consideration of the market price signals for the expansion of the transmission electric network, which are based on locational marginal nodal or zonal prices and congestion prices [24,25,60,62,64,65,67,69];
- Stratum Electricity Market (SEM) structure [59] – similar to the above mentioned SEM structure for generation expansion; the long-term market, similar to generation expansion, makes it possible to arrange auctions and attract investment in the construction of transmission lines, and thus the expansion of the transmission electric network.

(c) Many authors note that market electricity prices based on the current prices of the generating and network companies do not give appropriate price signals for the expansion planning of the transmission electric network and that there is a problem of "converting" these short-term signals to long-term ones [67]. One of the approaches is to determine marginal nodal or zonal prices, using not only the current prices, but also the investment component in the electric network expansion. Another approach is connected to the long-term forecasting of marginal prices in the wholesale market [65]. An alternative solution is the stratum electricity market structure [59], which forms the long-term market of investment in the transmission electric network.

(d) In most of the researches, using the above mentioned criterion of social welfare, the main solution for the expansion of the transmission electric network, to which the solutions assessed according to the welfare criterion should approximate, is the solution assessed by purely market factors (for example, by the maximum profit of competing generating and supply companies).

(e) The use of other criteria, apart from the social welfare criterion, is determined by the imperfection of real electricity markets, and first of all by the monopolism in the market (market power).

(f) The set of stakeholders that are interested in the expansion of the transmission electric network, and especially the set of criteria expressing their interests largely depend on certain conditions, i.e. the electric power industry organization structure, rules of electricity market organization and functioning, etc. That is why the corresponding suggestions should be tailored to the concrete conditions.

Joint generation and transmission expansion planning

Generally speaking, it is recommended that the generation expansion and expansion of the electric network should be coordinated by solving the corresponding system problem [36,49,70]. Different approaches are on this way.

In [71] the planning problem is modeled from the viewpoint of the transmission planner, as a four-level optimization problem. The interrelated problems A (GenCos bidding strategies), B (market strategy), and C (generation expansion) are solved by linking agent-based and search-based algorithms. Finally, problem D (transmission planning) is linked to the first three problems through evaluating a predefined set of planning criteria. When using such a framework, system planners need to be careful that the analytical models being used to represent GenCos capture reasonable behaviors. Solutions found from tools such as the presented in [71] should not be applied blindly in actual planning exercises, but rather help planners gain more insight to expected behavior.

The authors of [72] develop a three-level model of transmission and generation expansion planning in a deregulated power market environment. Due to long planning/construction lead times and concerns for network reliability, transmission expansion is considered in the top level as a centralized decision. In the second level, multiple decentralized GenCos make their own capacity expansion decisions while anticipating a wholesale electricity market equilibrium in the third level. The collection of bi-level games in the lower two levels forms an Equilibrium Problem with Equilibrium Constraints (EPEC) that can be approached by either the diagonalization method (DM) or a complementarity problem (CP) reformulation. The paper proposes a hybrid iterative solution algorithm that combines a CP reformulation of the three-level problem and DM solutions of the EPEC sub-problem.

The paper [73] suggests a pessimistic three-level equilibrium model for a market-based expansion of both transmission and generation. The lower (third) level models the market outcomes; the intermediate (second) level models the equilibrium in generation capacity expansion by taking into account the outcomes of the market equilibrium at the third level. The upper (first) level models the expansion of the transmission network. The second and third levels are modeled as an Equilibrium Problem with Equilibrium Constraints (EPEC) parameterized in terms of the optimal decisions of the transmission planner. This three-level hierarchy is motivated by the fact that transmission planners should consider expansions in generation that may take place, as well as the clearing of the market related to generation expansion, in order to make their decisions.

The other approach is proposed in [74]. By applying Monte Carlo simulation and scenario reduction techniques the authors propose a stochastic long-term generation and transmission capacity planning formulation for representing uncertainties in the availability of generating units and transmission lines, and inaccuracies in load forecasting. The Benders decomposition and Lagrangian relaxation methods are applied to simulate the interaction among market participants (GenCos and TransCo), and the interaction between the ISO and market participants in the long-term planning process under competitive electricity market. This stochastic market-based approach could provide signals to investors on the location of new generation and transmission facilities and help system planners, regulators, and local authorities concur in transmission planning together with generation planning.

Holistic Planning

Integrated resource planning has been actively used for vertically integrated electric power systems in their centralized expansion planning. Electric power system restructuring and liberalization, electric power industry division into monopolistic and competitive parts in accordance with the types of business, and a large number of stakeholders with different interests have made it rather complicated to use the advantages of the integrated resource planning. Therefore, with time, this approach has been transformed into a new one called the holistic planning of electric power systems [75] or the electric network in a special case [76].

