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Research on Multi-Module Smart Meter Based on Edge Computing

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ABSTRACT

In the construction of smart grid, the ubiquitous electric Internet of Things is playing an increasingly important role. The convergence of technologies such as Internet of Things, edge computing and artificial intelligence has created favorable conditions for the intellectualization of power terminal equipment. This paper combines edge computing technology and Fast Fourier Transform (FFT) windowed interpolation algorithm to propose a multi-module smart meter in IR46 International Recommendation. Based on the separation of metering function and non-metering function, the intelligent home control and harmonic metering function are realized based on edge computing technology. The accuracy of the electric energy measurement of the proposed meter is verified by experiments. The experimental results show that the multi-module smart meter runs reliably and stably with high measurement accuracy.

1. Introduction

Smart meter is the basic equipment on the demand side of smart power grid. With the rapid development of the power industry, smart meters not only need to have stable and accurate metering function, but also have the functions of energy data storage, multi-rate calculation and client control[1]. The development of smart meters around the world has been going on for 20 years. Many researchers devote themselves to the research and improvement of smart meters. And the direction of improvement is to modularize, networked and systematize smart meters[2]. The modularization of smart electricity meters divides smart electricity meters into modules according to their functions. When the smart electricity meters fail, the maintenance of the smart electricity meters can be realized only by replacing the corresponding fault modules. The International Recommendation IR46 formulated by the International Legal Metrometer Organization proposes to separate the metering part and the non-metering part of the electricity meter, which makes the dual-core meter (" management core "and" metering core ") enter the industry's attention[3]. Networking of smart electricity meters moves part of the functions of smart electricity meters from the access layer to the network layer and realizes more complex functions through data sharing and comprehensive analysis. Simplify the hardware design of smart meter[4]. The systematic use of mature computer technology and power system automation technology, smart meter on the data control platform to achieve the effective analysis and processing of massive electricity data[5].

In this paper, a multi-module smart meter is studied in combination with the modularize, networked and systematize design. The smart meter is divided into management module, metering module and communication module. This structure realizes the separation of the metering part and the non-metering part of the meter. And the metering part and non-metering part of the electricity meter are separated. The edge computing technology is applied to the multi-core modular smart electricity meter to realize the intelligent home control and high precision harmonic measurement. At the same time, the multi-module smart meter adopts edge computing technology to realize intelligent home control and high-precision harmonic measurement.

2. Edge computing technique

Edge computing refers to the network edge side, close to the content or data source integration of network technology and large data computing open platform, edge computing technology in the data source to big data and cloud computing center set up edge node operation, ensure the security of the data and reduce the cloud computing data center[6-8].

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Compared with the traditional cloud computing mode, edge computing can more fully explore the performance of terminal devices and better support the application of the Internet of Things, mainly in the following aspects:

(1)Edge computing can relieve the strain on network bandwidth and data center. The Internet of Things data is typically characterized by a high degree of redundancy, most of which is temporary. Edge computing can take full advantage of this feature to process large amounts of temporary data at the edge of the network, thus reducing the pressure on network bandwidth and data center[9].

(2)Edge computing can improve the responsiveness of services. In the complex application scenarios of network environment, the response ability of cloud computing mode is seriously affected by the data blocking and network delay limitation caused by communication links[10]. Edge computing can be used to process data near data sources and avoid network congestion and delay, thus improving the responsiveness of services.

(3)Edge calculation can improve the security of data. In the cloud computing mode, all data is concentrated in the data center. If the data in the data center is stolen, the security of users will be affected[11]. Edge computing, on the other hand, stores and uses the data in the network edge devices closer to the user, which improves the security of the data.

(4) Compared with cloud computing, edge computing produces less energy consumption. Data centers in the cloud consume a lot of energy. According to Sverdlik, the energy consumption of all data centers in the United States will increase by 5 percent to 78 billion kilowatt-hours by 2022, and China's data centers already consume more electricity than Hungary and Greece combined. With more and more user applications and more and more data processing, energy consumption will become a bottleneck limiting the development of cloud computing centers[12].

3. Multi-module smart meter hardware design

Multi-module smart meter includes management module, measurement module and communication module. The management module consists of a management chip, a display module, a load switch control module, a power-down alarm module and a storage module, which is responsible for the control of the load switch and the display, scheduling and storage of power data and information.

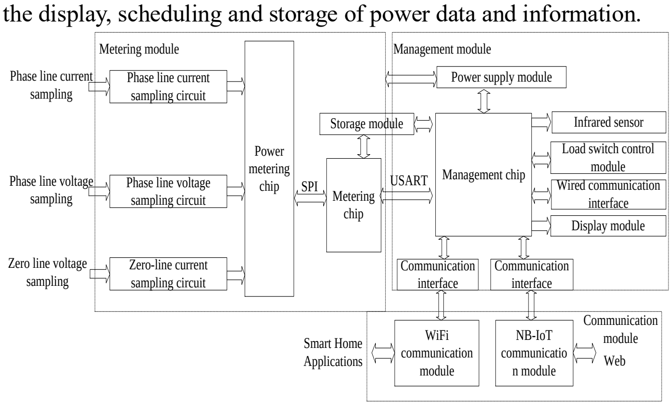


Fig.1. The diagram of multi-module smart meter.

