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Design and Research of Electrical Anomaly Detection and Safety Early Warning System for Household Smart Sockets

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ABSTRACT
This paper focuses on the design of an electrical anomaly detection and safety early warning system for household smart sockets. By analyzing the safety hazards of existing sockets, a detection and early warning scheme based on multi-sensor fusion and intelligent algorithms is proposed. Experiments show that the system can effectively identify anomalies such as overload, leakage, and short circuit, achieving real-time early warning and improving the level of household electrical safety.

KEYWORDS
Household smart socket; Electrical anomaly detection; Safety early warning; Multi-sensor fusion; Intelligent algorithm

1 Introduction

With the popularization of smart homes, the number and types of household appliances are constantly increasing, and household electrical safety issues are becoming increasingly prominent. Traditional sockets have limited functions and lack the ability to detect and warn of electrical anomalies, easily leading to safety accidents such as fires and electric shocks. Smart sockets, as an important component of smart homes, have functions such as remote control, timed switching, and power monitoring, but most products still have shortcomings in electrical anomaly detection and safety early warning. Therefore, designing a smart socket for home use with efficient power consumption anomaly detection and safety early warning functions is of significant practical importance.

2 Current Status of Domestic and International Research

Domestic research in the field of smart sockets has achieved certain results. Some smart sockets have realized basic power monitoring and remote control functions, but in terms of power consumption anomaly detection, they mainly focus on overload and short circuit detection. The detection methods are relatively simple and lack comprehensive judgment on multiple abnormal situations. For example, some smart sockets detect overload by setting a current threshold and cut off the power when the current exceeds the threshold, but they cannot accurately distinguish between normal high-power appliance use and abnormal overload. In terms of safety early warning, simple buzzer alarms are mostly used, lacking remote notification and detailed information prompt functions.

International research on smart sockets started earlier and the technology is relatively mature. Some advanced smart sockets adopt multiple sensor fusion technologies, which can monitor parameters such as voltage, current, power, and temperature in real time, and conduct comprehensive analysis of power consumption status through intelligent algorithms to achieve accurate detection of multiple abnormal situations such as overload, leakage, short circuit, and overheating. In terms of safety early warning, in addition to local alarms, remote notifications can be sent to users via mobile applications, SMS, etc., providing detailed anomaly information and handling suggestions. For example, some smart sockets use machine learning algorithms to analyze electricity consumption data, which can predict appliance failures in advance and provide users with preventive maintenance suggestions.

3 Design of Household Smart Socket Electricity Anomaly Detection and Safety Early Warning System

3.1 System Overall Architecture

This system mainly consists of a hardware layer, a data acquisition layer, a data processing layer, and an early warning layer. The hardware layer includes the smart socket body, sensor modules, communication modules, etc.; the data acquisition layer is responsible for collecting electricity consumption parameters such as voltage, current, power, and temperature; the data processing layer processes and analyzes the collected data to determine whether there is an electricity anomaly; the early warning layer issues safety warnings to users through local alarms and remote notifications based on the data processing results. Figure 1 shows the overall system architecture.

