Distribution transformer monitoring and reactive power compensation

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ABSTRACT. *To satisfy the growing demand of inductive reactive power, this paper proposes to monitor the distribution transformer and realize local dynamic compensation of reactive power through digital signal processing (DSP). A monitoring system was designed based on the DSP chip and the real-time operating system, aiming to achieve fast collection, calculation, processing, monitoring and real-time control of inputs and cuts of the power capacitor and match the reactive power required by the distribution transformer. Experimental verification shows that the proposed system can reduce the reactive power transmission of the grid and the reactive power load of distribution transformer, thereby saving the cost of power transmission. The research findings provide new insights to the monitoring of distribution transformer and local dynamic compensation of reactive power shortage.*

RÉSUMÉ. *Pour répondre à la demande croissante de puissance réactive inductive, cet article propose de surveiller le transformateur de distribution et de réaliser une compensation dynamique locale de la puissance réactive par le traitement numérique du signal (DSP, le sigle de «digital signal processing»). Un système de surveillance a été conçu sur la base de la puce de DSP et du système d'exploitation en temps réel, visant à obtenir une collecte, un calcul, un traitement, une surveillance rapide et un contrôle en temps réel des entrées et des découpes du condensateur de puissance et à correspondre à la puissance réactive requise par le transformateur de distribution. Une vérification expérimentale montre que le système proposé peut réduire la transmission de puissance réactive du réseau électrique et la charge de puissance réactive du transformateur de distribution, permettant ainsi d'économiser sur les coûts de transmission de puissance. Les résultats de la recherche fournissent une nouvelle perspective sur la surveillance du transformateur de distribution et la compensation dynamique locale de la pénurie d'énergie réactive.*

KEYWORDS: *transformer terminal unit (TTU), central processing unit (CPU), distribution transformer, digital signal processing (DSP), reactive power, local compensation.*

MOTS-CLÉS: *unité terminale du transformateur (UTT), unité centrale de traitement (UCT), transformateur de distribution, traitement du signal numérique (DSP), puissance réactive, compensation locale.*

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1. Introduction

Transformer Terminal Unit (TTU) (Zhu *et al.*, 2014; Lin, 2013) is a remote terminal used for monitoring, measuring and controlling various operating parameters of distribution transformer. It is the last monitoring unit in the distribution automation system, responsible for monitoring the voltage of low pressure side, current and frequency of the distribution transformer, calculating the active power, reactive power and power factor of the distribution transformer, and providing data support for some specialty analysis of power enterprises, such as load prediction and line loss analysis so as to realize the local control of switch of reactive capacitor, maintain the reactive balance of the system and increase the power factor of the total load of distribution transformer.

According to the "Key Points of Development Planning of 10KV Distribution Network Automation" of State Grid, the distribution automation system refers to a network system that uses modern communication and computer technology to remotely monitor the on-line operating equipment of the power grid. It includes 10KV feeder automation, automation of detection of switching station and community distribution substation, distribution transformer and capacitor bank automation, among which the distribution transformer is the power equipment that distributes voltage directly to low voltage users. As the final link of supplying power to users, the distribution transformer plays an important role in the whole power supply network, and its operation data is an important and basic part of the basic data of the whole distribution network. Operation data include: three-phase voltage, three-phase current, three-phase power, and power factor. Whether these data are normal or not is an important reflection of whether the distribution transformer works well or not, which plays a decisive role in improving the reliability of power supply. Therefore, it is an important link of distribution automation to conduct real-time monitoring of various parameters in distribution transformer operation and statistical analysis of the collected data so as to timely discover abnormal conditions in distribution transformer operation and timely control or solve to achieve stability and optimal operation of power grid. In the distribution automation system, the task of monitoring the distribution transformer is accomplished by TTU which is one of the basic and core equipment of the distribution automation (Kilishi *et al.*, 2014).

Along with the continuous improvement of industrial automation level, large-scale electric equipment has emerged constantly. All the large-scale electric equipment is inductive loads, which requires the system to provide reactive power to maintain its operation. Thus, the demand for reactive power of power system is increasing. If the reactive power is provided by the generator, the transmission of the active power of the power line will be greatly reduced and the line loss increases, causing a great waste (Jun, 2017).