The metering module is composed of metering core and electric energy metering module, which is responsible for the safe collection and metering of electric energy data and information. The communication module is compatible with NB-IoT and WIFI communication functions to realize data transmission between multi-module smart meter and home LAN and Internet. The hardware structure of multi-module smart meter is shown in Figure 1.

3.1. Management module design

Management module as multi-module smart meter control center, which is mainly composed of management core, display module, load switch control module, power alarm module and storage module, management module is responsible for the meter in the operation of all management functions, such as cost control display, data storage, the event log, data freeze, load control, etc. The management chip is STM32F407ZGT6 chip from STMicroelectronics. The chip has an internal integrated DSP instruction set, operating frequency up to 168MHz, 5 standard serial communication interfaces, large storage space and other characteristics, which are suitable for data management, operation and scheduling. The management chip and the metering core transmit electric energy data through UART, the management chip and storage module read and write data through SPI, the management chip and communication module transmit data through UART and network platform, the management chip and display module display data through 4 GPIO ports, the management chip controls the load control module through GPIO and extends additional interfaces for other auxiliary functions. The peripheral interfaces of the management core are shown in Figure 2.

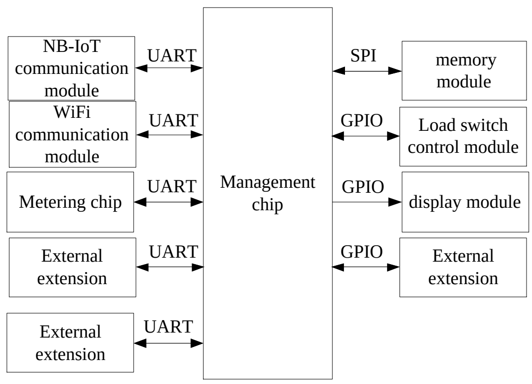


Fig.2. The peripheral interface diagram of the management chip.

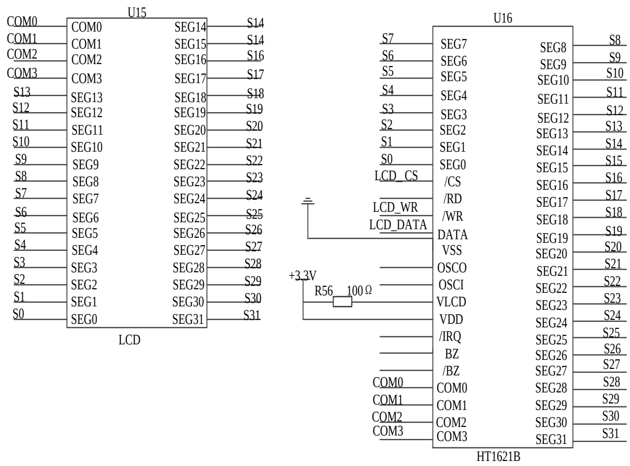


Fig.3. The principle diagram of the display module.

The display module consists of a segment code display screen and an HT1621 driver. In order to allow users to check the electricity consumption in real time, the multi-module smart meter displays the real-time electricity consumption of voltage, current, instantaneous power and total electricity consumption through the display screen, and sets 5S as the refresh time of the screen. The schematic diagram of the display module is shown in Figure 3.

Load switch control module adopts the transistor control relay to realize the load switch control of the multi-module smart meter. The schematic diagram of the load switch control circuit is shown in Figure 4.

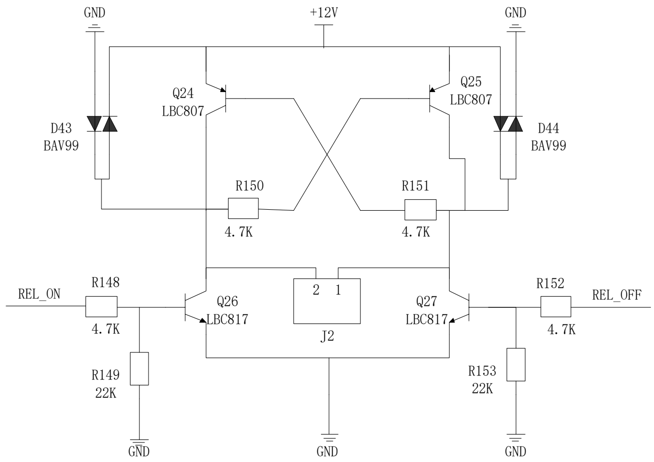


Fig.4. The principle diagram of the load switch control module.

In Figure 4, the management chip changes the on-state of the transistor by controlling the output level of REL_ON and REL_OFF, so that the voltage at both ends of the relay J2 changes constantly to achieve the control of the relay on and off the purpose.

