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A ZigBee-based monitoring and protection system for building electrical safety

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ABSTRACT

In this paper, a ZigBee monitoring and protection system for building electrical safety is proposed. The main components of traditional distribution systems in buildings are no-fuse breakers (NFBs) and electrical outlets, whose functions are power transmission and overload protection respectively. NFBs only have the function of overload protection and are not completely effective in preventing electrical fires caused by poor contact or dust contamination. In addition, all equipments are disconnected in the same branch circuit due to NFB trips, thus the security and intelligence of the traditional distribution systems still need improvement. In this paper, the proposed system was constructed with protection mechanisms in order to enhance the functions of traditional distribution systems. The system can dynamically set the overload limit of outlets and avoid the effects on other equipments in the same branch circuit when the outlet disconnects the power. In addition, a self-protection function with temperature control was built in the outlet for fire prevention. This paper provides a detailed description of the proposed system, from design to implementation, as well as the results of the demonstration experiment.

1. Introduction

According to the World Health Organization (WHO), there will be an increase in the elderly population from approximately 600 million in the year 2000 to close to 2 billion by 2050. The global average age rose from 23.6 years old in 1950 to 26.4 years old in 2000. Estimates indicate that by 2050, the average age of the world population will be 36.8 years old. In addition, according to the statistics from the WHO, approximately 10 percent of the population will experience some form of disability. In order to make people's living environment safer, more convenient, and comfortable, the concept of smart buildings or home automation has been developed. With increasing life expectancy, smart buildings are able to provide the aged and the disabled with a more independent lifestyle [1,2].

The research domains of smart buildings include environment monitoring, building security, monitoring and control of power systems, remote medical monitoring, etc. In addition to these functions, energy conservation is very important due to limited energy resources. Many energy management technologies have been developed in order to conserve power in hotels, convenience stores, and even for office equipment, thereby lowering energy utility rates [3–8].

As for research on the monitoring and control of building power systems, many studies on power outlet have been proposed recently, and this field has gradually become the core of power management in smart buildings. The primary focuses of this research include communication systems, power consumption monitoring, remote ON/OFF control of appliances, overload protection, and energy management.

The earliest smart building net systems used cabled communication. In the relevant literature [9], CAN Bus was used in fire detection systems. However, cabled communication systems were not very aesthetically pleasing solutions. As a result, the Power Line Carrier (PLC), used to transmit control data, was proposed [10]. However, the PLC communication was difficult to integrate other systems, such as the window- or door-mounted security insurance system. The above problems were solved by wireless sensor network (WSN), which is a group of sensors wirelessly linked to perform distributed sensing tasks [11]. Bluetooth was constructed with a point-to-multi-point communication structure [12]; however, at most, only eight nodes could be supported by a Bluetooth network. Therefore, Bluetooth could not form large and complex networks. ZigBee, which could form large networks, was used to solve this problem [13]. Theoretically, ZigBee network structure can connect over 65,000 nodes. However, in common applications, ZigBee connects about dozens or hundreds of node [14,15].

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In order to support the function of remote control, various kinds of gateway have been developed to integrate different communication interfaces. Once a WSN was designed to control appliances, there would be a building gateway that bridges between WSN wireless communication systems and an external network. The building gateway was integrated with Wi-Fi and ZigBee, and applied to a building automation network [16]. The former was used as a bridge, connecting the building's intranet with the Internet. The gateway integrated four different interfaces, including USB, Ethernet, RS232, and Bluetooth [17]. It therefore had greater compatibility with other facilities. In [12], the Ethernet and GSM modules were proposed, which could send control codes by Internet and Short Message Service (SMS) into the power outlet. Although it did not require a separate gateway, the power outlet was bulky and expensive.

As for research on measuring electrical power, a microprocessor for measuring electrical power was used to measure power parameters and apply to power monitoring [12]. A power outlet designed with ZigBee was proposed for cutting off power and energy saving when detecting lower power and judging the electrical facility in a stand-by condition [18]. A study proposed overloading protection [19], which allowed a power outlet to detect current, but in general, commercial outlets offered fixed current protection as overload protection, and lacked flexibility. If the set threshold value of the overload protection was too high, the current flowing through the outlet would be higher and would increase the possibility of overload in the branch circuit current; conversely, if the set threshold value of the overload protection was too low, the outlets for facilities with a high current demand would become useless.

Today, most electricity distributors provide NFB in branch circuits. When the current flows over the capacity, the double-metal device will disconnect the power line due to heating, in order to protect the electrical facilities. However, most electrical fires are not necessarily caused by overloading or short circuits. For example, an inductive facility not well connected to a circuit will result in sparking and generate massive heat around the connection point; the accumulated heat is enough to cause a fire. According to the statistics of the National Fire Agency of Taiwan, fire disasters in 2008 totalled 2886 cases, among which, 1016 cases occurred as a result of design faults, wire aging, poor contact, or overloading of branch circuits. Therefore, the concept of power monitoring for appliances in a smart building which provides the facilities with self-regulation, energy saving, and security functions has become an important concern.

As mentioned above, NFB could not guarantee the safety of electricity consumption, and all of the facilities in the same branch circuit are disconnected during a break-off. Furthermore, the related research on the protection function of outlets did not consider the power consumption situation of other outlets in the same branch circuit. To counter the defects mentioned above, this paper proposes an intelligent monitoring and controlling system for providing a novel protection strategy based on the ZigBee wireless communication system, which three main functions are as follows: (1) the intelligent overloading protection with an intelligent outlet design is able to transmit the power consumption status of a branch circuit and calculate how much power remains for dynamically setting the protection threshold value of every power outlet throughout the ZigBee wireless communication network; (2) the overheating protection with a temperature sensor is able to detect the working temperature of outlets; once the overheating occurs, it would cut off the power line to avoid fire; and (3) remote-monitoring and control, in which a smart node would be equipped with a General Packet Radio Service (GPRS) module connected to the Internet, allowing remote monitoring and control. In short, the intelligent outlet design would entirely and effectively increase the security of building power consumption.

