Oil Shale, 2011, Vol. 28, No. 1S, pp. 223–239
doi: 10.3176/oil.2011.1S.14

ISSN 0208-189X

REACTIVE POWER PRICING IN DISTRIBUTION NETWORKS

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Tariffs for electricity including these for reactive energy are a significant tool for raising energy efficiency in the economy. This paper focuses on practical reactive energy tariff formation in distribution networks under deficient primary information providing meanwhile sufficient revenue for the distribution utility in order to fulfil efficient transfer service and encourage adequate reactive power compensation by customers. Reactive energy pricing principles are observed and an overview of the reactive energy and power tariff structures implemented around the world is included. The article presents a simplified methodology of reactive energy pricing for practical use. The price for reactive energy consumed from the distribution network is expressed as the sum of the price of reactive energy consumed from the transmission network and the price of distribution network transfer service, which is complemented with a profit margin for the distribution network, excise tax and value-added tax. The paper delivers a practical calculation method for the variable and fixed components of reactive energy transfer service.

Introduction

Today's global and local energy issues along with environmental problems have drawn to agenda the need for efficiency and reliability of power systems as well as for energy saving. Therefore economic generation, distribution and consumption of electrical energy have become more essential. Energy tariffs, including electricity tariffs have proven to be an efficient tool for improving energy efficiency in the economy. Reactive energy tariffs are a part of the electricity tariffs system to which relatively little attention has been paid.

Reactive energy is an abstract value, which describes the effect of inductive and capacitive elements that on average neither generate nor

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consume useful active power. Reactive energy management is substantial to the distribution utility for at least three reasons:

- reactive power affects the voltage in the electricity network by increasing or decreasing it;
- reactive power flow generally increases losses in the electricity network, although it could sometimes balance other reactive power values and decrease losses;
- reactive power utilizes transmission capacity of the networks.

Reactive energy prices are affected by many factors. Therefore accurate cost-based pricing is highly difficult and appropriate exact payment examples are internationally lacking. This paper focuses on formation of practical tariff for reactive energy in distribution networks under deficient primary information providing meanwhile sufficient revenue for the distribution utility in order to fulfil efficient transfer service and encourage adequate reactive power compensation by customers. The pricing methodology presented is formed by taking into account the incompleteness of initial information and is sufficiently simple and transparent. The price for reactive electricity consumed from the distribution network is expressed as the sum of the price of reactive energy obtained from the transmission network and the price of distribution network transfer service, which is complemented with a profit margin for the distribution network, excise tax and value added tax. The paper delivers a practical calculation method for the variable and fixed components of the price of reactive energy transfer service in terms of deficient initial information. Tariff structures in medium and low voltage networks are evaluated.

About reactive energy tariff systems

A relatively short time ago rates with regard to reactive power were designed in distribution utilities according to the customer's power factor. Furthermore, reactive power costs were embedded inside a "dead band." For the first time in 1990 it was discovered that a separate charge for reactive power is just and reasonable [1].

However, nowadays there is no practical explanation of how to properly pay for services related to reactive energy. For the most part, it is difficult to distinguish these services from each other and also differentiate reactive and active energy services or determine their price. Regrettably, extensive literature concerning optimal reactive energy pricing [2, 3] contains no practically applicable recommendations [4]. That explains the worldwide multitude of existing tariff structures and their modifications in practice, among these are different charging formulas, various threshold values, penalties, special discounts (for example if $\cos\varphi = 1$), etc. [5–7].

The applied reactive energy payment methods around the world can generally be categorized depending on the chargeable indicator as follows:

- **Peak demand of apparent power**. The peak of the apparent power load in kVA is charged.
- **Apparent energy consumption in kVAh**.
- **Peak demand of reactive power**. The demand of reactive power in kvar is charged by measuring it during the peak demand of active power. Often a threshold value of active and reactive power ratio is applied in practice. The charge for reactive energy CH_Q is then proportional to the amount of the customer's maximum reactive load exceeding the threshold value:

$$CH_Q = H_Q \cdot \mathbf{max}\ \{0, Q_m - z^* P_m\}, \tag{1}$$

where H_Q – the price for reactive power; Q_m – the monthly peak of reactive load; P_m – the monthly peak of active load; z^* – the threshold value of the reactive power factor.

The price as well as the threshold value (on an average of 0.50 or $\cos\varphi = 0.89$) vary depending on the utility. Some companies establish a limiting value for reactive energy Q_{limit} which is the minimum consumption to pay for (an average of 2 Mvar is used in Finland for example). Some utilities stimulate customers to improve their load power factor by offering bonuses if it exceeds the trigger power factor.