The current large-scale electric equipment basically adopts the method of fixed compensation capacitor to deal with its own consumption of reactive power. However, this method has a lot of limitations. Firstly, the starting and stopping of electric equipment is random. Secondly, the power consumption of electric equipment is different because of different loads, which may cause undercompensation or over-compensation, exerting a great influence on the transmission quality of power grid. The state has proposed local compensation measures that are energy-saving measures to reduce power line reactive power transmission. Local compensation can adopt dynamic compensation and static compensation (Ozansoy & Zayegh, 2007). The dynamic compensation requires compensation in millisecond (ms) level, mainly for equipment with fast load variation such as spot welder. And the static compensation requires compensation in second (s) level, mainly for equipment with constant and slow load variation such as motor. Local compensation is to encourage the installation of energy-saving equipment and devices, reduce the demand for system reactive power with the increase of large-scale electric equipment, and reduce the capacity requirements for generators, transmission lines and transformers, which can achieve energy-saving effects.

In order to monitor distribution transformer and solve the problem of local compensation of transformer, TTU has been designed. In the design, hardware adopts digital processing chip DSP as the control core device while software adopts the real-time operating system to realize the fast collection, calculation and processing of data of power grid, as well as real-time control of the input and cut of power capacitor, matching the reactive power required by the power transformer. This design realizes the monitoring of distribution transformer and local dynamic compensation of reactive power shortage, reduces the reactive power transmission of power grid, improves the utilization rate of cable, saves the cost of power transmission, decreases the reactive power load of distribution transformer, increases the utilization rate of distribution transformer and saves the overall cost.

This paper is divided into three parts. The first part describes Control Plan of TTU, including System structure, hardware design, software design, schematic and Diagram of PCB, the second part is the Research Results, the third part is the conclusion.

2. Control plan of TTU

2.1. System structure

The main functions of the existing TTU focus on the recording of transformer's operation data and the forwarding of communication protocols (Wu *et al.*, 2013). However, there is almost no local compensation for reactive power. This study integrates local compensation of reactive power into TTU to combine transformer's operation data and local compensation of reactive power, which is easy to install, ensures the reliability of operation and reduces costs. The frame of diagram system is shown in Figure 1.

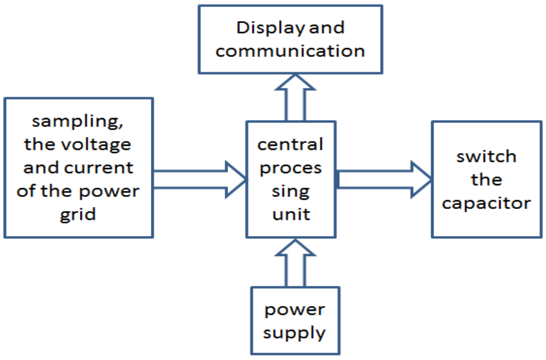

Figure 1. Frame diagram of system

The central processing unit (CPU) calculates the current reactive power shortage of the distribution transformer. According to the set compensation conditions, the local capacitor bank is operated in parallel in the system to balance the reactive power required by the distribution transformer in real time, reduce the demand for reactive power, increase the transmission of active power, and improve the transmission efficiency of the power grid.

2.2. Hardware design

The function frame diagram of hardware design is shown in Figure 2.

