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Modeling and Control of the Precision for the building energy consumption monitoring system

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Abstract. Building energy conservation has become to be one of the major tasks of promoting energy conservation and raise the efficiency of energy consumption. Meters are the source of data, it is important to study data precision model based on the accuracy of the error analysis method. This paper firstly introduces error analysis, error distribution and error control theory, then take electric and heat meters for example to describe the error analysis and error distribute methods. The results show that when the precision level of voltage is 0.2, current is 0.2 and power factor is 0.5, the maximum relative error of electrical quantity can be controlled less than 1%, meet the requirement of measurement. The total relative error of heat meter is inverse proportion with temperature difference of sensor and water flow, and when the temperature difference remains unchanged, the error of heat meter trends to main steady if the instant flow of water more than half of the normal flow value.

Introduction

The energy consumption of China has occupied 20.3% of global energy consumption, and has passed the U.S. to become the world's biggest energy consumer, according to the Statistical Review of World Energy by BP in 2011[1]. The future, the energy demand is still growing and the growing trend will continue in absolute terms. In all of kinds of energy consumption, industry, transportation, and construction are the three main aspects. Energy consumption of building can reach 40% of total energy consumption, according to the experience of developed countries. Therefore, energy-saving of buildings becomes to be one of the major tasks of promoting energy conservation and raise the efficiency of energy consumption [2].

Know yourself and know your enemy, and you will never be defeated. All the dwellers can obtain the bills of electricity and water consumption each month and know the amount of energy consumption exactly. However, almost nobody knows when and where the energy consumption occurs. People can make more sensible decisions to lower the energy consumption if they get these data. In order to achieve real-time data of energy consumption in buildings, and build the platform for evaluating energy saving effect, the building energy consumption monitoring and management system must be developed [3-6]. There are several key technology problems urgent to be solved, such as network architecture of system, data acquire and transmit method, database technology, and so on. These technologies have been studied in recent years, but little concerns on the research of data precision model of meters used in system. Meters are the source of data information, the measured value will lead to serious deviation if the error analysis model of meter could not meet the accuracy requirement, and this deviation will continue to grow. Therefore, it is crucial to study data precision model based on the accuracy of the error analysis method.

In the following section, this paper analyzes the basic physics of monitoring system, introduce error analysis principle and formula deduction, take electric and heat measurement for example to describe the error analysis and error distribute methods.

Monitoring object

There are many objects needed to be monitored in order to obtain the building energy consumption information data, the quantity of electricity, water, heat, cold and gas. The electrical monitored items include illumination and outlet system, motive force system, heating ventilating and air conditioning system and others. Measured electrical parameters contain three phase voltages, three phase currents, active power, reactive power, frequency factor and quantity of electricity. Measured heat parameters include the temperature of supply and return water, the flow and rate of hot water. Cold parameters are the same as heat. There is only one parameter monitored in the water and gas system, namely quantity. Three-phase multifunction watt-hour meter, intellectualized water meter, intelligent heat meter, gas meter are common meters used in the building energy monitoring system which needed to be equipped with field bus interface.

Error analysis principle

There two ways for physical quantities measurement, direct and indirect. The error of indirect measurement method which needs to be calculated by correlation function and the value measured through direct measurement, not only relates to the error of each part of direct measurement, but also the form of correlation function. This is usually called error propagation. Assume the factor caused indirect measurement error is random and independent one another and the function can be written as [7]

$$y = f\left(x_1, \ x_2, \ \ldots\ldots, \ x_{\mathrm{n}}\right) \tag{1}$$

There exists some error in the indirect method too, so the error of indirect measurement function can be express as

$$y + \delta_y = f\left(x_1 + \delta_{x_1}, x_2 + \delta_{x_2}, \ \ldots, x_{\mathrm{n}} + \delta_{x_n}\right) \tag{2}$$

Where y is indirect value, δ_y is the total error of indirect, x_{i} and $\delta_{x_{\mathrm{i}}}$ are the independent direct variable and the error caused by direct variable, respectively.

