QUALITY INSURANCE BASED ELECTRIC ENERGY PRICING WITH MULTI-QUALITY

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ABSTRACT

Deregulation of electricity market makes electric energy supplied with different quality levels and according different prices as common merchandise necessity. Quality insurance method provides a new approach to solve this problem. This paper introduces quality insurance method into pricing for electric energy with different quality, which is to add power quality (PQ) insurance to basic electric energy price. Consumers provide economic signals to the distribution provider for their desired quality of service through insurance contracts. PQ insurance provides economically efficient investment incentives and alleviates consumers’ PQ disturbances risk. It changes compensation for PQ accidents to compensation choices of everyone. The value of PQ to consumers is thereby made transparent, allowing distribution companies to make efficient investment decisions. Insurance also allocates PQ disturbances risk to the distribution company (which controls the system), instead of consumers (who have little or no control over distribution grids). PQ insurance effectively unbundles delivery and PQ services and enables consumers to receive differentiated PQ based upon their value for this service. This paper describes the potential for PQ insurance to improve both investment efficiency and risk allocation compared to conventional regulatory structures.

INTRODUCTION

Power loads in modern society have a tendency to complexity and diversity. Certain commercial and industrial equipment, such as computer systems, robots, PLC and compressors, is so sensitive to power quality (PQ) that even several cycles’ interruptions or voltage sags would bring about large losses in economy. Traditional PQ regulating methods in electricity distribution systems have displayed several drawbacks. For instance, the methods cannot guarantee the power quality accepted by consumers, or make compensations for PQ accidents rational, or give a transparent price to quality power, or decide a reasonable risk allocation of disturbances, or provide incentives for PQ improvement. Additionally, the regulatory structure offers no contribution to the utility’s making of investment decisions. Neither can the structure satisfy the increasing requirements for premium power.

Due to the restructuring of electricity industry, electric energy is transacted on the market like common commodities. Consequently, PQ, as one of the attributes of the product traded between electricity utilities and customers, plays an important role in the survival in the competition. Such requests as supplying multi-quality electric energy, setting prices of electric energy by its quality and providing rational compensation for PQ accidents become users’ urgent ones, which have been attracting scholars both at home and abroad all the time. References [1]-[2] discuss economic assessment on PQ, and reference [3] emphasizes pricing for electric energy considering PQ. On the whole, research on pricing for electric energy with multi-quality is still in the early stage with a lot of work to complete. This paper presents a method that introduces the concept of quality insurance to pricing for electric energy with multi-quality. Reference [4] researches on supplying electric energy with different reliability based on “reliability insurance” method. And [5] applies “provider insurance” method, and introduces reasonable insurance policy into reserve power service. Both the two papers offer helpful reference for supplying electric energy with multi-quality and electric energy pricing by quality through quality insurance method.

SUMMARY OF QUALITY INSURANCE METHOD

Basic Imagination

In order to actualize electric energy supply with multi-quality, electric utilities and electric consumers should reach a special power-consuming contract with pricing by quality, which is equal to signing a quality insurance contract. Besides such traditional terms as supply address and method, load capacity, electric energy measurement, electricity price and dispute settling method, the new contract is supposed to give a detailed and unambiguous illustration of PQ level and relevant compensation for PQ violations.

Firstly, the rational pricing mechanism, according to the belief of pricing by quality, should reflect the principle that the higher the quality, the higher the price. Electricity price comprises the price of basic electric energy and quality insurance premium as following:

\[ p = p_b + \sum_j p_{ij} \]  

(1)

where \( p \) means the electricity price for the energy at the expected quality grade, \( p_b \) is the unit price of basic electric energy, and \( p_{ij} \) represents unit insurance premium concerning PQ index \( j \) in grade \( i \). For any customer, the chosen PQ index allows for varying in terms of grade, and different customers are permitted to buy different amount of \( p_{ij} \). The higher users demand in quality, the higher insurance premium should be paid, and the higher the electricity price will be. This phenomenon doesnot contrast with the principle of high quality with high price.