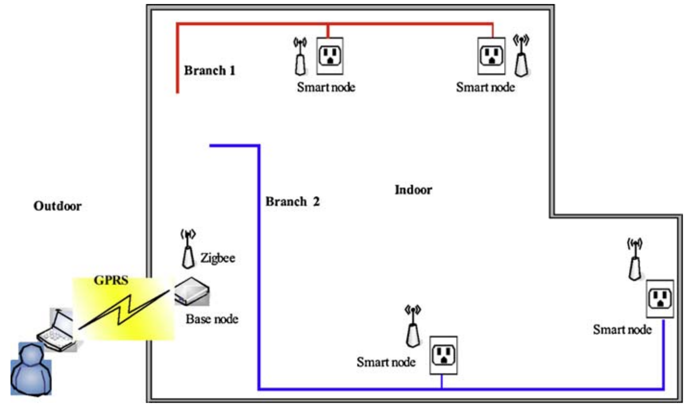


Fig. 1. Structure diagram of system.

The remainder of this paper is organized as follows: Section 2 provides the system overview. In Section 3, the system design and its implementation method are described. In Section 4, the experimental results are summarized. Section 5 presents the conclusions.

2. System overview

The proposed system structure offers the building power-consumption security mechanism with ZigBee, as shown in Fig. 1, in which the wireless communication platform, base node and smart node are the three major components in the system.

At present, the common wireless communication protocols include Radio Frequency Identification (RFID), ZigBee, Infrared Data Association (IrDA), Bluetooth and Wi-Fi. RFID and IrDA are not suitable for this system due to the short transmission distance and difficulty in node expansion. The performance comparison among ZigBee, Bluetooth and Wi-Fi is shown in Table 1 [14,15,20–22]. As each communication protocol has its suitable application occasion and this study requires a transmission distance of tens of meters, over 10 nodes, low power consumption and low cost, ZigBee is chosen as the communication protocol in the proposed system. The network structure of ZigBee in this study is a star structure, and the connection method between base node and smart node is polling. When the system update rate is 1 s, the maximal number of node is 30. The number of node can be increased by decreasing the system data update rate. In addition, the proposed system has constructed another communication platform using GPRS technology in order to implement remote control.

The smart node could measure the parameters of current, power and voltage in order to offer real-time information from the outlet. The protection function for the branch circuit was fulfilled by measuring outlet power and then transmitting the data to the base node through ZigBee. The base node would calculate the total current of the branch circuit according to the data transmitted from the smart node, and then send back the data on the remaining current value as a threshold value of the smart node overloading protection function. When electrical facilities plugged into the branch circuit began

Table 1
Comparison of ZigBee, Bluetooth, and Wi-Fi characteristics.

Characteristics	ZigBee	Bluetooth	Wi-Fi
IEEE standard	802.15.4	802.15.1	802.11 a/b/g
Max signal rate	250 kb/s	1 Mb/s	54 Mb/s
Nominal range	10–100 m	10 m	100 m
Max number of nodes	>65,000	8	2007
Power consumption	Low	Very low	High
Protocol complexity	Simple	Most complex	Complex
Cost	Low	Low	High

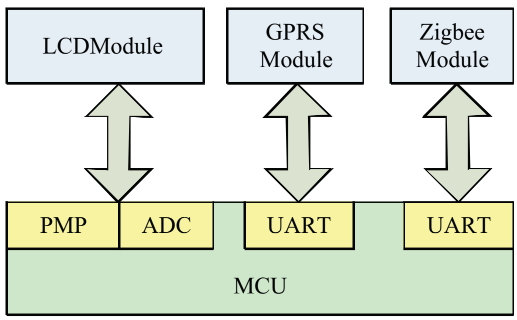


Fig. 2. Circuit structure of base node.

to overload, the smart node would cut off the power line instantly to prevent overloading. In addition, the smart node would measure the temperature of the plug point; if the temperature was too high, the smart node would also cut off the power line to prevent fire.

3. Methods of design and implementation

3.1. Base node

The base node is the monitoring and controlling center of all branch circuits, as well as the gateway for external communication and the user interface. Its main functions are as follows:

(1) Executing remote-control instructions through GPRS.
(2) Monitoring the power consumption of the smart node.
(3) Calculating the remainder power capacity of every branch circuit.
(4) Indicating all power consumption information.

The base node is composed of a microcontroller (MCU), LCD module, ZigBee module, and GPRS module. The GPRS and ZigBee modules connect the MCU with a universal asynchronous receiver and transmitter (UART) interface, while the LCD module connects the MCU to a Parallel Master Port (PMP) and Analog to Digital Converter (ADC) interface. The circuit structure is shown in Fig. 2.

3.1.1. Base node controller

The base node controller is a 16-bit MCU that has ADC, PMP, and UART modules, which adequately meet the demands of this system. Its software flowchart is shown in Fig. 3, in which the timer of the MCU interrupts once every 200 ms to detect the signal from the touch panel.

