Research and Analysis on the Reliability of Smart Energy Meters

Jintao Chen¹, Fang Zhao¹, Wenjun Zhu¹, Liang Huang¹, Qiang Zhou²,*, Zhaoguo Shan² and Liangtao Liu²

¹Electric Power Research Institute, State Grid Shanghai Municipal Electric Power Company, Shanghai, China
²Yantai Dongfang Wisdom Electric Co., Ltd, Yantai, Shandong, China

*Corresponding author: handongjun@dongfang-china.com

Abstract. Analysis and study the reliability theory of smart electric energy meters, as well as reliability analysis indicators and fault distribution rules. Starting from the distribution law of fault data and reliability indicators of fault life, the reliability of electric energy meters is analyzed by collecting field maintenance data. The reliability model is used to study the failure modes, causes and effects of smart electric energy meters. The research and analysis of the reliability of the smart electric energy meter ensure the normal operation of the intelligent electric energy meter and improve the stability and reliability of the intelligent electric energy meter.

1. Introduction

Smart electric energy meter is an important part of smart grid, which is gradually developed from traditional electric energy meter. The outstanding performance of smart energy meters in information collection, implementation of tiered electricity prices, real-time monitoring, and smart deductions can better serve users. Smart power meters are becoming more powerful and the number of users is increasing. Changing a smart power meter will cause a lot of manpower and material loss, which will affect the normal production and life of users, and it will also affect the normal operation of smart grids. Influences. Therefore, for the entire smart grid, it is very important to study the reliability of smart energy meters, to detect faults in smart energy meters, and to analyze the causes of failures.

The reliability of smart meters can be divided into two categories: inherent reliability and use reliability. Inherent reliability refers to the reliability of the smart energy meter under reasonable use conditions before leaving the factory. Reasonable use conditions refer to the application scenarios and working environment corresponding to the needs of users by smart meter designers, which are inherent attributes of the product. Reliability in use refers to the reliability of the smart electric energy meter in actual use; the same product has different reliability in different use environments. Product design, manufacturing, use, maintenance and environmental factors will affect the reliability of the product.

Analyze and study the reliability of the smart electric energy meter. After the smart electric energy meter is put into use, its reliability will decrease with the increase of use time. Studying its actual use level can provide a good reference for subsequent design.
2. Theoretical analysis of the reliability of smart meters

Reliability indicators can be used to indicate the reliability of products, which are quantitative indicators of product reliability; commonly used reliability indicators include reliability, unreliability, failure rate, failure probability density function, average life, reliable life, characteristic life, Median life etc.

Product reliability can be described as the probability that a product will perform a specified task under certain conditions and within a specified time. Product reliability can be represented by $R(t)$, and its mathematical expression is:

$$R(t) = P(T > t)$$  \hspace{1cm} (1)

$T$ represents the life of the product, that is, the life of the smart energy meter, and $t$ represents the specified time.

The reliability of a product is expressed by probability, which can be expressed as:

$$R(t) = \frac{N - r(t)}{N}$$  \hspace{1cm} (2)

In the formula, $N$ is the number of products planned to be used, and $r(t)$ is the number of equipment that has failed over time $t$.

The unreliability of a product refers to the probability that a product cannot complete a specified task under specified conditions and within a specified time. Unreliability, like reliability, is also a function of time and is the cumulative probability of failure.

$$F(t) = P(T \leq t)$$  \hspace{1cm} (3)

$$F(t) = 1 - R(t) = \frac{r(t)}{N}$$  \hspace{1cm} (4)

The failure probability density function refers to the failure probability of the product from the start time to the time $t$.

$$f(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt}$$  \hspace{1cm} (5)

Therefore, the relationship between failure probability density function and product reliability and unreliability can be derived.

$$F(t) = \int_0^t f(t) dt$$  \hspace{1cm} (6)

$$R(t) = \int_t^\infty f(t) dt$$  \hspace{1cm} (7)

Failure rate can also be called failure rate, which can be divided into instantaneous failure rate and average failure rate; after $t$ time, the probability of failure of a normal working product in unit time is called instantaneous failure rate.

$$\lambda(t) = \frac{f(t)}{R(t)} = -\frac{d \ln R(t)}{dt}$$  \hspace{1cm} (8)
Therefore, the relationship between instantaneous failure rate and product reliability and product failure probability can be derived.

\[ F(t) = 1 - e^{-\int_0^t \lambda(t) dt} \]  
\[ f(t) = \lambda(t) e^{-\int_0^t \lambda(t) dt} \]  

The cumulative failure rate and average failure rate in the interval [0, t] are:

\[ \xi(t) = \int_0^t \lambda(t) dt \]  
\[ \bar{\lambda}(t) = \frac{\xi(t)}{t} = \frac{\int_0^t \lambda(t) dt}{t} \]  

When a failure occurs, the product can be repaired, and the average life span represents the average product work between adjacent failures. When the product fails to be repaired, the average life span represents the average of the normal working time before the product fails. The theoretical value of the average product life is the mathematical expectation value of the product life T.

\[ E(t) = \int_0^\infty tf(t) dt \]  

For a given reliability r, the time from the normal operation of the product to the reliability r is called the reliable life of the product reliability r. The life time when the product works to a reliability of 1/e is called the characteristic life of the product. The life time of the product from normal operation to 50% reliability is called the median life of the product.

