Research on Test Method of Power Sensor Battery Considering the Influence of Air Flow

Wen Zhou1,2*, Yi Jiang1,2, Jing Zhang1,2, Chunlai Yu3 and Hao Zhu3

1 Nanjing NARI Group Corp., State Grid Electric Power Research Institute, Nanjing, China
2 Wuhan NARI Co Ltd., State Grid Electric Power Research Institute, Wuhan, China
3 Dalian Maritime University, Dalian, China
Email: zhouwen.nari@foxmail.com

Abstract. The reliability of sensor is an important index to determine the outdoor operation efficiency of power sensor, and the reliability detection of power sensor is an important means to ensure the reliability of network equipment. Based on the analysis of the thermal characteristics and thermal behavior of the battery, this paper studies the current detection methods of the low-temperature battery of the power sensor, and proposes a reliability test method of the power sensor considering the influence of outdoor airflow. Through multi-physical field simulation and analysis, the key parameters of relevant experiments are obtained, and the key test parameters are given.

Keywords. Power sensor; low temperature environment; reliability test.

1. Introduction
The on-line monitoring device can realize the functions of real-time perception, monitoring and early warning of the operation status of transmission lines and other equipment, and it is an important part of condition based maintenance. As an important way of energy storage in power sensor, battery plays an irreplaceable role [1]. General technical specification for intelligent monitoring device of transmission line which was published in 2010 specifies the ambient temperature on which the design is based: -25℃~+45℃ and a few equipment adopt -40℃~+45℃ extended industrial standard of ambient temperature. The outdoor temperature of Xinjiang, Heilongjiang and Inner Mongolia in northern China can reach below -40℃ (the minimum temperature is lower than -50℃), which is much lower than the above design index. The low reliability of power sensor in low temperature environment [2, 3] brings some difficulties to the actual operation. Although improving the reliability of equipment in low temperature environment is the fundamental method to improve the performance of sensors in low temperature environment, strict detection of the reliability of network access equipment is also one of the necessary technical means to improve the reliability of field equipment [4, 5], which is also of great significance to improve the application effect of power sensors.

2. Thermal Behavior of Battery and Thermal Analysis of Outdoor Battery
The process of heat generation and release is accompanied by the process of charge and discharge inside the battery, and the thermal process inside the battery is very complex [6]. All of its energy comes from the internal energy variation of the battery. In macroscopic view, the heat of the battery is released by reaction heat and Joule heat. Therefore, the thermal behavior of the sensor with battery is described according to the following model:
\[ Q = \Delta U + I^2 rt \]  

(1)

In this formula, \( Q \) is the total heat generated by the battery. \( \Delta U \) is the internal energy variation of the battery. \( I \) is the battery current, \( r \) is the total resistance of the battery and internal circuit, \( t \) is the time. It represents that all the heat of the sensor comes from the battery, one part is generated inside the battery, the other part is generated in the circuit outside the battery. The working temperature of the battery can be described by the following equation:

\[ \int \rho C \frac{dT}{dt} dv = \int Q dv + \int \nabla (\lambda \nabla T) ds \]  

(2)

In this formula, \( \rho \) is the density of the material, \( Q \) is the net heat production rate per unit volume of the electrode, \( C \) is the specific heat capacity, and \( \lambda \) is the thermal conductivity. The basic structure of the thermal process model is shown in figure 1.

![Battery cooling model](image)

Figure 1. Battery cooling model.

In this figure, \( C \) and \( C_s \) are the heat capacity of the battery and the battery to the shell, \( R_C \) is the internal thermal resistance of the battery, which can be ignored under steady-state conditions. \( R_a \) is the thermal resistance between the battery shell and the environment, \( T \), \( T_s \) and \( T_a \) are the average temperature inside the battery, the shell temperature and the environment temperature respectively.

