Using Computer-aided Technology to Error Analysis of Electric Energy Metering System

Jie Fan

State Grid Jiangsu Electric Power, Ltd., Jiangsu, Nanjing 210000, China, hxszq004@163.com

Corresponding author: Jie Fan, hxszq004@163.com

Abstract. With the continuous advancement of smart grids and the digital substations, transformers and electric energy meters in traditional metering systems will gradually be replaced by electronic transformers and meters, the electric energy metering will also enter the digital value. The accuracy of electric energy measurement is directly related to the benefits of power generation, power supply and electricity consumption in the settlement. As an emerging product, the computer-aided electric energy metering system (EES) is still being improved in all aspects. This article first introduces the development background and status quo of the computer-aided electric energy metering system, combining the computer-assisted electric energy metering system composed of electronic transformers, merging units and digital electric energy meters in the smart grid, and putting forward the factors that influence the results of electric energy metering. Aiming at the typical influencing factors, a test method for the verification of measurement errors is proposed, and part of the test is performed on the electric energy meter with the test equipment to verify the analysis results. Based on the analysis of the error factors of computer-aided electric energy measurement, suggestions for reducing errors are proposed, suggestions for improving the function of electric energy meters, and constructive opinions on error verification methods of computer-aided electric energy measurement systems.

Keywords: Computer aided; electric energy measurement; influencing factors; error analysis
DOI: https://doi.org/10.14733/cadaps.2022.S4.169-179

1 INTRODUCTION

Electricity is an important energy source for the national economy and people's lives, and in national development. The characteristic of electric power production is a system composed of four parts: power generation, transmission, power supply departments and users, which continuously generates, transmits, distributes, and consumes electricity at the same time. As an important basis for settlement between power supply and power consumption. Therefore, the accuracy of electric energy measurement will directly affect the interests of all parties in the power system and the fairness and rationality of transactions. The conventional electric EES mainly includes the electric energy metering system on the side of the substation and the electric energy remote terminal management system [1]. Among them, the electric energy remote metering management system on the remote dispatching side mainly completes the functions of electric energy data collection and metering management, and provides accurate and reliable electric energy data for electric power marketing. This data is particularly important for achieving the fairness and impartiality of electric energy settlement. For the electric energy measurement part on the substation side, it can realize the collection and transmission of primary voltage and current data and the calculation of electric energy. These functions are mainly completed by transformers, transmission cables and electric energy meters. The transmission between the traditional electric energy meter and the traditional electronic transformer adopts the "DL/T 645 multi-function electric energy meter communication protocol"[2]. This protocol is suitable for point-to-point or one-master-multi-slave half-duplex communication in the data transmission between the two, and unify and standardize the physical connection and protocol for data exchange. Each multifunctional energy meter has its own unique address code. The master station establishes and releases the communication link by sending out information frames. Each frame consists of 7 fields, which are: start character, slave station address field, control code, data field length, data field, frame information longitudinal check code and end of frame. In recent years, with the advancement of the State Grid Corporation of power grid construction, the power grid is developing in the direction of intelligence and digitization [3]. Electric energy metering has gradually realized automation, information and interaction, and digital substation information collection, transmission, processing and output which means the process will also be fully digital. At the same time, the standard electronic transformer manufacturing technology has been improved with the improvement of the digital substation standard system IEC61850 and the development of optoelectronic technology [4, 5]. The improvement of the related standards of electronic transformers also provides the reliability, stability and versatility of digital substation measurement. Therefore, the country has put forward higher requirements for electric energy measurement, in order to achieve the goal of high accuracy and high reliability of electric energy measurement.

This article first introduces the development background and status quo of the computer-aided EES, combining the computer-assisted EES composed of electronic transformers, merging units and digital electric energy meters in the smart grid, and putting forward the factors that influence the results of electric energy metering. Aiming at the typical influencing factors, a test method for the verification of measurement errors is proposed, and part of the test is performed on the electric energy meter with the test equipment to verify the analysis results. Based on the analysis of the error factors of computer-aided electric energy measurement, suggestions for reducing errors are proposed, suggestions for improving the function of electric energy meters, and constructive opinions on error verification methods of computer-aided electric energy measurement systems.