- **Reactive energy consumption over a settling period in kvarh.** There are two possibilities interpreting reactive energy consumption: the meter-measuring either total consumption (goes back if the load is capacitive) or only the energy amount taken from the network (the meter cannot roll back). Reactive energy charge CH_Q is proportional to the energy consumption exceeding the threshold value:

$$CH_Q = H_{W_Q} \cdot \mathbf{max}\ \{0, W_Q - z^* \cdot W_P\}, \tag{2}$$

where H_{W_Q} – the reactive energy price; W_Q – the consumed reactive energy; W_P — the consumed active energy; z^* – the threshold value of the ratio W_Q / W_P. The tariff can be differentiated according to the season, time or power factor.

- **Split kvarh method.** Reactive energy taken from the network and fed to the network is being measured separately. Each of these might have their distinct price and/or distinct calculating method. A limiting value can also be established to the power supplied to the network.
- **Power factor.** The fee is either based on an average power factor or on the peak demand period power factor. Usually there is a validated threshold value for the power factor, and the customer is being charged in case of the power factor proving to be below the threshold value.
- **The power factor limit.** During the billing period power factor is being measured, and in case its average value is below the validated limit (ranging from 0.85 to 0.995) the utility installs power factor adjusting equipment as an obligatory procedure at the customer's expense.

- **Adjusting active power or active energy bills** according to the customer's power factor – the customer's active power or active energy meter reading is multiplied by the factor $\mathbf{max}\{\cos\varphi_0, \cos\varphi_{aver}\}/\cos\varphi_{aver}$, where $\cos\varphi_0$ is the threshold value of the power factor (85 to 99%); $\cos\varphi_{aver}$ is the customer's monthly average load power factor. Practically reactive power is charged if the monthly average load power factor falls below the threshold value:

$$CH_Q = H_Q \cdot P_m \cdot \mathbf{max}\{0, \cos\varphi_0 - \cos\varphi_{aver}\}/\cos\varphi_{aver}. \tag{3}$$

- **Only active energy in kWh.** Charging is based on real power consumption only. It is the simplest tariff structure, but does not guarantee efficient investment and operation decisions concerning reactive energy. The approach is incidentally applied widely for charging retailers, mostly domestic consumers.

Sometimes several methods are used at the same time depending on the time of day, the season, the customer's consuming nature, etc. Additionally, tariffs are usually also ranked according to the voltage level and rated current of fuse elements. The paper [7] claims it is not possible to find two electricity utilities which make the same calculations for reactive energy charges.

Analysis of the tariff systems leads to the following general conclusions:

- There is no clear international consensual principle for "correct" reactive load charging.
- Since the value or price of reactive energy is influenced by many factors, the exact cost-based pricing along with tariff design are highly complicated.
- The great number of different tariff systems and their numerous modifications in use along with practical incompatibility of theoretical charging methods prove the utter complexity of the problem.
- The huge disagreement between pricing methods and tariff parameters results in a large variety of charges for reactive power service in different electricity utilities.
- Practically all the electricity utilities do not charge the domestic consumers for reactive energy, many of them also exclude the low or medium-voltage retailers.
- Most of the electricity utilities only apply either reactive load or reactive energy payment for the sake of simplicity, multicomponent tariffs are put into use rarely.

Even though the above-mentioned charging methods (except for the last one) may secure the adequate pricing of services offered by the electricity utility, not all of them guarantee sufficient customer's motivation to apply suitable cost reduction solutions. It is the obligation of the utility to choose a proper tariff strategy in order to motivate the customer to act for the benefit of both sides. A high motivation to compensate is created by tariff structures based on measuring two-way reactive energy as well as the peak of reactive load [7].

The structure of the tariff systems unlike the value of the tariffs is difficult and costly to change, because of the different structure designs needing different metering systems. The right structure has to be chosen not only for the existing loads but also for future ones expected. The last ones turn intrinsically continually more dynamic. Herein a tariff system based on two-direction metering of reactive energy is presumed.

Reactive energy pricing strategy

When setting the price for reactive energy, generally, the benchmark to proceed from would be considering electrical energy pricing principles by taking into account meanwhile its peculiarities. Reactive energy is not a separate purchasing or sales item, but a phenomenon accompanied by active energy transmission, distribution and consumption. Nevertheless, it is obvious that electricity network utilities presume payment for reactive energy-concerned services. Basically reactive energy prices depend on the optimal levels of compensating and voltage under different load conditions, the system's loading rate, voltage regulation rules, placement of compensation devices, etc. Therefore optimal reactive energy pricing turns out to be an extremely complicated multicriterion nonlinear optimizing assignment with a large number of inequality constraints that are extremely difficult to be solved in detail. That also explains the above-mentioned diversity of pricing methods.