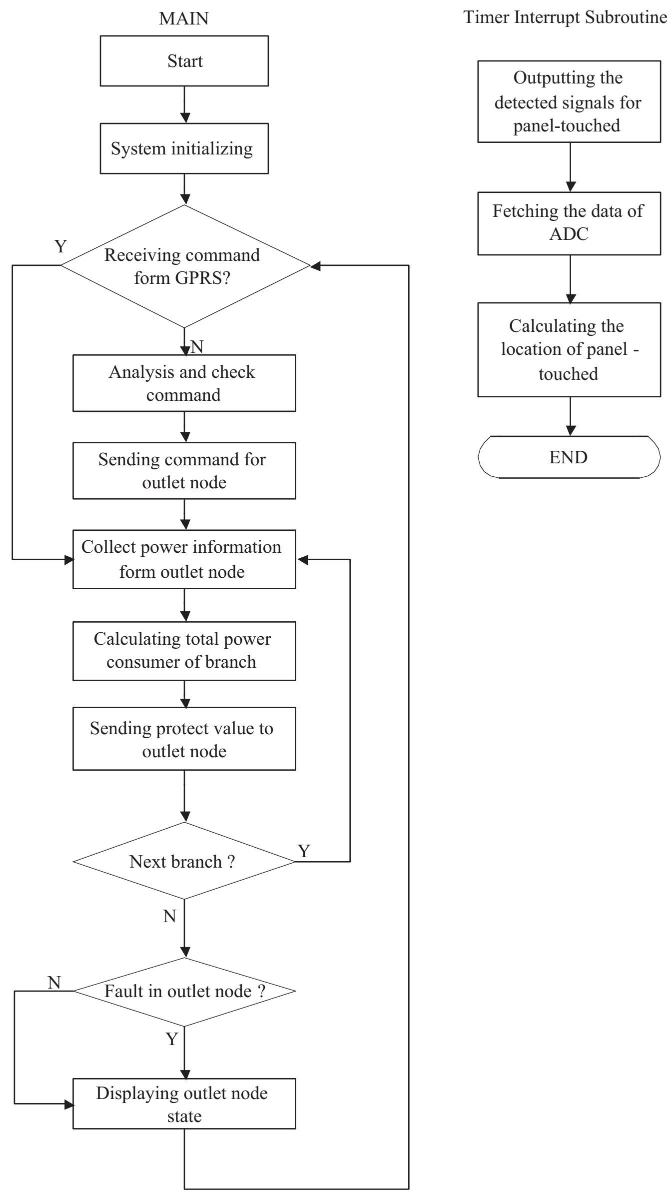


Fig. 3. Program flow-chart of base node.

3.1.2. LCD module

The LCD module includes an LCD controller and 4.3 in. TFT-LCD touch panel. The LCD controller receives the image information from the MCU through a PMP interface installed into built-in display RAM. It then delivers driver signals to fulfill the display function. In addition, the system selects the LCD display with a touch sensor. With the touch sensor technique, the system becomes simpler and more convenient. The touch sensor is four-line resistor-type, and is connected to the ADC module. The ADC module sends out testing voltage, fetches the signal of the touch-panel and calculates the touched location on the panel according to the signal. The structure of the LCD module is shown in Fig. 4.

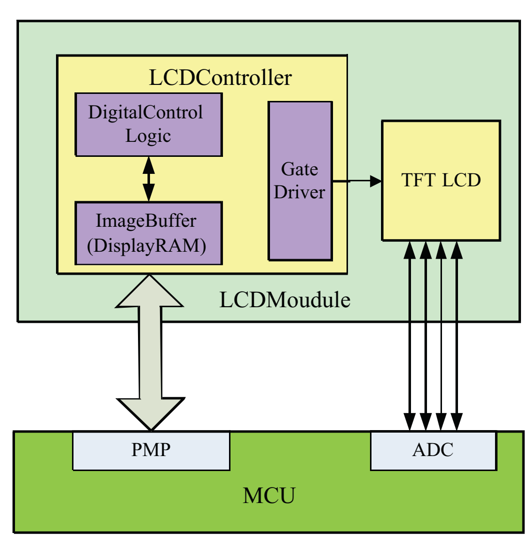


Fig. 4. LCD module.

3.1.3. ZigBee module

The ZigBee module is composed of a processor that executes the ZigBee protocol with 2.4G radio frequency (RF); its structure is shown in Fig. 5. ZigBee is a wireless network protocol and adapted IEEE 802.15.4 standard owned by ZigBee Alliance, which defines

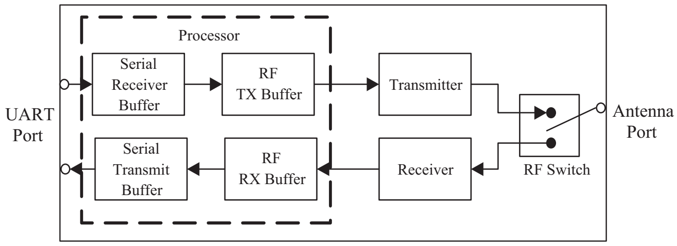


Fig. 5. ZigBee module.

the media layer and objective layer and possesses low transmission speed at low cost and low power consumption, with high security, and supports a large number of web node operations. Therefore, it is very suitable for use in building monitoring and controlling systems.

In the ZigBee, the effective transmission distance between nodes is determined by the transmission power designed for module. At present, the transmission distance of commercial module can reach about 100 m under a barrier-free condition. Although the partition blocks of buildings may reduce the communication distance, using ZigBee can support the network structure with tree or mesh, and setting some nodes in the network to router function can effectively overcome the issues of transmission in the same horizontal floor and different vertical floor with long distance [21]. Conceptually, ZigBee communication can be applied to buildings without restriction on the transmission distance.

As for the noise interference issue, ZigBee uses direct sequence spread spectrum (DSSS) to reduce the environmental interference. In addition, it uses Carrier Sense Multiple Access-Collision Avoidance (CSMA/CA) channel access mechanism, dynamic frequency selection and transmission power control to avoid channel collision [14,23,24].