2 RELATED STUDIES

According to the needs of various countries for the construction of smart grids, large foreign manufacturers such as SIEMENS, ABB and other companies have been developing smart electronic equipment that meets the standard, including transformers with digital interfaces, photoelectric transformers, etc., such as Rahimi et al. [6] announced the latest generation of fiber optic current sensor. The sensor follows the communication protocol and can achieve interoperability with equipment provided by different suppliers. Its digital interface performance makes it an ideal product in digital substations. The research on smart grids has also planned and implemented development ideas suitable for the country based on its own national conditions.

In the actual development of digital substations, our country first promotes the application of electronic transformers for substations. With the introduction and application of electronic current and voltage transformers in my country, the development of digital substations has received extensive attention from domestic power companies, and the digitalization of substation electric energy measurement technology has become an inevitable trend of development. The National Electric Power Enterprise Federation has been paying attention to the IEC61850 standard since 2001. In order to make the standard widely popular, a special working group was established to translate it, and in 2009, it promulgated the implementation of the IEC61850 standard DL/T860, announced by Panova et al. [7]. For example, the national standards for electronic transformers were promulgated in 2007 and have been used to standardize the operation of pilot digital substations. Early digital substations were put into operation. For example, in 2005, Shandong Power Grid ran the first 110kV digital substation-Liaocheng Station. This station uses electronic transformers, and all primary and secondary equipment are domestically produced. At the end of 2006, the country's first 220kV digital substation was launched in Ulanchabu, Inner Mongolia. All electronic transformers are used in this site, and the measurement, control, metering, and monitoring systems share a communication network. Subsequently, digital substations were put into operation in Jiangsu, Henan, Guangdong and other places. For example, China Southern Power Grid invested in the construction of the first 500 kV digital substation in 2014. The substation is based on the IEC61850 standard and communication protocol, which realizes the information sharing and interoperability between intelligent electrical equipment in the substation, and reduces the number of equipment maintenance and overhaul time. Which effectively improves the reliability of the equipment. At present, my country's research on digital substations mainly focuses on the application of electronic transformers and the IEC61850 standard, as well as the development and application of digital electric energy meters.

Smart meters can transmit energy consumption to the power company and local users at the same time, which facilitates real-time communication between the two. In addition to the functions of basic parameter measurement and two-way energy metering, smart meters also have two-way local and remote communication, remote control, power quality detection, and timely reflection of the latest power market information. The advanced measurement system can pass intelligent The electricity meter regularly obtains user electricity consumption information, and at the same time releases real-time grid-related information to power users through smart meters, such as time-of-use electricity prices, peak-valley electricity prices and other information. Users can reasonably adjust power consumption based on real-time electricity prices read from smart meters, thereby saving and optimizing power consumption.

Most countries have listed the construction of smart grids as a strategic plan to cope with the crisis of future energy shortages. In building a smart grid, the first step is to implement the Advanced Metering Infrastructure (AMI), which is a fully configurable infrastructure and needs to be integrated into the current and future power networks. The US Federal Energy Policy Commission defined AMI in 2006: AMI is a measurement system that can record user behavior or parameters at an hourly or higher frequency, and then transmit the measured data to a central measurement system through a communication network. This advanced metering system mainly consists of five parts: metering master station data management system, data concentrator, communication channel, smart meter and user's indoor network. Among them, the smart meter occupies a very important position in the implementation of AMI. It aims to adapt to the advanced measurement system and smart grid. Compared with the traditional electric energy measurement system, the advanced measurement system structure of the smart grid is more complicated, and the measurement function is also richer. In addition, the advanced measurement system can not only be used for power trade settlement, but also provide data support for grid load control, which has a beneficial impact on maintaining the stability of the grid. Therefore, measurement reliability cannot be ignored in the development of AMI.

