Ad Hoc & Sensor Wireless Networks, Vol. 50, pp. 173–192
Reprints available directly from the publisher
Photocopying permitted by license only

An Automatic RF-EMF Radiated Immunity Test System for Electricity Meters in Power Monitoring Sensor Networks†

SHISHENG FU[1], ZHENGYONG ZHANG[*,2], YANG JIANG[1], JING CHEN[1], XIAOXIAO PENG[1] AND WEIGUO ZHAO[3]

[1]*Zhejiang Institute of Metrology National Center of Quality Supervision and Testing on Electricity Meters & Zhejiang Key Laboratory of Energy Measurement and Environmental Protection, Hangzhou, 310018, China*
[2]*State Key Laboratory of Public Big Data, College of Computer Science and Technology, Guizhou University, Guiyang, 550025, China*
[3]*China Jiliang University, Hangzhou, 310018, China*

Received: June 16, 2021. Accepted: August 10, 2021.

With the advanced information technology, the power system becomes more efficient and reliable by widely deploying smart sensors in the field side, which construct a powerful monitoring sensor network. However, due to the complicated radiation environment, the sensors will be affected and thus present abnormal data to the control center, which might destroy the system's observability. Based on the radiation immunity test principle for radiofrequency electromagnetic field (RF-EMF), in this paper, we use LabView and GTEM cell to design an automatic RF-EMF radiated immunity (RI) test system for electricity meters. To improve the testing performance, we propose a new method to design the hardware and software to filter out signal noises. We verify the effectiveness, reliability, and consistency of the automatic testing system with a 3-meter anechoic chamber system by conducting extensive experiments.

Keywords: Power monitoring network, electricity meters, GTEM cell, anechoic chamber test, electromagnetic compatibility

1 INTRODUCTION

Networking is a fundamental requirement to realizing the overview context-aware and coordinated control. There are plenty of studies focusing on improving

†This work is supported by the Project of Research of Modular Smart Meters Using for Ubiquitous Electric Internet of Things (Important Science & Technology Specific Projects of Ningbo City) and the GZU cultivation project of NSFC (no. [2020]80).
*Corresponding author: Zhenyong Zhang, E-mail address: zyzhangnew@gmail.com

the performance of networked systems regardless of the wired and wireless connection. These researches promote the applications of networked devices in industrial scenarios such as home area sensing [1], secure edge computing [2], industrial internet of things [3], new human-machine interaction technologies [4], etc. However, there are still open problems and challenges to make the networked system better. For example, the author of [5] has summarized the motivations, scenarios, and challenges for the intelligence integrated networking systems.

An an important application, sensor network has enabled the power system to widely and timely monitor the operation states. However, in the electricity environment, there are many issues that the sensors should address to guarantee their stable working status. The sensor must report correct data to the control center even that there are inferences, especially, the electromagnetic radiation [6]. In recent days, RF electromagnetic radiation is widely used in advanced communication and computation devices, resulting in an increasingly complex electromagnetic radiation environment. On one hand, electronic devices emit electromagnetic radiation to the outside world, on the other hand, they are interfered with by the surrounding electromagnetic radiation environment. Therefore, it is critical to verify the anti-interference ability of electronic devices in the electromagnetic environment [7].

There are a lot of works investigating the RF radiation of the electronic devices and the anti-interference ability of the electronic devices [8-12]. The latter is usually termed Electromagnetic Compatibility (EMC) [13-16]. Gigahertz Transverse Electromagnetic (GTEM) cell is a popular test facility for evaluating the radiated emission of the integrated circuit. Chua et al. [17] improved the correlation between GTEM and semi-anechoic chamber through a correction factor. Xing et al. [18] theoretically derived the input impedance of dipole antenna in GTEM cell, which guided the test compensation and error analysis of Electro-Magnetic Interference measurements in GTEM cell. Hallon and Kovac [19] presented a solution to fulfill homogeneity requirements without the absorbers only by changing the antenna height between two positions and by appropriately controlling the tested electromagnetic field frequency. Cooper et al. [20] compared the current RF immunity test systems and demonstrated how consistent and repeatable RF measurements are achieved by the electricity meter examining service. Wang et al. [21] built a system to test the RF-EMF radiated immunity and improved the anti-jamming capability of electricity meters using the EMC technology.

The RF-EMF immunity tests conducted on electricity meters are the most demanding of all influence type tests [22]. To test the RF-EMF interference tolerance ability of the electricity meters, we need to construct a constant and stable electromagnetic radiation field that can be proactively changed to simulate the real-world electromagnetic radiation environment [23, 24]. In this paper, the RF-EMF radiated immunity test system of electricity meters is based on Gigaherrtz Transverse Electromagnetic, which is developed following the national standard, namely “Electromagnetic compatibility–Testing and measurement techniques–Radiated, radio-frequency, electromagnetic field immunity test". The mentioned standard for the immunity test of RF-EMF radiation is widely used for small electronic devices. It is a basic standard, that is, when the product needs the test, the test method specified in the standard shall prevail. In this paper, we specify the radiated immunity (RI) test for electricity meters.