Secondly, in order to realize rational compensation for PQ accidents, the compensation provided by electric utilities should be equal to the users’ economic losses caused by the
accidents. Electric utilities should make up all the electric energy that has been violated during the contract period. The indicators of PQ contain steady-state indice and transient-state indice. When the violation happens to a certain steady-state index, the compensation should be $TR$, where $T$ is the electricity quantity supplied in violation period and $R$ is the compensation price for unit electricity quantity. Meanwhile, $T$ of outage refers to the average electricity quantity supplied in that period of former days. When the violation happens to a certain transient-state index, the relevant compensation should be $mT_uR$, where $m$ is the times of the violation in a day, and $T_u$ means the electricity quantity supplied in unit period (1/3 hour). Because customers know their economic losses more exactly, unit prices of compensation should be chosen by themselves. In case of an unreasonably high unit price, the chosen $R$ should be in direct proportion to insurance unit price $p$ as following:

$$R=Kp$$

If customers want to get higher compensation, they need to buy higher insurance premium ahead. And compensation proportion coefficient $K$ should meet following terms. Compared to the electric energy supply without multi-quality, users’ expenditure will not increase while receiving basic electric energy service. Such kind of quality insurance method is likely to be comfortably taken by the customers.

So electricity providers are required to make promises for all the PQ indices in different grades. Then users can make economic assessment for buying quality insurance. Two qualitative parameters are further introduced as numerical criteria to assure steady- and transient-state indices of basic electric energy: Maximal Unqualified Rate (MUR) and Maximal Violation Times (MVT). For example, when it is laid out in the contract that the total time of basic electric energy with RMS value less than 0.9pu is 0.15. When the electricity quantity with $RMS<0.95pu$ is promised less than 25% each day, the $MUR_{0.95}$ against $RMS<0.95pu$ is 0.25. When the times of sags with residual voltage (RV) lower than 0.7pu are promised to be less than 20 in a day, the $MVT_{0.7}$ against sag $RV<0.7pu$ is 20. When the times of sags with $RV<0.8pu$ are promised to be less than 30 every day, the corresponding $MVT_{0.8}$ against sag $RV<0.8pu$ is 30. Let $MUR$ and $MVT$ be the reciprocals of $K$ for steady- and transient-state indices respectively, the relationship between $R$ and $p$ is given as

$$p_j=R_{ij}\cdot MUR_{ij}$$

$$p_j=R_{ij}\cdot (MVT_{ij}/72)$$

where the units of $p$ and $R$ are both USD/MWh. Equation (3) accords with steady-state indices and (4) accords with the transient-state ones.

Suppose a user has bought unit insurance $p_{ij}$ according to index $j$ in grade $s$, and the daily electricity quantity is $T_{jd}$. Then, according to equations (3) and (4), his daily insurance expenditure $Pay_j$ for index $j$ is:

$$Pay_j = p_jT_{jd}R_{ij}\cdot MUR_{ij}\cdot T_d$$

$$Pay_j = p_jT_{jd}R_{ij}\cdot (MVT_{ij}/72)\cdot T_d$$

If the electric utility only provides the basic energy service, it must pay the compensation $Com_j$ as the result of its violating electric energy whose quantity is $MUR_{ij}T_d$ (or $MVT_{ij}(T_d/72)$), described as following:

$$Com_j = R_{ij}\cdot MUR_{ij}\cdot T_d$$

$$Com_j = R_{ij}\cdot MVT_{ij}(T_d/72)$$

Obviously, to both steady- and transient-state indices, there exists the relation $Pay_j=Com_j$. The relation indicates if the electric utility only provides the basic energy service, all the insurance expenditure paid by the consumers will be paid back as compensation. On the other hand, the term in the contract that the users’ expenditure will not increase while accepting basic electric energy service is also satisfied.

If the provided PQ level is higher than that of the basic energy, some of the insurance expenditure will not be paid back to the customers. This has reflected principle of high price for high quality, and indicates that electric utility only bears the compensation responsibility for those PQ accidents lower than the bottom lines in the basic electric energy promises. Meanwhile, for those PQ accidents within the basic electric energy promises, whether they should be mitigated lies on whether user’s insurance premium can balance the mitigation expenses. In order to prevent electric utilities from escaping compensation responsibility, PQ Supervision Department (PQSD), with referring to the statistical records before putting the quality insurance method into practice, should prescribe the bottom PQ promises for the utilities. In addition, abundant competition in supply side may effectively alleviate the possibility of that kind of speculation behaviors in electric utilities. Because they will be discarded by millions of users if they run the risk of dampening the PQ promises concerning the basic electric energy.

**Advantage of Quality Insurance Method**

Generally, PQ always fluctuates more or less. Higher PQ with less compensation while lower PQ with more, electric energy pricing by quality based on quality insurance method reflects the principle of high quality with high price, and it can assure that users’ expenditure will not increase while accepting the basic electric energy service.