The failure rate of the product is related to time, and the failure rate can be divided into three intervals: early failure period, accidental failure period and depletion failure period. The product failure rate curve is shown in Figure 1.

![Figure 1. Product failure rate curve.](image)
The early failure period means that the failure rate of the product at this stage is relatively high, but the failure rate of the product gradually decreases over time. The reason is that the production process of the product is not good enough, the raw material problem, etc., with the improvement of manufacturing standards, the failure rate will rapidly decrease. The accidental expiration period indicates that the product is stable at this stage and the failure rate is low, which is a good use stage for the product. Regular maintenance of the product can effectively extend the accidental expiration period of the product. The expiration date means that due to the increase in service life and changes in the surrounding environment, the internal and external parts of the product will gradually wear, aging, and corrosion, and the failure rate of the product will increase.

3. Smart meter reliability data sampling
The reliability of the smart electric energy meter can reflect the reliability of the whole meter. Take the single-phase smart electric meter as the research object, analysis its reliability level in practical application, and discuss the reliability index of the electric meter. The basic data of the single-phase smart meter is shown in Table 1.

| Project          | Parameter                  | Project          | Parameter                  |
|------------------|----------------------------|------------------|----------------------------|
| Types            | Electronic energy meter    | Accuracy level   | Grade I                    |
| Voltage          | 220V                       | Current          | 5A                         |
| Frequency        | 50Hz                       | Power            | 1.5W                       |
| RS485 rate       | 2400bps                    | Infrared         | 1200bps                    |
| Energy pulse     | 80ms                       | communication   | Standard                   |
| width            |                            | rate             |                            |

In the design, production and put into use of intelligent electric energy meters, failures will occur due to various reasons. In order to improve the reliability of smart energy meters, reduce production costs, and increase product sales, collect field data of energy meters and analyze the causes of product failures. On-site data collection of smart energy meters may affect the reliability of energy meters due to different regions where the meters are installed, different climates, different usage times, and human activities, which may affect the collected data and cause deviations in the results.

When collecting data, you must ensure that the recorded data is true and valid. When querying data, unknown data can be inferred based on existing data, which can represent the overall trend of product reliability. When collecting data, data continuity must be ensured, and large-scale data loss or damage should not occur. The completeness of the data can reflect the performance of the product more truly and analyze the reliability of the product more accurately.

Select 200 sets of smart electric energy meters as samples, and classify the statistical data in detail, and sort them according to the time when the samples fail or quit working. The life unit is hour. In the reliability life test, there are two types of life tests, namely Complete life test and censored life test. According to the fault data of the smart electric energy meter obtained from the field, it can be considered as a censored life test. Censoring life test generally can have three states: time censoring, fixed number censoring, and random censoring.

Timing truncation refers to stopping from the start time to the specified end time. The data obtained during this period of product failure is random. Fixed number truncation refers to the determination of the number of product failures before the test. When the number of product failures has reached the expected requirement during the test, the test is stopped. Random censoring means that during the test, the test cannot be continued due to various factors before the product has failed. The data obtained in this way is randomly truncated.
The statistical fault data of the smart electric energy meter is shown in Table 2.

| Serial number | Operating hours | Fault type | Serial number | Operating hours | Fault type |
|---------------|----------------|------------|---------------|----------------|------------|
| 1             | 2088           | Drop out   | 21            | 10393          | Invalidation |
| 2             | 2320           | Drop out   | 22            | 11029          | Invalidation |
| 3             | 2458           | Drop out   | 23            | 11125          | Invalidation |
| 4             | 2826           | Drop out   | 24            | 12093          | Drop out    |
| 5             | 3024           | Drop out   | 25            | 12554          | Drop out    |
| 6             | 3201           | Drop out   | 26            | 14236          | Invalidation |
| 7             | 3653           | Drop out   | 27            | 15238          | Invalidation |
| 8             | 4021           | Invalidation | 28        | 16021          | Drop out    |
| 9             | 4554           | Invalidation | 29        | 16332          | Drop out    |
| 10            | 5108           | Invalidation | 30        | 16571          | Invalidation |
| 11            | 5422           | Drop out   | 31            | 16984          | Invalidation |
| 12            | 6257           | Drop out   | 32            | 17008          | Invalidation |
| 13            | 6658           | Invalidation | 33        | 17568          | Invalidation |
| 14            | 6852           | Invalidation | 34        | 17899          | Invalidation |
| 15            | 7122           | Invalidation | 35        | 18124          | Invalidation |
| 16            | 7569           | Drop out   | 36            | 18543          | Invalidation |
| 17            | 7865           | Drop out   | 37            | 18775          | Invalidation |
| 18            | 8562           | Invalidation | 38        | 19054          | Invalidation |
| 19            | 9786           | Invalidation | 39        | 19880          | Invalidation |
| 20            | 9986           | Invalidation | 40        | 20102          | Invalidation |