In summary, the contributions of this paper are as follows:

1. We design an RF-EMF RI test system for electricity meters with GTEM cell and LabView, which can automatically conduct the test process.
2. We design a filter device for the voltage and currents and develop an active current compensation device for hourly tests. Besides, we solve the problem to quantify the measurement errors during the RF-EMF RI test.
3. Finally, we conduct extensive experiments to compare the performance of the RF-EMF RI test for electricity meters between the automatic test system with GTEM cell and the electric wave anechoic chamber, which provides a solution for the RI test comparison between two different hardware platforms.

The organization of this paper is as follows. Section 2 provides some preliminary knowledge for the RF-EMF RI test. Section 3 and Section 4 present the hardware and software design of the RI test system, respectively. Section 5 shows the experimental results of the proposed system. Section 6 compares the performance of two different test systems. Section 7 concludes the paper.

2 PRELIMINARY

The power network is an important part of the power system. It is a typical cyber-physical integrated network. To achieve adequate situational awareness, providing secure and reliable operation of the grid when it is affected by system disturbances and natural events, the power network is deployed with many sensors. The operating data from sensors are collected and transferred to the cyber layer for control, scheduling, contingency analyzing, marketing, etc. One of the critical devices is the electricity meter, which collects the data of current, voltage, power flow, etc. However, the radiation environment might affect its functions. Therefore, it is important to test the radiation immunity of the electricity meter.

For the RF-EMF RI test, the constructed electromagnetic radiation field must meet the following conditions:

1. It must cover the frequency range of 80MHz-6GHz according to the GB/T17626.3-2016 standard;
2. It must provide field strengths that meet the GB/T17626.3-2016 standard, which is shown in Table 1.

Level	Field strength V/m
1	1
2	3
3	10
4	30

TABLE 1
Level of field strength

During the test, a sine wave with a starting frequency of 1kHz is used to modulate the signal by 80% amplitude to simulate the real-world environment. In fact, we can choose lower frequencies to modulate the frequency with other standards. Besides, with the expansion of the spectrum used by electronic devices, the upper limit of the frequency will increase in the future.

The electromagnetic radiation immunity test of electricity meters mainly carried out two tests of 10V/m (current in the current circuit) and 30V/m (no current in the current circuit). Meanwhile, the test system should also take into account the RF-EMF radiated immunity test for ordinary electronic devices.

3 HARDWARE DESIGN AND IMPLEMENTATION

Specifically, the structure of the proposed RI test system is shown in Fig. 1.1. Except the GTEM cell, the main components of the RF-EMF immunity test system of electricity meters include: RF signal generator, power amplifier, three-phase filter de-vice, three phases electricity meter test equipment, power probe, monitor, etc.

The GTEM cell is a device designed based on the principle of an asymmetric rectangular transmission line. In order to avoid the reflection and resonance of internal electromagnetic waves, the shape of the GTEM cell is a pointed cone. The input end of the GTEM cell is an N-type connector. The rectangular uniform field area is located between the bottom plate and the core plate. In order to improve the transmission of the spherical wave between the input end and the load end, the terminal of the core board is non-reflective, which adopts a resistance matching network. The bottom of the GTEM cell is pasted with special material to absorb interfered electromagnetic waves. Therefore, between the bottom and the core plate, there is a test area that has a relatively strong uniform field. The tested object is placed in the test area to reduce the change of the field strength caused by the other devices. The object's height should be less than one-third of the distance between the core and bottom plate. Fig. 1.2 shows the GTEM cell.

The electromagnetic field strength of the GTEM cell is proportional to the voltage value of the N-joint and inversely proportional to the vertical distance

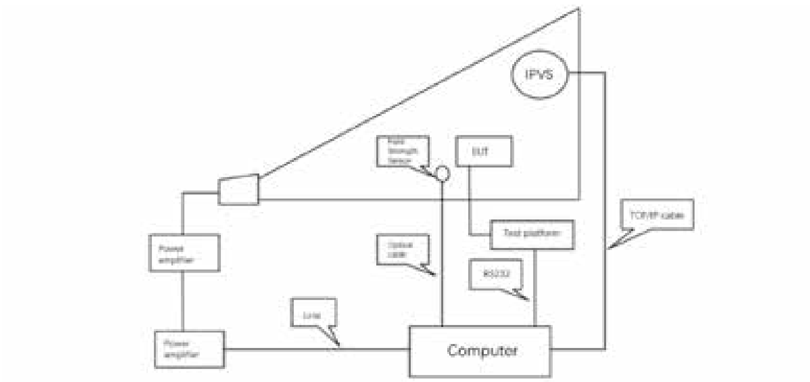

FIGURE 1.1
An illustration of the RI test system for electricity meters with GTEM cell

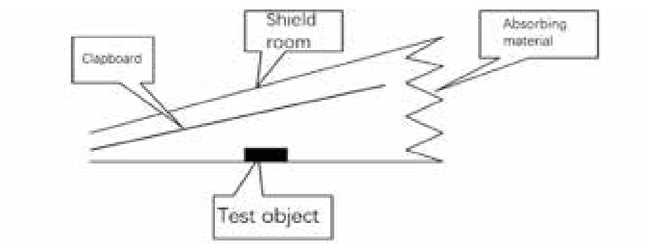

FIGURE 1.2
GTEM cell

of the core board. Therefore, if we inject the signals with the same power into the GTEM cell, then the closer the distance between the core and bottom plate, the greater the field strength. Therefore, for a small tested object, if we place it in front of the GTEM cell, we can obtain a strong electric field. However, since the core board is closer to the bottom board, the height of the tested object should be small enough, otherwise, the stability and uniformity of the field strength cannot be guaranteed.