Standard error used widely in practical project, which is square root of mean-square error, to estimate the reliability of the measurement data. The expression of standard error is

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \overline{y})^2}{n}} \tag{3}$$

It can be derived that the standard error of indirect measurement

$$\sigma_y = \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 \cdot (\sigma_{x_1})^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 \cdot (\sigma_{x_2})^2 + \ldots\ldots + \left(\frac{\partial f}{\partial x_n}\right)^2 \cdot (\sigma_{x_n})^2} \tag{4}$$

In the expression, $\delta_y = y - \overline{y}$ .The Eq.4 can be transformed into Eq.5.

$$\left(\frac{\partial f}{\partial x_1}\cdot\frac{x_1}{y}\right)^2\left(\frac{\sigma_{x_1}}{x_1}\right)^2+\left(\frac{\partial f}{\partial x_2}\cdot\frac{x_2}{y}\right)^2\left(\frac{\sigma_{x_2}}{x_2}\right)^2+\ldots\ldots+\left(\frac{\partial f}{\partial x_n}\cdot\frac{x_n}{y}\right)^2\left(\frac{\sigma_{x_n}}{x_n}\right)^2\le\left(\frac{\sigma_y}{\mathrm{y}}\right)^2 \tag{5}$$

Here, the conclusion is the value of $E(\sigma_{x_i})$ on the left side can be any value to satisfy the inequality (6). The equation can be simplified as (7) based on the principle of equal effect.

$$\left(\frac{\partial f}{\partial x_1}\cdot\frac{x_1}{y}\right)^2 E^2\left(\sigma_{x_1}\right)+\left(\frac{\partial f}{\partial x_2}\cdot\frac{x_2}{y}\right)^2 E^2\left(\sigma_{x_2}\right)+\ldots\ldots+\left(\frac{\partial f}{\partial x_n}\cdot\frac{x_n}{y}\right)^2 E^2\left(\sigma_{x_n}\right)=E^2\left(\sigma_y\right) \tag{6}$$

$$E\left(\sigma_{x_i}\right)=\frac{E\left(\sigma_y\right)}{\sqrt{n}}\left(\frac{\partial f}{\partial x_i}\cdot\frac{x_i}{y}\right)^{-1} \tag{7}$$

Electrical parameter precision

The active power is the product of voltage, current and power factor, and the calculation expression can be described as

$$\begin{cases} P=P_{\mathrm{A}}+P_{\mathrm{B}}+P_{\mathrm{C}} \\ P_{\mathrm{A}}=U_{\mathrm{A}}I_{\mathrm{A}}\cos\varphi_{\mathrm{A}} \\ P_{\mathrm{B}}=U_{\mathrm{B}}I_{\mathrm{B}}\cos\varphi_{\mathrm{B}} \\ P_{\mathrm{C}}=U_{\mathrm{C}}I_{\mathrm{C}}\cos\varphi_{\mathrm{C}} \end{cases} \tag{8}$$

Where P is the total active power (W), P_A, P_B and P_C are three-phase active power (W), U_A,U_B and U_C are three-phase line voltage (V), I_A, I_B and I_C are three-phase line current (A), $cos\varphi_A$, $cos\varphi_B$ and $cos\varphi_C$ are three-phase power factor. Here, with active power of A phase is example to deduce the maximum relative error.

The maximum absolute error of measured value of A phase active power is

$$\left|\sigma_{P_{\mathrm{A}}}\right|=\sqrt{(I_{\mathrm{A}}\cos\varphi_{\mathrm{A}})^2(\sigma_{U_{\mathrm{A}}})^2+(U_{\mathrm{A}}\cos\varphi_{\mathrm{A}})^2(\sigma_{I_{\mathrm{A}}})^2+(U_{\mathrm{A}}I_{\mathrm{A}})^2(\sigma_{\cos\varphi_{\mathrm{A}}})^2} \tag{9}$$

Thus, the maximum relative error is

$$E(\sigma_{P_{\mathrm{A}}})=\frac{\left|\sigma_{P_{\mathrm{A}}}\right|}{P_{\mathrm{A}}}=\sqrt{\left(\frac{\sigma_{U_{\mathrm{A}}}}{U_{\mathrm{A}}}\right)^2+\left(\frac{\sigma_{I_{\mathrm{A}}}}{I_{\mathrm{A}}}\right)^2+\left(\frac{\sigma_{\cos\varphi_{\mathrm{A}}}}{\cos\varphi_{\mathrm{A}}}\right)^2} \tag{10}$$

