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PRICING OF REACTIVE POWER SERVICE

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Reactive power service is one of the most important ancillary services in electricity market. In this article the combined reactive power market model is proposed, encompassed with regulated financial compensation of the costs for reactive power sources and value-based reactive power pricing. The methodology of calculation of costs of generators, synchronous condensers and static reactive power sources for economical evaluation of reactive power service was created. In the investigational part the reactive power market model was applied for Lithuanian power system to determine the amount of compensation for reactive power sources.

Introduction

Reactive power is required for transmission of active power, control of voltage and system and normal operation of power systems. Therefore reactive power service is one of the most important ancillary services in electricity market. Reactive power price is usually based on the costs of reactive power, which can be obtained directly or from the market. Reactive power value and its influence on system stability, especially during hard and congested regimes, can be very high. Reactive power value can influence the price, but they do not coincide all the time. Reactive power service and the complexity of its pricing are amply described in scientific literature, but proposed solutions are usually complicated and hardly applicable in practice even in the most advanced electricity markets. It should be noted that effective theoretical solutions are hardly applicable in practice, while practically applicable solutions have a lot of drawbacks.

Reactive power costs are usually divided into fixed and variable ones [1–4]. Fixed costs are independent of the quantity of production, and they consist of capital and maintenance costs. According to the methods of separation of capital costs of reactive power, capital investments for reactive

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power are calculated directly from the data on generators, or they are expressed using the costs of other reactive power sources. It should be noted that in practice capital costs of generators should not be separated, because they are included in the active power price anyway. Variable costs of reactive power are associated with active power losses in the process of reactive power generation or absorption, and even if they lack attention in scientific literature, usually they should be compensated, especially for generators.

Reactive power market is realized in power systems of a few countries only, but their methods and models of organization and schemes of reactive power pricing are usually different [5]. In the majority of electricity markets different payment methods for the reactive power supply are used, but there are no standard methods for system operators to calculate reactive power price in the system. Fixed and variable costs of reactive power are covered depending on the chosen reactive power model. Usually the rules for reactive power sources are set concerning minimal requirements for power factor. They describe basic conditions for connection and participation in the reactive power market. In power systems, power factor requirements vary from 0.85 (UK and Wales) for generated to 0.98 (Norway) for absorbed reactive power. Beside mandatory requirements for generators, other voltage control requirements for customers connected to the transmission grid and distribution companies are also set. In most cases there is a consensus that alternative costs of generators, when they must reduce production of active power, have to be compensated. So, the conclusion is that payments for reactive power supply are usually based on cost compensation, but reactive power value is not taken into account.

In this article the combined reactive power market model is proposed, encompassed with regulated financial compensation of the costs for reactive power sources and value-based reactive power pricing. The methodology of calculation of capital investments for generators, synchronous condensers and static reactive power sources, fixed, variable, reserve and alternative costs for economical evaluation of reactive power service was created. In the investigational part, reactive power market model was applied for Lithuanian power system to determine the amount of compensation for reactive power sources.

Purposes and characteristics of reactive power market

Reactive power is needed for normal operation of an electric power system, and its value grows dramatically during accidents within the system. Creating the market of ancillary services, reactive power market has to be established in the power system for the following purposes:

- To motivate economically installment of the necessary amount of required reactive power and its reserve.

- To compensate reactive power costs for reactive power sources, especially for independent generators.
- To enable system operator to choose the most suitable and the cheapest reactive power source for the control of reactive power.
- To improve the efficiency and decrease technical power losses in the power system by effective pricing and control of reactive power.
- To establish the rules describing the relations of the market players and economically base the requirements for keeping voltages at the buses in a certain range.

The establishment of reactive power market rises a lot of questions, which, compared with active power market, are usually related to the origin of reactive power. The main characteristics of reactive power market are:

- Reactive power service is local in its nature, and therefore it should be supplied at the appropriate location.
- The value of reactive power service depends on the location of the reactive power source in the system, and the value of 1 Mvar may not be the same at buses of different systems.
- In areas of some systems, suppliers of reactive power service may have some advantages in the market compared to the others.
- Reactive power market is usually monopsony (there is only one buyer in the market – usually system operator).