According to Fourier’s law of heat conduction, the average temperature inside the battery should meet the following requirements:

\[ m_i C \frac{dT}{dt} = \dot{Q} - \dot{Q}_s \]  

(3)

In this formula, \( Q_s \) is the heat transferred from the inside of the sensor to the shell per unit time:

\[ \dot{Q}_s = \frac{T - T_s}{R_s} \]  

(4)

\( M_i \) is the mass of the battery. According to Newton’s cooling formula, the heat \( Q_e \) emitted to the environment per unit time is as follows:

\[ \dot{Q}_e = \frac{T_e - T_s}{R_e} \]  

(5)

Besides [7]:

\[ R_e = \frac{t_{e,ra}}{A_{e,ra} k_{e,ra}} \]  

(6)

\( t_{e,ra} \) is the thickness of the surface shell, \( A_{e,ra} \) is the effective heat dissipation area of the sensor shell, and \( K_{e,ra} \) is the thermal conductivity of the shell.
In stable condition, the heat balance equation of battery and external system is as follows:

\[ m_s C_s \frac{dT_s}{dt} = Q_s - Q_a = \frac{T_s - T_a}{R_s} - \frac{T_s - T_e}{R_e} \]  

(7)

\( m_s \) is the mass of the sensor’s housing.

Considering air convection and neglecting radiation, the basic equation is as follows [8, 9]:

\[
\frac{\partial}{\partial x} \left( \rho u C_p T \right) + \frac{\partial}{\partial y} \left( \rho v u C_p T \right) + \frac{\partial}{\partial z} \left( \rho w c_p T \right) = - \nabla \cdot \left( \lambda \nabla T \right) + S_f
\]  

(8)

In the above formula: \( \rho \) is the density; \( S_f \) is the heat generated and transferred to the micro element; \( C_p \) is the specific heat capacity; \( \lambda \) is the thermal conductivity; \( u \), \( v \) and \( w \) are the velocities of the airflow in \( x \), \( y \) and \( z \) directions respectively. Macroscopically:

\[ Q = \int S_f ds \]  

(9)

The whole model is a layered structure with a battery inside, and the overall calorific value of the model is \( Q \). The middle layer is made of uniform heat conduction material and the heat density from the battery into the middle layer is \( S_f \). The outside of the sensor is convective with the air. Besides, the air flow field and shell temperature are set equal to the ambient temperature \( T_c \).

3. Analysis of Working Conditions and Current Detection Methods

The battery of power sensor usually serves the following types of power sensors: Micro meteorological sensors commonly used on transmission lines, video monitoring devices, tower anti-theft devices, breeze vibration online monitoring devices, etc. The working state of different kinds of equipment is different, and the energy consumption is also quite different. There are three main working conditions, as shown in table 1 below:

| Working condition          | Working hours | Current value | Sensor type                  |
|----------------------------|---------------|---------------|------------------------------|
| Long-time charging         | 8h~24h        | 1mA~10A       | Weather, vibration, etc      |
| Short-time discharging     | 0.01h~1h      | 10mA~10A      | Video, temperature, etc      |
| Long-time discharging      | 24h           | 1mA~100mA     | Vibration, etc               |

For the battery performance at low temperature, the current national standard mainly focuses on the energy retention rate test at low temperature. The specific method is to put the battery in a low temperature environment with specified ambient temperature level for 48 hours after standard charging. Then, the battery is discharged at constant current with \( I_{10} \) (A) current until the voltage drops to the discharge termination voltage specified by the manufacturer. The ratio between discharge energy \( E_1 \) and rated capacity \( E \) is calculated to obtain the low temperature energy retention rate. Obviously, this test method does not consider the actual working condition of the sensor, and the data obtained by the test method is far from the actual application.

4. Design of Testing Mechanism

Generally, the convection coefficient of solid in air under natural conditions is between 5 and 25.

\[ w = w_{10} \left( \frac{y_h}{10} \right)^a \]  

(10)
The wind speed $w_{10}$ is the reference meteorological wind speed at the height of 10 m; $y_n$ is the ordinate of the node in the calculation area.

The gas flow inside and outside the contactor satisfies the control equation of steady gas flow field, and the continuity equation and momentum equation are as follows [10]:

$$\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0$$

(11)

In this formula, $P$ is the air pressure; $P_r$ is the boundary pressure; $P_0$ is the ambient pressure.

The current test method does not consider the impact of wind speed on heat dissipation, so it has a great impact on the test results, which leads to high fault rate of power sensor at low temperature.

