Optimization Of The Measurement Precision Consistency Of Single-Phase Smart Electricity Meters In Full Temperature Range

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Abstract. With the development of smart power grids, smart electricity meters are widely applied to industrial production and the life. For interests of the power supply and consumption parties, electricity meters are required to have high quality, precision and consistency. As temperatures vary considerably in south and north of China and electricity meters work in complex temperature environments, studies on the effects of temperature on power metering are of significant importance. In this paper, an optimization method considering the effects of temperature is proposed for the consistency of electricity meters. The precision consistency of electricity meters is optimized in full temperature range through means such as electrothermal coupling simulation, orthogonal test, cost calculation, etc., and the design scheme of electricity meters with maximum cost performance can be delivered for their manufacturers.

1. Introduction

In the context of power grid automation, rapid development has been made by electricity meters. As the practice of one meter for one household is promoted, the use of electricity meters has increased significantly. The fairness, accuracy, and reliability of electricity meters are directly related to the interests of the power supply and consumption parties. Therefore, as a social focus, high quality, accuracy, and consistency are required for electricity meters.

In recent years, the error consistency of smart electricity meters has gradually drawn more attention, and it has been defined by Chinese national standards [1]. In literature [2]-[3], a qualitative analysis of error sources of smart electricity meters is presented, and the precision of the key components shown. In literature [4], it is demonstrated by tests that the error consistency for measuring load current by electronic current sensors improves considerably, which contrasts with traditional analog circuits. In literature [5], the source errors of smart electricity meters are analyzed from multiple perspectives, and effective ways for control of errors and consistency errors of the meters are concluded. In literature [6], a mathematical model for On-Off-Key dynamic load current signals is built, and a mathematical model is proposed for dynamic power load series; modes of dynamic load power are defined, i.e., transient, short-term and long-term dynamic load mode, based on which, an algorithm for measuring of dynamic errors of electricity meters is developed. In literature [7], a model is set up for electric vehicle charger, in which the line impedance and
distribution transformers are dealt with, and the simulation analysis of the effects of high-power direct-current charging and pulse charging on power metering is presented.

It's worth noting that different from electromechanical electricity meters, hardware debugging rather than software calibration, is used in factory inspection of smart electricity meters (i.e., electronic electricity meters) [8]. Although the precision of electricity meters is thus guaranteed in the factory, the error sources are not eliminated or reduced fundamentally; once external interference is present, measuring the stability and consistency of electricity meters are affected. However, only certainties are considered in the optimization design of smart electricity meters, and uncertainties in actual conditions, such as ambient temperature, harmonic wave, are not dealt with. Meter performance is impacted by such uncertainties, and failures are even caused. In that latitudes and temperatures are far different in southern and northern China, where electricity meters work in complex conditions and effects of temperature on the consistency of electricity meters' performance are not fully considered, exploring the effects of temperature on precision consistency of the meters has important significance.

Hence, in this paper, for optimization of the measurement precision consistency of single-phase smart electricity meters in full temperature range, measurement principle and error sources of such meters are first analyzed; then an optimization method considering the temperature is proposed for the consistency, using electrothermal coupling simulation, Monte Carlo analysis, orthogonal experiment and performance-cost model; at last, the consistency is optimized, and optimal design schemes are delivered to meet different requirements on costs.

2. Measurement principle and error sources of electricity meters

Smart chips are the core of electricity meters, which are electronic electricity meters with functions such as power metering, timing, charge calculation, communication with the upper computer, power consumption management, etc.[10] In Figure 1, the hardware block diagram of typical single-phase electricity meters is represented, which includes the metering system and the single-chip processing system. The metering system is the key part for metering accuracy; usually, voltage signals are sampled by resistance divider network, and current signals by microcurrent transformer; such signals are delivered to the metering chip, where they are converted into power signals by the multiplier, and output to the single-chip through SPI bus in the form of pulse signals. The pulse signals are accumulated and processed by the single-chip system, which calculates charges by the charge rate; the meter components are controlled and coordinated by this system.

![Figure 1. Measurement Module Schematic](image)

In Figure 2, the sampling circuit of resistance divider is demonstrated; the circuit of the copper-manganese current sampler is shown in Figure 3:
The sampled current and voltage signals are low-voltage analog signals; after being delivered to metering chip, the signals are amplified by PGA, and then undergo A/D conversion; after A/D conversion, current signals go through phase-correcting circuit to match voltage signal phase, and then high-pass filter for elimination of DC component. Phase correction and high pass filtering are not necessary for voltage signals. Following multiplication of current and voltage signals in multiplier and such signals going through low pass filters, instantaneous active power can be worked out.