Reactive power control in electricity market differs from that of active power by contractual agreements, payment structure or aspects of electricity market control. Reactive power market can be market-based or based on obligatory requirements for reactive power sources. Unbundling reactive power service as an ancillary service in electricity market, minimum requirements for reactive power capability and availability for generators, penalties for non-performance, compensation for capital investments for reactive power, compensation for variable costs of reactive power, and status of system operator of reactive power resources have to be evaluated [5]. Setting the price for reactive power service, charges for direct consumption of reactive power and energy, special voltage and uplift charges have to be evaluated.

Reactive power market model

From the commercial point of view, the main task of suppliers of ancillary services is to compensate fixed and variable costs, which are related to construction, operation and maintenance of reactive power compensation devices, and also costs of voltage control.

System operator has to organize reactive power market in such way that all the costs of reactive power were to be covered by the incomes from the consumers for reactive power supply (Fig. 1).

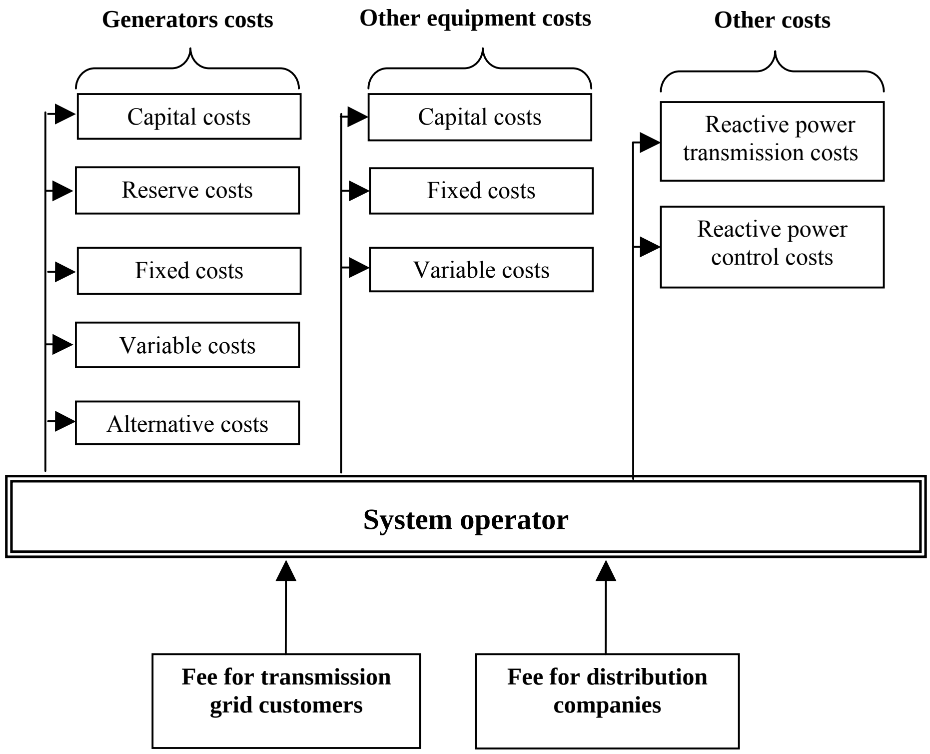

Fig. 1. Structure of reactive power market.

Total reactive power costs C, sustained by system operator and included into the price of reactive power and energy for customers connected to the transmission network and distribution companies, can be expressed

$$C = C_{\mathrm{G}} + C_{\mathrm{SC}} + C_{\mathrm{SR}} + C_{\mathrm{RT}}\,, \tag{1}$$

where C_{G} – payment for generators for reactive power service, C_{SC} – payment for synchronous condensers for reactive power service, C_{SR} – costs of static reactive power sources, C_{RT} – costs of reactive power transmission.

System operator incomes R for provision of reactive power service

$$R = M_{\mathrm{A}} + M_{\mathrm{Q}} + M_{\mathrm{W}}\,, \tag{2}$$

where M_{A}, M_{Q}, M_{W} – incomes from fees for subscription, reactive power and reactive energy.

System operator has to organize reactive power market in such way that total reactive power costs C were equal to total incomes R for provision of reactive power and of energy service.