3 ELECTRIC ENERGY METERING ALGORITHM

3.1 Electric Energy Measurement System and Error Composition

In the conventional EES, the error sources that affect the accuracy of the measurement include the following parts: the measurement error caused by the conventional transformer, the voltage drop error of the secondary transmission line, and the sampling and calculation error of the electric energy meter. Generally, the accuracy of the conventional transformer used for measuring is 0.2 or 0.25. The voltage transformer and current transformer of conventional analog output are transmitted to the electric energy meter through the cable. In the cable transmission, due to the existence of the cable impedance and the internal resistance of the electric energy meter, a certain loss will be caused. According to the "Electric Energy Measurement Technology Management Regulations", which cited by Liu et al. [8] in the electrical energy measurement device used for trade settlement, the voltage drop of the secondary circuit of the voltage transformer should not be greater than 0.2% of its rated secondary voltage. The secondary conductor cross-section of the voltage transformer, the reduction of contact resistance or the use of secondary voltage drop compensators and other measures can control the measurement error caused by the loss of the transmission system to 0.12. The cable is used to transmit analog voltage and current signals. This signal is converted into a digital signal by a power transmitter and an analog-to-digital converter in a conventional electric energy meter, and then various results of electric energy measurement are calculated by. Even high-accuracy power transmitters and analog-to-digital converters will bring 0.2% error. The error of the traditional EES is composed of the above three parts, and its comprehensive error will reach 0.7%. The composition diagram of the error is shown in Figure 1.

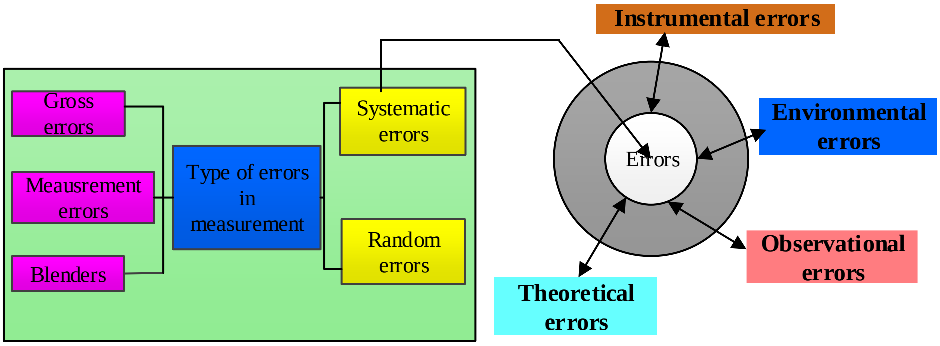

Figure 1: Error composition diagram of EES.

In the digital substation, the electric energy metering technology has undergone tremendous changes in the analog quantity acquisition and signal transmission methods with the traditional metering. The electronic transformer has realized full digital sampling and signal transmission through optical fiber, which eliminates the need for the traditional transformer secondary. The loss caused by the cable transmission between the side and the meter improves the system's ability to resist electromagnetic interference. The advantages of electronic transformers, such as high accuracy, wide dynamic range, and no saturation, also provide accurate and reliable data sources for computer-aided electric energy measurement. The collection and management in the digital substation follows the standard, and the entire system no longer contains errors caused by analog-to-digital conversion. The digital electric energy meter receives the data frame output by the merging unit and no longer contains the sampling link. It only receives the data transmitted from the merging unit and obtains the electric energy measurement result through the appropriate measurement algorithm, which is aimed at the calculation method itself. The calculation error of is so small that it is almost negligible. Therefore, the error of the digital metering system is mainly the sampling and synthesis error of the electronic transformer. The accuracy of the electronic voltage and current transformers can generally reach 0.2. It can be seen that the comprehensive error of the digital metering system is 0.4%.

The error comparison between traditional EES and computer-aided EES is shown in Table 1. It can be seen from the table that the use of computer-assisted electric energy measurement can reduce the loss in the transmission process and effectively improve the accuracy of electric energy measurement.

Measurement system error	Primary side voltage transformer error/%	Primary side current transformer error/%	Transmission loss error	Internal error of electric energy meter	Composite error
Traditional substation metering system	0.25	0.30	0.12	0.23	0.65
Digital Substation Metering System	0.23	0.24	0.00	Basically, no additional error	0.32

Table 1: Error comparison between traditional electric energy measurement system and computer-aided electric energy measurement system.