5. Simulation and Analysis of Multiple Physical Fields

5.1. Establishment of Sensor Model

The internal space of electronic equipment is mostly air, and has circuit device and mechanical structure for fixing [6]. Combined with the working environment of the transmission line sensor, the effectiveness of the detection device is verified by simulation, and the following model abstraction is made: (1) The shell is adiabatic boundary condition; (2) The internal material of the sensor is uniform; (3) The flow field is laminar; (4) Radiation is not considered; (5) The results in steady state are mainly considered, and the influence of heat capacity in thermal system for a long time is ignored [11]. The law of air flow distribution outside and temperature distribution inside the sensor is studied under the condition of large space. According to the actual situation, the diameter of the sensor is set to 54mm, and a battery18650 is installed inside, as shown in figure 2.

5.2. The Effect of Wind Speed on Temperature

The radius of the air passage is 0.5m. When the ambient temperature is -40°C and the wind speed is low ($v = 0.01$m/s), the maximum internal temperature of the sensor can reach -34.4°C. Under the medium wind speed ($v = 5$m/s, three-level wind), the temperature inside the sensor decreases to -39.7°C. When the wind speed continues to increase to high wind speed ($v = 10$m/s, level 5 wind), the internal temperature of the sensor still drops and is close to the ambient temperature. Figure 3 shows the temperature distribution inside the sensor at 10m/s wind speed.

Under different wind speeds, the temperature change trend is basically the same as the experimental data [12] and the maximum temperature difference inside the sensor is 5 degrees Celsius, which can be seen from figure 4.
5.3. The Coupling of Wind Speed and Internal Surface

From the simulation of figure 5, we can see that the coupling of the sensor shape and the boundary will be small and the velocity won’t be affected by the boundary when the outer diameter of the pipe is more than 10 times longer than the sensor diameter. However, it is difficult to build a large diameter air passage in the laboratory, both in terms of cost and technology. Through further analysis of the air velocity on the cross section, the air velocity changes significantly when it is close to the sensor. when the outer diameter of the pipe is much more than 3 times longer than the sensor diameter, the influence of the sensor on the flow rate will sharply decrease, which is also show in figure 5. Figure 6 is a cross-sectional view along the air flow direction. The air flow direction is from the negative direction of X axis to the positive direction. The attenuation of axial velocity on the windward side and leeward side of the sensor is large. As shown in figure 5, when the axial distance is 0.08m, the outer radial velocity value of the sensor is distributed near the sensor and its inner wall, which has a particularly obvious surface adhesion effect. But in the middle area, when the distance from the sensor surface reaches 0.2m, the air velocity is almost no longer affected by the sensor. When the radial distance of the inner wall surface is 0.09m, the influence of the inner wall on the air flow will decrease rapidly.

Figure 3. Temperature distribution sensor at 10m/s wind speed.

Figure 4. Maximum temperature curves inside the corresponding to different wind speeds.

Figure 5. Gas flow and pressure distribution in wide diameter (r > 10R).

Figure 6. Distribution diagram of the axial velocity of the sensor (x=0.08).
According to the above analysis, if we want to completely avoid the influence of the boundary, the radius of the pipeline should not be less than 0.3m. Through the simulation, we can see that the influence of boundary on air flow is eliminated when the axial distance is 0.2m. At this time, the diameter of the pipe is 0.6m, but the diameter of the experimental sample is only 0.054m, which will cause a huge waste of space.

If the pipe diameter is further reduced, the wind speed will change. As shown in figure 7, the decrease of pipe diameter results in the increase of air velocity around the sensor.

![Figure 7. Axial velocity and temperature distribution of sensor (x=0.08, R=0.1m).](image)

6. Conclusion
The effect of air flow on the internal temperature of the sensor is very obvious. When the wind speed is high, the temperature inside the sensor is much lower than that in the case of no wind. It can be seen that the original test method has great defects. Thus we suggest to consider the influence of air flow on temperature and environmental factors to further improve the accuracy of the test.

The detection method can adopt the channel type air flow detection method. In order to ensure the detection accuracy, the diameter of the channel should be at least three times longer than the diameter of the tested sample. The local airflow’s distortion will not influence the result of temperature detection obviously, so the pipeline measurement method is of great value.

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