3. An optimization method of consistency considering temperature

It's shown by analysis that temperatures have significant effects on the consistency of measurement precision of electricity meters. To improve such consistency in full temperature range, an optimization method considering the effects of temperature is proposed in this paper.

First, the electrothermal coupling simulation model is built for measurement module of electricity meters, and Monte Carlo simulation is applied for evaluation of the measurement precision; the simulation results show distributions of the precision consistency at the temperatures. Then tolerance optimization is conducted, with effects of temperatures considered; controllable factors influencing the measurement precision are analyzed; orthogonal experiment is performed with the noise factor of temperatures; through Monte Carlo simulation, measurement precision consistency is worked out for the tolerance combinations in full temperature range, and signal to noise ratio (SNR) is calculated. Finally, tolerance combinations with maximum cost performance are chosen, with SNR and component costs taken into account. See Figure 4 for details of the optimization process.

Figure 2. Resistor Divider Circuit
Figure 3. Manganese-copper Current Sampling Circuit

Figure 4. Optimization Process of Measurement Accuracy Consistency in the Full Temperature Range
3.1. Evaluation of the measurement precision consistency before optimization

With the component parameters gained from experiments and item list of electricity meter, distribution of resistance divider and copper-manganese sampler, and of the reference voltage of metering chip, etc. are obtained. Based on such distribution, random numbers are determined for the simulation model; thus, parameter values are generated randomly for simulation of parameter tolerance and parameter distribution in full temperature range; through simulation, component parameters and power measurement values are obtained; thus, distribution of measurement errors of electricity meters can be determined.

3.2. Orthogonal experiment considering temperature and noise

In an orthogonal experiment considering temperature and noise, the errors between measured and theoretical power values are the output; temperatures are the noise factors and components that have effects on measurement precision the controllable factors; factor level represents the tolerance range. In Figure 5, the number and levels of factors are 4 and 3 respectively; the inner table is orthogonal table L9, and the outer table orthogonal table considering temperature and noise. Only number 1 is given to the noise factor, and other noise factors are represented by T_i.

![Figure 5. Orthogonal Test Table Considering the temperature](image)

At the temperatures, relative error \( y \) is calculated for 100 power values in the tolerance combinations; the average value \( \mu_y \) of the 100 relative errors and the standard deviation \( \sigma_y \) are also calculated; on this basis, consistency of the measurement precision is analyzed. \( \mu_y \) closer to 0 indicates higher measurement precision, and smaller \( \sigma_y \) shows the smaller fluctuation in errors and better consistency of measurement precision. To deal with measurement errors and precision comprehensively, \( Y \) is introduced for evaluation of consistency, thus allowing quantitative evaluation. If \( y \) obeys normal distribution \( N(\mu_y, \sigma_y^2) \), it’s better \( \mu_y \) is small and \( \sigma_y^2 \) is also small (small fluctuation). Accordingly, \( Y \) is represented in formula (1):

\[
Y = \sqrt{\mu_n^2 + \sigma_n^2}
\]  

(1)

where \( \mu_n \) and \( \sigma_n \) are normalization results of \( \mu_y \) and \( \sigma_y \). The nomination of \( \mu_y \) is represented in formula (2):

\[
\mu_n = \frac{\mu_y - \mu_{y, \text{min}}}{\mu_{y, \text{max}} - \mu_{y, \text{min}}}
\]  

(2)

where \( \mu_{y, \text{max}} \) denotes the upper bound value of \( \mu_y \); \( \mu_{y, \text{min}} \) indicates the lower bound value of \( \mu_y \). Substitute \( \mu_n \) and \( \sigma_n \) into formula (1) for calculation of \( Y \). Smaller \( Y \) indicates \( \mu_n^2 + \sigma_n^2 \) closer to 0, higher measurement precision, and better consistency.

Signal to noise ratio (SNR) is a stability index measuring product quality; it shows products' resistance to quality fluctuation as a result of internal and external interference. According to the previous analysis, smaller \( Y \) is better; to measure the effects of temperature noise on measurement precision consistency, SNR is introduced, to judge quantitatively the resistance to temperature noise in the tolerance combinations.
If at 12 temperature points, $Y_i(i=1,2,3……11, n, n=12)$ is obtained in a certain tolerance combination, with smaller-the-better $Y$, $\eta$ is represented as:

$$\eta = -10\log\frac{1}{n}\sum_{i=1}^{n} Y_i^2 \quad (3)$$

3.3. Determination of optimal combinations considering SNR and costs

In practical production of electricity meters, high precision and performance should not be the only points of attention; otherwise, production costs will increase significantly, with cost performance reduced, which has negative effects on production and sales of the meters. Therefore, in the optimization of the measurement precision consistency, production costs should be taken into account; optimization schemes should be adopted according to the requirements of electricity meter manufacturer, and the meter performance and price.