3.1.4. GPRS module

For the purpose of remote control and monitoring, it was necessary to construct an Internet communication platform. Considering the convenience of building the base node, and the combination of Internet and platform in this system, the GPRS technique was used to construct the communication platform, in which the current GSM provides a 2.5G Internet service. GPRS uses the information package technique to replace the traditional circuit exchange technique of GSM, which makes it possible to transmit large amounts

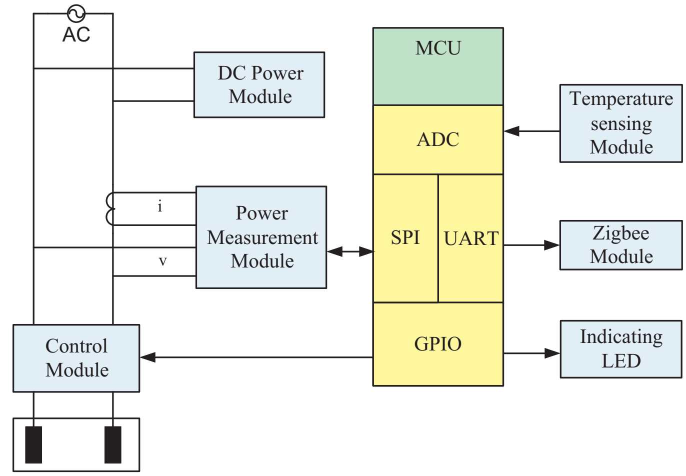


Fig. 6. Circuit structure of smart node.

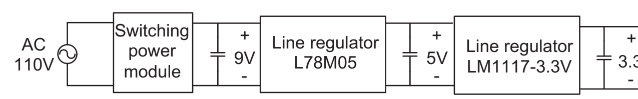


Fig. 7. DC power module.

of data in bursts, instant communication circuits; its transmission rate could reach 115.2 kbps.

3.2. Smart node

The smart node, which is the measure and control node, is shown in Fig. 6. The smart node comprises a DC power module, MCU, AC power control module, temperature-sensing module, indicator LEDs and a ZigBee module. The main functions of the smart node are as follows:

(1) Measuring the temperature and power parameters, such as voltage, current, and power of outlet.
(2) Control of power output of outlet.
(3) Security protection from overload and overheating.
(4) Transmission of information of each node to the base node through ZigBee.

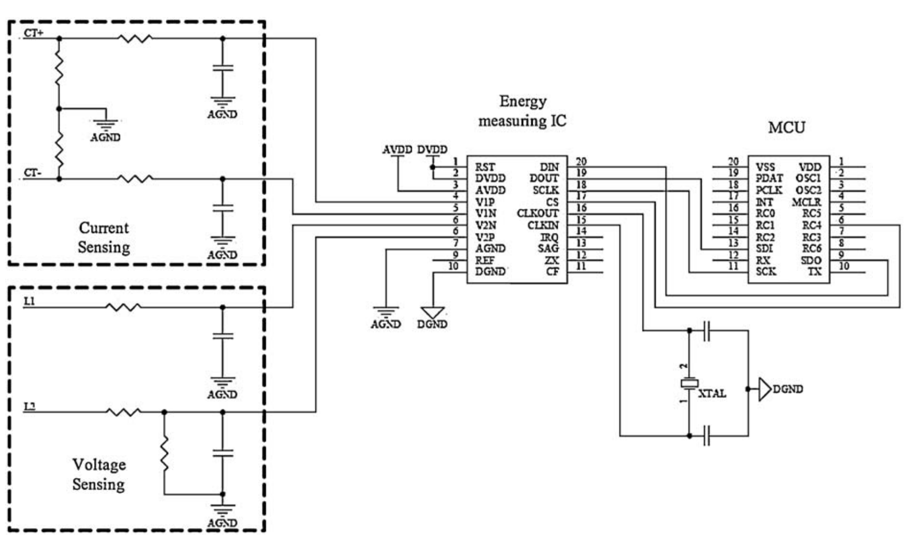


Fig. 8. Power measurement module.

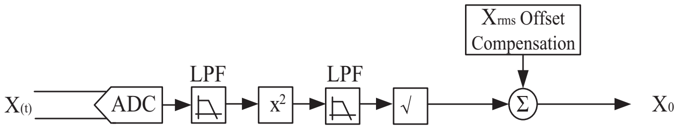


Fig. 9. The RMS calculated flowchart.

3.2.1. DC power module

The main function of the DC power module is to transfer AC 110 V to DC 5 V and 3.3 V in order to provide the operating power for all modules in the smart node. Its circuit structure is shown in Fig. 7. AC 110 V is transferred by switching the power module to DC 9 V, and then transferring to DC 5 V and 3.3 V by linear regulator.

3.2.2. Power measurement module

The power measurement module is primarily used for the power measuring IC, with an error margin of 0.1%, and matching the request of IEC61036/IEC60687, IEC62053-21, and IEC62053-22. This IC incorporates two second-order, 16-bit $\Sigma-\Delta$ ADCs; all the signal processing required to perform active and apparent energy measurements, line-voltage period measurements, and root-mean-square (rms) calculations on the voltage and current channels. It can provide a serial interface (SPI) to read data. The circuit of this module is shown in Fig. 8.

The flowchart of calculating the RMS of voltage and current can be divided into two steps, which are AD conversion, and digital signal processing.