"Holistic" means considering an object as a whole, and not just dealing with particular aspects. In [71], the electric power systems are comprehensively considered in terms of cost-effectiveness, required reliability, and acceptable environmental impact. The authors of [76] also consider the social welfare.

The following principles of holistic power system planning are considered:

- Comparison of alternative strategies for expansion, using integrated quantitative assessment and maximizing social benefits of expanding the system as a whole;
- Use of probabilistic reliability criteria to counterbalance the commonly used deterministic criteria, such as the reliability rule "n-1";
- Consideration of the entire expanding system in terms of how it is connected to other electric power systems around it and adjacent systems of different nature at the local, regional, and global levels;
- Assessment of costs and benefits from the standpoint of all the stakeholders in terms of their share in the used assets and fair cost and profit sharing among the parties;
- Behavior of individual parties in accord with the global goal of the system; in other words, each stakeholder should contribute to the improvement in the efficiency of the entire system, i.e. despite the individual goals of the stakeholders, they should make a contribution to the global goal.

Holistic planning is a new concept which attempts to take into account the characteristics of current split organization structure of the electric power industry, a methodology of gaining the common benefit from optimal allocation of resources with no return to a fully integrated and strictly regulated structure.

The author of [75] consider two aspects of holistic planning: electric network planning and resource planning. At present, the electric network planning involves great difficulties. The substantial uncertainty about the load forecast, placement of generating capacities, regulatory decisions, construction opportunities, etc. and a large number of stakeholders engaged in expansion planning necessitate the development of new approaches and methods for creating future flexible electric power systems which expand in an efficient manner. The electric network planning is impossible to perform holistically without consideration of resource planning, decisions on electricity consumption, and environmental constraints. The placement of new generating capacities can considerably affect the formation of the electric network. Social welfare implies making decisions optimal from a market viewpoint, under various alternatives, in accordance with the concept "Unity in Diversity", which is viewed as a way of reconciling individual decisions to the benefit of the society.

The new approach separates the problem of the electric network expansion planning from the problem of generation expansion planning. However, the decision-making about the investment in the electric network expansion should agree with the development of generation and consumption markets to the maximum.

The holistic resource planning under the conditions, where centralized expansion planning does not work and the free market mechanisms turn out to be ineffective, should be based on the above mentioned concept "Unity in Diversity", where individual decisions made by the stakeholders should agree with social welfare and goals of the society. The mechanisms for implementing such a concept should be developed by the government or by a community of consumers. One of the principles can be based on the inclusion of environmental costs, social needs, etc. in economic and financial criteria.

On the whole, the new approach called the holistic power system planning, which was considered in [75,76], gives only the main ideas of the new concept of expansion planning under electric power industry restructuring and liberalization. The ideas are aimed at reconciling the individual goals of stakeholders involved in the power system planning and the goals and benefits of the society as a whole. This promising approach needs further analysis and elaboration.

Conclusions

It is important to highlight a number of essential aspects which are common for the considered approaches. These aspects are considered both explicitly and implicitly in many studies that solve concrete problems of power system expansion planning.

The first aspect is connected to the systemic character of the studied object whose expansion planning we are dealing with. Electric power systems are objectively viewed as complex integral facilities with a complex, often hierarchical structure and quite strong ties with economic, social, and environmental systems. Such understanding of the systemic character of the object was mainly logical in the past, when the organization structure of electric power systems coincided with their physical and technological structure. It has to be mentioned however that not all specialists realized the systemic character of electric power systems, and therefore their structural complexity and complexity (systemic nature) of their operation and expansion problems. The holistic approach to the expansion planning of a seemingly split electric power system also considers the object of study and the problems of its expansion rather systemically.

Another aspect of the problem consists in the fact that apart from individual interests of the stakeholders in the course of the power system expansion planning, there are also some social interests and social welfare. Certainly, under the prescriptive control of the centralized electric power industry, the individual and local interests were minimal. Individual interests, for instance the interests of private energy companies, were most vividly seen in vertically integrated electric power systems operating in accordance with market principles. In the course of electric power system expansion, individual interests of stakeholders are most tangible in restructured and liberalized electric power industry. Moreover, the interests of different stakeholders contradict each other.

Centralized electric power industry, whose decisions were based on directives, implied that social goals and welfare were evidently prevalent, and the mechanisms for the accomplishment of these social goals were obvious. In the case of vertically integrated electric power companies, which work and develop on the basis of market principles, the social goals are achieved through the corresponding legislative and institutional mechanisms. Characteristically, the operation of competitive market mechanisms and restructured electric power systems, particularly in the holistic approach, also implies the involvement of certain institutions that can regulate the attainment of social goals connected to the electric power system operation and expansion. These institutions can be represented directly by the state or by independent structures, often with state property (communities of consumers, system operator, etc.).

All these considerations lead to the conclusion that in the power system expansion planning it is sensible to rationally combine market mechanisms and state regulation (to a greater extent, “soft” state regulation).

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