Structure of cost compensation for reactive power service suppliers

Payments to reactive power sources for the supply of reactive power have to cover all reactive power costs of the suppliers and also promote effective operation of the power system. Payments for reactive power sources are divided into payments for generators and other reactive power sources including cost compensation for system operator for the control of reactive power. Generators and other reactive power sources should be compensated for reactive power supply in the whole range of their reactive power capacity, because this approach promotes investments into new reactive power capacity and enables better utilization of current reactive power sources.

Cost structure of generators reactive power

Reactive power costs of generators C_{G} are divided into reactive power capital investments, and fixed, variable and alternative costs. For covering these costs, the following payments are distinguished:

$$C_{\mathrm{G}} = C_{\mathrm{G,C}} + C_{\mathrm{G,R}} + C_{\mathrm{G,F}} + C_{\mathrm{G,V}} + C_{\mathrm{G,A}}\,, \qquad (3)$$

where $C_{\mathrm{G,C}}$ – capital investments, $C_{\mathrm{G,R}}$ – costs of reactive power reserve, $C_{\mathrm{G,F}}$ – costs of fixed losses, $C_{\mathrm{G,V}}$ – costs of variable losses, $C_{\mathrm{G,A}}$ – alternative costs.

Capital investments should be covered by distributing all capital investments for the planned lifetime or payback period of the equipment. Annual sum of capital investments $C_{\mathrm{G,C}}$, which should cover the depreciation, equals

$$C_{\mathrm{G,C}} = C_{\mathrm{C}}\left[\frac{i}{1-(1+i)^{-n}}\right], \qquad (4)$$

where C_{C} – total capital investments including construction cost, i – market interest or discount rate, n – lifetime or payback period of the equipment.

Separation of capital investments of generator’s reactive power from capital investments of active power is complicated, therefore in practice capital investments of generator’s reactive power should not be separated and individually covered. They are part of generator’s total capital investments, and these are covered by supplying active power and ancillary services, including reactive power. Capital investments of reactive power should be separated in those cases in which the system operator asks the owner of the generator for additional investments in generator’s reactive power equipment.

Costs of reactive power reserve are fixed and competitively determined payments for the availability to supply reactive power service. These payments depend on generator's reactive power capacity and its value to the system. This component could include also the part of capital investments associated with generator's reactive power, fixed operation and maintenance costs. Costs of generator's reactive power reserve $C_{G,R}$ can be calculated by the formula

$$C_{G,R} = C_{MC} \cdot VI_G \cdot Q_G \,, \quad (5)$$

where C_{MC} – capital investments of marginal reactive power unit in the system, VI_G – index of generator's reactive power value to the system, Q_G – generator's reactive power capacity calculated by summing lagging and leading capacities of reactive power.

Capital investments of marginal reactive power unit in the system C_{MC} are calculated using Expression (4) as the sum of capital investments of static reactive power sources for the defined period. Capital investments of marginal reactive power unit in the system based on capital investments of static reactive power sources show that generator as the reactive power source in that particular place in the system can be replaced by a static reactive power source. Capital investments of marginal reactive power unit can be regulated and revised at the end of the regulation period.

Index VI_G of generator's reactive power value to the system is the measure of generator's reactive power value to the system and is determined using Voltage Sensitivity, PV Curves, Equivalent Reactive Compensation and Back-up Generation methods [6]. For a more accurate investigation of the influence of different factors on reactive power price, multi-objective optimization criterions are included: technical power losses of active power in the system, compensation for reactive power service of reactive power sources, balancing energy (deviation of active power contracts), average voltage deviation in buses, reactive power reserve of the system, voltage stability margin of the system or some of its buses. Index of reactive power value can be differentiated according to the time of day or year, because reactive power value of the source can vary with changing load and situation in the system.

Costs of fixed losses $C_{G,F}$ depend on the active power demand and technical power losses, and are calculated by summing all fixed active power losses due to reactive power generation:

$$C_{G,F} = c_P \int_0^T P_{FL} \, \mathrm{d}t \,, \quad (6)$$

where P_{FL} – fixed active power losses of the generator due to reactive power generation, c_P – active power price, T – operation time of the generator during the investigated period.

Costs of variable losses are determined evaluating technical losses of variable active power due to generation or absorption of reactive power in the generator and the step-up transformer if it belongs to the power station.