Assume maximum relative error $E(\sigma_{P_{\mathrm{A}}})=\varepsilon$, the maximum range of permitted error can be obtained according to the formula (7) and equal effect principle.

$$\begin{cases} E(\sigma_{U_{\mathrm{A}}})\le\dfrac{\varepsilon}{\sqrt{3}} \\ E(\sigma_{I_{\mathrm{A}}})\le\dfrac{\varepsilon}{\sqrt{3}} \\ E(\sigma_{\cos\varphi_{\mathrm{A}}})\le\dfrac{\varepsilon}{\sqrt{3}} \end{cases} \tag{11}$$

Take some electrical meter for example to explain error control method, its voltage range is 0~250V, current range is 0~200A, power factor range is 0~1, with voltage accuracy is 0.2, current accuracy is 0.2 and power factor accuracy is 0.5, respectively. To ensure ε less than 1%, the error accuracy of voltage, current and power factor must less than 0.46%, under the principle of equal effect. On the basis of definition of accuracy of meter, namely, the maximum absolute error and the range ratio, so the maximum absolute voltage error is 0.5V, the maximum absolute current error is 0.4A and the maximum absolute power factor is 0.005. Set measured voltage is 220v, current is 150A and power factor is 0.9 in the current working condition. Then, the maximal relative error of voltage is 0.23%, the maximal relative error of current is 0.27% and the maximal relative error of power factor is 0.56%. In this case, the calculated relative error of active power is 0.66%, meet the demand that ε is less than 1%.

Heat parameter precision

The calculate formula of heat quantity is as Eq.12, where Q is measuring value (kW), q is water mass flow (kg/s), h_1 and h_2 are inlet and outlet enthalpy values (kJ/kg), respectively, t is cumulative time (s).

$$Q = \int_0^t q(h_2 - h_1)dt$$

(12)In the application, mass flow is obtained from the product volume flow and density of fluid, and the measurement is volume flow. Enthalpy is a function of temperature. Hence, the value of heat quantity is related to volume flow and temperature. The relative error of flow sensor is$\left(3+0.05\,q_{\mathrm{p}}/\mathrm{q}\right)\%$, temperature sensor is$\left(0.5+3\theta_{\min}/\Delta\theta\right)\%$, and the relative error of calculator is$\left(0.5+\theta_{\min}/\Delta\theta\right)\%$. On these grounds, the total relative error of heat meter is

$$E(\sigma_Q) = 4\% + 4\frac{\Delta\theta_{\min}}{\Delta\theta}\% + 0.05\frac{q_{\mathrm{p}}}{q}\%$$

(13)Where $\Delta\theta$ is temperature difference between inlet and outlet water (°C),$\Delta\theta_{\min}$ is the minimum of $\Delta\theta$, (°C),q is mass flow (kg/s),and q_{p} is normal flow (kg/s).

As shown in Eq.13, relative error and not only temperature difference, but also flow are negative ratio. However, the weight of temperature is 4, while flow is only 0.05. Thus, the effect of temperature difference must be greater than the flow. Take some heat meter for example to describe the effects on the relative error. Set normal flow is 6m^3/h, minimum and maximum flow is 0.156m^3/h and 12m$^{3/}$h, respectively.

The relative error of heat meter reaches peak value at 10% when temperature difference and flow are at minimum value at the same time from Fig.1. When the flow rate remains unchanged, the error will decrease with increasing temperature difference. Nevertheless, the error changes little while the flow is greater than normal value, because the weight of flow is lower. Fig.2 shows relative error tendency with the flow of water under the condition that temperature difference is at minimum value, 2 times, 4 times and 6 times minimum values. The error changes obviously when the flow is less than half normal flow value, otherwise, maintains stability.