Besides, in order to ensure the performance of the GTEM cell, a filter is used, which is composed of capacitors, inductors, and resistors. In order to ensure high insertion loss, large common-mode capacitors are used. Large-capacity capacitors increase the leakage current of the line and cause reactive power. In general, the loss rises during the dummy load test. Because the current will pass through the inductive components of the filter, and in the general AC transformer, the excitation current I0 is required to supply the excitation and power consumption of the core. Therefore, it is necessary to design a compensation device to solve this problem.

The active current compensator, which is shown in Fig. 1.3, consists of two iron cores. The corresponding hardware is shown in Fig. 1.4. A set of

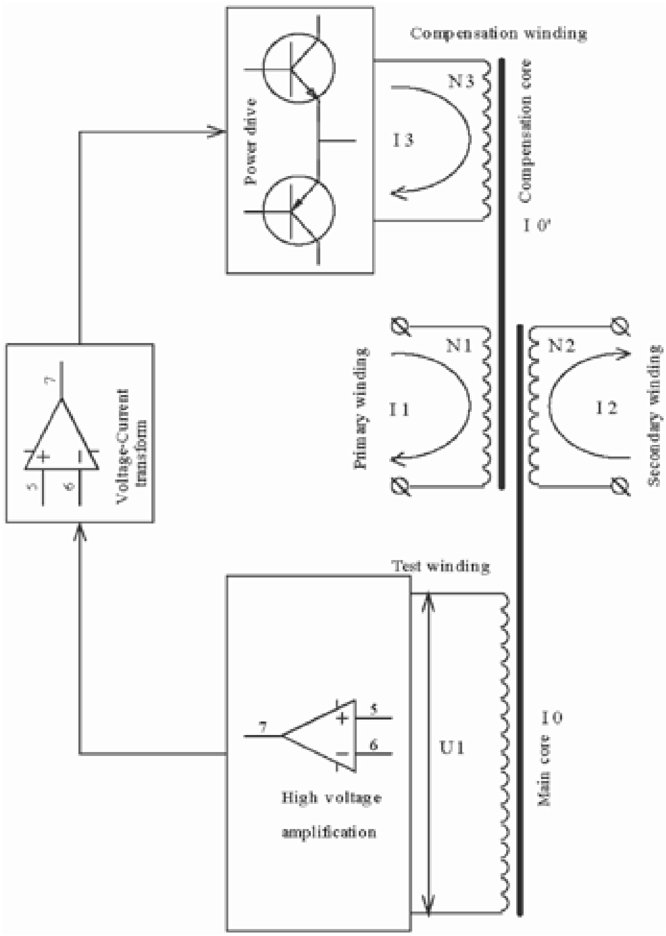

FIGURE 1.3
Schematic diagram of the active compensator

detection windings is wound on the main iron core, while a set of compensation windings (the number of windings is N3) are wound on the compensation iron core, and (the number of windings is N1) is wound on both iron cores at the same time. As for the primary and secondary winding (the number of windings is N2), its magnet-motive voltage balance equation is:

Main iron core: I1N1+I2N2=I0N1, where I0 is the induced current of the main iron core.

Compensation core: I1N1+I2N+I3N3=I'0N1, where I’0 is the induced current of the compensation iron core.

To make the error of the current transformer zero, i.e. I0N1=0, it results in that I3N3=I'0N1. That is, if an external potential is provided on the compensation iron core, the exciting current generated by it makes I3N3=I'0N1, then

FIGURE 1.4
Hardware design of active compensator

the magnetomotive voltage balance equation of the compensation iron core is I1N1+I2N=I'0N1-I3N3 =0. It follows that I1N1+I2N2=0 on the main iron core, that is, the error of the current transformer is zero.

In Figure 1.3, the U1 on the main iron core is the induced electromotive voltage of the main iron core, which is amplified by electronic power and output to the N3 winding of the compensation iron core to provide excitation current for it. After the feedback adjustment, I3N3=I'0N1 is satisfied. And the error compensation of the current transformer is achieved. Since the compensation is provided by the external power supply, it is called active compensation. In practice, since U1 cannot be zero, that is, the induced electromotive voltage of the main iron core of the current transformer is not zero, its error accuracy depends on the magnification of the electronic compensation circuit. Under the premise of ensuring its stable operation, active compensation is used. The accuracy of the current transformer is generally below 0.01%, which can fully meet the daily test requirements of electricity meters.

4 SOFTWARE DESIGN AND IMPLEMENTATION

In fact, the software development for the RI test system will affect its effectiveness in different applications. The software is designed to control the instrument, monitor the test process and data transmission, analyze the data after the test and handle the emergency operations in case of abnormal conditions. Therefore, in order to guarantee the effectiveness of the test system, we need to select a software platform that meets the system development requirements.