3.2 Power Measurement Algorithm

In a period *T*, the active power is the average value of the instantaneous power in a period

$$W = \int_0^T pdt = \int_0^T f(t)x(t)dt \tag{1}$$

If the number of sampling points per cycle is N, when the instantaneous value of voltage and current sampled by the electronic transformer is transmitted to the digital EES through the merging unit, after the electric energy meter receives it, it is given to the microprocessor for multiplication according to the definition, and n is obtained. The instantaneous power values p_1, p_2, p_3,...,p_n, and then the sum of these instantaneous values, the average power p is:

$$\overline{P} = \int_1^N p(t)dt / N = \sum_{i=1}^{N} P_i / N \tag{2}$$

According to the time period required to measure the electric energy, the electric energy value can be obtained by summing the corpses of each cycle. Refer to the calculation formulas of reactive power and active power in the analog multiplication method. The difference is that the phase angle of the voltage lags the original voltage vector by 90 degrees. Therefore, the reactive power calculation formula is obtained by imitating the active power calculation:

$$\mathrm{P_r} = \int_0^N f(t+i)x(t)dt / N = \sum_{i=1}^{N} f(t+i)x(t)_i / N \tag{3}$$

The above equations (2) and (3) have ideal measurement effects for standard sine waves with stable frequency under synchronous sampling conditions. However, when the frequency fluctuates, occurs frequency deviation or contains harmonics, if the calculation is still carried out according to equations (2) and (3), the results may deviate. In the case of harmonics, Jie [9] provided the formula which can be used:

$$W = \int_0^T pdt = \int_0^T f(t)x(t)\cos\theta dt \qquad (4)$$

In order to calculate the active power, but if a similar method is used to calculate the reactive power, a large error will occur. This is because formula (3) only shifts the phase of the fundamental wave of the voltage signal. With the development of the power industry, a large number of power electronic rectifiers, converter equipment and other non-linear loads are installed in the power system. It will bring distortion to the voltage and current in the power system, so that both contain more high-order harmonics. The angle of the phase shift of the harmonics cannot be determined, which is the root cause of the large errors in the calculation of reactive power using this formula. The error analysis and calculation scheme for electric energy measurement is shown in Figure 2.

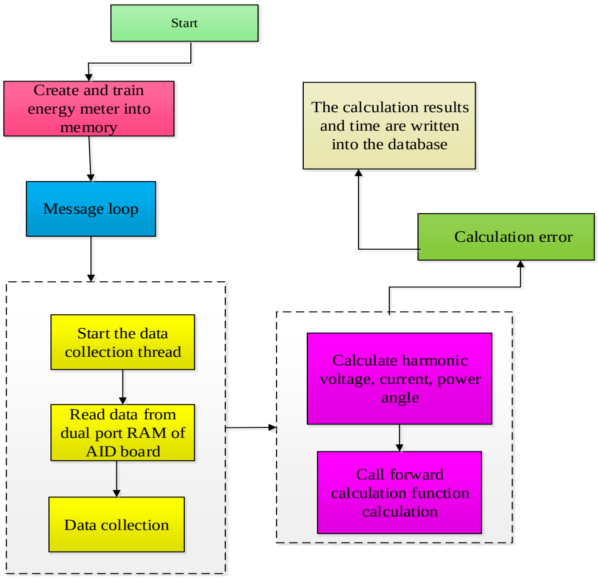

Figure 2: Error analysis and calculation scheme for electric energy measurement.

4 MEASUREMENT ERROR SIMULATION TEST AND RESULT ANALYSIS

The test signal generator adopts the programmable merging unit simulator to simulate the sampling frame conforming to the protocol, and set the relevant input parameters of the digital EES. The merging unit simulator can change the effective value and power factor of the measured signal voltage and current, change the signal frequency, add different sub-harmonics and change its content, simulate adding white noise to the signal, simulate frame dropping, and adjust the sampling frequency.

The digital watt-hour meter used in the test is a class 0.25 three-phase smart meter from Yantai East Weston. The voltage and current signals of the electric energy meter are all digital signal inputs, which can automatically identify digital messages. The data of the digital electric energy meter displays the effective value of voltage/current, the value of active power and reactive power, and the measured quantities of electric energy. This electric energy meter has 5 effective digits for measurement, 5 effective digits for power measurement, and 4 effective digits for voltage/current effective value. The effective value of the rated voltage signal of the digital electric energy meter is 220V, the effective value of the rated current signal is I=1.5A, the rated operating frequency is 50Hz, and the sampling frequency can be set to 5kHz and 12.5KHz, parameters are adopted from Abdullah and Ali [10].

