Software Quality Evaluation of Smart Meter Based on Fuzzy Analytic Hierarchy Process

Fuli Yang[1], Xingzhe Hou[1], Guangze Pan[2,*], Qin Luo[2], Chuangmian Huang[2]

[1]State Grid of Chongqing Electric Power CO. Electric Power Research Institute Chongqing, China

[2]Reliability and Environmental Engineering Research Center China Electronic Product Reliability and Environmental Testing Research Institute Guangzhou, China

hcyfuli@163.com,panguangze@126.com

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Abstract: With the development of smart grid, smart meters are gradually moving towards intelligent and multi-functional development, which puts higher demands on the quality of embedded software. According to the functional characteristics of the smart meter, the software quality evaluation index system the of the smart meter is constructed, and the weights of each software quality evaluation of the smart meter are determined by the fuzzy analytic hierarchy process (FAHP) method. At the same time, by establishing the membership functions of the software quality evaluation indexes of the smart meter, the membership values are determined. The software quality evaluation value is realized according to the weights and the membership values. The method proposed in this paper takes both qualitative and quantitative methods into consideration, reduces the adverse effects caused by subjective factors and improves the credibility. Finally, the method is applied to the case analysis.

1. Introduction

Smart meters are an important part of the smart grid, with real-time acquisition, accurate measurement, data storage and analysis and other features. The quality of smart meters is directly related to the quality of electricity and the operating costs of the system, as well as the fairness and fairness of the implementation of electricity management and the settlement of electricity consumption. The software quality of smart meters is the core factor affecting the quality of smart meters and the software quality also has a huge impact on the promotion and use of smart meters. Therefore, the establishment of a reasonable comprehensive software quality evaluation method of smart meters can not only provide objective scientific basis for the development of quality assessment and quality supervision of smart meters, but also has very important practical significance for the construction and development of smart grid [1-4].

At present, there is relatively little literature on the evaluation methods and applications of smart meter quality. The literature [5] establishes an evaluation index system for the operating state of the energy metering device, and comprehensively evaluates the operating state of the energy metering device. The life cycle quality evaluation model of smart meters is established by using the defect deduction method and the triangular fuzzy number analytic hierarchy process [6]. There are fewer literatures specifically for the quality evaluation of smart meter software. Literature [7] proposed an analytic hierarchy process to evaluate the quality of smart meter software, but the analytic method has less quantitative data and more qualitative components.

According to the functional characteristics of smart meters, this paper refers to the index system of software quality assessment, extracts the relevant factors that affect the software quality of smart meter, and establishes a hierarchical analysis model. The fuzzy analytic hierarchy process is used to evaluate the software quality of smart meters, which reduces the adverse effects caused by subjective factors and provides a more objective and scientific basis for the evaluation and supervision of smart meter quality.

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2. Evaluation model of Smart Meter Software Quality

Combined with the various functional characteristics of the smart meter, the smart meter software evaluation model is divided into three levels: the target layer, the criterion layer and the indicator layer. The elements of the previous level serve as the criteria to dominate the next level of related factors. The target layer is the software quality of smart meter, and the criteria layer includes: metering characteristic, communication characteristic, event recording characteristic, load curve characteristic and reliability. The indicators of each criterion layer are further divided into several different evaluation indicators according to their main influencing factors, as shown in Fig. 1.

Metering characteristic is one of the important performances of smart meters. It is the key indicator for evaluating the quality of smart meter. It is evaluated from the perspective of the influence of instantaneous quantities such as voltage, current, frequency and phase.

Communication is an important data interaction method for smart meter, and it is also a guarantee channel for data analysis and data processing of smart grid. It is important to verify the success rate of communication for reliability. Therefore, the communication characteristic is mainly scored from the operating conditions and environmental changes or even the limit conditions, and the communication success rate in the case of illegal data attacks.