LabVIEW is an easy-to-use test software for simulations developed by National Instruments. It can be used to develop various professional modules that meet actual applications based on the original software platform according to different requirements. We can also develop specified modules according to our own needs, and self-motivated modules that can be called at any time in the next programming work. In this paper, we adopt LabVIEW to design the test system.

4.1 Design details

1. Main functions

According to the requirements, the RI test system is able to calibrate the three-phase electricity meter and automatically record the errors, control the signal generator, power amplifier, and field strength; automatically calibrate the electric field according to the specified field strength and record the calibration data; display the calibration data in real-time and store the corresponding frequency and strength, and automatically increase or decrease the signal strength according to the change of the field strength; display and record the frequency error between the measured value and the electricity meter output; automatically generate the recording table; monitor the test process; store and export the test results; pause when the error happens and prompt the alarms.

2. Architecture

We divide the software of the RI test system into 4 subVIs. For the first VI, we realize the management tasks including the user login, the selection of equipment required for the test, the communication interface and etc. For the second VI, we realize the functions including the control of the field strength, the real-time transmission of field strength data, the monitoring of the signal generator and power amplifier, the real-time display and recording of signal frequency and power magnitude. For the third VI, we mainly realize the control of the test platform, the modification of the electricity meter parameters, the selection of sensors, and the real-time display of errors. For the fourth VI, we realize the control of the signal generator and power amplifier, the real-time acquisition and display of the corresponding frequency of the measurement error (pulse signal), and the switch between the electricity meter RI test and the ordinary RI test. The overall architecture of the system software is shown in Fig. 2.1.

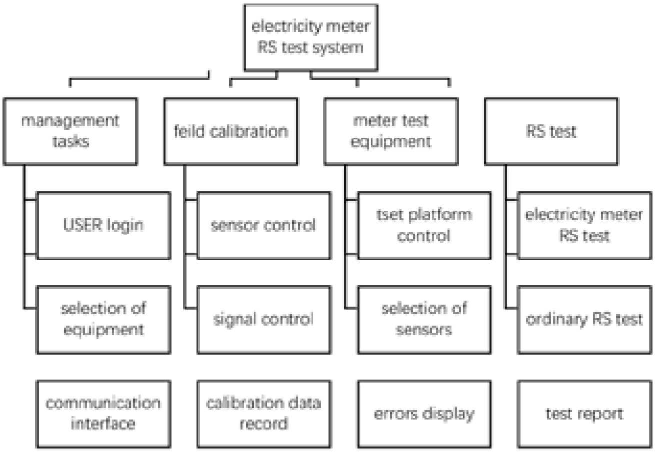

FIGURE 2.1
The architecture of the system software

4.2 Implementation

1. Field calibration

The field calibration module enables the electromagnetic field in the GTEM cell to maintain the uniformity and size of the field strength required for the test within a certain range.

Generally, the calibration process is carried out at a certain interval or when the experimental equipment has wide-scale changes (movement or replacement). The test steps are as follows:

1. Energize all instruments and equipment to preheat and make sure that the instruments and equipment are turned on and programmed, and carry out the configuration process;
2. Select the frequency band to be calibrated and click “Initialize” to check whether the instrument in the system is connected normally (the green light means the connection is normal). If the connection fails, check whether each instrument is in a normal working state, whether the remote mode is turned on, and whether the instrument configuration is correct until the connection returns to be normal;
3. Place the field strength probe at the position where the object will be placed. The parameter setting interface is shown in Fig. 2.2 and Fig. 2.3. According to the test requirements of the targeted object, we need to select the appropriate calibration field strength (3V/m, 10V/m, 30 V/m, or custom) and the start and end frequency, and then start the calibration.
4. After the calibration, the parameters and calibration data are stored in the database for further debugging.

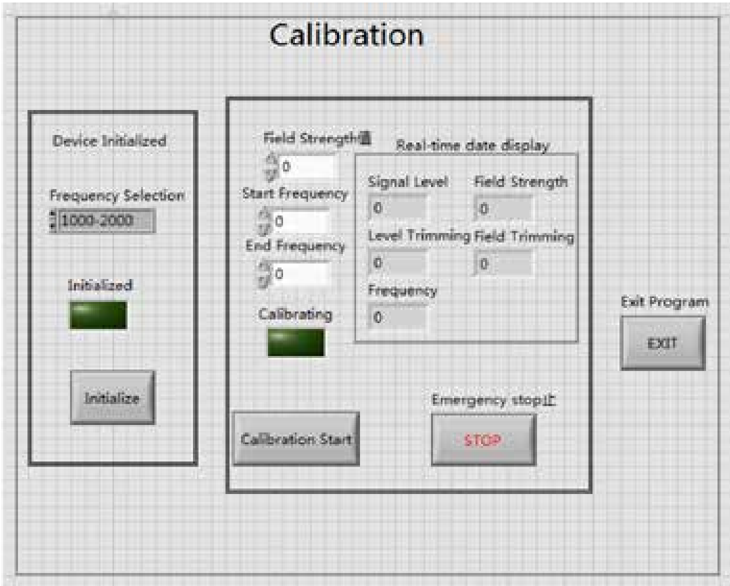

FIGURE 2.2
The programming diagram for the field calibration module

2. Evaluation module

This module is used to evaluate the RI test of electricity meters. It provides energy resources for the electricity meter during the RI test and feedbacks the errors in real-time. According to the parameters of the power mete, we determine the input voltage and current, and some constants. Then, we click the “initialization” button. This module will automatically input voltage, current and constant signals into the detection device. If the initialization fails, we need to check whether the detection device and the computer are properly connected. If it is well connected, we click the single-step execution button. The test station will power on the electricity meter, and meanwhile, output an error signal according to the feedback signal from the pulse signal. The error value will be displayed simultaneously with the frequency.