Step 1: analog to digital converter

ADC is used to convert analog signal to digital signal. The measuring IC has two 16-bit, second-order $\Sigma-\Delta$ ADCs, one of which is used to convert voltage signal and the other to convert current signal. The maximum signal input into the measuring IC is ± 0.5 V. Therefore, a high-resistance voltage divider with properly designed resistance, which can transfer AC 130 V into ± 0.5 V, is used. In addition, the current sampling can use a current transformer to measure current signal with proper resistance, and can transfer AC 30 A into ± 0.5 V. Transferred voltage and current are respectively input into the measuring IC in order to proceed to the next calculation.

Step 2: digital signal processing

For time-sampling signals, the RMS calculation involves squaring the signal, taking the average, and obtaining the square root as in (1):

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{N}\sum_{k=1}^{N} x_k^2} \quad (1)$$

where x_{rms}, RMS voltage or RMS current; N, sampled numbers in one period; x_k, the kth sample of voltage or current.

As discussed above, the calculating processes of voltage and current RMS in the measuring IC are shown in Fig. 9. After voltage sampling and passing by 260 Hz low-pass filter, it then calculates the square of the signal, passes through another low-pass filter again, and finally finds the root of the square. The data are sent to a certain register in the measuring IC to proceed to offset compensation, followed by the plus root of the square and value adjusted for precise measurement. Finally, the data are stored in a 24-bit register with a refresh every 698 μs. The relation between the indicated and RMS value of voltage and current is shown in Eqs. (2) and (3):

$$V_{\mathrm{rms},i} = V_{\mathrm{rms}} \times \frac{1}{1,561,400} \times \frac{0.5}{\sqrt{2}} \times G_v \quad (2)$$

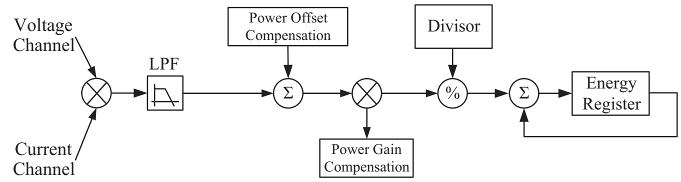


Fig. 10. Calculating processes of real power.

where V_{rms}, the fetched RMS value of voltage; G_v, ratio of divided voltage; $V_{\mathrm{rms},i}$, the indicated RMS value of voltage.

$$I_{\mathrm{rms},i} = I_{\mathrm{rms}} \times \frac{1}{1,868,467} \times \frac{0.5}{\sqrt{2}} \times G_i \quad (3)$$

where I_{rms}, fetched RMS value of current; G_i, transfer ratio of current sensor; $I_{\mathrm{rms},i}$, indicated RMS value of current.

Instantaneous power signal is defined in an ac system as in (4).

$$p(t) = V_{\mathrm{rms}}I_{\mathrm{rms}} - V_{\mathrm{rms}}I_{\mathrm{rms}} \cos(2wt) \quad (4)$$

where w, angle frequency.

The average power over an integral number n of line cycles is given by the expression in Eq. (5):

$$P_{av} = \frac{1}{nT}\int_0^{nT} p(t)dt = V_{\mathrm{rms}}I_{\mathrm{rms}} \quad (5)$$

where T, line cycle period; P_{av}, average active power; $p(t)$, instantaneous power.

The active power is equal to the DC component of the instantaneous power. Therefore, in measuring IC, the DC component of the instantaneous power signal is extracted by LPF to obtain the active power information. The cut-off frequency of the LPF is approximately 8 Hz. The processes of calculating real power are shown in Fig. 10. After sampling and transferring voltage and current, voltage is multiplied with current to obtain the instant power, and then put into a 8 Hz low-pass filter to get average power. By adjusting the offset and gain to increase the range of stored energy with a divider, the final result is stored in a 48-bit Energy Register. Under the 3.57 MHz operating frequency, the data accumulate once every 1.1 μs. The MCU merely fetches the most significant 24-bit. In order to determine the power, the Energy Register data must be differentiated. The relation between the indicated and average power value is shown in Eq. (6):

$$P_{av,i} = \frac{E \times 2^{25} \times 1.12 \times 10^{-6}}{S} \times \frac{0.125}{838,861} \times G_v \times G_i \quad (6)$$

where E, fetched value of energy register; S, fetching period of MCU; $P_{av,i}$, indicated average active power.

3.2.3. Temperature measurement module

The main function of the temperature sensor circuit is to measure the temperature of an outlet to avoid overheating and fire resulting. The temperature sensor adopted in this system is a SMD-typed NTC (negative temperature coefficient) thermistor, which is small and easily mounted on the outlet box, as shown in Fig. 11. The temperature sensor circuit is an instrument amplifier with high input impedance, high CMRR and low noise, as shown in Fig. 12. The NTC thermistor reading is amplified and input into the ADC of the MCU to calculate the temperature.

According to CNS3907, outlets adopt thermoplastic materials with heat-proofing of 80 °C. Therefore, in this system, the overheating protection threshold value is set at 75 °C. In the practical application, the proper protection threshold value can be adjusted according to the heat-proofing of the outlet.

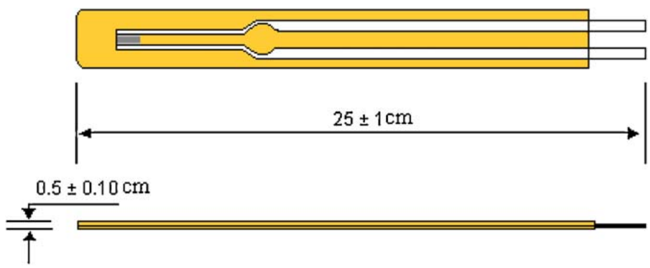


Fig. 11. SMD type NTC thermistor.