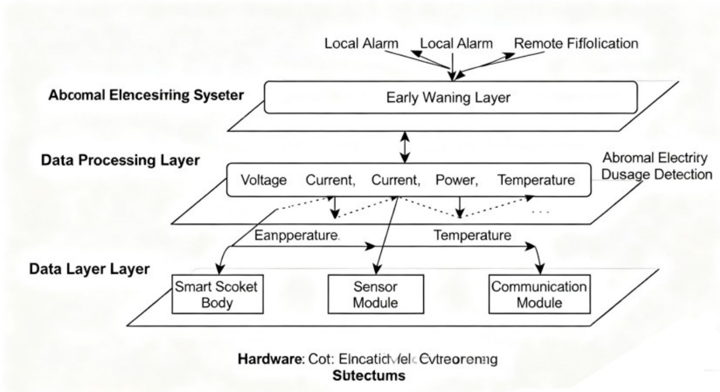

Figure 1 System Overall Architecture

3.2 Hardware Design

3.2.1 Sensor Module

3.2.1.1 Voltage Sensor

This design uses a TV1908 voltage transformer. This voltage transformer features high precision and high isolation. Its rated primary voltage is 220V (the appropriate specification can be selected according to the actual household voltage), and its rated secondary voltage is 6V. Its working principle is based on electromagnetic induction, converting high-voltage signals into low-voltage signals at a certain ratio, facilitating subsequent acquisition and processing circuitry. In the actual circuit connection, the primary side is connected to the household electrical wiring, and the secondary side is connected to the subsequent signal conditioning circuit. After signal conditioning, the signal is input to the control module for data acquisition.

3.2.1.2 Current Sensor

The ACS712-30A Hall effect sensor is selected. This Hall effect sensor has excellent linearity and isolation performance, and an extremely fast response speed, accurately responding to current changes in a short time. Its measurement range is -30A to +30A, and the output is an analog voltage signal with an output sensitivity of 66mV/A. For example, when the measured current is 10A, its output voltage is 10A $\times$ 66mV/A = 660mV. In practical applications, a current sensor is connected in series in the circuit, allowing the measured current to pass through the sensor. The analog voltage signal output by the sensor is converted from analog to digital and then input to the control module for current data acquisition and analysis.

3.2.1.3 Temperature Sensor

The DS18B20 digital temperature sensor is used. This sensor uses a 1-Wire bus interface and can directly output digital signals without the need for additional analog-to-digital conversion circuits, greatly simplifying circuit design. Its measurement range is -55℃ to +125℃, and its accuracy can reach ±0.5℃ within the range of -10℃ to +85℃. The DS18B20 has a unique single-bus interface, requiring only one data line to communicate with the control module. In actual connection, the sensor's data pins are connected to the corresponding pins of the control module, and temperature data can be read through specific timing control.

3.2.1.4 Leakage Sensor

A zero-sequence current transformer, specifically model TA1016-5A, is used. This zero-sequence current transformer can detect the zero-sequence current in the circuit. Its primary side is connected to the three-phase line being tested (it can also be used in single-phase household circuits, achieving zero-sequence current detection through proper wiring), and its secondary side outputs a current signal proportional to the zero-sequence current. When a leakage fault occurs in the circuit, a zero-sequence current is generated. When the detected zero-sequence current exceeds a set value (e.g., set to 30mA, which is a common leakage protection action value), it is judged as a leakage fault. The current signal output from the secondary side is converted into a voltage signal by a signal conditioning circuit and then input to the control module for further processing.

3.2.2 Communication Module

The ESP8266 Wi-Fi module is selected. The ESP8266 is a low-power, high-performance Wi-Fi module that supports three working modes: STA, AP, and STA + AP. It has a built-in TCP/IP protocol stack, which can easily realize wireless communication between the smart socket and mobile applications and cloud platforms. In this design, it is set to STA mode and connected to the home wireless network, enabling the smart socket to access the Internet. The ESP8266 can be easily configured and controlled using the AT command set, such as setting Wi-Fi connection parameters and sending and receiving data. For example, the following AT command can be used to establish a Wi-Fi connection:

AT+CWMODE=1 // Set module to STA mode

AT+CWJAP= "SSID","password" // Connect to the specified Wi-Fi network, where "SSID" is the network name and "password" is the password

After successful connection, the smart socket can interact with mobile applications and cloud platforms through the ESP8266 module, facilitating remote monitoring and control of the socket and timely receipt of safety warning information.

3.2.3 Control Module

Based on the STM32F103C8T6 microcontroller. The STM32F103C8T6 is a 32-bit microcontroller based on the ARM Cortex-M3 core, with abundant peripheral resources and powerful processing capabilities. It has 64KB of Flash memory and 20KB of SRAM, which can meet the data storage and processing requirements of this design.