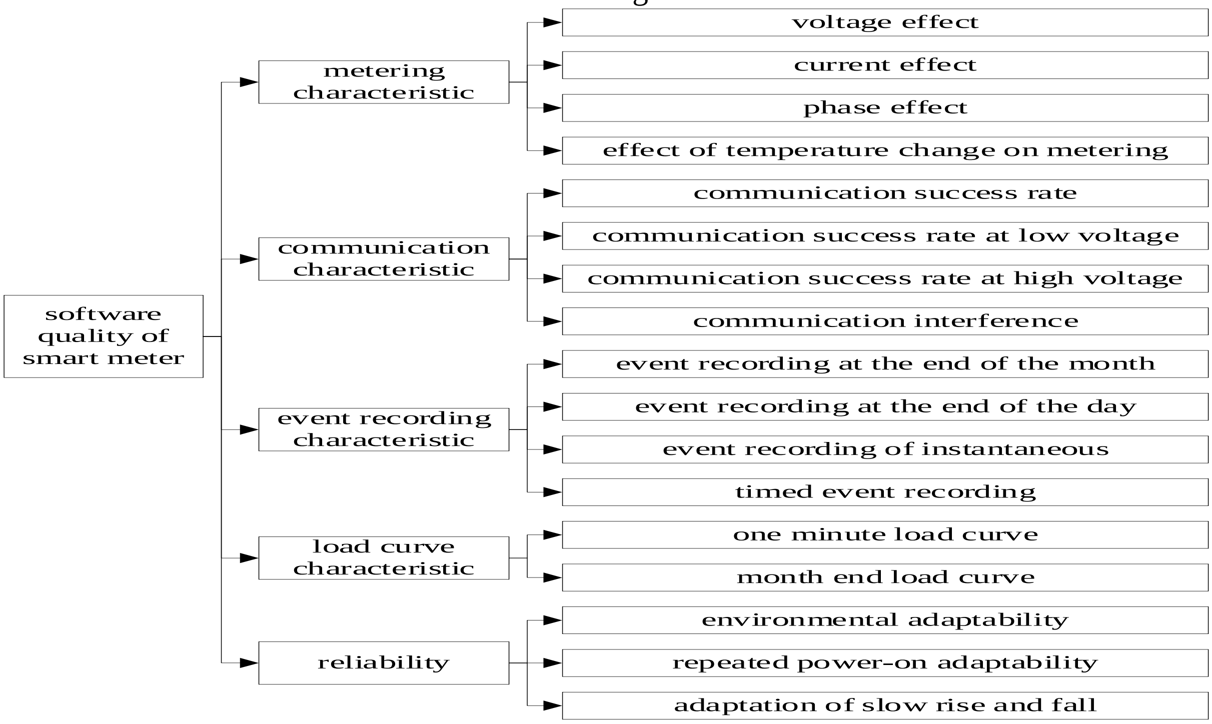

Figure 1. Evaluation model of the smart meter software quality.

The event recording characteristic is to save various data and records during the operation of the smart meter. When the smart meter working condition or environment is abnormal, the power can be recovered according to the event record. The event recording characteristic is used to determine whether a smart meter will make an abnormal change in the functional characteristics of the energy meter when processing a large number of storage events.

The load curve characteristic is to analyze the quality characteristics of the energy meter from the aspect of large data storage. The load curve needs to store 196 bytes each time, which is the important raw data for pursuing the analysis curve of the smart meter.

Reliability mainly considers the impact of grid environment instability, electromagnetic environment and climate environment on power and electricity bill functions.

3. Fuzzy Analytic Hierarchy Process

In this paper, the fuzzy analytic hierarchy process (FAHP) is chosen instead of the general analytic hierarchy process (AHP) to evaluate the software quality of smart meter, because the fuzzy analytic hierarchy process takes into account the ambiguity of human judgment. It combines qualitative and quantitative methods, which largely solves the problem that the point value is not flexible, which not only reduces the adverse effects caused by subjective factors, but also ensures the accuracy and rationality of the model.

3.1 Definition of Triangular Fuzzy Function

When $M \in F(R)$, $F(R)$ is the total fuzzy number on R. If the following conditions are met, then M is called a triangular fuzzy number, which can be recorded as (l, m, u).

1) The membership function $\mu_m : R \rightarrow [0,1]$ of M can be expressed as follows.

$$\mu_m(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l} & x \in [l,m] \\ \frac{x}{m-u} - \frac{u}{m-u} & x \in [l,u] \\ 0 & other \end{cases} \tag{1}$$

Among it, $l \le m \le u$.

2) There is $x_0 \in R$ such that $\mu_m(x_0) = 1$.

3) For any $\lambda \in (0,1)$, $M_\lambda = \left\{ X \,|\, \mu_m(x) \ge \lambda \right\}$ is a convex set.