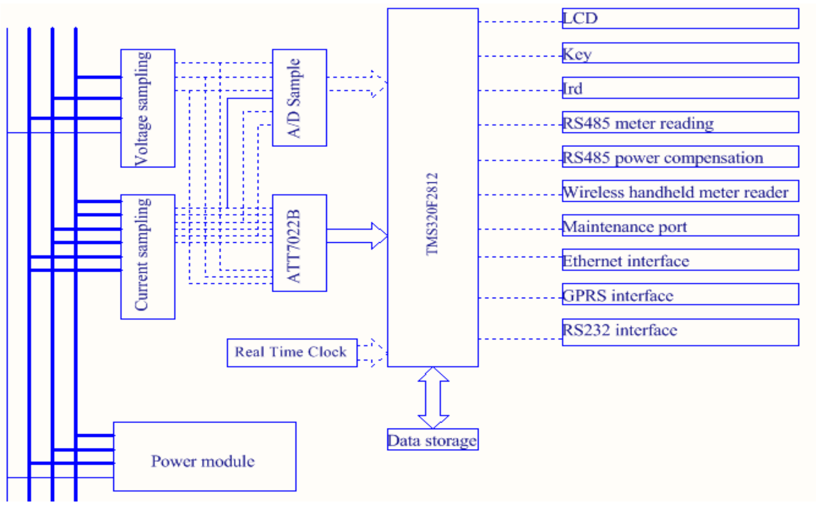

Figure 2. Frame diagram of system

Working principle: After sampling, the voltage and current of the power grid are input into the metering chip ATT7022B (Yu *et al.*, 2015), and the calculation result is transmitted to CPU through SPI bus by ATT7022B. After calculation and analysis, CPU switches the capacitor for reactive power compensation, and realizes functions, including data statistics, display, and communication.

ATT7022B is a high-precision three-phase electric energy special metering chip, which can not only measure the active power, reactive power, apparent power, active energy and reactive energy of all phases and coupled phases, but also measure the current, voltage effective value, power factor, phase angle, and frequency of every phase. It integrates six-channel second-order sigma-delta ADC, reference voltage circuit and all digital signal processing circuits of power, energy, effective value, power factor and frequency measurement. It can measure the active power, reactive power, apparent power, active energy and reactive energy of all phases and coupled phases, and can also measure the current, voltage effective value, power factor, phase angle, and frequency of each phase to fully meet the demand of three-phase multi-rate multifunction watt-hour meter. It supports all digital domain gain and phase correction, namely, pure software meter Active and reactive power pulse outputs CF1 and CF2 provide instantaneous active and reactive power information, which can be directly connected to the standard table for error correction. For detailed meter method, please refer to the meter method in part three. The active power and reactive power of fundamental wave can be measured to provide pulse outputs CF3 and CF4, active power of instantaneous fundamental wave and reactive power information fundamental wave, which can be directly used to correct the fundamental wave. Two types of apparent energy outputs are provided, namely RMS apparent energy and PQS apparent energy. CF3 and CF4 may also be configured as apparent energy pulse output. An SPI interface is provided to facilitate the transfer of measurement parameters and meter parameters with the external MCU.

CPU is composed of TMS320F2812 and corresponding memory circuita. TMS320F2812 is a digital control chip of Texas Instruments (TI). It has a main frequency of 150MHz with I2C, SPI, CAN, PWM and other bus interfaces, applicable to various control industrial equipment. It is also suitable for a variety of handheld devices for its small size, strong performance, high portability. It conforms to high and low temperature and vibration test, meeting the industrial environment application.

1) Schematic diagram of CPU

The schematic diagram of CPU is shown in Figure 3.

CPU is composed of TMS320F2812 and corresponding memory circuits. It consists of DSP TMS320F2812, real-time clock chip DS3231 (Xu *et al.*, 2014), data memory chip AT45DB321C and FM25V02. DS3231 is a real-time clock chip with temperature compensation provided by DALLAS, and its annual error is less than 2 seconds. AT45DB321C is Atmel’s mobile Flash chip, which has 32M-bit (4M-byte) storage space so that it can write pages and bytes separately. FM25V02 is the latest fast storage serial data memory, characterized by unlimited erase in the 3.3V environment.