4.1 Truncation and Rounding Error Test and Analysis

When the effective value of the output voltage of the merging unit simulator is 220V, the effective value of the current is 1.5A, the signal frequency is 50Hz, and the power factor is 1, 0.7C, 0.6L, read the single-phase active power of the merging unit simulator. Output power and digital electric energy meter display single-phase active power. Regardless of whether the sampling frequency is 5kHz or 12.5kHz, the readings of the digital energy meter are the same. The measurement results are shown in Figure 3.

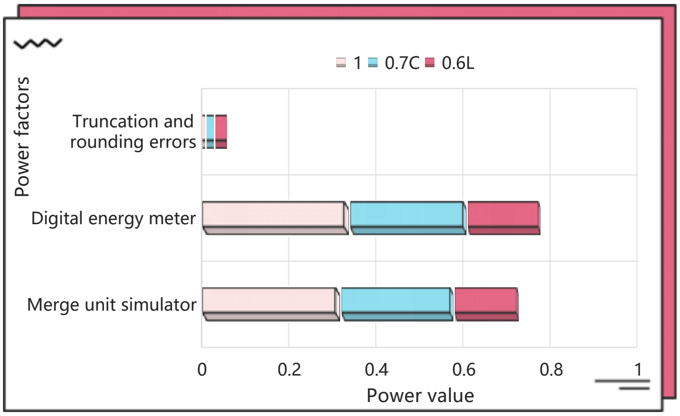

Figure 3: Truncation and rounding error test results.

From the measurement results that as the absolute value of the power factor decreases, the influence of the truncation error and the rounding error increases, but it can basically be kept within three ten thousandths. Compared with the simulation results, it can be seen that when the sampling frequency is 5kHz, the truncation and rounding error errors are less than the theoretical simulation value; when the sampling frequency is 12.5kHz, the actual measurement of the combined error of the cutoff and rounding except for the power factor is 1. When it is larger than the cutoff and error of the theoretical calculation, this may be due to the fact that the error in the actual measurement contains cutoff and rounding errors, and the resolution of the electric energy meter will also bring certain errors to the measurement results.

4.2 Frequency Offset Test and Analysis

In the frequency offset test, the standard signal frequency offset range is adjusted to 48Hz-49Hz, with 0.1 Hz as the step value. The sampling starting point in the existing equipment cannot be controlled. When the sampling frequency is 5kHz and the signal frequency is 50Hz, if $\cos\theta=1$, the single-phase active power is 0.33kW; if $\cos\theta$ = 0.7C, the single-phase active power is 0.27kW; if $\cos\theta$=0.6L, the single-phase active power is 0.16kW and the display value of the digital electric energy meter remains stable. It is synchronous sampling, and the measurement result is consistent with the theoretical analysis. When the frequency shifts, the single-phase active power test results are shown in Figure 4.

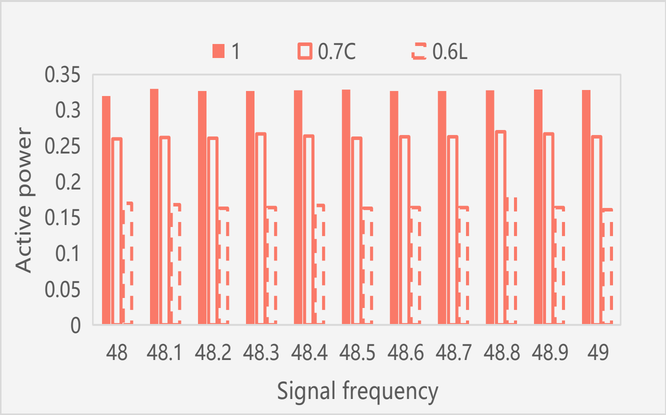

Figure 4: Frequency deviation test single-phase active power.

The active power and the standard power when there is no frequency deviation are brought into equation (5), namely:

$$e = (W_a - W_s) / W_s \tag{5}$$

The results of the relative error of the single-phase active power are shown in Figure 5.