Assuming that $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two triangular fuzzy numbers, the operation for defining the triangular fuzzy number is shown as follows.

$$M_1 \oplus M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{2}$$

$$M_1 \otimes M_2 = (l_1 \bullet l_2, m_1 \bullet m_2, u_1 \bullet u_2) \tag{3}$$

$$1/M_1 = (1/u_1, 1/m_1, 1/l_1) \tag{4}$$

$$\lambda \otimes M_1 = (\lambda \times l_1, \lambda \times m_1, \lambda \times u_1) \tag{5}$$

3.2 Steps of Fuzzy Analytic Hierarchy Process

The fuzzy analytic hierarchy process consists of several steps: establishing an analytic hierarchy model, constructing judgment matrixes in each level, consistency checking, determining the weights of the judgment matrixes; determining the total weights of the hierarchy.

3.2.1 Establish an analytic hierarchy model

The hierarchical structure is established according to the importance degree of the decision-making factors. The highest level is the target layer, that is, the final achievement goal. Below the target layer, each influence sub-factor layer is formed, and the bottom layer is composed of various possible indicators.

3.2.2 Construct judgment matrixes in each level

There are T experts participating in the scoring, and each expert scoring is in the form of triangular fuzzy numbers, that is, the scoring is a triangular fuzzy number with m as the median. When $l = m = u$, it is divided into constants, which cannot reflect the ambiguity of expert knowledge. If $|l - u|$ is too large, the ambiguity is too large. Appropriate scoring is very important for the outcome of the judgement. The scoring rules for triangular fuzzy numbers are shown in Table I.

If factor i has m_{ij} compared to factor j, then j has an $m_{ji} = 1/m_{ij}$ compared to i.

TABLE I. The scoring rules for triangular fuzzy numbers

Level	Degree of language description	1~9 scale
1	Equally important	$m_{ij}=1$
(1,3]	Slightly important	$m_{ij}=3$
(3,5]	Obviously important	$m_{ij}=5$
(5,7]	Strongly important	$m_{ij}=7$
(7,9]	Extremely important	$m_{ij}=9$

The expert's score constitutes a fuzzy judgment matrix to eliminate the influence of the expert's personal preference on the score. It is assumed that T judgment matrices can be obtained and the judgment matrix formed after the comparison of the two levels are as follows.

$$A^t=\begin{bmatrix} a_{11}^t & a_{12}^t & \cdots & a_{1n}^t \\ a_{21}^t & a_{22}^t & \cdots & a_{1n}^t \\ \vdots & \vdots & & \vdots \\ a_{n1}^t & a_{n2}^t & \cdots & a_{nn}^t \end{bmatrix} \tag{6}$$

Among them, $a_{ij}^t=(l_{ij}^t,m_{ij}^t,u_{ij}^t)$, because things have the same importance when compared with themselves, so there is $a_{ii}^t=(1,1,1)$. The comprehensive score of the hierarchical judgment matrix can be obtained by the following formula.

$$a_{ij}=\frac{1}{T}(a_{ij}^1+a_{ij}^2+\cdots+a_{ij}^T) \tag{7}$$

Due to the reciprocal nature of the judgment matrix, it can be shown as follows.

$$a_{ji}=\frac{1}{a_{ij}}=[\frac{1}{u_{ij}},\frac{1}{m_{ij}},\frac{1}{l_{ij}}] \tag{8}$$

Because the judgment matrix has reciprocal properties, in the actual scoring process, only the elements of the upper triangle or the lower triangle need to be played, and the remaining elements can be calculated by the formula (8), and the actual judgment matrix can be obtained as follows.

$$A^t=\begin{bmatrix} (1,1,1) & a_{12}^t & \cdots & a_{1n}^t \\ & (1,1,1) & \cdots & a_{1n}^t \\ & & \ddots & \vdots \\ & & & (1,1,1) \end{bmatrix} \tag{9}$$

3.2.3 Consistency check

The consistency ratio CR is the ratio of the consistency index CI to the same-order average random number consistency index RI, and the RI values are shown in Table II.

TABLE II. RI value table

Order of the matrix	RI
1	0
2	0
3	0.58
4	0.90
5	1.21
6	1.24

$$CR=CI/RI \tag{10}$$

When CR = 0.1, the degree of inconsistency is within the allowable range.

3.2.4 Determine the weights of the judgment matrixes

Weight calculation is the core problem of the triangular fuzzy number analytic hierarchy process. At present, the most commonly used method is the weight calculation method of fuzzy analytic hierarchy process based on triangular fuzzy numbers proposed by Chang Dayong [9]. However, the scope of its application is limited, so this paper uses the improved calculation method of Tongji University, Ming Minggang and Wei Wei [10].