On the one hand, the price for reactive energy should cover any transfer service costs made by the distribution network; on the other hand, it should encourage customers to compensate their reactive energy consumption. In principle, the price should also stimulate using more expensive compensating equipment in the case of rapidly changing loads. At the same time pricing should be simple enough and transparent. The consumers must be charged fairly according to the costs made by the producer. Therefore reactive energy prices turn out to be dependent on the network connection voltage level. Basically, the prices should be differentiated in compliance with the consumer's point of location since consumers in different districts have various transmission and distribution expenses as well as different transfer capacities. This kind of local pricing is being recommended by many theoretical sources. Local prices would create more effective incentives for customer reactive energy compensation, yet giving up homogeneous pricing principles, especially within one electricity utility, would be a tough mission from righteous point of view.

Theoretical sources refer also to implementation expedience of spot prices. Theoretically the best solution would be introducing local spot prices. In principle the prices should be differentiated to static and dynamic reactive loads. Highly sophisticated pricing accompanied by numerous technical difficulties, as well as implementing spot prices or local prices, are the main obstacles at this kind of approach.

Generally the reactive energy price must reflect capital costs for reactive energy transmitting and compensating as well as operating costs, which are practically determined by the value of network losses related to reactive energy transfer. Therefore the price for reactive energy supplied from the distribution network H_{W_Q} can be expressed as follows:

$$H_{W_Q} = H_{W_Q}^{T} + H_{W_Q}^{D} = H_{W_Q}^{T} + h_Q + h_{W_Q} + h_L , \tag{4}$$

where $H_{W_Q}^{T}$ – the price for reactive energy consumed from the transmission network; $H_{W_Q}^{D}$ – the price for the reactive energy transfer service of the distribution network; h_Q – the fixed component of reactive energy transfer service price that derives from the distribution network's capital costs for reactive energy transmitting and compensating; h_{W_Q} – the variable component of reactive energy transfer service price that derives from the distribution network's costs made on active and reactive energy losses due to reactive energy transmitting; h_L – the distribution network profit margin.

Basically, electricity supply prices based on long-term marginal costs [2, 8] stimulate the consumers as well as the producers to optimal behaviour. Unfortunately, valuation of these marginal costs for reactive energy transmitting and compensating with the sufficient accuracy is highly complex. On the other hand, there also exists the point of view that the price should be based on average costs. For that reason it may be reasonable to depart from long-term marginal cost based approach in practical calculations. It is also supported by the fact that reactive energy charges form a small share in the total electricity bill, and therefore reactive energy tariffs deviating from cost-based tariffs disappear into the imprecisions of components included in the total tariff.

Determination of the fixed price component of reactive energy transfer service

Determining the fixed price component h_Q for transfer service of reactive energy the following costs are being taken into account:

- Costs on compensating installations, including reactive energy metering and billing costs. Simplifying, only the already installed compensating devices should be included;
- Costs of the network transfer capacity share needed for reactive power transmission in the network. Namely, the transmission capacity of the network is utilised not only by active power but also by reactive power. This factor is much more valid than the previous one.

Charges for compensating devices M_{comp} can be estimated with the following relation:

$$M_{comp} = Q_{\Sigma comp} \cdot m_{comp} , \tag{5}$$

where $Q_{\Sigma comp}$ – the total power set up in the network for compensating devices; m_{comp} – the average charge made per compensating device unit (which could approximately take operation and maintenance costs into account as well).

Assessment of the cost of the transfer capacity share needed for transmitting reactive power is based on the book value M_{bil} of distribution network's substation equipment, transformers and power lines as major elements determining the transfer cost (separately for low- and medium voltage levels). At that one has to consider that generally domestic customers are not charged for reactive energy, among them are neither apartment buildings nor low-voltage small customers whose power lies beneath contractual threshold values. Therefore only the part of transmitting costs corresponding to charged reactive energy has to be taken into account while calculating the reactive power tariff.

Summing up, the part of network transmitting capacity necessary for reactive power transfer is expressed as:

$$M_{Q\,transf} = M_{bil} \cdot \eta \cdot \zeta \,, \tag{6}$$

where M_{bil} – the book value for elements mainly influencing the distribution network's transmitting capacity (such as substation equipment, transformers and power lines); η – the share of transfer capacity necessary for reactive power transmitting; ζ – the share of charged reactive power.