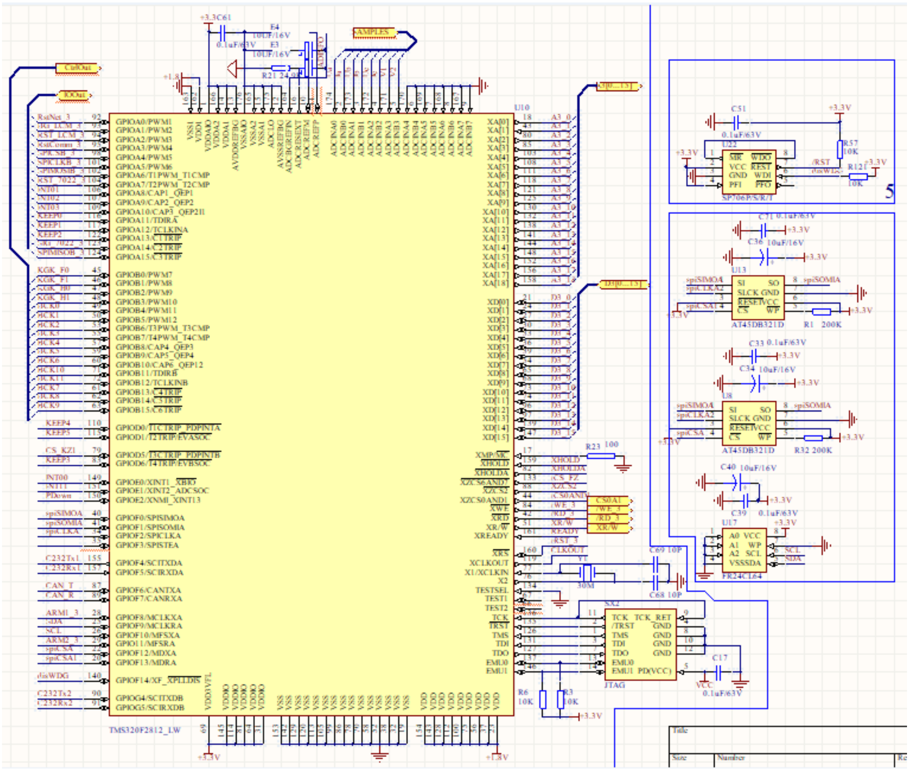

Figure 3. Schematic diagram of CPU

2) Schematic diagram of meter

The schematic diagram of meter is shown in Figure 4.

The schematic diagram of meter mainly consists of a special metering chip ATT7022B. In this design, the voltage and current of the distribution transformer are input to ATT7022B by converting to milliampere level after sampling. ATT7022B calculates the real-time data such as voltage, current, active power, reactive power, frequency and phase of the distribution transformer. Then the calculation result is transmitted to CPU through SPI bus for processing (Sharma & Saini, 2015).

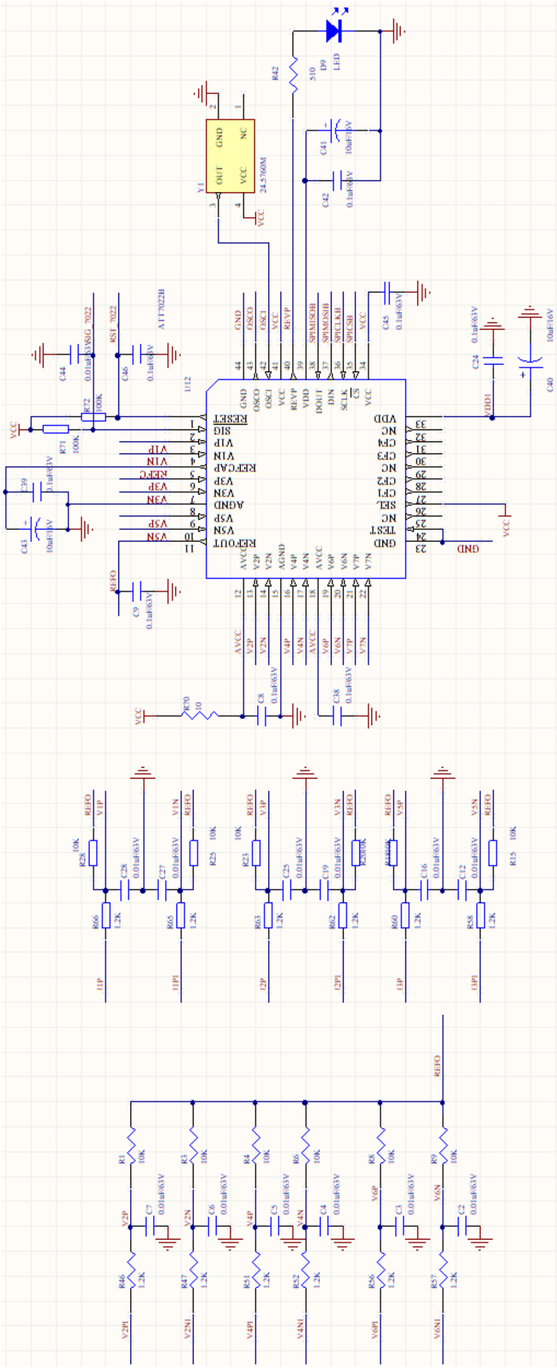

Figure 4. Schematic diagram of meter

3) Schematic diagram of power supply

The schematic diagram of power supply is shown in Figure 5.