1) Construct a fuzzy judgment factor matrix E

$$A^t = \begin{bmatrix} 1 & 1\text{-}\frac{u_{12}-l_{12}}{2m_{12}} & \cdots & 1\text{-}\frac{u_{1n}-l_{1n}}{2m_{1n}} \\ 1\text{-}\frac{u_{21}-l_{21}}{2m_{21}} & 1 & \cdots & 1\text{-}\frac{u_{2n}-l_{2n}}{2m_{2n}} \\ \vdots & \vdots & & \vdots \\ 1\text{-}\frac{u_{n1}-l_{n1}}{2m_{n1}} & 1\text{-}\frac{u_{n2}-l_{n2}}{2m_{n2}} & \cdots & 1 \end{bmatrix} \tag{11}$$

Among them, $e_{ij} = \frac{u_{ij}-l_{ij}}{2m_{ij}}$ is the standard deviation rate, which represents the degree of ambiguity of the expert evaluation. The larger e_{ij} is, the larger the ambiguity is, and the lower the credibility is. On the contrary, the smaller e_{ij} is, the smaller the ambiguity is, and the higher the credibility is.

2) Calculate the adjustment judgment matrix Q

$$Q = M \times E = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{12} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{bmatrix} \times \begin{bmatrix} 1 & 1\text{-}\frac{u_{12}-l_{12}}{2m_{12}} & \cdots & 1\text{-}\frac{u_{1n}-l_{1n}}{2m_{1n}} \\ 1\text{-}\frac{u_{21}-l_{21}}{2m_{21}} & 1 & \cdots & 1\text{-}\frac{u_{2n}-l_{2n}}{2m_{2n}} \\ \vdots & \vdots & & \vdots \\ 1\text{-}\frac{u_{n1}-l_{n1}}{2m_{n1}} & 1\text{-}\frac{u_{n2}-l_{n2}}{2m_{n2}} & \cdots & 1 \end{bmatrix} \tag{12}$$

3) The adjustment judgment matrix Q is transformed into a judgment matrix Q' with a diagonal line of 1 by column transformation.

4) Calculate the nth root of each row of elements.

$$t_i = (\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}, i = 1, 2, \cdots, n \tag{13}$$

5) Normalize t_i.

$$w_i = \frac{t_i}{\sum_{i=1}^{n} t_i}, i = 1, 2, \cdots, n \tag{14}$$

$W = [w_1, w_2, \cdots, w_n]^T$ is the weight vector of the judgment matrix.

3.2.5 Determine the total weights of the hierarchy

The total weights of the hierarchy refer to the relative weight of the lowest factor to the target layer (the top layer).

Suppose the upper layer contains m factors, its hierarchical weight is $a_1, a_2, \cdots, a_m$ and the next layer contains factors. Its hierarchical single-order weights for a certain m factors in the previous layer are $w_{j1}, w_{j2}, \cdots, w_{jn}$. Then the weight of each factor on the next level is shown as follows.

$$Y_i = \sum_{j=1}^{m} a_j w_{ji} \tag{15}$$

3.3 Determine the Evaluation Set and Membership Function

3.3.1 Quantification of quantitative evaluation indicators

Based on the maximum and minimum values of customer satisfaction, the membership interval of quantitative evaluation indicators is established. When the evaluation index value is lower than c_i, the customer i is very dissatisfied with the software quality evaluation of the smart meter. When the evaluation index value is higher than d_i, the customer is very satisfied with the software quality evaluation of the smart meter. Statistical analysis of c_i, d_i of different customers obtained the membership interval $[c, d]$ of the evaluation index. The actual value of the quantitative indicator of the smart energy meter is investigated, and the membership degree of the evaluation index is evaluated according to the membership function.

3.3.2 Quantification of qualitative evaluation indicators

Since the qualitative evaluation index cannot get the exact value, in the statistical analysis of the customer's software quality evaluation of the smart meter, five levels can be used for evaluation. Let V_1 be very dissatisfied, V_2 be dissatisfied, V_3 be normal, V_4 be satisfied, and V_5 be very satisfied. The indicator evaluation set $V = \{V_1, V_2, V_3, V_4, V_5\}$ is established by this method. Subsequently, the value of each evaluation level is counted, and the corresponding evaluation value is used as the lower bound and upper bound of the membership function interval of the evaluation index respectively, and the membership degree of each level of evaluation index is calculated according to the membership function.

Through the above method, the quantitative values of quantitative indicators and qualitative indicators are all in [0, 1], and different indicators are quantified to become dimensionless and comparable values.