3. RI test module

As a key module to realize the RI test function of electricity meters, the data location refers to the calibration data to be used. According to different test frequency bands and strengths of the test field, we need to select different calibration data and determine the testing time. The programming diagram of the RI test for electricity meters is shown in Fig. 2.4.

Before starting the test, we need to make sure that the testing devices are in normal working condition and can output error data, and then select the

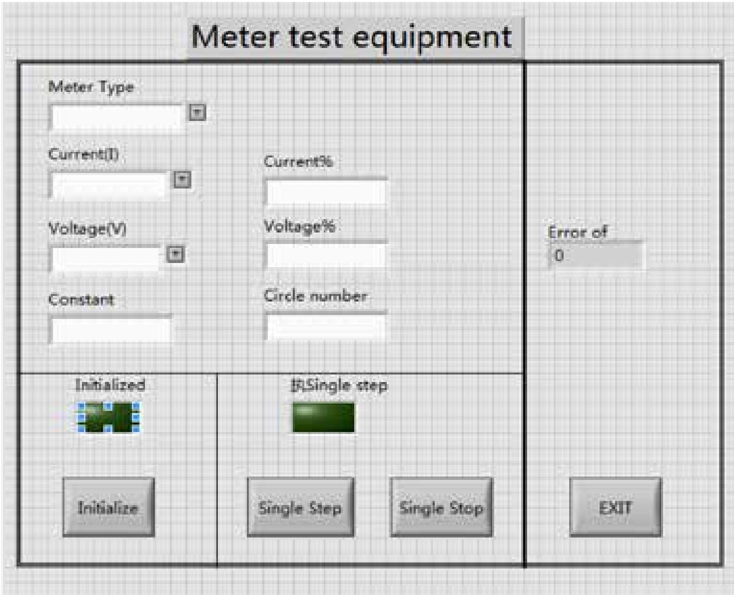

FIGURE 2.3
Parameter setting interface

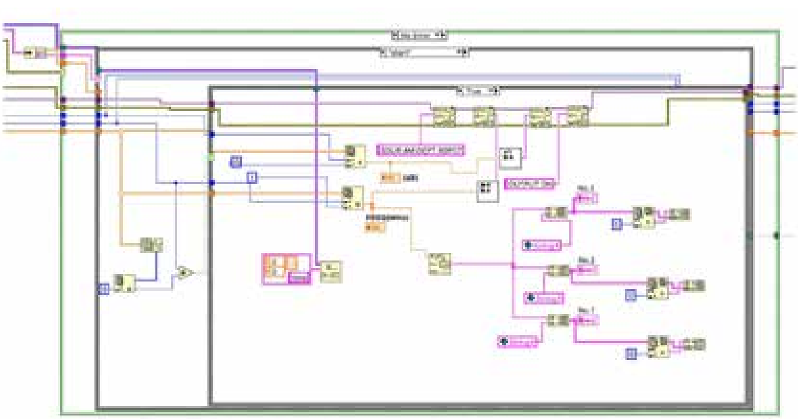

FIGURE 2.4
Programming diagram of RI test for electricity meters

output location of the error data and test results. After starting the test, the RI test system will first prompt to select the field strength files to be used and then automatically complete the test according to the selected files and output a report. When the test is over, the RI test system will prompt whether to repeat the test or start a new test or stop the test.

5 EXPERIMENTS

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

The RI test system mainly includes the field calibration module, RI test module, control module for the electricity meter testing platform, and the evaluation module. We determine the basic functions of each module and the communication between hardware through testing.

5.1 Evaluation for the field calibration

The field calibration module is a very important module for the RI test system. The field calibration will affect the subsequent test processes. If the field is not correctly calibrated, we cannot obtain qualified test data. The field calibration module is mainly divided into two parts: data analysis and field strength real-time reading.

The evaluation for the field strength sensing is fundamental for data analysis. The data can only enter the cycle when the field strength value reaches the specified range, which requires that the field strength data is read in real-time. To test the data reading function, we need to run the field strength sensor for a long time and compare whether the field strength displayed on the computer is consistent with the field strength displayed on the instrument or not. And we also need to observe whether the reading on the computer is delayed. The experimental results show that the reading module is normal and effective.

In Table 3.1, the computer display refers to the field strength displayed on the computer, the instrument display refers to the field strength on the instrument, the time delay refers to whether there is a time difference between these two values, and the duration refers to the existing time of specified field strength. The testing time is counted by seconds considering that it takes a certain time to stabilize the field strength during the field calibration process.