Costs of generator's variable losses $C_{G,V}$ during the operation time T of the generator are

$$C_{G,V} = \int_0^T C_{G,V}(t)\,dt\,, \tag{7}$$

where $C_{G,V}(t)$ – function of costs of variable losses of generator's reactive power.

Calculating costs of variable losses during the investigated period, those of the generator and the step-up transformer while generating and absorbing reactive power should be distinguished:

$$C_{G,V} = C_{G,V,Q+} + C_{G,V,T+} + C_{G,V,Q-} + C_{G,V,T-}\,, \tag{8}$$

where $C_{G,V,Q+}$ and $C_{G,V,Q-}$ – costs of variable losses of the generator generating and absorbing reactive power, $C_{G,V,T+}$ and $C_{G,V,T-}$ – costs of variable losses of the generator's transformer due to reactive power generated to and absorbed from the network.

Costs of generator's variable losses due to generating or absorbing reactive power are calculated:

$$C_{G,V,Q} = \int_0^T Q_G(t)\cdot c_{G,V}(Q)\,dt = \frac{W_Q}{T}c_{G,V}(Q)\,, \tag{9}$$

where $Q_G(t)$ – time function of reactive power generated or absorbed by the generator, W_Q – reactive energy generated or absorbed by the generator during the investigated period, T – operation time of the generator during the investigated period, $c_{G,V}(Q)$ – function of generator's reactive energy price and generated or absorbed reactive power.

Costs of variable losses of generator's transformer due to reactive power generated to and absorbed from the network are:

$$C_{G,V,T} = \frac{W_Q^2 P_K k_{ls}^2}{S_N^2 T}c_P\,, \tag{10}$$

where W_Q – reactive energy generated or absorbed by the generator during the investigated period, P_K – losses of rated short-circuit active power of the transformer, k_{ls} – shape coefficient of load curve, S_N – rated power of the transformer, T – operation time of the generator during the investigated period, c_P – active power price of the generator.

When system operator indicates the generator to decrease generation of active power in order to increase generation or absorption of reactive power, he is obliged to cover so-called alternative costs. Decreased generation of active power means money losses for the generator, but this also allows to save some variable costs of active power. So, the decreased profit or incurred alternative costs of the generator $C_{G,A}$ during the period Δt are:

$$C_{G,A} = [c_P(P_1 - P_2) - \int_{P_2}^{P_1} C_{P,V}(P)\,\mathrm{d}P] \cdot \Delta t = \left(c_P(P_1 - P_2) - [C_{P,V}(P_1) - C_{P,V}(P_2)]\right) \cdot \Delta t, \quad (11)$$

where c_P – active power price of the generator, P_1 and P_2 – current and new points of active power generation, $C_{P,V}(P)$ – function of variable costs of active power generation, $C_{P,V}(P_1)$ and $C_{P,V}(P_2)$ – variable costs of active power generation at points P_1 and P_2 generating active power.

System operator payments for generators depend on generated and absorbed reactive power. Three payment zones are distinguished (Fig. 2):

- 1st zone ($-Q_{base-} \leq Q \leq +Q_{base+}$): in this zone capital investments for reactive power, costs of reserve and fixed losses ($C_{G,C} + C_{G,R} + C_{G,F}$) are compensated for generators, i.e. generators are paid for the availability of reactive power service. At determining $-Q_{base-}$ and $+Q_{base+}$, it is necessary to take into account technical requirements of the generator and its ancillary equipment.
- 2nd zone ($-Q_{C-} \leq Q \leq -Q_{base-}$ and $+Q_{base+} \leq Q \leq +Q_{C+}$): in this zone capital investments of reactive power, and costs of reserve, fixed and variable losses ($C_{G,C} + C_{G,R} + C_{G,F} + C_{G,V}$) are compensated for generators. This zone defines the capacity of the generator to generate or absorb reactive power, when there is no need to change dispatch of active power. Because of generated or absorbed reactive power, operation in this zone increases technical losses of active power in the generator and the step-up transformer (if it belongs to the power station). The compensation for the generator is variable and concerns the amount of generated and absorbed reactive energy.