3.2.4. Smart node controller

The smart node controller is a low cost 8-bit high performance microcontroller, which contains built-in ADC, UART, SPI, and general purpose input and output (GPIO) modules that adequately meet the function demands of the smart node. The controller periodically fetches voltage, current, power and temperature data. There are three conditions under which the controller would cut off the outlet power output, as described below:

(1) The measured current surpasses the protection current value of the smart node.
(2) The temperature is higher than the protection threshold value.
(3) Control by remote control center.

The smart node's protection threshold value of current and temperature is dynamically set by the base node, which depends on the loading condition of the branch circuit. The operating software of the smart node controller is shown in Fig. 13.

3.2.5. Control module

The control module includes a relay and its driving circuit, as shown in Fig. 14. This module mainly receives control instructions from the MCU in order to acquire the status of the relay, and then control the output power of the outlet. The MCU controller signal is amplified by transistor and then to drive relay. The freewheeling diodes set on both sides of the relay are used to provide a release method for the diode to generate reversed voltage, instantly transferring the relay from ON to OFF and preventing damage to the transistor.

3.2.6. Indicator LED

In order to allow users to monitor the condition of the outlet, three indicator LEDs, which respectively indicates normal power-supply, low capacity, remote control, and cut-off protection due to over-loading and over-heat four statuses, are installed, as shown in Table 2. Under low capacity status, the remaining useable power of a branch circuit is lower than the preset value in this system, and LED1 lights up, warning users not to use high powered appliances such as electric kettles, hair-dryers or electric ovens.

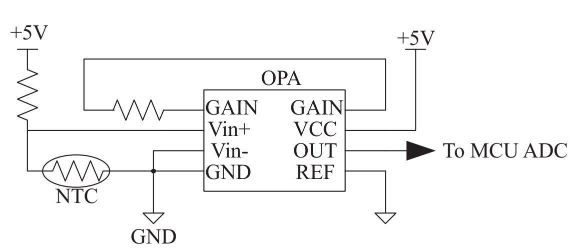


Fig. 12. Temperature measurement module.

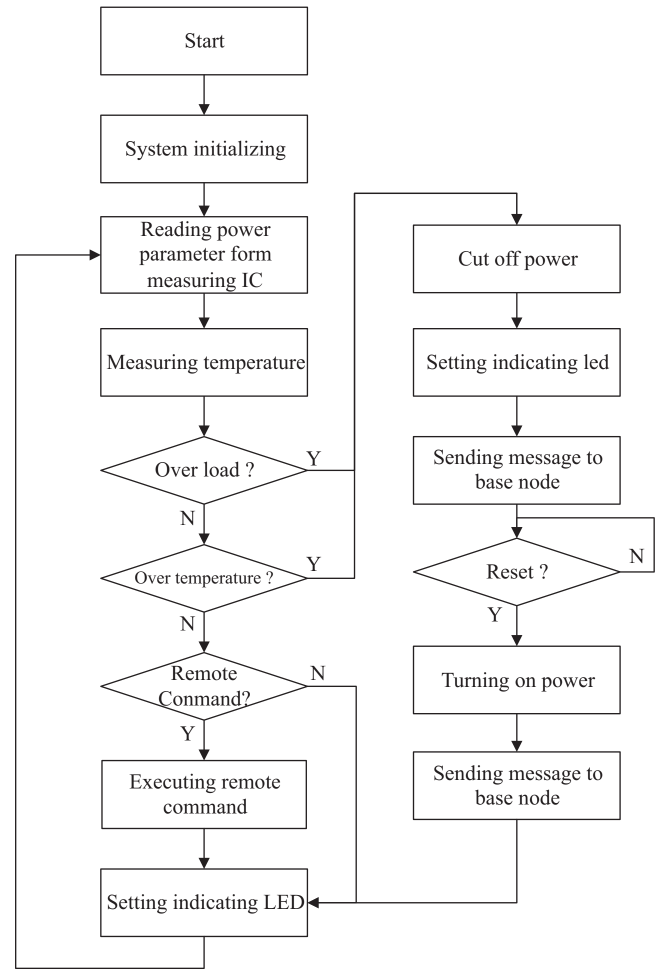


Fig. 13. Program flow-chart of smart node.

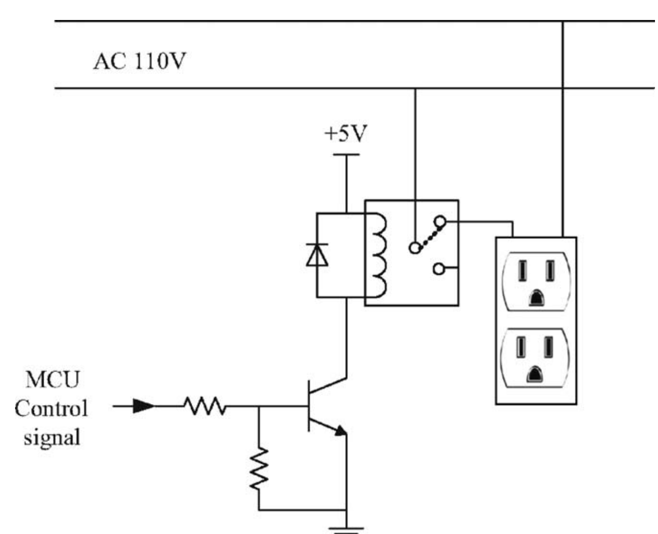


Fig. 14. Control module of outlet.

Table 2
Indicators of LED status.