Evaluating the factor η we proceeded from the fact that network transfer capacity is mainly determined by the maximum apparent power transmitted S_{max}. Just S_{max} determines the needed cross-section for conductors, the rated power of transformers, network losses, etc. If at maximum load $\tan\varphi = 0$, that is if reactive power transmitted $Q = 0$ and $\cos\varphi = 1$, then $S = P$ and the total transfer capacity could be used for transmitting active power. If, however, $\tan\varphi > 0$ ($\cos\varphi < 1$), some of the transfer capacity is used for reactive power transmitting. That part is determined by the increase of apparent power due to reactive power (see Fig. 1):

$$\frac{P}{\cos\varphi} - P = \left(\frac{1}{\cos\varphi} - 1\right) P \,. \tag{7}$$

Here the factor ($1/\cos\varphi - 1$) actually is the share η spent on reactive power transfer:

$$\eta = \frac{1}{\cos\varphi} - 1 \,. \tag{8}$$

If, for example, the average reactive power factor on the boundary of the transmission and medium-voltage grids and on the boundary of medium-voltage and low-voltage grids is $\tan\varphi = 0.30$, then $\cos\varphi = 0.96$ and $\eta = 0.044$ or 4.4%.

The factor ζ value is generally within the limits of ζ^{Ma} = 0.5–0.7 in the low-voltage grid. However, as a rule the value lies in the medium-voltage grids within the limits of ζ^{Ke} = 1.0.

The fixed component of the price for reactive energy transfer is calculated according to the total cost:

$$M_Q = M_{komp} + M_{Q\,edast}\,. \tag{9}$$

For assessment of the fixed component h_Q the capital cost annuity for compensating and transmission devices could be served as a basis:

$$A_Q = M_Q \frac{i(1+i)^n}{(1+i)^n \; -1}\,, \tag{10}$$

where i is the discounting rate; n is the depreciation rate of capital assets.

Finally, the fixed price component h_Q for reactive energy transmitting service:

$$h_Q = \frac{A_Q}{W_Q}\,, \tag{11}$$

where W_Q – the amount of annual average reactive energy transmitted in the corresponding network.

The fixed price component for transfer service must be determined separately for the medium-voltage as well as the low-voltage network.

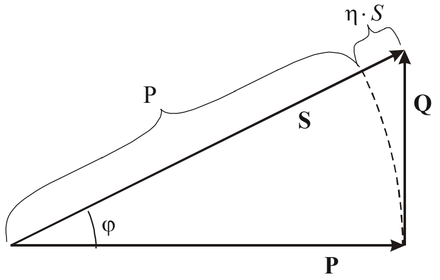


Fig. 1. Increase of the apparent power due to the presence of reactive power.

Evaluating the variable price component for reactive energy transmission service

To explain determination of the variable price component we first have to simplify things up by featuring the distribution network as a compact entity, without dividing it between voltage levels. The same was presumed for the formula (4). Variable price component C_{W_Q} of reactive energy transmission in the distribution network can be expressed as follows:

$$C_{W_Q} = \Delta W_{P,Q} \cdot H_{W_P}^T + \Delta W_{Q,Q} \cdot H_{W_Q}^T, \tag{12}$$

where $\Delta W_{P,Q}$ and $\Delta W_{Q,Q}$ – the reactive energy losses caused by active and reactive load, respectively; $H_{W_P}^T$ and $H_{W_Q}^T$ – the prices of active and reactive energy obtained from the main grid.

The distribution network's variable price component for reactive energy transfer service, which is based on marginal cost, is given as follows:

$$h_{W_Q} = \frac{\partial C_{W_Q}}{\partial W_Q} = \beta_{P,Q} \cdot H_{W_P}^T + \beta_{Q,Q} \cdot H_{W_Q}^T . \tag{13}$$

The variable price component grounded on average cost would be

$$h_{W_Q} = \frac{C_{W_Q}}{W_Q} = \alpha_{P,Q} \cdot H_{W_P}^T + \alpha_{Q,Q} \cdot H_{W_Q}^T . \tag{14}$$

The factors

$$\beta_{P,Q} = \frac{\partial \Delta W_{P,Q}}{\partial W_Q} \text{ and } \beta_{Q,Q} = \frac{\partial \Delta W_{Q,Q}}{\partial W_Q}$$

along with

$$\alpha_{P,Q} = \frac{\Delta W_{P,Q}}{W_Q} \text{ and } \alpha_{Q,Q} = \frac{\Delta W_{Q,Q}}{W_Q}$$

are named here as reactive energy equivalent factors in relation to active power.