In the event of regional power failure or battery under voltage, the communication module of the multi-module smart meter will stop working immediately, resulting in failure to report the power loss information to the network platform in time, which is not conducive to the troubleshooting of the electricity meter and may lead to the measurement dysfunction of the multi-module smart meter.

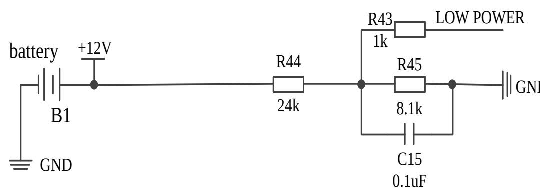


Fig.5. The principle diagram of the power down alarm module.

To solve the above problems, the multi-module smart meter depressurizes the power supply voltage through the resistance voltage division method, and then inputs the power supply voltage signal to the AD sampling port of the management chip. As shown in Figure 5, when the multi-module smart meter is running normally, the sampling voltage at about 3V. when the AD sampling the voltage is lower than a certain value, the supply voltage signal is below the lower limit, multi-module smart meter into power down mode. The multi-module smart meter immediately stops other work, sends the power down alarm to the network platform, and stores the current power data and parameters to prevent data loss. It will continue to work when the power supply of the electricity meter is restored.

Storage module is mainly used to store the power data and event records of the past year, to prevent the data loss caused by sudden power failure and to facilitate the retrieval of data at any time when the data is traced. The storage module uses W25Q128 chip for data storage, and W25Q128 chip has 128MB Flash memory. The schematic diagram of the storage module is shown in Figure 6

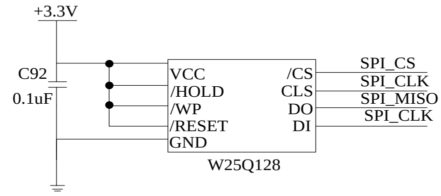


Fig.6. The principle diagram of the storage module.

3.2. Metering module design

The metering module is the data acquisition center of multi-module smart meter. The metering module is composed of metering chip, electric energy metering circuit and power supply circuit. It mainly realizes the collection of electric power data information such as current, voltage and power in the circuit.

The electric energy metering circuit is responsible for collecting the current and voltage signals in the circuit, and sending the data to the metering chip to calculate the electric power data. Electric metering circuit is composed of voltage sampling circuit, phase current sampling circuit, zero line current sampling circuit and electric power metering chip ATM90E26. The voltage sampling circuit and the phase-line current sampling circuit convert the current and voltage in the circuit into the equivalent small signal of current and voltage, and then input the signal to the electric power metering chip ATM90E26 to realize the measurement of electric power data. In order to prevent the phenomenon of stealing electric power by human interference in private connected lines, the zero-line current sampling circuit is added to detect the behavior of stealing electric power. Figure 7 is the working principle diagram of electric energy metering circuit.

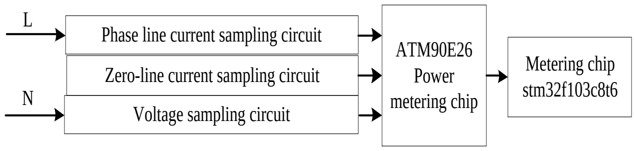
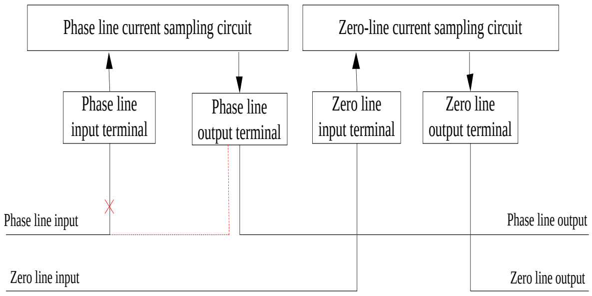


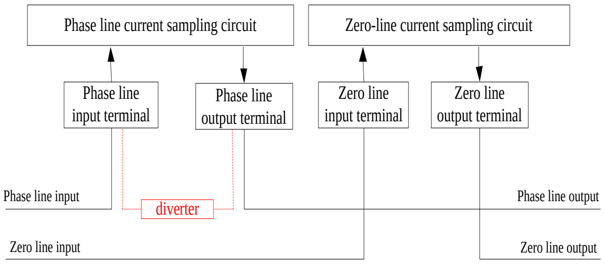
Fig.7. The principle diagram of the electricity metering circuit.

The power metering chip ATM90E26 has three Σ-△ type analog-to-digital converters. Each digital-to-analog converter converts the analog voltage signal in the sampling circuit into digital voltage signal and sends it to the DSP module inside the chip. After DSP module processing, the power data, power, voltage, frequency and other power data are stored in the register inside the chip.Then the power data is transmitted to the metering core through the UART communication interface[13].

