Analysis of Failure Mechanism of Smart Meter Capacitance

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Abstract. In practical applications, smart meters will fail, and even have batch quality problems. In addition to the sampling inspection of the arrival quality of smart meters, the analysis of the failure mechanism of smart meters has become an important and long-term task. This article mainly analyzes the component capacitance commonly used in smart meters, and analyses the failure of chip multilayer ceramic dielectric capacitors from appearance observation, electrical parameter testing, metallographic slicing, and at the same time from electrolytic appearance observation, electrical parameter testing, X-RAY, SEM and EDS for failure analysis. The results of failure mechanism research not only help to improve the reliability of the domestic energy meter manufacturing level, but also can save energy meter maintenance and transformation costs, and have very important practical significance for the construction of smart grids.

1. Introduction

The energy meter is responsible for the important task of electricity metering, and it needs continuous and stable operation. Due to the complex site environment, most energy meters are subject to long-term severe temperature and humidity changes, lightning, power grid fluctuations and electromagnetic interference. Under the influence of the external environment and load factors, the failure of the energy meter is inevitable. This not only brought great maintenance costs, and even caused economic disputes and compensation for electricity use, and the consequences were extremely bad. The failure mechanism is the physical, chemical, thermodynamic or other process that leads to the failure of components. In this process, stress causes damage to the components, which ultimately leads to system failure. Failures mainly come from manufacturers' neglect or contempt for user needs and expectations, improper design, improper material selection and management or improper material combination, improper manufacturing or assembly processes, lack of appropriate technology, improper user use, and product quality out of control. In order to develop a reliable product, one must understand the product's potential failure mechanism.

2. Chip multilayer ceramic capacitor components

Chip multi-layer ceramic dielectric capacitors are mainly used for single-phase electric energy meters. During the use of single-phase electric energy meters, it is found that part of the electric energy meters have unstable errors during verification or after a period of operation. Sometimes the measurement is stopped and sometimes the error is large. After preliminary inspection, it is caused by the failure of the chip reference voltage filter multilayer chip ceramic capacitor. After the failure, the capacitor leakage at this position is very large.
Analyze the cause of capacitor failure, and analyse whether the appearance of other 6 capacitors of the same type on the same circuit board is damaged or whether the electrical parameters are within the qualified range. A total of three failure templates were extracted from the analysis, numbered F1# ~ F3#, and the capacitors at their corresponding positions were numbered Fi#-Cj (i = 1, 2, 3, j = 1, 2, 3, 4, 5, 6).

2.1. Appearance observation
After disassembling the sample, the typical appearance of a failed ceramic capacitor is shown in Figure 1, and no obvious abnormality was seen. At the same time, the appearance of the other six capacitors of the same type on the same circuit board did not show obvious abnormalities.

![Figure 1. Appearance of failed samples and capacitors in other positions of the same type (F1#)](image)

2.2. Electrical parameter test

| Test Conditions | C and tgδ: f=1kHz, Vrms=1V; R: Reading after 1 minute at 50VDC |
|-----------------|---------------------------------------------------------------|
| Eligibility criteria | C=100.0nF±10%, tgδ≤2.5%, R≥5×10^9Ω                          |
| status          | Direct test on board                                          |
| sample          | F1#-C6 F2#-C6 F3#-C6                                         |
| C(nF)           | 92.88 93.17 99.82                                            |
| tgδ(%)          | 1.27 885 1.43                                                |
| R(Ω)            | 7.62×10^3 110.4 1.35×10^5                                    |
| status          | Test after welding is removed                                 |
| sample          | F1#-C1 F1#-C2 F1#-C3 F1#-C4 F1#-C5 F1#-C6                    |
| C(nF)           | 98.50 97.21 101.26 104.64 101.04 97.85                      |
| tgδ(%)          | 1.38 1.37 1.49 1.54 1.35 274                                 |
| R(Ω)            | 6.0×10^9 5.7×10^9 7.0×10^9 6.1×10^9 8.6×10^9 674           |
| status          | Alcohol scrub after high temperature baking                  |
| sample          | F1#-C6 F2#-C6 F3#-C6                                         |
| C(nF)           | 97.70 99.53 105.25                                           |
| tgδ(%)          | 237 19.9 1.61                                                |
| R(Ω)            | 697 10.8×10^3 1.5×10^6                                       |

Table 1. Capacitor parameter test results
Directly test the capacitance (C), loss (tgδ) and insulation resistance (R) of F1 # -C6, F2 # -C6, F3 # -C6 on the board. At the same time, remove the capacitors at the C1, C2, C3, C4, C5 and C6 positions of the three failed samples with a hand soldering iron, and test the capacitance (C), loss (tgδ) and insulation resistance (R). Scrub the welded F1 # -C6, F2 # -C6, F3 # -C6 with alcohol, then bake at high temperature for 18 hours, and cool to room temperature. The test results are shown in Table 1.

It can be seen from Table 1: The insulation resistance of capacitors at F1 # -C6, F2 # -C6, F3 # -C6 position is less than the acceptance criterion no matter in which state, so confirm that the failure mode of the sample is insulation. The resistance decreases. The parameters of capacitors in other positions are within the acceptance criteria.