The evaluation for the field calibration module mainly consists of the setting parameters and the storage of the calibration data. Field calibration mainly includes the following parameters: start frequency, end frequency,

Number	Ground Truth	Sensor reading	Delay(s)	Duration(s)
1	0.24	0.24	0	5
2	3.22	3.22	0	2
3	1.78	1.78	0	4
4	0.33	0.33	0	7

TABLE 3.1
Reading test for the field strength sensor

field strength, and stepping manner. According to the requirements of the testing standard and equipment status, the field calibration process is divided into two parts, one is with a start frequency of 80MHz and an end frequency of 1GHz, the other is with a start frequency of 1GHz and end frequency of 2GHz, and the stepping manner is 1%. The electromagnetic field intensity is 3V/m, 10 V/m, and 30 V/m, respectively. Take the start frequency of 80MHz, end frequency of 1GHz, and electromagnetic field strength of 30 V/m as an example, we evaluate whether the module can realize normal functions. According to the experimental results, we find that the second frequency point is 80.8 MHz, while the third frequency point is 81.608 MHz, which increases 1% compared with that of the second frequency point. The largest field strength is 31.2 V/m and the smallest is 29.0 V/m, which are both within the 5% error of the expected value of 30 V/m. The largest output voltage of the signal generator is -1.5dB and the smallest is -13.5dB, which are both within the rated voltage range. The calibration data is automatically generated and stored in a TXT file. Overall, the testing results are satisfactory.

5.2 Evaluation for the RI test module

After the test for the communication between devices and the module functions, we select a single-phase electricity meter for the RI test. The test frequency range is 80MHZ to 1GHZ. The RI test system automatically completes the test and obtains the corresponding test report. The test result is shown in Fig. 3.1.

The report will point out the testing errors corresponding to each frequency. We select the representative frequencies which are with large testing errors, which are shown in Table 3.2.

According to the national standard, the maximum ranges of the allowed testing change for the RS test of electricity meters are different for different levels, which dis-tributes in [1%, 3%]. Table 3.2 shows that the maximum change is 0.3%, which is much smaller than 1%. The test meets the requirements predetermined by the system design.

5.3 Comparison between the RI test system and anechoic chamber test

As a non-standard test system, the GTEM cell, with its convenience and high efficiency, still occupies a certain test market after the standard is updated. We also choose a 3-meter anechoic chamber to conduct the RI test for the unqualified electricity meters. We also put it in the GTEM cell and use the RI test system to test it, and compare the results with the 3-meter anechoic chamber test.

5.4 Requirements for the RI test of electricity meters

According to standard requirements, the frequency range involved in the test is 80MHz~2GHz. The testing steps are as follows:

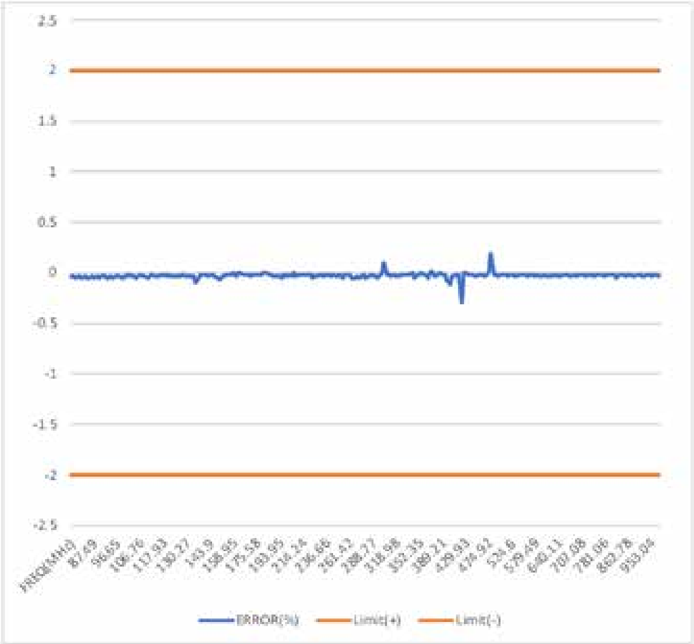

FIGURE 3.1
Testing results

Error without disturbance(%)	–0.016	
Sensitive frequency(MHz)	**Test result(%)**	**Change(%)**
80	–0.016	0.0
100	–0.106	0.1
425	–0.292	0.3
484	0.187	0.2
800	–0.017	0.0
1000	–0.026	0.0

TABLE 3.2
Testing results

1. Test with the current. The field strength is 10V/m. The voltage line is with the reference voltage. The current line is with the reference current. The change of electricity meter's testing error during the test should not exceed the specified maximum limit.
According to the national standard, the maximum limits of the RF immunity test errors of electricity meters with different accuracy levels are shown in Table 4.1.

Accuracy level	0.2S	0.5S	1	2
Limits of the test error (%)	1.0	2.0	2.0	3.0

TABLE 4.1
The limits for RF immunity test error

FIGURE 4.1
Prepaid single-phase electricity meter

2. Test without current. The field strength is 30V/m. The voltage line is with the reference voltage. The current line has no current, and the current terminal should be open. During the test, the electricity change of the electricity meter should not exceed its specified requirement. The formula for the maximum allowable change is as follows:

$$x = 10^{-6} m U_n I_{max}$$

where m is the number of sensors, U_n (V) is the reference voltage, and I_{max} (A) is the maximum current.