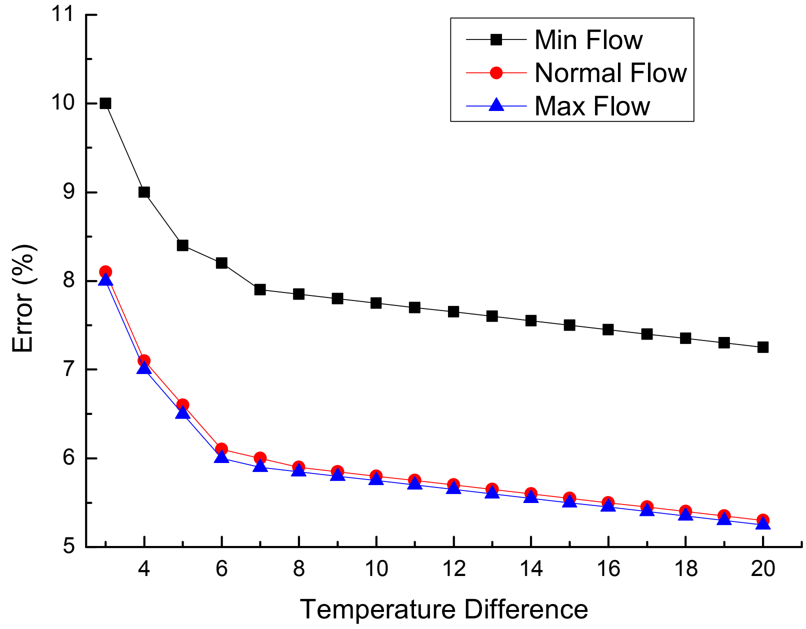

Fig.1 Relationship between relative measuring error of heat meter and temperature difference between inlet and outlet

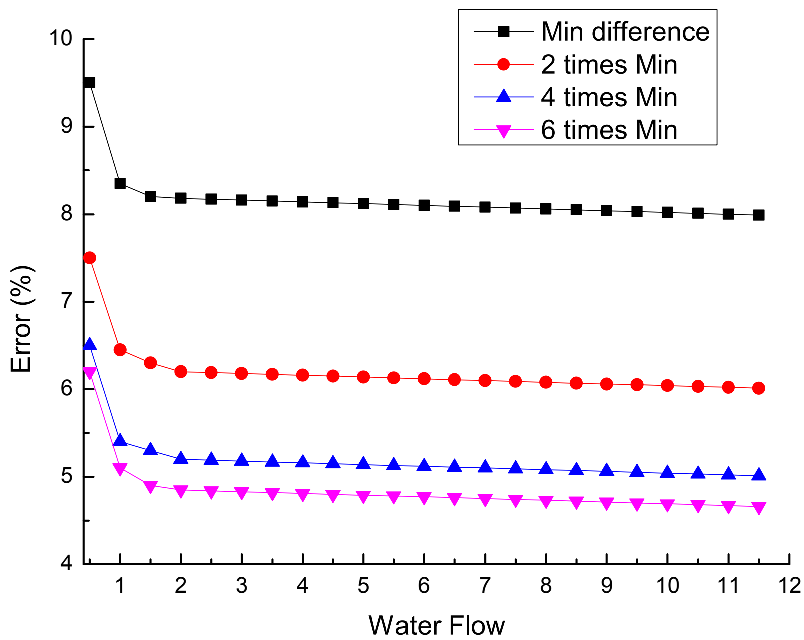

Fig.1 Relationship between relative measuring error of heat meter and water flow

Summary

Data precision model of meters play an important role in the building energy consumption monitoring system, which determines the availability of energy data. This paper establishes the equation of data accuracy model based on the error analysis theory. Introduces error control method of electrical and heat energy consumption. The results of this paper are as following:

（1） In order to achieve the maximum relative error of electrical quantity less than 1%, the voltage and current precision can be selected 0.2 level, with the accuracy of power factor is 0.5.

（2） When the flow keeps constant, the total relative error of heat meter and temperature difference of sensor is inverse proportion, the error reduces quickly while the temperature difference increasing. While the difference remains unchanged, the relative error of heat meter trends to main steady when the instant flow of water more than half of the normal flow value.

（3） The accuracy of meter needs to be adjusted flexibly according to the different proportion in the system in order to realize the best performance. The precision of meter is as higher as better when it plays an important role in the monitoring system, otherwise, the requirements of meter can be loosed to reduce the cost of project, under the promise of error analysis.

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