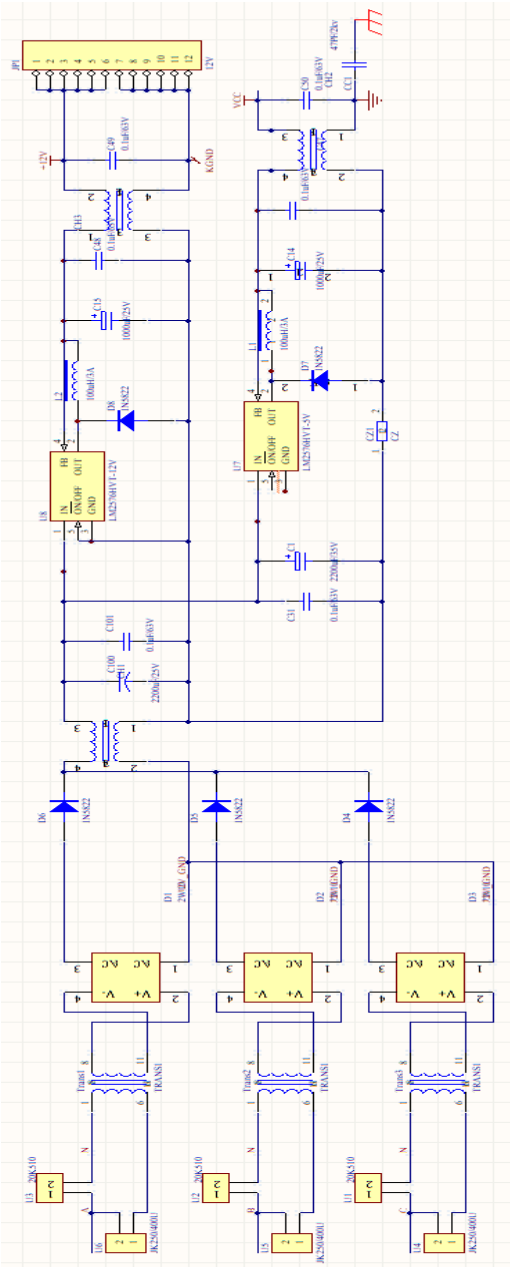

Figure 5. Schematic diagram of power supply

The power supply adopts three-phase power supply. As long as there is power supply in one phase, the equipment can work normally to ensure that the system can work normally when there is no phase.