3.4 Evaluate the Software Quality of smart meter

After knowing the weights and memberships of the underlying indicators, the score of the software quality of the smart meter is calculated.

$$Q = \sum_{i=1}^{n} Y_i \bullet U_i \tag{16}$$

Q - the score of the quality of the smart meter software; U_i - the score of the i element U_i in the underlying layer.

4. Case

There are three smart meters E_1, E_2, E_3 that are produced by three manufacturers. The software quality of the three different smart meters are evaluated and their ordering is determined.

Taking the metering characteristic in the criterion layer as an example, the four indicators below the metering characteristic are scored. The columns 1 to 4 of the judgment matrix A represent voltage effect, current effect, phase effect and effect of temperature change on metering.

$$A=\begin{bmatrix} (1,1,1) & (1,2,3) & (2,4,5) & (4,6,8) \\ (\frac{1}{3},\frac{1}{2},1) & (1,1,1) & (1,2,4) & (2,4,6) \\ (\frac{1}{5},\frac{1}{4},\frac{1}{2}) & (\frac{1}{4},\frac{1}{2},\frac{1}{1}) & (1,1,1) & (1,2,3) \\ (\frac{1}{8},\frac{1}{6},\frac{1}{4}) & (\frac{1}{6},\frac{1}{4},\frac{1}{2}) & (\frac{1}{3},\frac{1}{2},1) & (1,1,1) \end{bmatrix}$$

The median matrix M is shown as follow.

$$M=\begin{bmatrix} 1 & 2 & 4 & 6 \\ \frac{1}{2} & 1 & 2 & 4 \\ \frac{1}{4} & \frac{1}{2} & 1 & 2 \\ \frac{1}{6} & \frac{1}{4} & \frac{1}{2} & 1 \end{bmatrix}$$

The maximum eigenvalue $\lambda_{\max}$ of the M is obtained as 4.0103, and then the consistency test index $CI=0.0034$ is obtained. $CR=0.0038<0.1$. The fuzzy judgment matrix satisfies the consistency test.

The fuzzy judgment factor matrix E is constructed according to the fuzzy judgment matrix A.

$$E=\begin{bmatrix} 1 & 1/2 & 5/8 & 2/3 \\ 1/3 & 1 & 1/4 & 1/2 \\ 2/5 & 1/4 & 1 & 1/2 \\ 5/8 & 1/3 & 1/3 & 1 \end{bmatrix}$$

The adjustment judgment matrix Q is obtained from the formula (4).

$$Q=\begin{bmatrix} 7.0167 & 5.5000 & 7.1250 & 9.6667 \\ 4.1333 & 3.0833 & 3.8958 & 5.8334 \\ 2.0667 & 1.5417 & 1.9479 & 2.9167 \\ 1.0750 & 0.7917 & 1.0000 & 1.4861 \end{bmatrix}$$

The judgment matrix Q' is adjusted by the column transformation.

$$Q'=\begin{bmatrix} 1 & 1.7838 & 3.6578 & 6.5047 \\ 0.5891 & 1 & 2 & 3.9252 \\ 0.2945 & 0.5 & 1 & 1.9626 \\ 0.1532 & 0.2568 & 0.5134 & 1 \end{bmatrix}$$

TABLE III. THE WEIGHTS OF INDICATORS

the criteria layer	weight	the indicator layer	weight
metering characteristic	0.3215	voltage effect	0.4976
		current effect	0.2859
		phase effect	0.143
		effect of temperature change on metering	0.0735
communication characteristic	0.2412	communication success rate	0.5421
		communication success rate at low voltage	0.2345
		communication success rate at high voltage	0.1505
		communication interference	0.0729
event recording characteristic	0.1854	event recording at the end of the month	0.0975
		event recording at the end of the day	0.3211
		event recording of instantaneous	0.3021
		timed event recording	0.2793
load curve characteristic	0.1441	one minute load curve	0.5
		month end load curve	0.5
reliability	0.1078	environmental adaptability	0.637
		repeated power-on adaptability	0.2583

The weight vector of the matrix obtained by solving formula (13) and (14) is as follows.

$$W = [0.4976, 0.2859, 0.1430, 0.0735]^T$$

The weights of other indicators can be calculated in the same way. As shown in the Table III.

The total weights of indicators are obtained according to formula (15). And the membership values of the smart meters E_1, E_2, E_3 are shown in Table IV.