It can be shown that $\beta_{P,Q} = 2\alpha_{P,Q}$ and $\beta_{Q,Q} = 2\alpha_{Q,Q}$, which results in the fact that only one of the factors α or β need to be assessed and the rest remain easily revealed. Further on the problem of reactive energy pricing is mainly reduced to evaluating the values of equivalent factors α or β.

Calculating exact equivalent factors is extremely difficult and voluminous since the annual active and reactive energy losses caused by reactive load need to be calculated. That might be done through calculating active and reactive power losses in different representative parts of distribution network at different seasons, varying hours of the day, different weekdays and rest days. Next, based on these calculations the spatially and time weighted averages of equivalent factors should be found. Applying the method of differences could be one possibility by assessing derivatives through calculating states corresponding to two comparable reactive loads. That kind of approach, however, is very unwieldy and approximate. A more practical, simple and reliable method for equivalent factor estimation would be grounding on the concept of equivalent resistances [9]. The method presumes that distribution utilities possess (or might be assessed through certain calculations) information at least on real energy losses as well for the whole network as for different levels of voltage.

The method consists of assessing approximate equivalent resistances of the network or its parts on the basis of power flows and energy losses registered on the previous financial year and ensuing determination of corresponding equivalent factors. At that, binding energy and maximum load or energy loss and maximum load according to a utilisation period at maximum capacity or utilisation time of power losses are being used. On the previous assumption and the approximate presumption that $U \approx U_N$ it can be indicated that equivalent factors are disclosed as follows:

$$\beta_{P,Q} = \frac{2\,\Delta W_P \cdot \tau_Q}{T_{Qm}^2 \left(\frac{W_P^2}{T_{Pm}^2} + \frac{W_Q^2}{T_{Qm}^2} \right) \cdot \tau} W_Q \quad \text{and} \quad \beta_{Q,Q} = \frac{2\,\Delta W_Q \cdot \tau_Q}{T_{Qm}^2 \left(\frac{W_P^2}{T_{Pm}^2} + \frac{W_Q^2}{T_{Qm}^2} \right) \cdot \tau} W_Q, \tag{15}$$

where ΔW_P and ΔW_Q – annual active and reactive energy losses; W_P and W_Q – annual consumption of active and reactive energy; T_{Pm} and T_{Qm} – maximum power operating life for active and reactive loads; τ and τ_Q – equivalent hours of loss and utilisation time of reactive power losses.

By applying some rather natural presumptions ($T_{Qm} \approx T_{Pm}$ and $\tau_Q \approx \tau$) the equivalent factor formulas take simpler shapes:

$$\beta_{P,Q} = \frac{2 \cdot \Delta W_P}{W_P^2 + W_Q^2} \cdot W_Q, \tag{16}$$

$$\beta_{Q,Q} = \frac{2 \cdot \Delta W_Q}{W_P^2 + W_Q^2} \cdot W_Q = \frac{\Delta W_Q}{\Delta W_P} \cdot \beta_{P,Q}. \tag{17}$$

Equivalent factors for different voltage levels

Up to now the whole distribution network has been featured as equivalent resistances *R* and *X*. To find separate tariffs for medium and low voltage customers the method viewed has to be employed in two stages – individually in the medium and low voltage networks.

For medium-voltage customers the transmission grid generated reactive energy price has to be complemented with the cost of net services in the medium voltage network, and for low-voltage customers additionally with the cost of net services in the low-voltage network. Therefore, similarly to the formula (4), the price of reactive energy obtained from the distribution network without a profit margin is expressed at the medium-voltage level as:

$$H_{W_Q}^M = H_{W_Q}^T + h_Q^M + h_{W_Q}^M, \tag{18}$$

and on low voltage level using the formula:

$$H^L_{W_Q} = H^M_{W_Q} + h^L_Q + h^L_{W_Q} = H^T_{W_Q} + h^M_Q + h^M_{W_Q} + h^L_Q + h^L_{W_Q} \ , \qquad (19)$$

where $H^T_{W_Q}$ – the price for reactive energy obtained from the transmission grid; h^M_Q and $h^M_{W_Q}$ – the fixed and variable components of the price for medium voltage distribution network reactive energy services; h^L_Q and $h^L_{W_Q}$ – the fixed and variable components of the price for low voltage distribution network reactive energy services.

For determination of variable components of these prices one has to find corresponding equivalent factors for medium- and low-voltage networks separately.