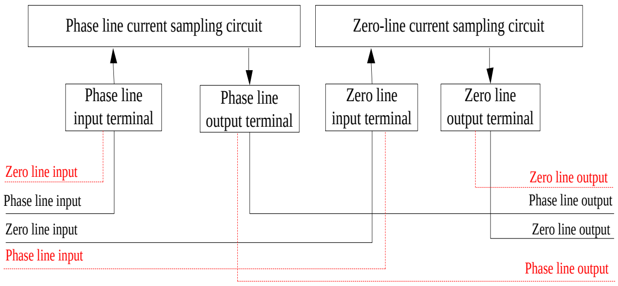
Before the design of the zero sampling circuit, the analysis of the common means of stealing electricity includes several specific. Generally, there are three means of stealing electricity by human interference. The first is to pull the phase wire out of the terminal of the electricity meter, skip the current sampling circuit of the phase wire and directly short connect it.Second, a shunt is connected to the input terminal and output terminal of the phase line of the electricity meter, which affects the accuracy of current sampling. The third method is to swap the input and output terminals of the phase line and the input and output terminals of the zero line so that the electricity meter cannot measure the phase line current[14-16]. Figure 8 is the wiring diagram of three common methods of stealing electricity.



(a) Sub phase line.



(b) Illegal access to the shunt.



(c) The phase line is inversely connected with the zero line.

Fig.8. Wiring diagram of three common means of stealing electricity.

If the multi-module smart meter does not have the zero-line current sampling circuit, it will be stolen by criminals, resulting in inaccurate measurement accuracy.If the zero-line current sampling circuit is added to conduct current sampling on the zero-line terminals, and the sampling value is compared with the sampling value of the phase-line current sampling circuit, the user can be judged whether there is electric theft.

3.3. Communication module design

The communication module is the communication center of multi-module smart meter, which is composed of NB-IoT communication module and WIFI communication module.

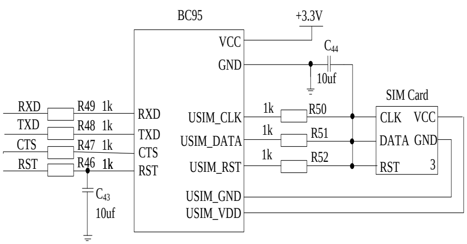


Fig.9. The principle diagram of the NB-IoT communication module.

The NB-IoT communication module is designed by the BC95 communication module of Quectel, and it supports MQTT protocol, COAP protocol and UDP protocol. At the same time, the communication of NB-IoT communication module is based on the cellular network, and the corresponding SIM card is needed to realize the data transmission to the network. The schematic diagram of NB-IoT wireless communication module is shown in Figure 9.

Multi-module smart meter need to form a home LAN with smart devices in the home. The most common network communication protocol in the home is WiFi communication protocol. The communication module uses the ESP8266 communication module to communicate with home devices in the home LAN, and the module is connected with the management chip through the USART interface. It can constitute a network with smart devices with WiFi function in the home, and it can also control non-smart devices by expanding the ESP8266 wireless module and relay. Figure 10 shows the control scheme of home equipment[17].

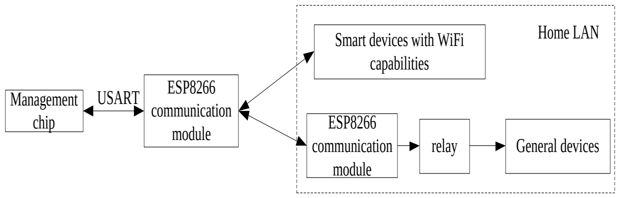


Fig.10. IoT overall design.

ESP8266 communication module has three operating modes, which are softAP mode, station mode and softAP+station mode. ESP8266 communication module in multi-mode smart meter adopts softAP mode to establish a WiFi access point. Connect home equipment to the access point to communicate with ESP8266 communication module. The ESP8266 communication module sends the received information to the management chip through the USART serial port, and then transmits the data to the network platform through the NB-IOT communication module of the communication module. The schematic diagram of the ESP8266 wireless communication module is shown in Figure 11.

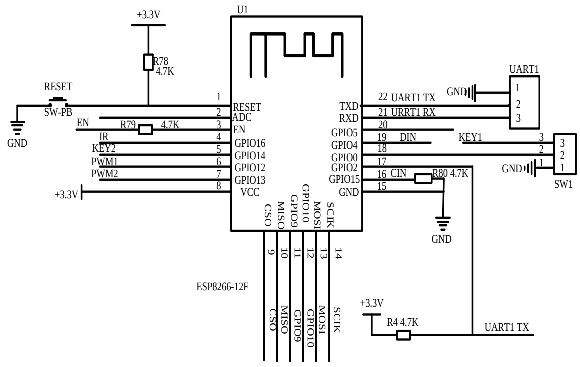


Fig.11. The principle diagram of the ESP8266 module.