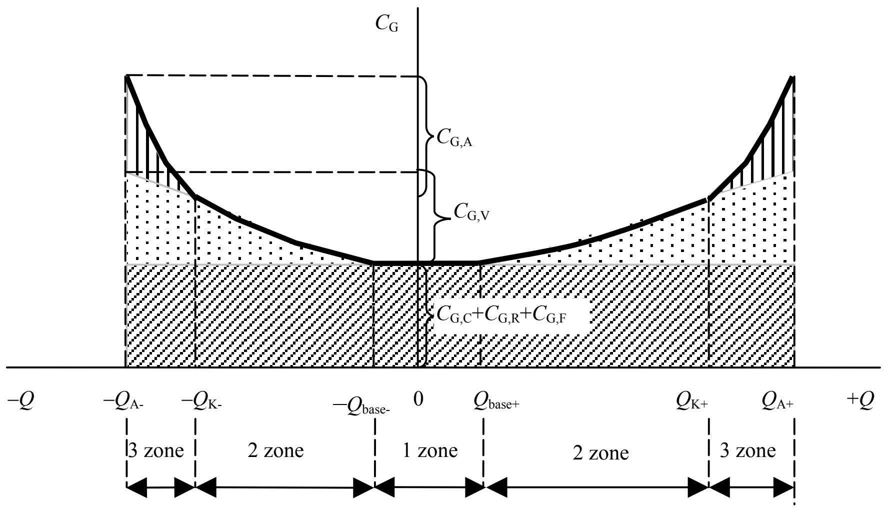

Fig. 2. Compensation structure for reactive power service for synchronous generators.

- 3rd zone ($-Q_{A-} \le Q \le -Q_{C-}$ and $+Q_{C+} \le Q \le +Q_{A+}$): in this zone capital investments of reactive power, costs of reserve, fixed and variable losses and alternative costs ($C_{G,C}$+$C_{G,R}$+$C_{G,F}$+$C_{G,V}$+$C_{G,A}$) are compensated for generators. This zone defines possible capacity of the generator to generate or absorb reactive power taking into account the decreased dispatch of active power. Generator is forced to lose incomes from decreased generation of active power in this zone, therefore system operator must compensate for this shortage.
  Reactive power costs C_G of the generator are:

$$C_G = C_{G,C} + C_{G,R} + C_{G,F} + C_{G,V} + C_{G,A} =$$
$$= C_{G,C} + C_{G,R} + C_{G,F} + \int_{-Q_{A-}}^{-Q_{C-}} c_{A-}\,\mathrm{d}Q + \int_{-Q_{A-}}^{-Q_{baz-}} c_{V-}\,\mathrm{d}Q + \int_{Q_{baz+}}^{Q_{A+}} c_{V+}\,\mathrm{d}Q + \int_{Q_{C+}}^{Q_{A+}} c_{A+}\,\mathrm{d}Q; \quad (12)$$

where $C_{G,C}$, $C_{G,R}$, $C_{G,F}$, $C_{G,V}$, $C_{G,A}$ – capital investments of reactive power, costs of reserve, fixed and variable losses and alternative costs; c_{V-}, c_{V+} and c_{A-}, c_{A+} – price components of variable losses and alternative costs in zones of reactive power generation and absorption.

Capital investments of generator's reactive power, and costs of reserve and fixed losses are fixed and are not included in the amount of produced reactive power, while variable losses and alternative costs concern generator operation mode.

Cost structure of reactive power generated by synchronous condensers

Structure of compensation for the costs C_{SC} of synchronous condensers and generators operating under the mode of synchronous condenser is as follows:

$$C_{SC} = C_{SC,C} + C_{SC,R} + C_{SC,F} + C_{SC,V}, \quad (13)$$

where $C_{SC,C}$ – capital investments, $C_{SC,R}$ – costs of reactive power reserve, $C_{SC,F}$ – costs of fixed losses, $C_{SC,V}$ – costs of variable losses.

Capital investments $C_{SC,C}$ of synchronous condensers have to be compensated also for generators capable to operate under the mode of synchronous condensers, but only if capital investments of synchronous condensers can be separated from capital investments for the generator. Capital investments should be covered by distributing all capital investments for the planned lifetime or payback period of the equipment. Annual sum of capital investments $C_{SC,C}$, which should cover the depreciation, is calculated using Expression (4).