4) Schematic diagram of communication

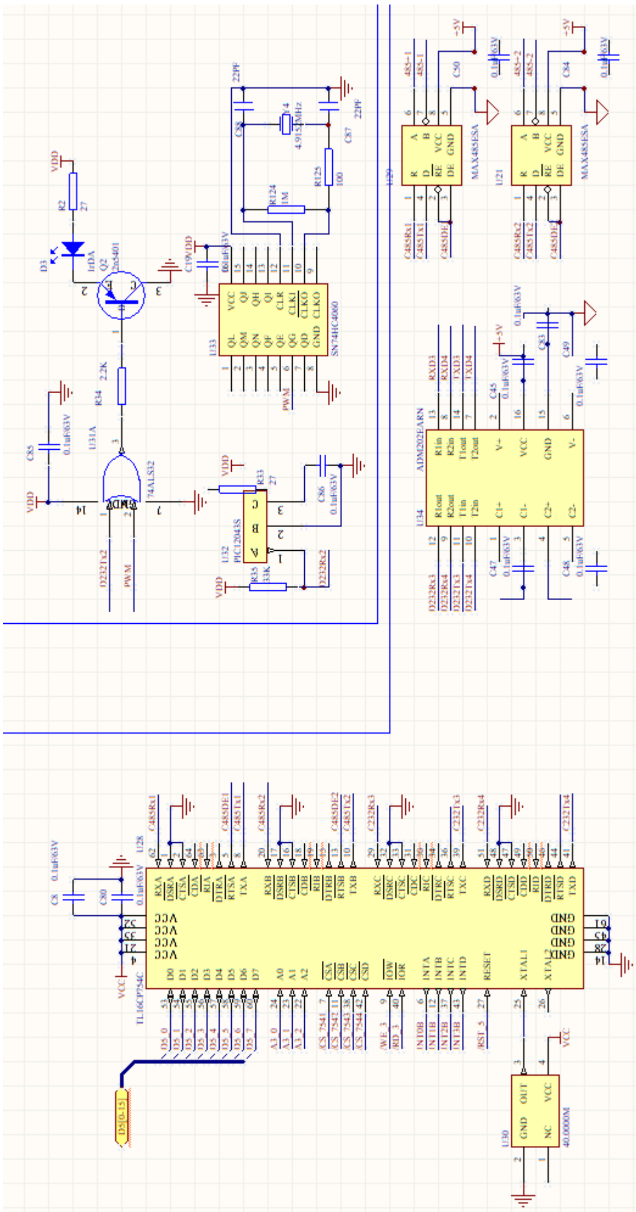

Figure 6. Schematic diagram of communication

The schematic diagram of communication is shown in Figure 6. There are five communication ports, two RS232 bus forms, two RS485 communication forms and one infrared communication form, one RS232 communication form with computer, one RS232 communication form with network equipment (GPRS or Ethernet), and two 485 communication forms with controlled components, including smart capacitor and power meter with 485 communication (Yin, 2017). Onr infrared communication form is mainly used to communicate with palmtop computer for local maintenance and data copying.

5) Schematic diagram of liquid crystal display (LCD)

The schematic diagram of LCD is shown in Figure 7. LCD has three-phase voltage, current, active power, reactive power, power factor, and frequency.

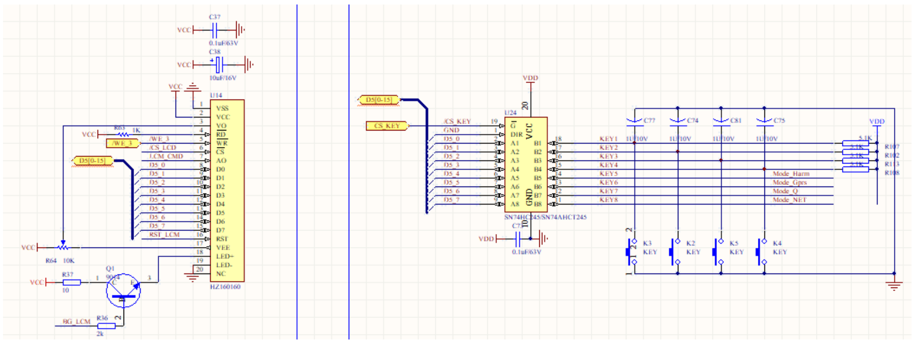

Figure 7. Schematic diagram of LCD

2.4. Software design

In this design, the real-time operating system with time slice scheduling is adopted. After each task is established, the operating system kernel schedules according to the time and task priority (He *et al.*, 2013).

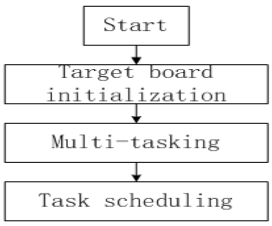

Figure 8. Flow chart of system kernel

Figure 8 is a flow chart of the operating system kernel software. First, various ports and configurations of CPU are initialized according to the peripheral devices of the target board, and various tasks are established. Finally, the task scheduling function of the system kernel is started to operate the system.

After the system kernel is set up and run, it is necessary to establish various tasks, including data measurement task, data analysis and statistics task, reactive power balance task, display task, keyboard input task and communication task of distribution transformer.

The two software flow charts of the data measurement task and display task of distribution transformer are shown in Figure 9 and Figure 10 illustrating the implementation flow of tasks.

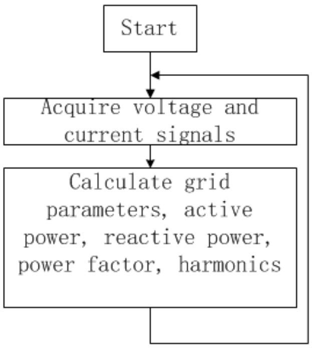

Figure 9. Flow chart of data measurement task of distribution transformer

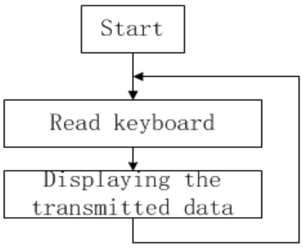

Figure 10. Flow chart of display task

2.5. Diagram of PCB

1) PCB diagram of control panel

The PCB diagram of control panel is shown in Figure 11.