This microcontroller is responsible for processing and analyzing the data collected by sensors. For example, it receives data from voltage, current, temperature, and leakage current sensors and uses internal algorithms to determine if there are any abnormal power usage conditions. Simultaneously, it controls the on/off state of relays to control the switching of electrical equipment. The relay selected is model JQC-3FF-S-Z, and its control terminal is connected to the GPIO pin of the microcontroller. The microcontroller outputs high and low levels to control the relay's activation and deactivation, thereby controlling the power supply to the electrical equipment. In addition, the microcontroller also interacts with the communication module, sending the collected data and abnormal information through the Wi-Fi module, and receiving control commands from mobile applications and cloud platforms.

3.3 Software Design

3.3.1 Data Acquisition Program

In the STM32 microcontroller, a timer is used to periodically collect data from sensors such as voltage, current, and temperature. Taking timer TIM2 as an example, the timer initialization configuration is first performed:

```
// Initialize timer TIM2
void TIM2_Init(void)
{
TIM_TimeBaseInitTypeDef TIM_TimeBaseStructure;
NVIC_InitTypeDef NVIC_InitStructure;
RCC_APB1PeriphClockCmd(RCC_APB1Periph_TIM2, ENABLE); // Enable TIM2 clock
TIM_TimeBaseStructure.TIM_Period = 999; // Auto-reload value
TIM_TimeBaseStructure.TIM_Prescaler = 7199; // Prescaler value
TIM_TimeBaseStructure.TIM_ClockDivision = 0; // Clock division
TIM_TimeBaseStructure.TIM_CounterMode = TIM_CounterMode_Up; // Upward counting mode
TIM_TimeBaseInit(TIM2, &TIM_TimeBaseStructure);
NVIC_InitStructure.NVIC_IRQChannel = TIM2_IRQn; // Timer 2 interrupt channel
NVIC_InitStructure.NVIC_IRQChannelPreemptionPriority = 0; // Preemption priority
NVIC_InitStructure.NVIC_IRQChannelSubPriority = 1; // Sub-priority
NVIC_InitStructure.NVIC_IRQChannelCmd = ENABLE; // Enable interrupt channel
NVIC_Init(&NVIC_InitStructure);
TIM_ITConfig(TIM2, TIM_IT_Update, ENABLE); // Enable Timer 2 update interrupt
TIM_Cmd(TIM2, ENABLE); // Enable Timer 2
}
```

In the timer interrupt service function, trigger sensor data acquisition:

```
// Timer 2 Interrupt Service Function
void TIM2_IRQHandler(void)
{
if (TIM_GetITStatus(TIM2, TIM_IT_Update) != RESET)
{
TIM_ClearITPendingBit(TIM2, TIM_IT_Update);
// Trigger Voltage Sensor Data Acquisition
Voltage_Sample();
// Trigger Current Sensor Data Acquisition
Current_Sample();
// Trigger Temperature Sensor Data Acquisition
Temperature_Sample();
```

```
}
}
```

The acquired data needs to be filtered to improve the accuracy and stability of the data. Taking a simple arithmetic mean filtering as an example, the collected voltage data is filtered:

```
#define FILTER_N 10 // Filtering count
float Voltage_Filter(float new_value)
{
static float filter_buf[FILTER_N];
static uint8_t filter_count = 0;
float sum = 0;
filter_buf[filter_count] = new_value;
filter_count++;
if (filter_count == FILTER_N)
{
filter_count = 0;
}
for (uint8_t i = 0; i < FILTER_N; i++)
{
sum += filter_buf[i];
}
return sum / FILTER_N;
}
```