With SNR and costs considered, $V$ is introduced for evaluation of performance and costs, as represented in formula (4):

$$V = w_1 \eta - w_2 P_n \quad (4)$$

where $w_1$ represents the weight of SNR and $w_2$ weight of the costs $0 < w_1 < 1, 0 < w_2 < 1, w_1 + w_2 = 1$. $\eta_n$ and $P_n$ indicate the normalized SNR and costs, respectively. Greater $V$ means higher performance and lower costs.

4. An optimization example for measurement precision consistency of smart electricity meters in the full temperature range

4.1. Measurement modeling of smart electricity meters based on electrothermal coupling

4.1.1. Power loss modeling of the transformer.

The transformer is the main heating element in smart electricity meter, so it is necessary to establish its power loss model. Build its power loss model in Saber, and obtain its heating power by combining the measured excitation parameters and vector method analysis. The transformer model in Saber is shown in Figure 6.

![Figure 6. The transformer model in Saber](image)

Where $r_1$, $r_2$, $r_3$, and $r_4$ are DC resistance of primary and secondary sides; $L_1, L_2, L_3$, and $L_4$ are the primary and secondary leakage inductance; $R_{10}, L_{10}$ are the primary excitation resistance and inductance of the transformer. After simulation analysis, the error between the simulated power loss and the measured data is about 8.5%.
4.1.2. Electrothermal coupling simulation.

The establishment of the whole meter model is to export the 3D model of PCB board and components through Altium designer software, then assemble and simplify with other 3D models, and finally get the simulation model that can be used in Icepak software. Because there are many problems in the 3D model after assembly, there is a lot of interference and non-meshing surface, so ANSYS SCDM software is used to modify the whole model.

The thermal simulation takes into account the coupling effect of temperature and component performance, that is, the electrothermal coupling effect. Firstly, according to the results of temperature field simulation, the parameter values of each component in the power circuit of the meter are calculated, and the heating power of the transformer and related components is obtained by running saber simulation. The newly obtained heating power is input into the ANSYS Icepak model to obtain the new temperature field distribution of the meter. Compared with the temperature of the main components obtained by the previous temperature simulation, if the temperature difference is less than the threshold value, the thermoelectric balance is achieved. With the increase of the number of coupled simulation iterations, the input temperature of the main devices gradually stabilized. The temperature distribution of the whole meter is shown in Figure 7. The temperature simulation and measurement results of key components at 70 ℃ are shown in Table 1.

![Figure 7](image_url)

**Figure 7.** Cloud chart of temperature distribution at ambient temperature of 70 ℃

**Table 1.** Simulation results and the measured temperature of key components of the transformer

|                     | Ambient temperature | PCB  | PTC   | Relay | Transformer | Chip   |
|---------------------|---------------------|------|-------|-------|-------------|--------|
| simulation °C       | 70.0                | 73.6 | 76.5  | 72.3  | 78.3        | 72.7   |
| After 2h°C          | 70.8                | 74.3 | 73.4  | 70.7  | 74.5        | 72.5   |
| After 4h°C          | 70.9                | 74.6 | 74.0  | 71.1  | 74.1        | 72.7   |
| Relative error      | 1.3%                | 1.73%| -3.23%| -2.98%| -5.17%      | 0.01%  |

By comparing the simulation data with the measured data, it can be seen that the simulation results are basically consistent with the measured results. The temperature simulation error of the PTC thermistor is about -5.17%.
4.1.3. Metering model of electric meter considering temperature effect.

Temperature and tolerance factors should be considered in the establishment of partial voltage resistance and manganese copper strip model. The variable resistance model of them can be expressed as follows:

\[ v = i \times R \times (1 + (t_{do} - 25) \times coeft) + u \]  

(5)

where \( v \), \( i \) is expressed in volts and amperes, \( R \) is defined as the nominal resistance at 25 °C in ohm, \( t_{do} \) is defined as the current temperature, \( coeft \) is defined as the temperature coefficient, and \( u \) is the effect of resistance tolerance.

The model reflecting the change of reference voltage with temperature can be established as follows:

\[ V_S = \frac{v_1}{v_{ver}} \times 1.25 \]  

(6)

The variable \( v_1 \) is in volts. \( v_{ver} \) represents the actual value of the reference voltage at the current temperature. After the voltage signal \( v_1 \) is input, after conversion, the output voltage \( V_s \).