Status	LED1	LED2	LED3
Normally power-supply	OFF	OFF	OFF
Low capacity indicate	ON	OFF	OFF
Power cut-off with overload and overheat	OFF	ON	OFF
Power cut-off controlled by remote-control	OFF	OFF	ON

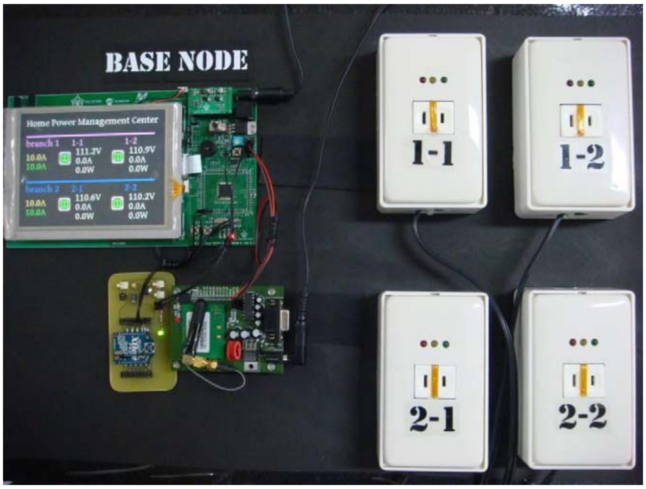


Fig. 15. The prototype system.

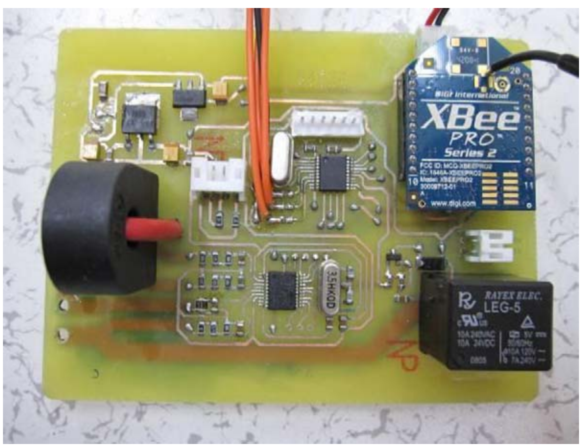


Fig. 16. Practical circuits of smart node.

4. Experimental results

In order to verify the accountability and implementation of the system, a practical demo system was produced; the methods, design procedures and the practical work are shown in Fig. 15. This demonstration system was equipped with one base node which managed two branch circuits, each of which included two smart nodes. The voltage rating of each branch circuit is 110 V, with a current rating of 10 A, and power rating of 1100 kW. The overheating protection threshold of the smart node was set at 75 °C.

Fig. 18. Graphic user interface on base node.

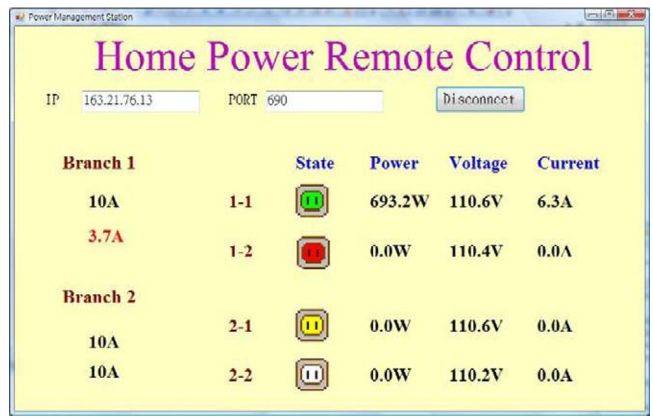
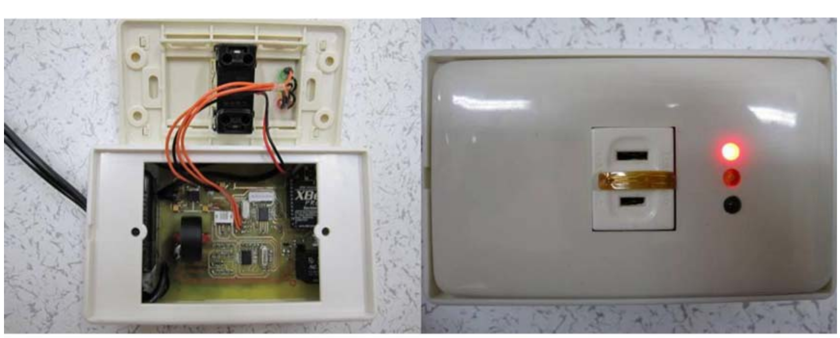


Fig. 19. Remote monitoring and control screen.

Each smart node is composed of a ZigBee module, microcontroller, power measuring IC, voltage, current measure circuits, and relays. The practical work is shown in Fig. 16. The manufactured smart nodes are in regular size, so that they can be set in the outlet box, as shown in Fig. 17.

The graphic user interface on the base node is shown in Fig. 18, in which there are two branch circuits Branch 1 and Branch 2, in the demonstration system. The protection value of current for each branch circuit is 10 A. The outlets in every branch circuit are shown as 1-1 and 1-2 of Branch 1, 2-1 and 2-2 of Branch 2. There are two information districts, one is for the branch circuit, which shows the current rating (with yellow words), and remaining useable current on the left (For interpretation of the references to color in this text, the reader is referred to the web version of the article.). If



a b

Fig. 17. (a) Smart node was equipped in regular box and (b) appearance of smart node.