Reactive energy pricing has no need for constant losses in the network (mainly no-load losses of transformers) to be taken into account since these have no direct relations to reactive energy transmission. As active energy transmission is the basic function of an electrical network and reactive energy is only an accompanying phenomenon, according to the general theory of pricing, costs related to constant losses should be considered in the price for main services (active energy transmission services).

Determination of the equivalent factors for medium- and low-voltage networks correspondingly to the formulas (15) or (16) and (17) demands knowledge of the previous financial year's energy flows and energy loss assessments for corresponding network or its components. At that generally low-voltage bus-bars in regional transmission substations should be considered as the border between transmission and distribution networks. Distribution transformers feeding low-voltage networks are considered belonging to low-voltage networks as shown in Fig. 2.

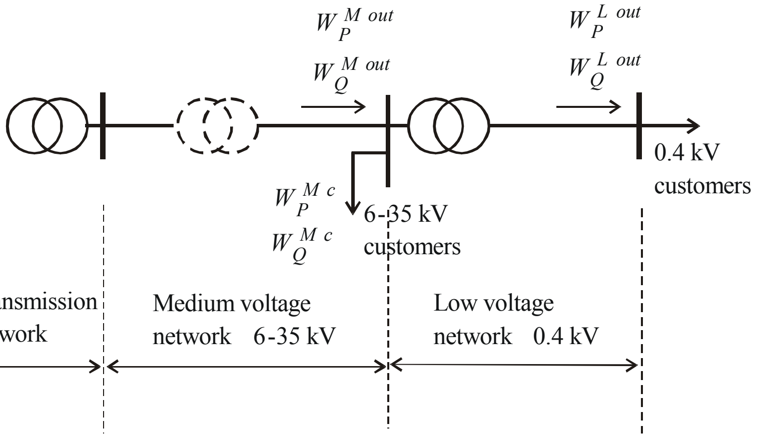


Fig. 2. The equivalent diagram of a distribution network. Superscript *out* denotes the energy flowing out of a network.

The formula (18) for the price $H_{W_Q}^M$ of reactive energy taken from the medium voltage network includes the variable price component for reactive energy transfer service $h_{W_Q}^M$ which can be analogically to (13) be expressed in the form of

$$h_{W_Q}^M = \beta_{P,Q}^M \cdot H_{W_P}^T + \beta_{Q,Q}^M \cdot H_{W_Q}^T , \tag{20}$$

where similarly to (15) and (16)

$$\beta_{P,Q}^M = \frac{2 \cdot \Delta W_P^M}{(W_P^{M\ out})^2 + (W_Q^{M\ out})^2} \cdot W_Q^{M\ out} , \tag{21}$$

$$\beta_{Q,Q}^M = \frac{2 \cdot \Delta W_Q^M}{(W_P^{M\ out})^2 + (W_Q^{M\ out})^2} \cdot W_Q^{M\ out} . \tag{22}$$

The formula (19) for price $H_{W_Q}^L$ of reactive energy taken from the low-voltage network includes the variable price component $h_{W_Q}^L$ which can be analogically to (13) be expressed in the form of

$$h_{W_Q}^L = \beta_{P,Q}^L \cdot H_{W_P}^M + \beta_{Q,Q}^L \cdot (H_{W_Q}^T + h_Q^M + h_{W_Q}^M) , \tag{23}$$

where $H_{W_P}^M$ and $H_{W_Q}^M = H_{W_Q}^T + h_Q^M + h_{W_Q}^M$ are the active and reactive energy prices on the border of medium and low voltage networks.

Similarly to the formulas (21) to (22) equivalent factors for low voltage network can be expressed as:

$$\beta_{P,Q}^L = \frac{2 \cdot \Delta W_P^L}{(W_P^{L\ out})^2 + (W_Q^{L\ out})^2} \cdot W_Q^{L\ out} , \tag{24}$$

$$\beta_{Q,Q}^L = \frac{2 \cdot \Delta W_Q^L}{(W_P^{L\ out})^2 + (W_Q^{L\ out})^2} \cdot W_Q^{L\ out} . \tag{25}$$

If there is no real possibility to estimate reactive energy loss ΔW_Q from network's previous operation data (e.g. in low-voltage networks), the equivalent factors also cannot be assessed using formulas (17) or (25). In such case an approximate approach which consists of load loss ratios being considered equal to equivalent resistance ratios might be used:

$$\frac{\Delta W_Q^M}{\Delta W_P^M} = \frac{X^M}{R^M} \qquad \frac{\Delta W_Q^L}{\Delta W_P^L} = \frac{X^L}{R^L} . \tag{26}$$