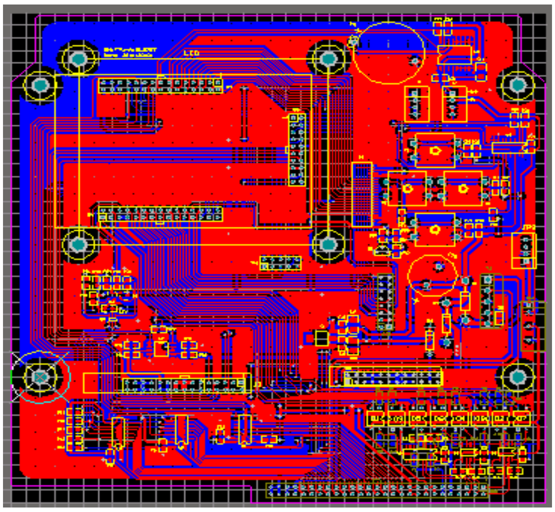

Figure 11. PCB diagram of control panel

2) PCB diagram of power supply

The PCB diagram of power supply is shown in Figure 12.

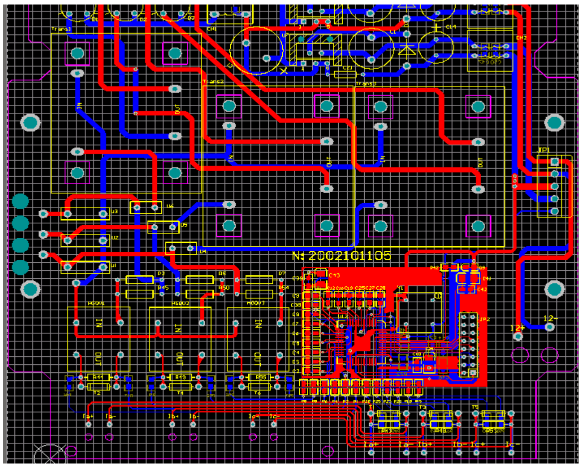

Figure 12. PCB diagram of power supply

3) PCB diagram of terminal connection

The PCB diagram of terminal connection is shown in Figure 13.

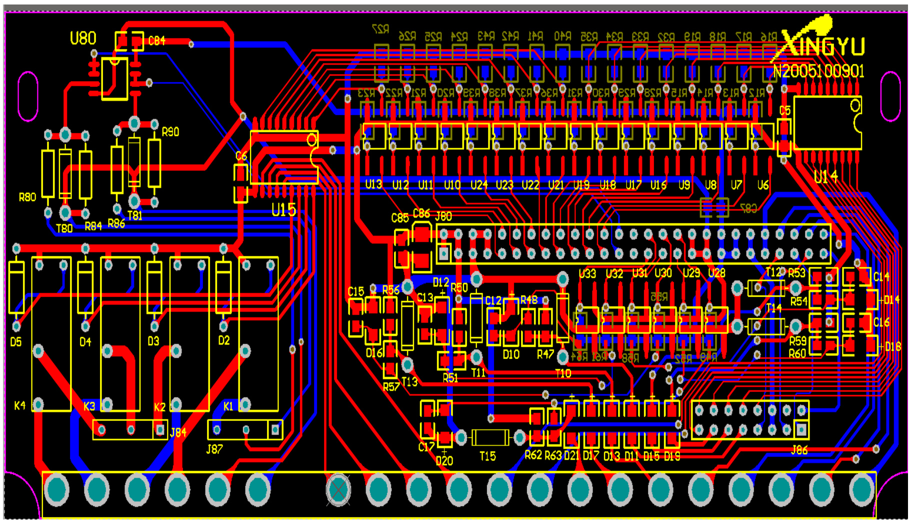

Figure 13. PCB diagram of terminal connection

Research Results

1) Overall physical maps

The overall physical map are shown in Figure 14.