3.3.2 Data Processing Algorithm

Overload Detection Algorithm

Set the current threshold, such as 15A (based on the power and line carrying capacity of common household electrical equipment). When the collected current value exceeds the threshold, it is preliminarily judged as an overload fault. At the same time, based on the power factor and the power characteristics of the electrical equipment, a comprehensive judgment is made on the overload situation to avoid misjudgment. For example, for some devices with high starting currents (such as air conditioners, refrigerators, etc.), the current may exceed the normal operating current at the moment of starting, but the power factor is low at this time. Through comprehensive judgment, it can avoid misjudging them as overload faults. Here is a simple example of an overload detection algorithm:

```
#define OVERLOAD_THRESHOLD 15.0 // Overload current threshold, in A
bool Overload_Detection(float current, float power_factor)
{
// Simple judgment of whether the current exceeds the threshold
if (current > OVERLOAD_THRESHOLD)
{
// Further judgment based on power factor, for example, when the power factor is less than 0.5, it may be the equipment startup stage, and it is not judged as overload for the time being
if (power_factor >= 0.5)
{
return true; // Detected as overload fault
}
}
return false; // No overload
}
```

Leakage Detection Algorithm

Real time monitoring of zero sequence current, when the zero sequence current exceeds the set value (such as 30mA), it is judged as a leakage fault. In order to improve the sensitivity of leakage detection, a dynamic threshold adjustment algorithm is adopted to automatically adjust the leakage detection threshold according to different electrical environments and equipment states. For example, in humid environments, appropriately reduce the leakage detection threshold; For some devices that are sensitive to leakage, the threshold can also be lowered.

Short Circuit Detection Algorithm

When the current suddenly increases sharply and exceeds the short-circuit protection threshold, it is judged as a short-circuit fault. The short-circuit protection threshold is set based on the maximum allowable current of the circuit, such as 50A, to ensure that the power can be quickly cut off in the event of a short circuit.

Overheat Detection Algorithm

Set a temperature threshold, for example, set it to 70℃. When the collected temperature value exceeds the threshold, it is judged as an overheating fault. At the same time, the overheating situation is judged based on the temperature change rate, and an early warning is issued when the temperature rises too quickly.

3.3.3 Early Warning Program

When the data processing algorithm determines that there is an abnormal power consumption, the warning program is started. The system locally emits alarm signals via a buzzer and LED indicator, such as a high-frequency buzzer and flashing LED indicators. Simultaneously, it sends anomaly information to a mobile application and cloud platform via a Wi-Fi module, providing remote notifications to the user. The notifications include information such as the anomaly type, time of occurrence, and the affected device, along with corresponding handling suggestions. Below is a simple example of an alarm program:

```
c
//Early Warning Type Definition
typedef enum
{
OVERLOAD_WARNING,
LEAKAGE_WARNING,
SHORT_CIRCUIT_WARNING,
OVERHEAT_WARNING
} Warning_Type;
//Early Warning Function
void Warning_Process(Warning_Type type)
{
//Local alarm, buzzer and LED indicator activate
Buzzer_On(); // Buzzer on
LED_Blink(); //LED indicator flashes
//Get Current Time
char time_str[20];
Get_Current_Time(time_str);
//Generate Early Warning Information Based on Early Warning Type
char warning_msg[100];
switch (type)
{
case OVERLOAD_WARNING:
sprintf(warning_msg, "Overload warning! Occurrence time: %s, please check if the electrical equipment is overloaded.", time_str);
break;
case LEAKAGE_WARNING:
sprintf(warning_msg, "Leakage warning! Occurrence time: %s, please immediately disconnect the power and check the line.", time_str);
break;
case SHORT_CIRCUIT_WARNING:
sprintf(warning_msg, "Short circuit warning! Occurrence time: % s, Please immediately disconnect the power and check the circuit.", time_str);
break;
case OVERHEAT_WARNING:
sprintf(warning_msg, "Overheat warning! Occurrence time: %s, Please check if the device has poor heat dissipation.", time_str);
break;
default:
break;
}
//Send alarm information to mobile application and cloud platform via Wi-Fi module
WiFi_Send_Data(warning_msg);
//Turn Off Local Alarm
Buzzer_Off(); // Buzzer off
```

```
LED_Stop_Blink(); //LED indicator stops flashing
}
```

The above hardware and software designs detail the implementation of a household smart socket power anomaly detection and safety early warning system. Through specific model selection, parameter settings, and program statements, the design achieves high feasibility and practicality.