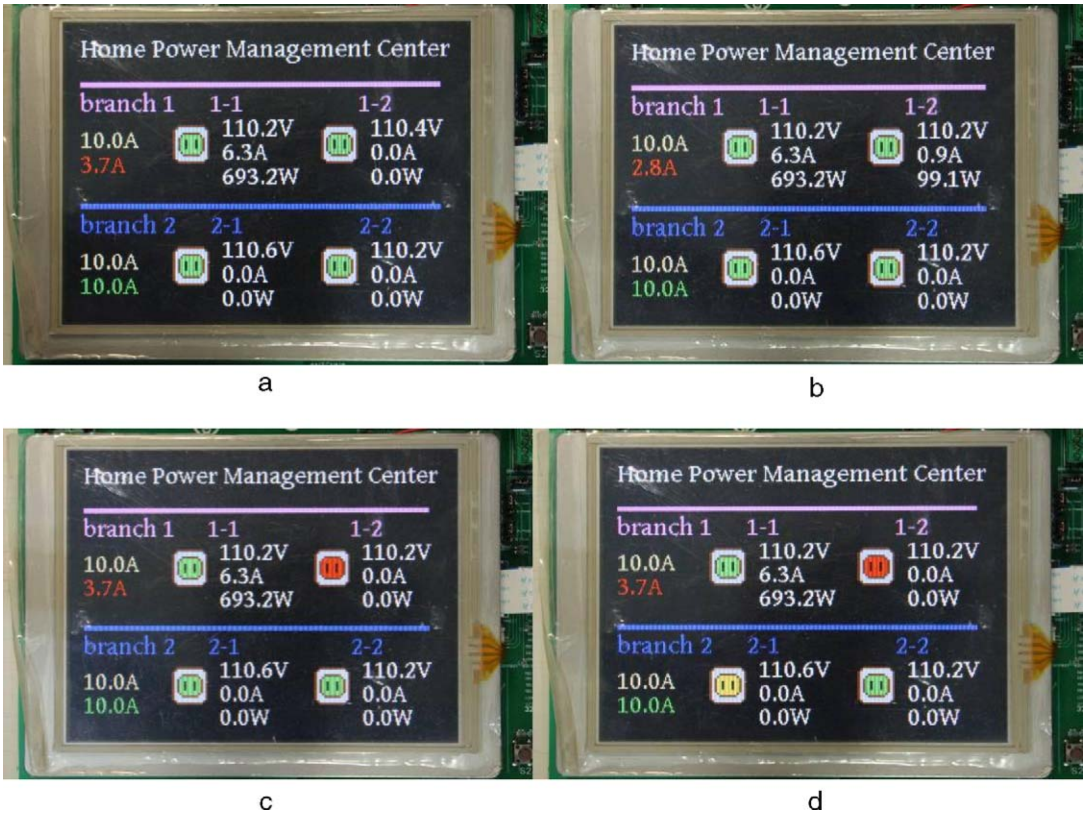


Fig. 20. Result of test steps: (a) Step 1, (b) Step 2, (c) Step 3, and (d) Step 4.

the remaining useable current is lower than 7 A, the text will be displayed in red for warning purposes, as shown with Branch 1; otherwise, the text is displayed in green, as in Branch 2. The other information district is for the outlet, indicating the consumption of power, voltage and current of each outlet. The displayed type of voltage, current and power are shown with character mode, while the condition of the outlet is shown in color mode. Green means normal power supply, red means over-load protection status, yellow means overheating protection status, and white means power supply cut-off via remote-control.

In this system, VB.NET was used to program the user interface of the remote monitoring and control center, which would communicate with the base node through GPRS. The operating screen is shown in Fig. 19. The picture of the branch circuit and outlet information is the same as with the base node. The user could click the outlet icon with the mouse, and the system would send out control instruction through GPRS to control whether the outlet should output power.

The test steps of all designed protection functions in this system are as follows.

Step 1: plug heavy-load facility into smart node 1-1

A hair dryer was plugged into smart node 1-1, and the consumption power and current of smart node 1-1 were respectively 693.2 W and 6.3 A, as shown in Fig. 20(a). The remaining current rating of Branch 1 was 3.7 A, while the other smart nodes were in normal status.

Step 2: plug light-load facility into smart node 1-2

A 100 W load was plugged into smart node 1-2. Since the loading current did not surpass the remained rating 3.7 A, smart node 1-2 remained in normal status and the remaining current rating of Branch 1 was 2.8 A, as shown in Fig. 20(b).

Step 3: plug heavy-load into smart node 1-2

A hair dryer was plugged into smart node 1-2 after removing the100 W load. The overloading of smart node 1-2 was observed, and the power consumption was more than the remaining rating of the branch circuit, so smart node 1-2 changed to the overloading protection condition, as shown in Fig. 20(c). Smart node 1-2 did not provide power to the circuit, so the values of power and current in the screen were 0.

Step 4: increasing the temperature of smart node 2-1

A small flame was used to heat smart node 2-1, causing smart node 2-1 to overheat. Then a 100 W load was plugged into smart node 2-1. As seen, smart node 2-1 was in over-heating protection condition, as shown in Fig. 20(d); therefore, no power was provided to the load and the power and current values were 0.

Step 5: remote-control and cut-off of smart node 2-2

The remote-control platform was used to cut smart node 2-2 off, and then a 100 W load was plugged. As shown in Fig. 18, smart node 2-2 was in remote-control protection condition, and was prevented from providing power, so the power and current values of smart node 2-2 were 0.

As discussed above, the protection functions provided by the designed system were confirmed as well as the related software and hardware.

5. Conclusions

In this paper, a cost-effective ZigBee-based monitoring and protection system for building electrical safety was proposed. A demonstration system was constructed with a low cost and high performance microcontroller, energy metering IC, ZigBee, and GPRS. This system contained traditional remote control functions, and branch circuit protection strategy was designed to avoid unexpected disasters caused by the overloading or overheating of outlets. This system could improve the functions lacking in traditional NFB systems, and enhance the electrical safety of buildings. In addition, the extended functions, such as power saving strategies and building energy management, can be easily implemented based on the proposed system.

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