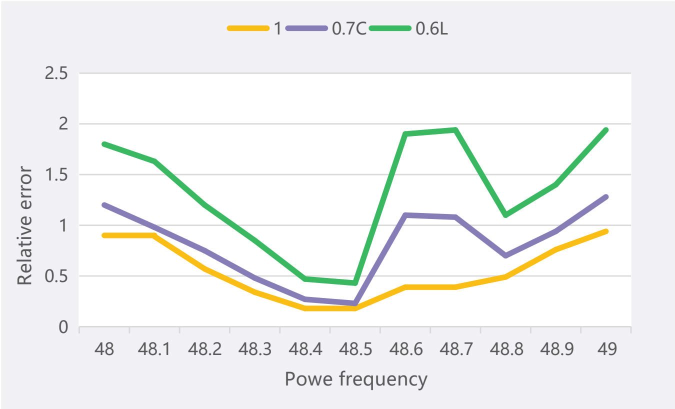

Figure 5: Relative error of single-phase active power when frequency offset.

Because the starting point of each sampling is unknown, the relative error fluctuates, and there are positive and negative. This is consistent with the correlation between the relative error of active power and the sampling starting point in the theoretical analysis;

(2) Within the frequency deviation of 48Hz-49Hz, the power error of the measured electric energy meter basically fluctuates within ±2%.

When the sampling frequency is 12.5KHz and the signal frequency is 49Hz, if $\cos\theta$ =1, the single-phase active power is 0.33kW; if $\cos\theta$=0.7C, the single-phase active power is 0.27kW; if $\cos\theta$=0 6L, the single-phase active power is 0.16kW and the display is stable, and it is the same as when the sampling frequency is 5kHz. When the frequency shifts, the test result is shown in Figure 6.

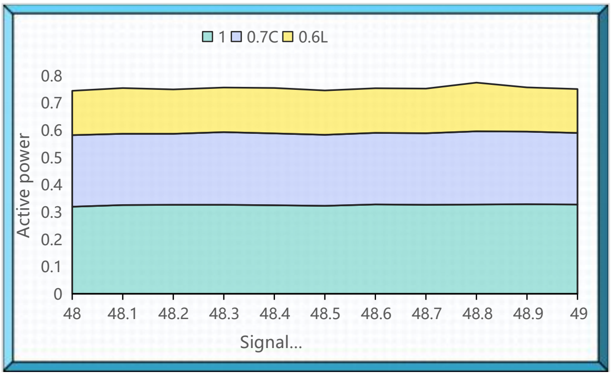

Figure 6: Frequency deviation test single-phase active power (f=12.5kHz).

The active power and the standard power when there is no frequency deviation are brought into equation, and the result of the relative error of the active power is shown in Figure 7.

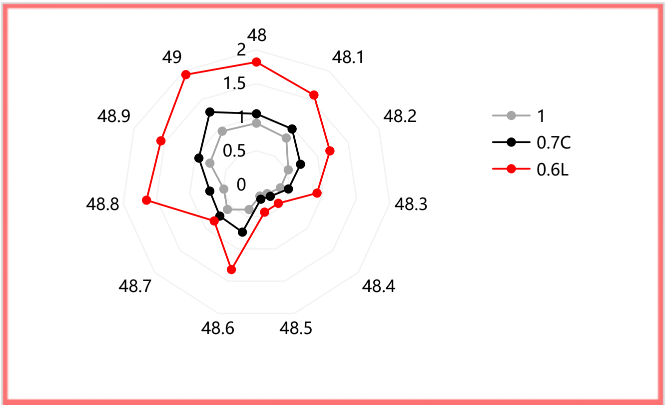

Figure 7: Relative error of single-phase active power P(%) (f=12.5kHz) when frequency offset.

It can be seen from Figure 6 and Figure 7:

(1) Compared with the sampling frequency of 5kHz, the relative error variation range of power is slightly reduced, which is consistent with the simulation results;

(2) Same as when the sampling frequency is 5kHz, within the frequency deviation range of 48 Hz-49Hz, the power error of the measured electric energy meter basically fluctuates within ±2%.

It can be seen that the electric energy meter works stably and reliably under rated conditions, and the increase of the sampling frequency from 5kHz to 12.5kHz has no effect on the sampling results. When the signal frequency shifts, the measurement of active power is greatly affected, that is, the power error of the measured electric energy meter may fluctuate within ±2%. Combining the analysis, it can be seen that the digital electric energy meter in the calculation, the offset voltage and current were not compensated by interpolation, which resulted in a large measurement error.