Costs of reactive power reserve $C_{SC,R}$ are used to evaluate availability of a synchronous condenser to supply reactive power service, and they are calculated using Expression (5) based on the same principles as for costs of generator's reactive power reserve.

Costs of fixed losses $C_{\mathrm{SC,F}}$ depend on the demand of active power and losses of technical power of the synchronous condenser and are calculated using Expression (8) by summing all fixed active power losses due to generation of reactive power.

Costs of variable losses $C_{\mathrm{SC,V}}$ of hydrogenerator operating under the mode of synchronous condenser depend on active power losses due to loading and cooling of the unit and are calculated:

$$C_{\mathrm{SC,V}} = c_{\mathrm{P}} \int_{0}^{T} P_{\mathrm{VL}} \,\mathrm{d}t + c_{\mathrm{w}} \int_{0}^{T} D \,\mathrm{d}t , \qquad (14)$$

where P_{VL} – losses of variable active power of the synchronous condenser, c_{P} – active power price of the power plant if the generator is operating under the mode of synchronous condenser, or price of active power supplied from the network, D – water yield used for the hydrogenerator operating under the mode of synchronous condenser, c_{w} – water price, T – operation time of the synchronous condenser during the investigated period.

Cost structure of reactive power generated by static reactive power sources

Static reactive power sources, shunt reactors and capacitors are installed and operated by system operator in the transmission network. Therefore all costs associated with this equipment should be included in the costs of reactive power service. In some cases the transmission system operator can ask the distribution system operator to install sources of static reactive power in the distribution network in order to improve the performance of the transmission network. For covering the costs C_{SR} of static reactive power sources such payments are distinguished:

$$C_{\mathrm{SR}} = C_{\mathrm{SR,C}} + C_{\mathrm{SR,F}} , \qquad (15)$$

where $C_{\mathrm{SR,C}}$ – capital investments, $C_{\mathrm{SR,F}}$ – costs of fixed losses.

Capital investments of static reactive power sources have to be covered by distributing all capital investments for the planned lifetime or payback period of the equipment. Annual sum of capital investments $C_{\mathrm{SR,C}}$, which should cover the depreciation, is calculated using Expression (4).

Costs of fixed losses $C_{\mathrm{SR,F}}$ of static reactive power sources are associated with losses of technical power and maintenance of this equipment and are calculated:

$$C_{\mathrm{SR,F}} = c_{\mathrm{P}} \int_{0}^{T} P_{\mathrm{L}} \,\mathrm{d}t , \qquad (16)$$

where c_P – active power price, P_L – technical losses of active power; T – operation time of the equipment during the investigated period.

Costs structure of reactive power transmission

Compensation structure of the costs C_{RT} for transmission of reactive power is as follows:

$$C_{RT} = C_{RT,F} + C_{RT,V}, \quad (17)$$

where $C_{RT,F}$ – costs of fixed losses, $C_{RT,V}$ – costs of variable losses.

Costs of fixed losses of reactive power transmission $C_{RT,F}$ are determined calculating fixed annual costs of transformer substations and power lines of the transmission network for maximum transmitted reactive power [7]:

$$C_{RT,F} = \frac{\left(C_{TS} + C_{PL}\right) \cdot Q_{max}}{S_{max}^2}, \quad (18)$$

where C_{TS} and C_{PL} – annual fixed costs of transformer substations and power lines of the transmission network, Q_{max} and S_{max} – maximum values of reactive and apparent power transmitted through the transmission network.

Costs of variable losses of reactive power transmission are determined calculating technical losses of active power in the system due to transmission of reactive power. These costs are associated with redistribution of reactive power flows, for example switching off high-voltage power lines during low-load conditions with the intention to reduce generation of reactive power in the power lines. Technical losses of active power in the system due to transmission of reactive power are calculated as the difference in power losses at real and optimized regimes of the system. Annual maximum- and minimum-load regimes of the power system are usually investigated. Evaluating the duration of typical regimes of the power system, annual technical losses of active power can be calculated.

Costs of variable losses of reactive power transmission $C_{RT,V}$:

$$C_{RT,V} = c_P \int_0^T P_L \, dt, \quad (19)$$

where c_P – active power price, P_L – technical losses of active power, T – investigated period.