In order to minimize the sum of PQ-improvement expenses and compensation for PQ accidents, electric utilities will adjust their PQ according to insurance bought by customers. If customers want to relieve economic risk caused by PQ fluctuations completely, they can buy suitable unit insurance. This will reflect the principle of high price for high quality, and indicate that electric utilities will adjust their PQ according to insurance bought by customers. If customers want to relieve economic risk caused by PQ fluctuations completely, they can buy suitable unit insurance. This will reflect the principle of high price for high quality, and indicate that electric utilities will adjust their PQ according to insurance bought by customers.

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economical PQ levels according to quality insurance contracts by all means. So this method creates incentives for electric utilities to provide suitable PQ for each customer. Electric utilities will manage PQ more actively and effectively. Individual users can choose their favorite PQ levels, instead of all users at the same PQ level. Those customers requiring low PQ value will avoid paying excessive costs for unneeded high PQ.

Quality insurance method contributes to parrying economic risks caused by PQ accidents for customers through providing compensation. On the other hand, insurance reasonably diverts risk from users to electric utilities. Because electric utilities can synthetically manage PQ of all users, while single user’s control ability is much limited. Furthermore, risk always goes along with benefit, so electric utilities can obtain profits through effectively handling of risks. For example, electric utilities are more likely to keep insurance premium as profits if they manage to improve power quality for some quality-sensitive industries, e.g. high-tech companies. And insurance premium can provide fund for technology innovation and equipment update.

PQ-service is not bundled with basic electric energy service by quality insurance, and the price of PQ-service is no longer average cost for all customers bundled in energy charge. And customers can buy economically attractive PQ-service via buying suitable PQ insurance premium. Investment in transmission and distribution and that in PQ can be assessed separately, instead of combining them. Power-consuming contracts reveal PQ demands on user sides. PQ varies with consumers’ preferences, so the burden to determine the most efficient level of the quality for the system is removed from the regulators.

Additional Remarks on the Quality Insurance Method

In order to prevent electric utilities from suffering economic losses or bankrupt from quality insurance, relevant regulations on the users in the quality insurance contract must be made clear. Firstly, characteristics and the maximum polluting current (including harmonic, unbalanced current, surge current, irregular and flicker current and reactive power current) of users’ load should be described unambiguously. Those PQ accidents caused by users’ irresponsibility will not be compensated, because the PQ investment decision is made according to information described in insurance contract.

Secondly, in order to parry speculation behaviors of the insurance users, the validity period of the contract should be long enough. Otherwise, some users may choose very high quality level at the beginning, and then switch to a lower insurance level after electric utilities have made great PQ investment. Consequently, the electric utilities may lose confidence on PQ investment. So the long-term contract of insurance positively guarantees that the quality level will be elevated continuously and cannot be lowered at will, which will contribute to preventing this kind of speculation behaviors. Thus, electric utilities can extract correct economic signal of PQ investment from the PQ insurance contracts.

Moreover, some PQ accidents are brought about by weather or some other natural disasters from which electric utilities may suffer enormous economic losses. These irresistible accidents can be stipulated beyond the insurance coverage (leaving these risks for users) or be offset via reinsurance.

The implementation of the quality insurance method prerequisites rational price lists of basic electric energy, which is not required in the traditional electricity supply. The price of basic electric energy supply should produce rational profits for electric utilities, and the price after superposing quality insurance premium can offer proper fund for compensation and PQ improvement.

After a period of PQ investment, electric utilities has been strengthened in PQ management; the bottommost promises of basic electric energy quality can be heightened properly. So users can share benefit created by quality insurance system with the whole society. But this needs longer time (at least 5 years), during which electric utilities can make correct investment decisions.

EXAMPLES

Analysis From User’s Side

Daily electric consumption of a certain paper mill is $T_d=240\text{MWh}$, the connect voltage is 35kV, and the price of electricity is 50USD/MWh. So its daily electricity rate is: $240\times 50=1.2\times 10^6\text{USD}$.