According to formula (16), the software quality scores of smart meters E_1, E_2 and E_3 are 0.7006, 0.6301 and 0.6830. It can be seen that the smart meter E_1 has the highest software quality.

5. Conclusion

This paper proposes a fuzzy analytic hierarchy process to evaluate the software quality of smart meters. The fuzzy analytic hierarchy process can effectively solve the difficulty of expert scoring, describe the expert experience with more appropriate fuzzy methods, reduce the preference of experts' individual scoring, and make the result of software quality evaluation of smart meters more objective and reasonable. According to the method, the software quality of the smart meters of the same specification and model of each manufacturer can be evaluated, and the user has a certain reference value for the selection of the smart meters. However, different smart meters have different emphasis on the software due to the needs of the application environment. Therefore, this method has certain limitations to some extent. It is still necessary to further study a more general evaluation method for the quality of smart meter software.

TABLE IV. The weights of indicators and the the membership values of the smart meters

the criteria layer	**the indicator layer**	**the total weight**	**the membership value**		
			E_1	E_2	E_3
metering characteristic	voltage effect	0.1600	0.7284	0.5161	0.6022
	current effect	0.0919	0.7474	0.9120	0.6381
	phase effect	0.0460	0.7197	0.5691	0.5883
	effect of temperature change on metering	0.0236	0.7883	0.7188	0.8626
communication characteristic	communication success rate	0.1308	0.8239	0.6074	0.7351
	communication success rate at low voltage	0.0566	0.7111	0.8130	0.4226
	communication success rate at high voltage	0.0363	0.6603	0.6872	0.8048
	communication interference	0.0176	0.8688	0.6219	0.7595
event recording characteristic	event recording at the end of the month	0.0181	0.5456	0.6489	0.9689
	event recording at the end of the day	0.0595	0.5948	0.8326	0.6303
	event recording of instantaneous	0.0560	0.4267	0.5476	0.4643
	timed event recording	0.0518	0.4417	0.6393	0.5284
load curve characteristic	one minute load curve	0.0721	0.8870	0.4991	0.8875
	month end load curve	0.0721	0.7814	0.8343	0.7157
reliability	environmental adaptability	0.0687	0.5007	0.2181	0.9834
	repeated power-on adaptability	0.0278	0.7920	0.4799	0.5871

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References

[1] XIO Yong, HUANG Youpeng, ZHOU Tong, FANG Yanjun.Quality Evaluation of Intelligent Electric Meter Software Based on Fuzzy Analytic Hierarchy Process[J].Automation & Instrumentation,2016,31(07):20-24.

[2] Wang Qiang.Design of smart meter system in smart grid AMI[J].Shandong Industrial Technology,2015(20):186-187.

[3] Kang Wei, Li Jie. Analysis of the role and application prospect of smart meters in smart grid[J]. Technology and Market, 2015, 22(08): 190-191.

[4] Ji Jing, Hou Xingzhe, Chen Hongfang, et al. Quality Evaluation of Intelligent Energy Meter Based on Analytic Hierarchy Process[J]. Electric Measuring & Instrumentation,2015,52(08):5-9.

[5] Zhai Xingli, Wen Fuzhen, Lin Zhenzhi, Li Yuling. Comprehensive Evaluation and Sensitivity Analysis of Power Quality Based on Fuzzy Analytic Hierarchy Process[J]. Journal of North China Electric Power University (Natural Science Edition), 2013, 40(05): 48-53 .

[6] Cheng Yuying, Wu Wei, Yang Huabiao, Hou Xingzhe, Xiao Wei, Li Chengxiang, Yao Chenguo.Study on state fuzzy comprehensive evaluation and inspection strategy of electric energy metering device[J].Electrical Measurement & Instrumentation,2012,49(12): 1-6.

[7] Meng Ming, Stretch. The whole life cycle quality evaluation of smart energy meter based on defect deduction method and triangular fuzzy number analytic hierarchy process[J].Power System Protection and Control, 2012, 40(22): 88-93.

[8] Li Baoshu, Chen Wankun. The role and application prospect of smart meter in smart grid[J].Electric Times, 2010(09):28-30.

[9] Jing Enbo. Design of smart meter system in smart grid AMI[J]. Electric Measurement & Instrumentation, 2010, 47(S2): 36-39.

[10] He Yuanyuan, Zhou Dequn, Wang Qiang. Ranking method of triangular fuzzy number complementary judgment matrix based on likelihood[J]. Operations Research and Management Science, 2009, 18(01): 65-68.