Investigation of reactive power market model

The proposed reactive power market model was theoretically applied for Lithuanian power system, determining the amount of compensation for reactive power sources and the price structure for reactive power consumers. Lithuanian power system data of the year 2005 was used in the calculations.

In Lithuania, AB “*Lietuvos energija*” as the system operator is responsible for organization of reactive power as an ancillary service market (Fig. 3). Power stations, installed shunt reactors and capacitors are the main reactive power suppliers. Beside these suppliers, additional costs are incurred in the process of transmission and control of reactive power. Reactive power customers are customers connected to the transmission network and distribution companies, which pay for the reactive power service and compensate suppliers’ costs.

The international experience shows that reactive power price reaches 1% of active power price or 10% of the price of ancillary services. During the year 2005, in Lithuanian power system 14.085 TWh electric energy was supplied to the transmission network. Based on the average weighted energy price (2.4 EURct/kWh) of Lithuanian power plants during the year 2005, electric energy for 0.34 bill. EUR was produced and sold [8]. So, 1% of this amount is 3.4 million EUR. Calculating reactive power value in the context of ancillary services, it is assumed that all produced energy is supplied to the transmission network, and the price of ancillary services is 0.37 EURct/kWh. In this case 10% of the incomes from ancillary services reaches 5.2 million EUR. So, annual volume of reactive power market in Lithuania could reach 3.4–5.2 mill. EUR.

Total costs of reactive power in Lithuanian power system are obtained by summing all reactive costs of generators, synchronous condensers, static reactive power sources and costs of transmission and control of reactive power (Fig. 3).

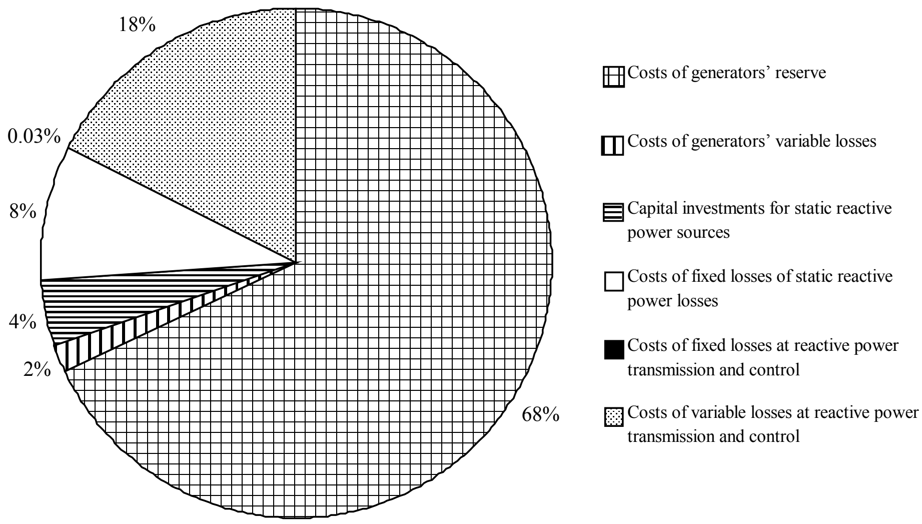

Fig. 3. The structure of total annual costs of reactive power service.

The analysis of the results shows that annual payments for reactive power supply can reach 3.3 million EUR, constituting 0.95% of the price of generated and sold active energy in the year 2005 (0.34 billion EUR), which is calculated using average price of Lithuanian power plants (2.4 EURct/kWh). The biggest payments are provided for generators' reactive power reserve (68%).

Conclusions

1. The performed investigations of reactive power as an ancillary service demand, characteristics and pricing problems of electricity market together with data on technical losses and costs of reactive power sources – generators, synchronous condensers and static reactive power sources – enable economical evaluation of generation and transmission of reactive power.
2. The created combined model of reactive power market encompasses regulated financial compensation for the costs of reactive power sources and value-based reactive power pricing.
3. The proposed model of reactive power market enables improvement of reactive power control in the electric power system by setting the means of compensation for reactive power sources and the price structure for reactive power consumers.
4. The methodology of calculation of capital investments for generators, synchronous condensers and static reactive power sources, as well as fixed, variable, reserve and alternative costs for economical evaluation of reactive power service was created. It was found that annual financial compensation for reactive power supply can reach 0.95 % of active power price.

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