The papermaking equipments are sensitive to harmonic voltage and voltage sags. The current national standard “Harmonics in Public Grid” (GB/T14549-1993) restricts that total harmonic distortion (THD) in 35kV voltage can't exceed 3%, while there is no national standard to restrain voltage sag yet. But electric energy with $THD>2\%$ will make paper production trashy, and the economic loss $\eta_{THD}$ is about 1000USD/MWh. Average economic loss $\eta_{\Sigma\text{sag}}$ caused by sags with $RV<0.8pu$ is 100USD/time. Inspected at connect point, electric energy with $THD>2\%$ takes up 12.5%, and the percentage of $THD>3\%$ is 8.3%. Voltage sags with $RV<0.8pu$ happen to 20 times every day averagely. Without quality insurance, according to “power supply business rules”: when power factor satisfies standards, but power voltage oversteps standard, electric utility should compensate for user’s losses. The compensation is 20% product of electricity quantity that is unqualified for voltage and average electricity price in this month of user. Without national standard restricting voltage sags, paper mill can only gain compensation of the electric energy with $THD>3\%$. Economic losses caused by PQ accidents and compensation paper mill can gain are shown in Table 1.

Data in Table 1 indicates that current unified PQ standards cannot satisfy the special request of this paper mill. Ordinary electric energy supply will make it suffer serious economic loss that is 2.67 times of total electricity rate; while compensation offered by electric utility only is 0.625% of its economic loss. Present compensation method cannot reflect PQ actual value to the paper mill, and cannot
help electric utilities make correct investment decision and cannot promote reasonable electric energy supply with multi-quality according to special requirements of users.

If the percentage of electric energy with THD>2% rises from 12.5% to 20%, and that of THD>3% rises to 12.5% from 8.3%, additional economic loss $\Delta L_{THD}$ of this mill is:

$$\Delta L_{THD}=v_{THD}\times T_{d}(0.2-0.125)=18000\text{USD}$$  \hspace{1cm} (9)

Additional compensation $\Delta C_{THD}$ offered by electric utility is

$$\Delta C_{THD}=0.2\times 50\times T_{d}(0.125-0.083)=100\text{USD}$$  \hspace{1cm} (10)

The paper mill nearly bears all the risk caused by THD fluctuation, which cannot make electric utility protect user’s PQ actively. Adopting quality insurance method, paper mill should buy quality insurance for harmonic voltage and voltage sags. Suppose $R_{THD}=v_{THD}$ is the compensation price corresponding to $p_{THD}$, bought by the paper mill to assure $THD<2\%$, then when THD fluctuates as above-mentioned, additional economic losses $\Delta L_{THD}$ of this mill are

$$\Delta L_{THD}=v_{THD}\times T_{d}(0.2-0.125)$$

$$=T_{d}(0.2-0.125)\times (v_{THD}-R_{THD})$$

Equation (11) indicates if compensation price bought by the mill satisfies $R_{THD}=v_{THD}=1000\text{USD/MWh}$, same to $p_{THD}=1000\times 0.125=125\text{USD/MWh}$, then this paper mill will not suffer extra economic losses because of the increase in THD. Therefore, that risk has been shifted completely to the electric utility.

Similarly, if the advent of voltage sags with $RV<0.8pu$ occurs as often as 30 from 20 times per day, without quality insurance, the additional economic losses $\Delta L_{sag}$ of this mill could be:

$$\Delta L_{sag}=100\times (30-20)=1000 \hspace{1cm} (12)$$

And there is no compensation at all. Suppose $R_{sag}=v_{sag}$ is the compensation price corresponding to $p_{sag}$ bought by paper mill to assure the 0.8pu plus $RV$ of sags, additional economic losses $\Delta L_{sag}$ of this mill become:

$$\Delta L_{sag}=100\times (30-20)-(30\times R_{sag}\times 0.8pu\times T_{d}(0.2-0.125))=100\times (100-R_{sag})\times 0.8pu\times T_{d}/72$$

Equation (13) indicates if the compensation price bought by paper mill satisfies $R_{sag}=v_{sag}=72\text{USD/MWh}$, same to $p_{sag}=30\times 20/72=8.3\text{USD/MWh}$, then this paper mill will not suffer extra economic losses because of voltage sags with $RV<0.8pu$ rising. That risk has all been shifted to electric utility.

Table 2 lists the PQ indices parameters of basic electric energy supplied by a certain electric utility. While electric utility supplies power with diverse THD, Table 3 summarizes actual electricity rate (ER), PQ accident losses (PQAL) and total both-inclusive costs (TC), when this mill buys different insurance prices corresponding to $THD<2\%$ separately. Similarly, Table 4 summarizes those data for voltage sags. Data in Table 3 and 4 indicates, based on quality insurance method, this paper mill pays electricity rate according to actual quality of electric energy, that reflects the principle of high quality with high price. As the consumer chooses $R_{sag}=v_{sag}$ (unit compensation price of steady state indices) and $R_{THD}=v_{THD}$ (unit compensation price of transient state indices), $TC$ that contains $PR$ and $PQAL$ is constant. That indicates that economic benefits of this mill will not be influenced by PQ fluctuations. On the contrary, if the user chooses other insurance prices, although they have a chance to make additional profit, but the risk of suffering economic losses will be taken at the same time. Furthermore, electric utilities will adjust their supplying PQ according to the insurance premium that the users have paid, so the users’ chance to make profit is very slim.