5.5 Electricity meter test and analysis

We select a prepaid single-phase electricity meter, which is shown in Fig. 4.1. The reference voltage of the meter is 220V. The reference current of it is 10(100)A. The pulse constant is 800imp/kWh. The experimental layout in a 3m anechoic chamber is shown in Fig. 4.2.

The experiment was carried out in accordance with gbt17626.3-2016. The experimental data is shown in Table 4.2.

According to our test, the reading error of the electricity meter is beyond 99.99% when the field strength is 10 V/m and the frequency is 158 MHz in

FIGURE 4.2
Experimental layout of electricity meter in 3m anechoic chamber

Field strength	Antenna polarization direction	Frequency range	Results	Description
10 V/m	Vertical	80M~1000MHz	Not qualified	Sensitivity frequency is 158MH and the 99.99% of the test result is wrong
10 V/m	Horizontal	80M~1000MHz	Not qualified	The error in the range of 450M~540MHz is beyond 6%
10 V/m	Vertical and horizontal	1G~2GHz	Qualified	The error in the range of 450M~540MHz is beyond 6%
30 V/m	Vertical and horizontal	80M~2GHz	Qualified	/

TABLE 4.2
Original test data for the electricity meter

the vertical polarization direction, which means that the electricity meter is obviously not qualified. The maximum reading error of the electricity meter is more than 6% when the field strength is 10 V/m and the frequency in the horizontal polarization direction is 450M-540 MHz, which is larger than 3% permitted by the standard.

FIGURE 4.3
Experiment layout in the front

FIGURE 4.4
Experiment layout in the side face

From Table 4.1, we can calculate that the maximum change of the power reading of the electricity meter is 0.022kWh when the field strength is 30 V/m.

Error without disturbance (%)	**–0.026**	
Sensitive frequency (MHz)	**Test results (%)**	**Changes(%)**
80	–0.026	0.0
100	–0.071	0.1
160	99.99	99.99
222	0.779	0.8
509	6.247	6.3
666	1.28	1.3
800	0.171	0.2
1000	–0.026	0.0

TABLE 4.3
Recordings of the error

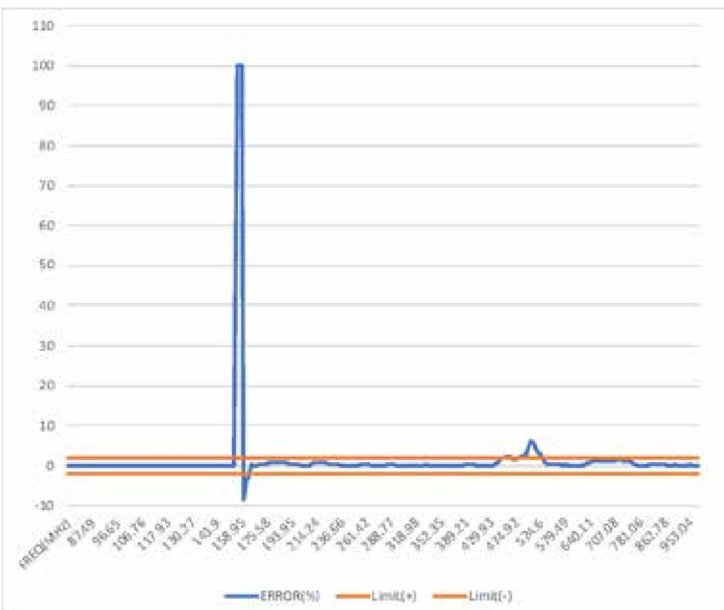

FIGURE 4.5
Recordings of the error

While the corresponding value is 0.0 kWh without our real-world test, which indicates that the meter is qualified.

5.6 With the automatic RS test system

We place the electricity meter in the GTEM cell. The experimental layout is shown in Fig. 4.3 and Fig. 4.4.

The experiment is carried out in accordance with the test standard. The errors are automatically recorded as shown in Table 4.3 and Fig. 4.5.

There is no pulse during the 30 V/m test without load. The change of the power reading is 0.0 kWh. The test result is consistent with that of the 3-meter anechoic chamber. The experimental results show that the test is qualified.

When the field strength is 10 V/m, the 99.99% reading error happens at the electromagnetic sensitive point of 160M and 158M with the 3-meter anechoic chamber. Another electromagnetic sensitive point is 590M, which corresponds to the reading error change of 6.3%. The testing result shows that the electricity meter is not qualified.

The investment cost for the 3-meter anechoic chamber is 10 times that of the GTEM cell and the testing results with the 3-meter anechoic chamber cannot be read automatically. The GTEM cell is more efficient with an automatic test structure, which reduces the uncertainty brought in by human involvement.

CONCLUSIONS

Since GTEM cell is cheap and the test performance can meet the requirements of current test standards, it is a well-designed test equipment to conduct electromagnetic compatibility tests for a long time. Based on the RI test principle, we developed an automatic system for the RI test of electricity meters with GTEM cell and LabVIEW. We verify the consistency of the test results of the system with the 3-meter anechoic chamber test. Significantly, the automatic RI test system of electricity meters has been used in practice.