At the same time determination of equivalent resistance ratios precisely is practically impossible. These could be assessed only using highly rough analysis of representative feeder's diagrams of the network. Since the vast majority of energy losses in the distribution network feeders take place in their trunk lines only confining the assessment of average ratios X/R for trunk lines is enough. In the case of such kind of expert estimates affected results, any influences of assessment accuracy to variable price components $h_{W_Q}^{M}$ and $h_{W_Q}^{L}$ are of interest. From the price component formulas (20) and (23) appears that the ratio inaccuracy influences the second term of the price component which is due to the large distinction between reactive and active energy prices by one order of magnitude smaller. That enables to conclude that relative importance of the second term in the expressions (20) and (23) is so small that even experiential expert estimates for equivalent resistance ratios cannot have any significant influences on reactive energy prices.

Price of the reactive energy fed to network by customers

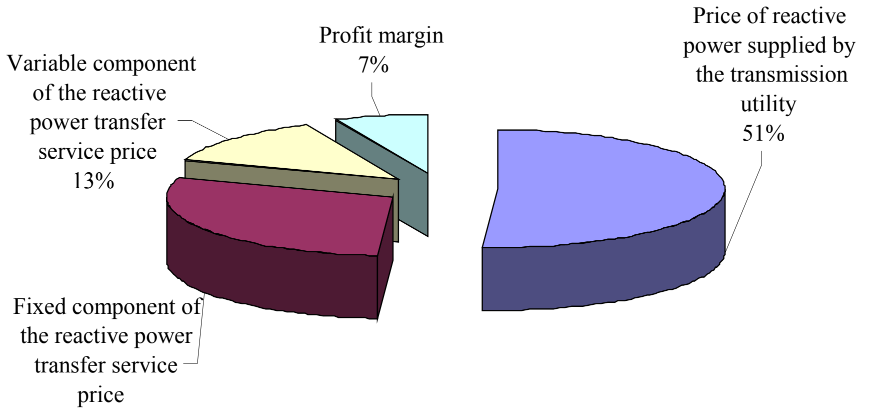
In addition to the fixed and variable price components of reactive energy transfer service the reactive energy tariff system should consider the price of reactive energy fed to the network by customers. Precisely, the effect of reactive power compensation appears first of all in case of large loads. At minimum loads the overcompensation may require big extra costs from a distribution utility for warranting the voltage quality. In principle, feeding reactive power into a network can be beneficial or unfavourable for the utility depending on the relationship of the actual and so called economic value (warranting minimum losses) of reactive power generated in the network. If the difference between actual and economic reactive loads is negative, there is a surplus of reactive power in the system and over-compensation is disadvantageous and should be avoided. Inversely over-compensation is beneficial and should not be charged or in some cases even encouraged.

World-wide experience shows that the tariff system based on split kvarh method provides high customer motivation to install controlled compensation systems. It is extremely difficult to give universally proper recommendations to determine compensation devices allocation and size due to huge number of possible alternatives. The benefits and expenses made on compensating devices have to be compared taking into account a number of different restrictions, first of all voltage quality. Therefore it is very complicated to recommend a general-purpose methodology for calculation of the price of reactive energy fed into the network. That is the reason why the most utilities actually do not apply distinct charge for customer-consumed or customer-generated reactive energy, despite the fact that it could create higher customer motivation. The distribution utility's interest to make a distinction will be weakened in case of the transmission utility not distinguishing the price for consumed or generated reactive power.

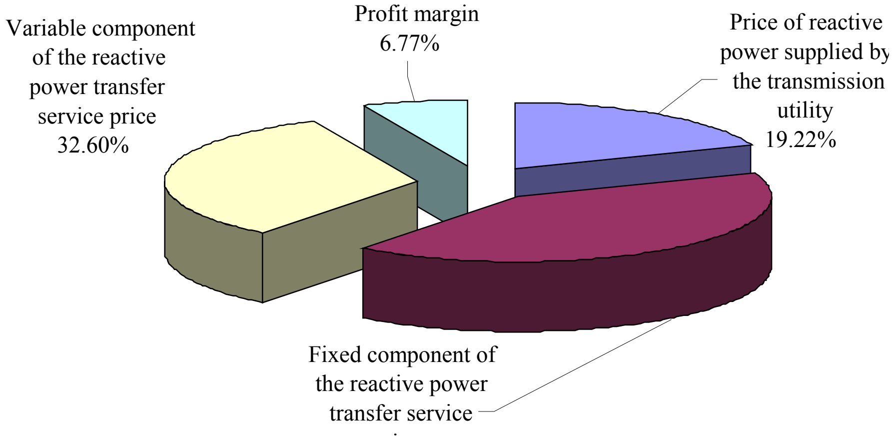
However, the price for reactive energy fed to the network could be calculated with reference to the perception that overcompensation compelled the distribution utility to provide the installation of controllable compensating devices with prices much higher. So the capital costs of conventional capacitors are 8–10 US$ per unit, but for different thyristor-controlled compensation devices like SVC, STATCOM, etc. are 45–55 US$ [10]. An extremely simplistic approach is equalizing the price for reactive energy fed to the network with the double price of consumed reactive energy. Such an approach has been used for instance, in some Finnish and Estonian distribution utilities, providing high motivation to limit the amount of reactive energy fed to the network.