4. Application of edge computing in Multi-module smart meter

4.1. Smart home control

Multi-module smart meter is not only the data acquisition equipment of electric energy, but also the data manager of the whole smart home equipment. In the home local area network, the smart home equipment is connected with the multi-core modular smart electricity meter through WiFi technology, and the data is transmitted through the NB-IoT base station. The NB-IoT base station transmits the data to the server and stores the data to the database by accessing the Alibaba Cloud Internet of Things platform. The user monitors and controls the running state of multi-core modular smart electricity meters and smart home devices through the mobile terminal application. The control process of smart home is shown in Figure 12.

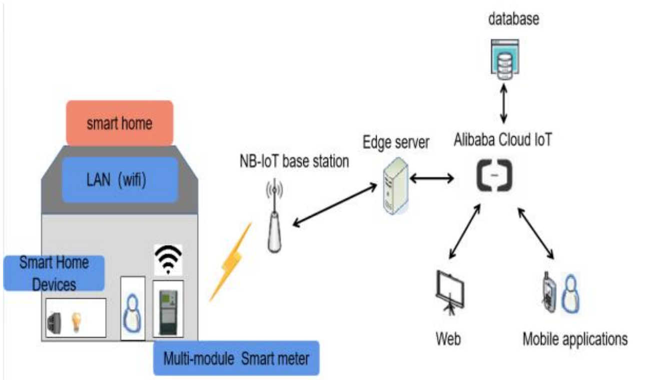


Fig.12. Smart home control process diagram.

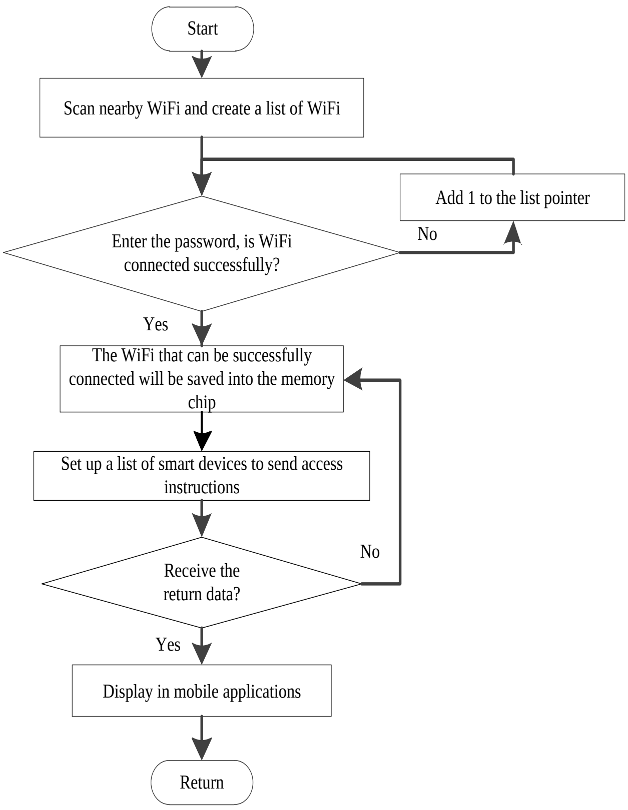


Fig.13. Smart home control program flow chart.

The multi-module smart meter builds a data transmission channel with home devices through WiFi. Scans the nearby WiFi through the ESP8266 communication module, and try to connect with the WiFi access point with a fixed password. If the connection password is successful, the device is a smart home device that can be connected to a multi-module smart meter, and then recorded in a linked list in the program for quick connection of the device. When the multi-module smart meter is successfully connected to the device, it will send the device access command, and the smart home device will pack the current device information and send it back to the multi-core modular smart electricity meter. Finally, the multi-core modular smart electricity meter transmits the data of smart devices to the mobile terminal application. Figure 13 is the flow chart of the smart home control program.

4.2. Harmonic measurement

With the rapid development of power industry, various types of nonlinear load device (for example: semiconductor rectifier and inverter) connected to the electricity grid in the signal distortion is harmonics, harmonic generation loss of the grid, the output load equipment, reduce the electricity load equipment efficiency, may also cause damage to the harmonic load flow caused by equipment. At the same time, harmonics will affect the measurement accuracy of electrical measuring instruments and increase the measurement error.

In life, the voltage and current signals of the power network are affected by the nonlinear load and contain harmonics. The fundamental current will be distorted to generate the distorted wave of non-sinusoidal signal. At this time, the electrical signals in the power network are represented by a periodic function.

$$f(t) = f(t + kT)(k = 0,1,2\ldots\ldots) \tag{1}$$

According to the principle of Fourier transform, $f(t)$ is represented by the sum of 1 direct component and n harmonic components, and its expression is shown in Formula (2).

$$\begin{aligned} f(t) &= A_0 + A_1\sin(\omega t + \varphi_1) + \ldots + A_n\sin(n\omega t + \varphi_n) \\ &= A_0 + \sum_{n=1}^{\infty} A_n \sin(n\omega t + \varphi_n) \\ &= \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n\cos n\omega t + b_n \sin n\omega t) \end{aligned} \tag{2}$$

In Formula (2), A_0 is the direct component; ω is the angular frequency; A_n and φ_n are respectively the amplitude and initial phase Angle of n harmonic waves; a_n and b_n the cosine and sine coefficients of the n harmonics, respectively.