2.3. Metallographic section observation

Metallographic slice observation of F1 # -C6, F2 # -C6, F3 # -C6 capacitors. The cracks of about 45° can be seen in the ceramic media of the three samples. The morphology is shown in Figure 2 to Figure 4.

![Figure 2. Appearance of failed samples and capacitors in other positions of the same type (F1 # -C6)](image1)

![Figure 3. Morphology of dielectric crack in F2 # -C6 ceramic capacitor](image2)

![Figure 4. Morphology of dielectric cracks in F3 # -C6 ceramic capacitors](image3)

2.4. Comprehensive analysis

The failure mode of the capacitor on the sample is shown as reduced insulation resistance. It can be known from the metallographic section that a crack of about 45° exists in the ceramic dielectric of the ceramic capacitor on the failed sample. The existence of cracks will reduce the insulation resistance and cause leakage failure of the sample. From the shape and location of the ceramic dielectric cracks in the failed sample, the occurrence of cracks is related to mechanical stress.

Ceramic capacitors fail due to a reduction in their electrical insulation resistance due to cracks in the internal ceramic dielectric. The occurrence of ceramic dielectric cracks is related to mechanical stress.
3. Analysis of Failure Mechanism of Electrolytic Capacitor
The sample showed a decrease in capacity after a period of use in the energy meter. The failed sample numbers are F1 #, F2 #; suspected failed samples 1 # ~ 5 #; good products G1 # ~ G4 #.

![Sample appearance](image)

**Figure 5.** Sample appearance

3.1. Appearance observation and electrical parameter test
Observe the appearance of the sample. Among them, the rubber plug of sample 4 is prominent, and the pin of sample 5 is detached. Test the capacitance (C), loss (tgδ), and leakage current (LC) of the sample at room temperature. The test results are shown in Table 2.

| Numbering | C(μF)   | tgδ(%)  | LC(μA)  |
|-----------|---------|---------|---------|
| 1#        | 0.061   | 83.5    | 50      |
| 2#        | 0.021   | 157.5   | 90      |
| 3#        | 0.028   | 9.6     | 92      |
| 4#        | 0.003   | 228.9   | 11      |
| F1#       | 0.027   | 84.5    | 70      |
| G1#       | 0.049   | 99.91   | 8       |
| G2#       | 0.028   | 99.83   | 6       |
| G3#       | 0.003   | 98.58   | 5       |
| G4#       | 0.027   | 98.39   | 8       |

As can be seen from Table 2, the capacitance of the first sample (including good and failed products) is far lower than the qualification criterion, and the loss and leakage current of some samples are greater than the qualification criterion; The parameters of the sample to be sent are within the qualification criteria.

3.2. X-RAY observation
X-RAY observations were performed on all samples, and the internal anode lead-out piece of all samples for the first sample delivery was disconnected. The typical morphology is shown in Figure6.
3.3. Kaifeng Observation

Unpack and observe F1 #, F2 #, 3 #, G2 #.

Among them, F1 #, F2 #, and 3 # can be observed that the internal anode lead-out piece is disconnected, and there are a large number of foreign objects in the disconnected part, while the G2 # sample has no obvious abnormalities. The morphology after opening is shown in Figure 7.

![Figure 6. Typical X-RAY morphology of the sample](image)

**Figure 6.** Typical X-RAY morphology of the sample

![Figure 7. The appearance of the sample after opening](image)

**Figure 7.** The appearance of the sample after opening

3.4. Scanning electron microscope (SEM) and energy spectroscopy (EDS) analysis

SEM and EDS were performed on the foreign matter on the rubber plug at the anode disconnection position of the unsealed sample, and it was found that Cl was present in the foreign matter at the disconnection position. A typical SEM and EDS are shown in FIG. 8.
3.5. Comprehensive analysis

The failure mode of the sample is manifested as unqualified electrical parameters (capacity reduction, loss and leakage current increase). It can be seen from X-RAY: the position of the internal anode lead-out piece has been disconnected, and there are a lot of loose foreign objects in the disconnected position. At the same time, EDS proved that the foreign matter in its loose disconnection contains abnormal Cl elements. The presence of Cl-containing substances will lead to the corrosion disconnection of the
internal anode lead-out sheet, resulting in the failure of the capacitor open circuit. The anode lead-out piece of the sample is disconnected due to the corrosion of the Cl-containing substance, which leads to the failure of the open circuit of the capacitor.

4. Conclusion
Some typical failures are caused by the production process. For example, the manual board operation defects in the production process cause serious inaccuracy of the supplied product during operation, and the circuit board cleaning quality defects lead to the serious inaccuracy of the supplied product during operation. Some of them are caused by failures in the supply and marketing process. For example, the defects in the management of the supplier's manufacturing process lead to the potential of the energy meter. Some are caused by hardware design process failure, such as the energy meter cannot work normally after the AC voltage test, and the insufficient capacity design of the transformer causes the energy meter to show a positive error. Some are caused by software design failure, such as software design defects lead to automatic zero clearing of electricity meter energy.

Energy meter quality improvement measures, classify and filter failure modes and mechanisms, remove overstress failure cases, analyze which modules the failure is concentrated in, and feedback the obtained information to the design, manufacturing, materials and management departments for improvement to improve the inherent reliability of the product. At the same time, the life of its components is predicted through theoretical calculations, which paves the way for more accurate positioning of the problem and finally comes up with countermeasures to improve the quality of the energy meter.

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