It should be mentioned that in principle the price for reactive power service should be different for customers with static and dynamic reactive loads. In the case of variable reactive power consumption voltage control is substantial and at times critical. Loads with variable reactive power like arc furnaces, wind turbines, etc. cause voltage fluctuations in the connection point and have an effect on all the loads belonging to different customers connected to that point. Therefore the electricity providers are obliged to keep the voltage between certain limits in points of supply. Reactive power compensation plays a big role there. The plainest way to improve the voltage quality is reinforcing the network, but at the same time it is a very expensive way followed by the increase of fault currents level. Considerably more economical is the application of static thyristor-controlled compensation devices. Since the latter are significantly more expensive, it would be possible to apply the above-mentioned principle of higher taxation for customers with such variable loads. Furthermore, the reactive power tariff system could encourage reactive power consumption in certain districts and at certain time of day (at night, for example) by liberating from reactive energy payments or by awarding premiums. It is also necessary to issue the principle that premiums derive from expenses on more costly compensation devices. However – whereas the stimulation of reactive power consumption is of local nature and depends on specific conditions to a large extent, it requires voluminous information about loads and complicated utility side analysis. Besides, introduction of such a tariff component means abandoning the regional equality of tariffs.

Finally, to get an idea of relations between reactive energy tariff components, Fig. 3 presents the structure of reactive energy tariffs for medium- and low-voltage networks based on the example of Estonia's biggest distribution network utility. The calculation results also manifest that the variable price component due to reactive energy transfer has mainly been determined rather by active than reactive energy losses. The sample calculations showed that the share of price caused by reactive losses did not exceed 1% of the total variable price component for the reactive energy transmission service. It means that taking into consideration reactive energy losses and even more their assessment accuracy has no noteworthy effect on reactive energy pricing.



Medium voltage network



Low voltage network

Fig. 3. Tariffs structure for reactive power in medium and low voltage networks on the example of Estonia's distribution network (without excise and VAT).

Conclusions

- Till now there is no unified standpoint how to pay for reactive power services, because of the most difficult part of how to distinguish these services from each other and also to differentiate reactive and active energy services or to determine their price.
- On the one hand, the reactive energy price should cover the costs for reactive power transfer service; on the other hand, it should encourage customers to compensate their reactive energy consumption. In principle the price ought to stimulate the use of more expensive compensation equipment in the case of rapidly changing loads. At the same time the pricing should be sufficiently plain and transparent.

- The price for reactive energy consumed from the distribution network is expressed as the sum of the price for reactive energy obtained from the transmission network and the price for distribution network transfer service.
- The price for the distribution network transfer service comprises a fixed component, issued from the capital expenditure on compensation and transfer reactive power, and a variable component determined by the value of active and reactive energy losses due to reactive energy transmitting.
- Assessment of the fixed part is based here on the expenses made on compensation devices installed by the distribution network and on the cost of the share of the network transfer capacity needed for transmitting reactive power.
- Determining the variable component is rather complicated. A simplified methodology for its assessment is proposed.
- The price for reactive power transfer service for customers of low voltage network is significantly higher than for customers on medium voltage level. The reasons include relatively low prices for the reactive energy entering the medium voltage network and moderate reactive power losses due to small number of transformers and to reactive power compensation.
- It became evident that the variable component of the price for reactive power transfer service is determined mainly by the cost of active but not reactive power losses due to reactive power transfer. Thus the assessment accuracy of reactive power losses has minor effect on the reactive energy price.
- Sample calculations confirm the reality that the charge for reactive energy constitutes only a few per-cents of the whole electricity price. So the inaccuracies of the simplified determination of reactive energy prices will be lost in the inexactnesses of other components of the total tariff.
- The great number of different tariff systems and their numerous modifications in use worldwide along with practical incompatibility of theoretical charging methods prove the utter complexity of the problem.

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Received October 11, 2010