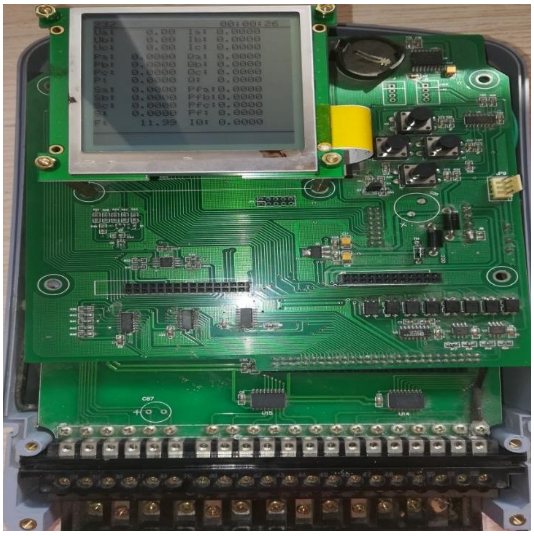

Figure 14. Overall physical maps

2) Physical map of mainboard

The physical map of mainboard is shown in Figure 15.

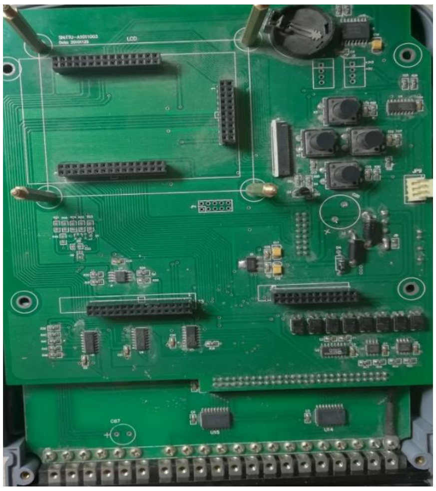

Figure 15. Physical map of mainboard

3) Physical map of power supply

The physical map of power supply is shown in Figure 16.

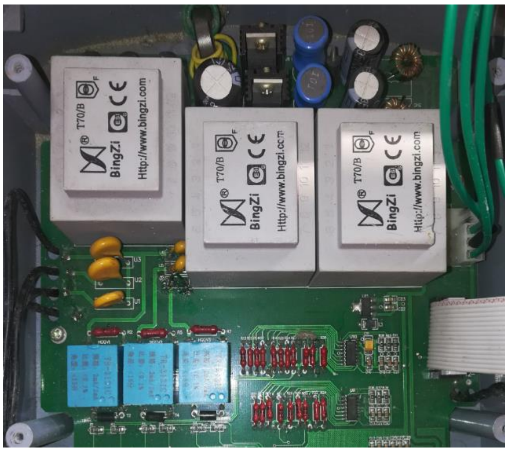

Figure 16. Physical map of power supply

4) Physical map of terminal connection board

The physical map of terminal connection board is shown in Figure 17.

Figure 17. Physical map of terminal connection board

5) Physical map of LCD

The physical map of LCD is shown in Figure 18.

Figure 18. Physical map of LCD

4. Conclusions

TTU is applied to the end of power grid, such as enterprises and workshops. Its electric load is generally inductive load, so it is necessary to compensate the reactive power of transformer. In design, the terminal is required not only to monitor the data of the transformer, but also to compensate the local reactive power of the transformer.

This design collects the active power, reactive power, apparent power, active energy and reactive energy, effective value of current and voltage of each phase, power factor, phase angle, and frequency through the high-precision three-phase electric energy special metering chip ATT7022B. Then ATT7022B transmits the calculation result to CPU through SPI bus. After calculation and analysis, CPU switches the capacitor for reactive power compensation, and realizes functions, such as data statistics, display, and communication.

In addition, the monitoring of TTU and real-time calculation of reactive power, control of the input and cut of the capacitor bank are realized, which achieves local dynamic compensation, meets real-time balance of reactive power required by inductive load, reduces the load of power transformer and power grid, and improves the operation efficiency of power transformer and power grid. Through field operation test, the design can greatly improve the phenomenon of insufficient reactive power or reverse transmission in the operation of distribution transformer and power grid, meeting various indexes.

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