In the model of measurement chip, the current signal and voltage signal is first to gain, and the gain ratio is consistent with the default value inside the metering chip, and then the zero-order holder is transformed into discrete signal. A high pass filter is added to the current channel to simulate the high pass filtering process inside the metering chip to eliminate low-frequency noise. Because the filter module will add the current signal phase offset, the phase compensation module is added to adjust the signal to the initial phase. After calculating the active power, the signal is connected to a low-pass filter to simulate the low-pass filtering process inside the metering chip, and the active energy measurement is completed through the integration module.

4.2. Evaluation of the measurement precision consistency of electricity meters before optimization

With the existing parameter distribution, the 100 power values obtained at the temperature points using Monte Carlo simulation are recorded, and the relative errors are calculated. Histogram with the normal distribution of measurement errors at the temperatures is shown below in Figure 8.

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4.2. Evaluation of the measurement precision consistency of electricity meters before optimization

With the existing parameter distribution, the 100 power values obtained at the temperature points using Monte Carlo simulation are recorded, and the relative errors are calculated. Histogram with the normal distribution of measurement errors at the temperatures is shown below in Figure 8.
After data processing, the normal distribution histogram of measurement error at each temperature before the optimization is obtained, as shown in Figure 8. It can be seen that the measurement error before the optimization is 1.47% ~ 3.03%, the measurement accuracy is low, and the standard deviation is about 0.06. Taking the measurement error distribution of electric energy meter at 70 ℃ as an example, when the confidence probability is 99.76%, the measurement error distribution interval is \([\mu - 3\sigma, \mu + 3\sigma] = [-0.1533, 0.2139]\), and the maximum measurement error can reach 21.39%. This shows that the consistency of measurement accuracy before the optimization is poor, and it is easy to be affected by temperature.

4.3. An orthogonal experiment considering temperature and noise

In an orthogonal experiment considering temperature and noise, the output is the relative error of power measurement; temperature is the noise factor, and the controllable factors are reference voltage \(V_{\text{ref}}\), resistance divider 1, and 2, and copper-manganese sampler. Levels of the factors represent tolerance ranges. Resistance divider 1 and 2 are chip resistors; 3 accuracy classes available in the market are chosen for the resistors: 2%, 1%, 0.5%; 3 precision classes which are available in factories are chosen for the copper-manganese sampler: 6%, 4%, 2%. Besides, as the reference voltage is not stable in a metering chip, the voltage tolerance should be determined through practical measurement. Thus, levels of the factors are determined, as shown in Table 2.

| Table 2. The Factors and Their Values of Each Level |
|-----------------------------------------------|
| Factor | Type            | Number of levels | The value of each level |
|--------|-----------------|------------------|------------------------|
| \(V_{\text{ref}}\) | controllable     | 3                | \(A_1=0.2\%, A_2=0.15\%, A_3=0.1\%\) |
| Voltage divider 1 | controllable | 3                | \(B_1=2\%, B_2=1\%, B_3=0.5\%\) |
| Voltage divider 2 | controllable | 3                | \(C_1=2\%, C_2=1\%, C_3=0.5\%\) |
| Manganese-copper sheet | controllable | 3                | \(D_1=6\%, D_2=4\%, D_3=2\%\) |
| Temperature | controllable | 12               | \(T_1=-40^\circ C, T_2=-30^\circ C, T_3=-20^\circ C, T_4=-10^\circ C, T_5=0^\circ C, T_6=-10^\circ C, T_7=20^\circ C, T_8=30^\circ C, T_9=40^\circ C, T_{10}=50^\circ C, T_{11}=60^\circ C, T_{12}=70^\circ C\) |

There are 4 controllable factors in total, each of which has 3 levels; \(L_{13}\) is the inner orthogonal table, and temperature noise represents the outer table. Order of SNR for the tolerance combinations is as below:

\[ L_5 > L_{13} > L_9 > L_7 > L_3 > L_{10} > L_6 > L_{12} > L_5 > L_{16} > L_{15} > L_4 > L_6 > L_4 > L_{16} > L_{15} > L_1 > L_7 \]

With smaller-the-better characteristics, higher SNR indicates better measurement precision consistency of the combination in the full temperature range. Below is the example of \(L_5\) combination—which has the maximum SNR—for comparison with that before optimization.