The multi-module smart meter converts the voltage and current of the electrical signal into the standard voltage value through the voltage and current sampling circuit, and then converts the signal into the digital signal through the A/D converter in the power metering chip. The signal is truncated and converted into a discrete signal sequence $x(n)$ of length n. The expression of the spectrum function is shown in Equation (3).

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j\frac{2\pi k}{N}n}, k = 0,1,2,\cdots,N-1 \tag{3}$$

$x(n)$ was decomposed into strange sequence $x(1), x(3), x(5),\ldots, x(N-1)$ and even sequence $x(0), x(2), x(4),\ldots, x(N-2)$ by the Fast Fourier transform. The expression of an electrical signal is as follows:

$$X(k) = \sum_{n=0}^{N/2-1} x(2n) W_N^{2nk} + \sum_{n=0}^{N/2-1} x(2n+1) W_N^{(2n+1)k} \tag{4}$$

Formula (2) is obtained by the reducibility of the rotation factor.

$$W_N^{mk} = W_{nN}^{mnk} = W_{N/n}^{mk/n} \tag{5}$$

Substitute formula (5) into formula (4) to get formula (6).

$$X(k)=\sum_{n=0}^{N/2-1}x(2n)W_{N/2}^{nk}+W_N^{nk}\sum_{n=0}^{N/2-1}x(2n+1)W_{N/2}^{nk} \tag{6}$$

Plug $W_{N/2}=e^{-j\frac{2\pi}{(N/2)}}=e^{-j4\pi/N}$ into Equation (6), assuming functions $Y(k)$ and $Z(k)$.

$$Y(k)=\sum_{n=0}^{N/2-1}x(2n)W_{N/2}^{nk},k=0,1,2,\ldots\ldots,N/2-1 \tag{7}$$

$$Z(k)=\sum_{n=0}^{N/2-1}x(2n+1)W_{N/2}^{nk},k=0,1,2,\ldots\ldots,N/2-1 \tag{8}$$

According to $W_N^k=-W_N^{k+N/2}$, the formula is as follows:

$$X(k+N/2)=Y(k)-W_N^kZ(k) \tag{9}$$

After the above transformation, $X(k)$ can be expressed by $Y(k)$ and $Z(k)$, and the operation process of Formula (7) and (8) is called butterfly operation. The specific calculation process is shown in Figure 14.

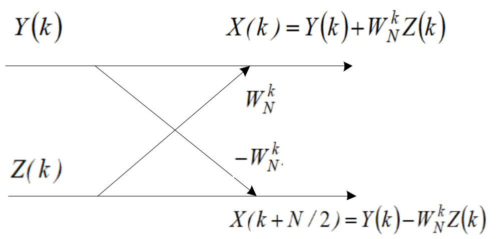


Fig.14. Butterfly operation.

In the case that the acquisition rate of the power metering chip is 2kHz and the fundamental frequency of the sampled signal is 50Hz. A signal cycle can be described by 40 sampling points. Data were collected for 6 cycles in each harmonic analysis, i.e., 240 samples. Fast Fourier transform algorithm uses the basis 2 algorithm to process the signal, so the number of sample values should be an integer power of 2. The 240 samples were linearly interpolated to obtain 256 target data. And Fast Fourier transform algorithm uses Hanning window function to optimize the data to solve the spectrum leakage and spectrum aliasing problems. The function expression of the Hanning window is Formula (10).

$$W_H(\omega)=\frac{1}{2}W_R(\omega)-\frac{1}{4}\left[W_R(\omega-\frac{2\pi}{N})+W_R(\omega+\frac{2\pi}{N})\right] \tag{10}$$

In Formula (10), $W_R(\omega)$ is called Dirichelet kernel, and its expression is as follows:

$$W_R(\omega)=\frac{\sin(\omega N/2)}{\sin(\omega/2)}e^{-j\omega(N-1)/2} \tag{11}$$

The amplitude, frequency and phase of the fundamental wave and each harmonic of the electrical signal are obtained by the above method. Then these parameters are calculated through Equations (9-11) to obtain the power parameters.

$$U=\sqrt{\left[U_0+\sum_{n=1}^{\infty}U_n\sin\left(n\omega_0t+\theta_n\right)\right]^2dt} \tag{12}$$

$$I=\sqrt{\left[I_0+\sum_{n=1}^{\infty}I_n\sin\left(n\omega_0t+\theta_n\right)\right]^2dt} \tag{13}$$

$$P=U_0I_0+\sum_{n=1}^{\infty}U_nI_n\cos\left(\theta_n-\partial_n\right) \tag{14}$$

5. Experiment

5.1. Smart home control experiment

Multi-m1multi-module smart meter transmits electric energy data to the network platform, and the mobile terminal interacts with the network platform through the application program. In this test, the mobile terminal is Android phone terminal (model: Huawei NOVA 5 Pro, system version of Android OS 6.1). Figure 15 shows the physical display of the test system.