5 CONCLUSION

When the sampling frequency is 5kHz, the synthetic error of the simulation is less than 0.2%, and the cutoff and simulation synthetic errors in the experiment are both within the theoretical value; when the sampling frequency is 12.5KHz, only when the power factor is 1, the synthetic error of the experiment is less than the simulation calculation The combined value of truncation error and rounding error in the power factor is 0.7C and 0.6L, and the combined error is greater than the simulated value. When the signal frequency deviation occurs, the relative error of the active power measurement result is relatively large. This is similar to the analysis when the compensation algorithm is not used in the simulation. It can be seen that the digital EES does not adopt the signal frequency deviation when it encounters the signal frequency deviation. Appropriate compensation algorithm, resulting in larger measurement errors. When the signal contains harmonics, the relative error of the test single-phase active power is much smaller than the relative error of the active power that does not include the harmonics in the simulation. Therefore, when the electric energy meter measures the active power, the harmonic power is included. When the signal contains a offset, the active power measurement result of the digital EES used in the test is the same as the measurement result without the offset, which does not match the simulation result. It is speculated that the digital electric energy meter did not perform the power calculation process. When the signal contains random interference, if the random interference is white noise, from the test results that the trends of the test and the simulation are roughly the same, but the fluctuation range of the active power error of the test results is larger than the simulation expectation.

Jie Fan, https://orcid.org/0000-0002-4005-0788

REFERENCES

[1] Razali, A.-H.; Abdullah, M.-P.; Hassan, M.-Y.; Hussin, F.: Comparison of new and previous net energy metering (NEM) scheme in Malaysia, ELEKTRIKA-Journal of Electrical Engineering, 18(1), 2019, 36-42. https://doi.org/10.11113/elektrika.v18n1.141
[2] Berselli, G.; Balugani, F.; Pellicciari, M.; Gadaleta, M.: Energy-optimal motions for Servo-Systems: A comparison of spline interpolants and performance indexes using a CAD-based approach, Robotics and Computer-Integrated Manufacturing, 40(1), 2016, 55-65. https://doi.org/10.1016/j.rcim.2016.01.003
[3] Lysenko, D.; Chelyshkov, P.: The method of optimization of energy-efficient engineering solutions by varying criteria in CAD, In IOP Conference Series: Materials Science and Engineering, 365(2), 2018, 22-27. https://doi.org/10.1088/1757-899X/365/2/022027
[4] Begich, Y.; Babanina, A.; Ziiaeva, K.; Barinov, S.: Energy efficiency with the use of innovative materials in the Far North, using CAD, In E3S Web of Conferences, 110, 2019, 1004. https://doi.org/10.1051/e3sconf/201911001004
[5] Shalaevskii, D.-L.; Kozhevnikov, A.-V.: Computer-Aided Design (CAD) of Energy-Efficient Cold Rolling Technology, Steel in Translation, 50, 2020, 36-41. https://doi.org/10.3103/S0967091220010106
[6] Rahimi, N.; Kerfriden, P.; Langbein, F.-C.; Martin, R.-R.: CAD model simplification error estimation for electrostatics problems, SIAM Journal on Scientific Computing, 40(1), 2018,196-227. https://doi.org/10.1137/16M1078641
[7] Panova, E.-A.; Varganova, A.-V.; Patshin, N.-T.: CAD in Electrical Engineering: New Approaches to an Outdoor Switchyard Design, In International Russian Automation Conference, 9(1), 2019,536-544). https://doi.org/10.1007/978-3-030-39225-3_58
[8] Liu, S.; Deng, Z.; Li, H.; Feng, K.: Contribution of electrodes and electric current to process stability and methane production during the electro-fermentation of food waste, Bioresource technology, 288, 2019, 121536. https://doi.org/10.1016/j.biortech.2019.121536

[9] Jie, D.: Thermal performance analysis of motor based on motor-CAD, In AIP Conference Proceedings, 2073(1), 2019, 20-49. https://doi.org/10.1063/1.5090703
[10] Abdullah, A.-T.; Ali, A.-M.: Thermal analysis of a three-phase induction motor based on motor-CAD, flux2D, and matlab, Indonesian Journal of Electrical Engineering and Computer Science, 15(1), 2019, 46-53. https://doi.org/10.11591/ijeecs.v15.i1.pp46-53