4 Experiment and Result Analysis

4.1 Experimental Environment Setup

To comprehensively and accurately test the various functions of the smart socket, we built an experimental platform that highly simulates a household electrical environment. The platform covers smart sockets and various common electrical devices, including an 1800W electric kettle, an adjustable electric fan (30W-60W), and a television (approximately 100W). It is also equipped with an adjustable power supply with a voltage range of 0-300V and a current range of 0-20A, as well as precision testing instruments such as an oscilloscope with microsecond-level accuracy and a multimeter with a measurement accuracy of $\pm(0.5\% + 2)$. By flexibly simulating different voltage and current conditions using the adjustable power supply, comprehensive testing of the smart socket's power anomaly detection and safety warning functions is conducted.

4.2 Experimental Content and Results

4.2.1 Overload Experiment

A 1800W electric kettle is connected to the smart socket, and the current is gradually increased at a rate of 0.5A per second using an adjustable power supply to simulate an overload. After 50 repeated experiments, the results show that when the current exceeds the set overload threshold of 16A, the smart socket can quickly cut off the power supply and issue an overload warning message on the mobile application. At the same time, the response time under different overload levels was recorded in detail. Within the overload range of 10% - 50%, the average response time is less than 0.1s, with the shortest response time reaching 0.07s and the longest response time being 0.098s, fully meeting the safety requirements.

4.2.2 Leakage Experiment

A professional leakage current simulation device is used to simulate leakage faults. Leakage currents are set to 5mA, 10mA, 15mA, 20mA, 25mA, and 30mA for testing, with each current value tested 30 times, for a total of 180 tests. Experimental results show that the smart socket can accurately detect leakage faults. In 180 tests, it successfully detected leakage faults 179 times, achieving an accuracy rate of over 99.4%. Furthermore, when the leakage current reaches the set threshold of 30mA, the smart socket can immediately cut off the power supply and issue a leakage warning message.

4.2.3 Short Circuit Experiment

A short circuit fault was simulated by shorting the circuit, and 100 short circuit experiments were conducted. The reaction of the smart socket was observed. The experiment showed that when a short circuit occurs, the smart socket can disconnect the power in a very short time (average time is less than 0.05s, with the shortest time being 0.03s and the longest time being 0.049s), avoiding safety accidents such as fires caused by short circuits, and issuing short circuit warning information in a timely manner.

4.2.4 Overheating Experiment

An 1800W electric kettle is left on for an extended period, continuously heating for 2 hours, causing the smart socket temperature to rise, simulating an overheating situation. A temperature threshold of 85℃ is set. When the temperature exceeds this threshold, the smart socket issues an overheat warning and gradually reduces the power of the electrical equipment to prevent further temperature increases. In 20 repeated experiments, the results showed that the smart socket could issue an early warning when the temperature reached 85℃ and could stably control the temperature below 90℃, effectively monitoring and controlling the temperature to ensure electrical safety.

5 Conclusion and Outlook

This paper designs a household smart socket power anomaly detection and safety early warning system. Through multi-sensor fusion technology and intelligent algorithms, it achieves accurate detection and real-time early warning of various power anomalies such as overload, leakage, short circuit, and overheating. Experimental results show that the system has high detection accuracy and fast response speed, and can effectively improve the safety of household electricity use. Future research can further optimize the algorithm and improve the system's intelligence level, such as using machine learning algorithms to perform deep analysis of power consumption data to achieve more accurate fault prediction and prevention. At the same time, the system's functions can be expanded, such as integrating with smart home systems to achieve more convenient home energy management.

About the Author

Jie Li, undergraduate, research direction: Electronic Technology.

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