A comparison of the measurement error probability distribution before and after the optimization is presented in Figure 9. It can be seen that (reference voltage fluctuation range is 0.15%, 150k Ω partial voltage resistance accuracy range is 1%, 680Ω partial voltage resistance accuracy range is 0.5%, manganese copper sheet precision range is 2%), the relative error is optimized from 1.47% ~ 3.03% to -0.68% ~ 0.81%, the standard deviation is reduced from 0.06 to 0.02, and the measurement accuracy consistency at full temperature is significantly improved.
4.4. Optimization results considering costs

In practical production, as no requirements are put on quality control of the metering chip materials, production costs of the chips are identical; therefore, prices of metering chips are not included in the costs here. According to purchase prices of the key components (except metering chips), the total costs of components in the combinations, are calculated. As the calculation results are substituted into formula (5), the value of V can be determined for the combinations with different weight ratios of performance and costs, which are presented below in Table 3. If measurement precision in full temperature range prevails in the factory, it’s better to choose optimum combinations with high SNR; if cost reduction is a priority, it’s better to choose optimum combinations with low component costs.

Table 3. The Best Tolerance Combination with Different Weight Ratios of Performance and Costs

| Weight Distribution | $V_{max}$ | Best Tolerance Combination |
|---------------------|-----------|---------------------------|
| $w_1=0.9$           | 0.8165    | $L_5$                     |
| $w_2=0.1$           | 0.6331    | $L_4$                     |
| $w_1=0.8$           | 0.4497    | $L_5$                     |
| $w_2=0.2$           | 0.2663    | $L_5$                     |
| $w_1=0.7$           | 0.1361    | $L_8$                     |
| $w_2=0.3$           | 0.0286    | $L_{14}$                  |
| $w_1=0.6$           | 0.0088    | $L_7$                     |
| $w_2=0.4$           | 0.0058    | $L_7$                     |
| $w_1=0.5$           | 0.0029    | $L_7$                     |
| $w_2=0.6$           |           |                           |
| $w_1=0.4$           |           |                           |
| $w_2=0.7$           |           |                           |
| $w_1=0.3$           |           |                           |
| $w_2=0.8$           |           |                           |
| $w_1=0.2$           |           |                           |
| $w_2=0.9$           |           |                           |
| $w_1=0.1$           |           |                           |

5. Conclusions

Aiming at the problem of the uniformity of measurement accuracy of single-phase intelligent electricity meter in the whole temperature range, this paper analysis the measurement principle of single-phase intelligent meter, builds a simulation model of calculation considering various uncertain factors, designs orthogonal test, combined with the cost analysis, improves the consistency of the measurement accuracy in the full temperature range.

- This paper proposes a method to evaluate the consistency of measurement accuracy of smart meters considering both temperature noise and manufacturing noise. The temperature model of the main components of the smart electricity meter is built. Considering the temperature noise and manufacturing noise, the consistency analysis and evaluation of the measurement accuracy of batch smart electricity meters are realized by using the Monte Carlo simulation method. The results show that the average measurement error is 1.47% ~ 3.03% and the standard deviation is 0.06. When the ambient temperature is 70°C, the maximum measurement error can reach 21.39%. Before optimization, the accuracy of the meter is low, the consistency is poor, and it is easy to be affected by temperature.
The optimization method proposed in this paper can improve the consistency of the product in the whole temperature range. At the same time, it can provide the most cost-effective optimal design. Through optimization, the optimal solution is obtained as a reference voltage fluctuation range of 0.15%, a 150kΩ voltage divider resistance accuracy range of 1%, a 680Ω voltage divider resistance accuracy range of 0.5%, and a manganin sheet accuracy range of 2%. Before calibrating the meter, the mean value of measurement error in the whole temperature range was reduced from 1.47% ~ 3.03% to -0.68% ~ 0.81%, and the standard deviation was reduced from 0.06 to 0.02.

References
[1] Li Shen and Yiyi Gan. 2014 Electrical Measurement and Instrumentation. 51 89-95
[2] LI Jianhua. 2014 Jiangsu Present Day Metrology. 000 24-288
[3] Wenbin Zhou and Yan Huang. 2012 China Metrology. 11 69-70
[4] Mcneill N, Dymond H and Mellor P. H. 2011 IEEE Transactions on Power Delivery. 26 2309-17
[5] Xiao Huahui. 2015 Ence, Technology, and Innovation. 000 143-4
[6] Wang Xuewei, Wen Lili and Jia Xiaolu. 2014 Electr. Power Autom. Equip. 9 143-7
[7] Zhu X, Qin Y and Su X. 2015 Electric Power Automation Equipment 35 52-7
[8] Huang Yan, ZHOU Wenbin and WU Xiaoyu. 2012 Electrical Measurement and Instrumentation. 49 36-9
[9] Li Q, Li X and Wang S. 2016 Electric Power Automation Equipment. 36 102-7
[10] Dai Zhihui, Wang Zengping and Jiao Yanjun, 2011 Proceedings of the Chinese Society of Electrical Engineering. 19 105-13