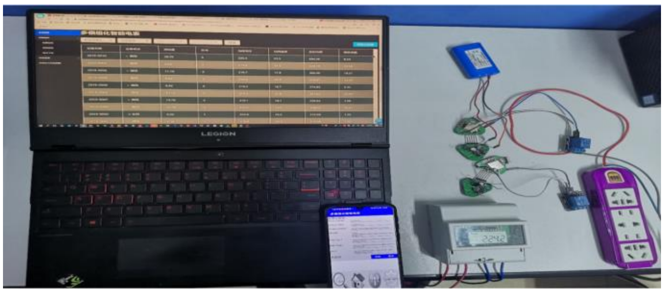


Fig.15. Actual diagram of the experimental system.

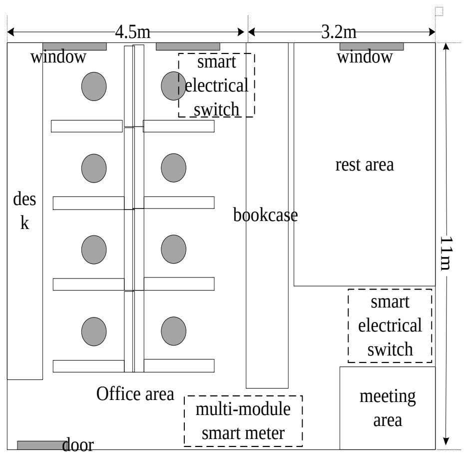


Fig.16. Simulate residential planar graph.

In order to test the smart home control function of the multi-module smart meter system, the laboratory was taken as the test site to simulate the family model with one room and one living room, with an overall area of 7.7m ×11m. The structure of the laboratory is shown in Figure 16.

Multi-module smart meter and smart switch in the specified position as shown in Figure 17. Open the mobile terminal application, enter the smart home device access interface and search for smart devices. The smart switch are successfully searched in the page.

Press the control button of the smart switch to view the switching status and other data information of the smart switch. Figure 18 shows the interface diagram of the smart switch control.

Fig.17. Simulate residential planar graph.

Fig.18. Smart switch control interface.

5.2. Experimental measurement

An error test bench was established, and three multi-core modular smart electricity meters were selected as the test tables to measure the basic active power errors with power factors of 1.0 and 0.5L respectively. Figure 19 is the wiring diagram of the workbench, and Table 1 is the active power error table.

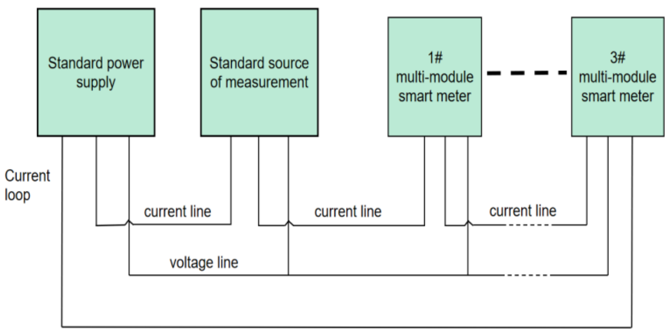


Fig.19. Workbench wiring diagram.

Experiments were set up to verify the accuracy of harmonic power calculated by Fast Fourier transform algorithm for multi-module smart meter. In this experiment, UTE1010A Intelligent Electrical Parameter Quality Analyzer is used as the harmonic detection tool, the measured harmonic signal data is taken as the actual value and compared with the measured data of the multi-module smart meter. The multi-module smart meter is connected to the power grid for harmonic test, and the test results are shown in Table 2.

Table.1. Active power error table.

Current value	Power factor	Allowed values	Actual relative error		
			1#	2#	3#
$0.05I_b$	1.0	±2.5	0.1	0.1	0.1
$0.1I_b$	1.0	±2.0	0.0	0.1	0.1
$0.5I_b$	1.0	±2.0	0.1	0.0	0.0
I_b	1.0	±2.0	0.0	0.0	0.0
$0.5I_{max}$	1.0	±2.0	0.0	0.0	-0.1
I_{max}	1.0	±2.0	0.1	0.1	0.1
$0.1I_b$	0.5L	±2.5	0.2	0.1	0.2
$0.2I_b$	0.5L	±2.0	0.1	0.1	0.1
$0.5I_b$	0.5L	±2.0	0.1	0.1	0.0
I_b	0.5L	±2.0	0.1	0.0	0.0
$0.5I_{max}$	0.5L	±2.0	0.1	0.0	0.1
I_{max}	0.5L	±2.0	0.2	0.1	0.2

Table.2. The experiment results of harmonic metering.

harmonic frequency	actual voltage （V）	actual current （A）	test voltage （V）	test current （A）
1	219.913	10.305	219.857	10.276
2	0.534	0.021	0.539	0.024
3	1.713	0.076	1.724	0.074
4	0.094	0.004	0.095	0.004
5	1.543	0.075	1.532	0.072
6	0.072	0.007	0.073	0.007
7	0.325	0.020	0.312	0.018
8	0.053	0.005	0.055	0.006
9	0.593	0.024	0.587	0.027

According to the active power measurement errors and harmonic measurement values in Table 1 and Table 2, the multi-module smart meter can metering the active power and harmonic signal data in the power grid more accurately.