Remove the smart meters that quit working when they do not fail, sort the faulty smart meters according to the time of failure, establish an analysis model, and analyze the reliability of the sample meters.

4. Calculation and Analysis of Reliability of Smart Meter

Establish a distribution model based on the data of the smart electric energy meter, simulate various parts problems, and complete data fitting. The least square method is selected for analysis to reduce the interference of human factors and improve the accuracy of the results. The least square estimation method obtains the linearization result of the distribution function, which can better ensure the accuracy of the distribution parameter estimation. The least squares estimation method is a technique for optimizing mathematics. It can easily and conveniently obtain unknown data from existing data, and can minimize the sum of squared errors between the obtained unknown data and the existing data. When using the least squares method for curve fitting, it can fit the existing data well and make the results have high accuracy.

Analyze the reliability and unreliability functions of the smart electric energy meter as shown in Figure 2.
As the working hours of smart meters continue to increase, the reliability $R(t)$ of the smart meters gradually decreases, and the unreliability $F(t)$ gradually increases. Especially within 10,000 hours, the reliability and unreliability decrease and increase significantly, indicating that there were more faults in the smart energy meter during the previous period. And it can be analyzed that the reliability of the sample smart energy meter is reduced to 50% after 600 hours of operation.

Analyze the failure probability density and failure rate function of the smart electric energy meter as shown in Figure 3 and Figure 4 respectively.

The probability density function changes with time, and its trend is to increase first and then decrease. The failure probability density function reaches its peak after a period of time when the smart electric energy meter has been in operation. During this time, the number of failures of the intelligent electric energy meter is large, and then the failure probability density function begins to decrease, indicating that the number of failures of the intelligent electric energy meter is gradually decreasing.
The failure rate $\lambda (t)$ gradually increases with the increase of the working time of the smart electric energy meter, and the change rate of the failure rate first rapidly increases, and then gradually decreases. The time of the failure is accidental.

5. Conclusion
Because the smart electric energy meter is composed of various electronic components, its complexity and systematic nature make the traditional single fault detection method unable to meet the current demand. Analyze and study more types of reliability research technologies, which play an important role in the reliability research of smart energy meters.

This article explores and researches the basic theory and research methods of reliability, focusing on the reliability failure model and product distribution function model. Through the research on the reliability theory of the smart electric energy meter and combining the specific maintenance data, the distribution model of the smart electric energy meter is obtained. Reliability function graph, failure probability density function graph and failure rate function graph, and use this to analyze the trend of failure of the smart energy meter during use. The analysis and research in this article play an important basic role in the reliability research of smart energy meters.

References
[1] Wang Xianqiang, Hao Jinwei, Chen Xinchun, et al. Reliability prediction of smart electric energy meters based on component stress method[J]. Technological Innovation and Productivity, 2014, 35(8): 76-80.
[2] Wang Peng, Zhang Jinbiao. Reliability selection and application control specification of electronic components[J]. Electronic Testing, 2016(09):118-119.
[3] Guo Xingxin, Jia Jun, Guo Xiaoyan. The development history and application prospects of smart energy meters [J]. Jiangsu Electrical Engineering, 2012, 31(01): 82-84.
[4] Chen Ming, Wang Guohua, Chen Yun. Using the failure mechanism model to analyze the failure mode effect of large-scale complex products[J]. Mechatronics, 2006(02): 40-43.
[5] Kang Rui, Zheng Tao. Fuzzy Mathematics Method in Hazard Analysis[J]. Journal of Beijing University of Aeronautics and Astronautics, 1995(04):60-65.
[6] Rhee S J, Ishii K. Using cost based FMEA to enhance reliability and serviceability[J]. Advanced Engineering Informatics, 2003, 17(3):179-188.
[7] Shahin, Arash. Integration of FMEA and the Kano model[J]. International Journal of Quality & Reliability Management, 2004, 21(7):731-746.
[8] Dugan J B, Bavuso S J, Boyd M A. Dynamic fault-tree models for fault-tolerant computer systems[J]. IEEE Transactions on Reliability, 2002, 41(3):363-377.