<table>
<thead>
<tr>
<th>Harmonic voltage</th>
<th>Loss/(USD)</th>
<th>Compensation/(USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3\times 10^{4}$</td>
<td>$2\times 10^{2}$</td>
<td></td>
</tr>
<tr>
<td>$2\times 10^{4}$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$3.2\times 10^{4}$</td>
<td>$2\times 10^{2}$</td>
</tr>
</tbody>
</table>

Note: $AUR$ means actual unqualified rate of electric energy with THD>2%.
For example, the profit gained from the insurance service for a certain steady state index at a certain level can be expressed as:

$$B = \sum \limits_n p_n \cdot T_n - \sum \limits_n UR_n \cdot R_n \cdot T_n - TZ_{j1}$$  \hspace{1cm} (14)

The profit gained from the insurance service of a certain transient state index in a certain level can be given as:

$$B = \sum \limits_n p_n \cdot T_n - \sum \limits_n VT_n \cdot R_n \cdot (T_n / 72) - TZ_{j2}$$  \hspace{1cm} (15)

where \( n \) means user’s serial number, both \( TZ_{j1} \) and \( TZ_{j2} \) mean PQ investment corresponding to index \( j1 \) and \( j2 \) respectively.

In (14) and (15), as the insurance premium is chosen by users themselves, the only way for electric utility to increase profit is to reduce the sum of compensation and unnecessary PQ investment. Suppose the PQ investment is zero, PQ will be maintained as that of basic electric energy. Data in Tables 3 and 4 indicates that insurance premium received is totally equal to the compensation. Electric utility doesn’t obtain any profit because nothing has been done. For instance, electricity users have various options for the insurance prices to assure \( THD \) less than 2%, and electric utility maintains \( AUR=MUR=12.5\% \) steadily:

$$B = \sum \limits_n p_n \cdot T_n - \sum \limits_n AUR_n \cdot R_n \cdot T_n = 0$$

$$= \sum \limits_n MUR \cdot R_n \cdot T_n - \sum \limits_n AUR_n \cdot R_n \cdot T_n = 0$$  \hspace{1cm} (16)

Electric utilities, whose investment must be compared with the reduced difference of compensation, should figure out to what extent the viability of improving some users’ PQ is. For example, the paper mill buys insurance premium that makes users can use electric energy with acceptable PQ. Insurance realizes electric energy supply with multi-quality and users only have to pay the necessary expenses corresponding to their quality requirements.

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CONCLUSIONS

Compared to traditional single standard PQ managing methods, the quality insurance method presented in the paper highlights several advantages. Though the bottommost PQ promises (\( MUR \) and \( MVT \)) of the basic electric energy prescribed by PQSD may include some error, yet much of the disadvantages of traditional PQ managing methods can be effectively overcome. The quality insurance method can promote electric energy supply with multi-quality in electricity market. It realizes pricing by quality. Users’ choices to quality insurance price can display the actual value of PQ. So, any quality accidents can be rationally compensated. Economic risks, therefore, are shifted from users who have lower PQ-control capability than electric utilities, which provides momentum for electric utilities to protect PQ for users and offers suitable PQ-service according to users’ actual needs. This method can guide rational PQ investment decision making. PQ is chosen by users, so the burden for the supervisors of PQ is removed, and the chance of error is reduced greatly. Examples of user and electric utility prove the feasibility and effectiveness of this method.

PQ-service is unbundled from basic electric energy service by quality insurance. So users can compare this method with that in other ways when they are to make decisions, such as installing STATCOM by themselves. Quality insurance realizes electric energy supply with multi-quality that make users can use electric energy with acceptable PQ and users only have to pay the necessary expenses corresponding to their quality requirements.

ACKNOWLEDGMENTS

This work was supported in part by Specialized Research Fund for the Doctoral Program of Higher Education, the State Education Ministry of China (No. 20040079002) and Preliminary Research Fund for Significant Subject, North China Electric Power University.

REFERENCES