6. Conclusion

This paper designs a multi-module smart meter, and detailed discussion on software and hardware design project about multi-module smart meter. Described in the multi-module smart meter using modularization design dibides the whole meter into management module, communication module and metering module. This structure conforms to the standard of the international recommendation IR46 to realize the separation of the metering part and the non-metering part of the electricity meter. The multi-module smart meter combines the idea of edge calculation and Fast Fourier transform algorithm to realize the smart home control function and the harmonic measurement function. The experimental results show that the multi-core modular smart electricity meter designed in this paper can measure the active power and harmonic power more accurately, it can provide reference for the smart meter manufacturers to develop the next generation of smart meters.

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References

[1] Yuan XM, Han P, Duan Y, et al. Residential Electrical Load Monitoring and Modeling – State of the Art and Future Trends for Smart Homes and Grids[J]. Electric Power Components and Systems, 2020, 48(11): p. 1125-1143.

[2] Karabiber A. Detecting and Pricing Nontechnical Losses by Using Utility Power Meters in Electricity Distribution Grids[J]. Journal of Electrical Engineering & Technology, 2019, 14(5): p. 1933-1942.

[3] Huang JT, Zhou YF, Liang F, et al. A survey of hardware detection using IR46 meter test as an example[J]. Power System Protection and Control, 2020, 48(03): p. 99-105.

[4] Sun Y, Wang YS, Gu BC, et al. Design of multi-core smart meter with edge computing capability[J]. Electronic Measurement Technology, 2019, 42(23): p. 194-199.

[5] Kouache I, Sebaa M, Bey M, et al. A new approach to demand response in a microgrid based on coordination control between smart meter and distributed superconducting magnetic energy storage unit[J]. Journal of Energy Storage, 2020, 32(12): p. 101748.

[6] Zhang JW, Zhou XC, Ge TY, et al. Joint Task Scheduling and Containerizing for Efficient Edge Computing[J]. IEEE Transactions on Parallel and Distributed Systems, 2021, 32(8): p. 2086-2100.

[7] Zhang TY, Wen H, Tang J, et al. Cooperative Jamming Secure Scheme for IWNs Random Mobile Users Aided by Edge Computing Intelligent Node Selection[J]. IEEE Transactions on Industrial Informatics, 2021, 17(7): p. 4999-5009.

[8] Ning ZL, Ngai E, Kwok RYK, et al. Editorial: Special Section on Pervasive Edge Computing for Industrial Internet of Things[J]. IEEE Transactions on Industrial Informatics, 2021, 17(7): p. 5010-5011.

[9] Lin, S., et al., An Intrusion Detection Method of Internet of Things Based on Agent. International Journal of Applied Mathematics in Control Engineering, 2018. 1(2): p. 149-156.

[10] Zhao GM, et al. Offloading Tasks With Dependency and Service Caching in Mobile Edge Computing. IEEE Transactions on Parallel and Distributed Systems, 2021. 32(11): p. 2777-2792.

[11] Li, YY., Ma, JF., Miao. YB., et al., Secure and Verifiable Multikey Image Search in Cloud-Assisted Edge Computing, IEEE Transactions on Industrial Informatics[J]. 2021, 17(8): p. 5348-5359.

[12] Liu J, Yang TF, Bai TF, et al. Resource allocation and scheduling in the intelligent edge computing context. Future Generation Computer Systems-The International Journal of Science[J]. 2021, 121(1): p. 48-53.

[13] Zhang YJ and Tian YA. Design of the Intelligent Digital Remote Transmission Three-Phase Electric Meter Based on NB-loT and ADE9078[J]. Automatic instrument, 2019, p. 40(07)-47-49+53.

[14] Aslam Z, Javaid N, Ahmad A, et al. A Combined Deep Learning and Ensemble Learning Methodology to Avoid Electricity Theft in Smart Grids[J]. Energies, 2020, 13(21): p. 5599.

[15] Du, W., et al., Fault Diagnosis of Sensors based on Empirical Mode Decomposition and Neural Network. International Journal of Applied Mathematics in Control Engineering, 2019. 2(1): p. 66-73.

[16] Du, W., et al., Fault Diagnosis of Analog Circuit based on Extreme Learning Machine. International Journal of Applied Mathematics in Control Engineering, 2018. 1(1): p. 9-14.

[17] Wang H. and X Jin. Pedometer for Obtaining Sensor Information of Android Phone Based on Matlab. International Journal of Applied Mathematics in Control Engineering, 2019. 2(2): p. 210-216.

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