REFERENCES

[1] R. Zhang, X. Jing, S. Wu, C. Jiang, J. Mu, and F. Richard Yu, "Device-Free Wireless Sensing for Human Detection: The Deep Learning Perspective," IEEE Internet of Things Journal, vol. 8, no. 4, pp. 2517-2539, Feb. 2021.

[2] M. Liu, F. Richard Yu, Y. Teng, V.C.M. Leung, and M. Song, "Distributed Resource Allocation in Blockchain-based Video Streaming Systems with Mobile Edge Computing," IEEE Trans. Wireless Comm., vol. 18, no. 1, pp. 695-708, Jan. 2019.

[3] M. Liu, Richard Yu, Y. Teng, V.C.M. Leung, and M. Song, "Performance Optimization for Blockchain-Enabled Industrial Internet of Things (IIoT) Systems: A Deep Reinforcement Learning Approach," IEEE Trans. Industrial Electronics, vol. 15, no. 6, pp. 3559-3570, June 2019.

[4] J. Du, F. Richard Yu, G. Lu, J. Wang, J. Jiang, and X. Chu, "MEC-Assisted Immersive VR Video Streaming over Terahertz Wireless Networks: A Deep Reinforcement Learning Approach," IEEE Internet of Things Journal, vol. 7, no. 10, pp. 9517-9529, Oct. 2020.

[5] F. Richard Yu, "From Information Networking to Intelligence Networking: Motivations, Scenarios, and Challenges," IEEE Network, accepted, Apr. 2021.

[6] M. Ammari, N. Gomes, M. Jacques, B. Maxim, and etc. A Survey of Sensor Network Applications and Architectural Components, Ad Hoc & Sensor Wireless Networks, vol. 25, issue 1/2, p1-44. 44p, 2015
[7] Jr. Marino and A. Michael. System and method for method for measuring RF radiated emissions in the presence of strong ambient signals.US patent 6980611. 2000-02-03.
[8] D. A. Weston. Electromagnetic compatibility: principles and applications : Marcel Dekker, 1991, 704pp, $132.25, ISBN 0 8247 8507 X[J]. Materials & Design, 1992, 13:189.
[9] I. Nevlyudov, V. Palagin, and I. Botsman. The general principles of electromagnetic compatibility improving with microsystem technology using[C]// Problems of Infocommunications Science and Technology. IEEE, 2017.
[10] C. Schuster and W. Fichtner. Parasitic modes on printed circuit boards and their effects on EMC and signal integrity[J]. Electromagnetic Compatibility IEEE Transactions on, 2001, 43(4):416-425.
[11] D. Gedney. The application of the finite-difference time-domain method to EMC analysis, IEEE Symposium on EMC, PP. 117-120, 2009.
[12] R. Perez. Steps for the proper development of an EMC Control Plan[C]// IEEE International Symposium on Electromagnetic Compatibility. IEEE, 2002:766-771 vol.2.
[13] Paul C R. Introduction to Electromagnetic Compatibility (EMC)[J]. IEE Review, 2006, 38(7-8):1-12.
[14] C. R. Paul. Introduction to Electromagnetic Compatibility (EMC)[J]. IEE Review, 2006, 38(7-8):1-12.
[15] K. Zdeněk, N. Denys and K. Pavel.Optimization of electrical properties of parallel plate antenna for EMC testing.Journal of Computational and Applied Mathematics[J], 2014,270:283-293
[16] S. P. Litrán and P. Salmerón. Electromagnetic compatibility analysis of a control strategy for a hybrid active filter[J].Electric Power Systems Research, 2017,144:81-88.
[17] K. L. Chua, M. Jenu, M. Wong, S.-H. Ying. Radiated emissions estimation of an integrated circuit based on measurements in GTEM cell. 2013 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC), IEEE, 2013.
[18] S. Xing, X. Lv, and C. Ding. Research on Input Impedance of Dipole Antenna in GTEM Cell. Journal of Electronics, vol. 31, no. 6, Dec. 2014.
[19] J. Hallon and K. Kovac. Simplified generation of electromagnetic field within EMC immunity test area. Procedia Engineering, no. 69, pp. 27-34, 2014.
[20] J. D. Cooper, G. Evans, and J. T. Hudson. Testing electricity meters for susceptibility to radio frequency interference. pp. 180-189, 1996.
[21] P. Wang, C. Li, Z. Zhang, Y. Dai, Y. Dan, X. Dong, Z. Chen, J. Yang, and L. Lin. The research and rectification on the test of immunity to electromagnetic RF fields for electrical energy meter. 2017 IEEE 13th International Conference on Electronic Measurement and Instruments, pp. 1-4, 2017.
[22] B. L. Capehart. New technology for electrical metering monitoring and control instrumentation[J]. Energy Conversion and Management, 1984,24(3):177-180
[23] De. Leo. Radiated Immunity Tests: Reverberation Chamber vs. Anechoic Chamber Results[J].Instrumentation and Measurement Technology Conference. Proceedings of the IEEE, 2004: 337-341.
[24] L. Ge, L. Quan. Efficiency improvement and evaluation of electric hydraulic excavator with speed and displacement variable pump[J].Energy Conversion and Management, 2017,150:62-71.