Design of socket with load identification and control

Kai Xu 1, Yilong Li 1*, Zisong Jiang 2 and Xianyu Feng 2
1State Grid Zhejiang Marketing Service Center, Hangzhou, Zhejiang, 310000, China
2Zhejiang Chint Instrument & Meter Co., Ltd. Hangzhou, Zhejiang, 310000, China
*Corresponding author’s e-mail: liyilong@zj.sgcc.com.cn

Abstract—Under the background of demand-side power management, one solution to the problem of seasonal and intermittent power shortages is to involve residential users. The power supply company can sense and control the energy-consuming equipment such as air conditioners and water heaters in residential users’ homes. A socket with load identification and control functions is designed in the article. Through this socket, it is possible to sense and control the loads such as air conditioners and water heaters connected behind it. The socket adopts a combination of "sensing core" and "measurement core", uses an algorithm based on events and Gaussian model to identify the load, uses a magnetic latching relay for control, and has protection functions such as overvoltage and overcurrent. In terms of installation method, it is fully compatible with the 86-size ordinary panel sockets used in residential houses on a large scale, and has certain application value.

1. Introduction
With the progress of urbanization and the promotion of electric energy substitution strategies have brought about rapid growth of power load, and the problem of seasonal and intermittent power shortages are prominent. Starting from the supply side, the utilization rate of supporting power grid equipment is at a low position, causing a great waste of grid equipment resources. Starting from the demand side[1-2], take State Grid Hebei Electric Power Company as an example, the industrial load is 11 million kilowatts, and the maximum reduction capacity is 6 million kilowatts. Only regulating the industrial load can no longer meet the requirements for safe operation of the power grid. At the same time, the residential air-conditioning load exceeds 15 million kilowatts, which accounts for 40% of the peak load, has a huge adjustable capacity. In order to adjust these residential loads, have to identify the load type and master the equipment operating status before using. At present, most of the electrical appliances in the house currently do not have the ability to report the type and operating status of the electrical appliances to which the machine belongs, which brings great obstacles to the control of the power system. In order to implement the above-mentioned functions for these electrical appliance, there are two solutions. One is to install the electrical appliance and embed the random measurement module to make it have relevant functions; the other is to not add the electrical appliance, just connect an external socket which can realize related functions outside of it. The first solution is applicable to the electrical appliance itself having an interface that transmits its electrical parameters and characteristics. The second solution has a wider application range and can be used without paying attention to the capabilities of the device itself. This research proposes a design scheme of a smart socket with load identification function[3-5], which not only has the load identification ability, but also has the ability to interact with the superior equipment. The smart socket is mainly used in low-voltage user load sensing measurement and control systems. When electrical appliance is running, according to the system requirements, the smart socket uploads the load
type and operating conditions (current, power), and the system sends instructions to a certain socket according to the agreement with the user as needed, and the socket can cut off the subsequent load.

2. Overall design solution

The current load identification technology is divided into two types, Intrusive Load Monitoring, NLM and non-intrusive load monitoring technology, NILM. NLM technology requires the installation of an intelligent collection device at each electrical appliance, which is costly and technically easy to implement; the essence of NILM technology is to decompose users' aggregated electricity consumption information into individual electrical appliance. Electricity information[6] only needs to install an intelligent acquisition device at the entrance of the tested building, which has a lower cost and technically complex.

For smart sockets, the load connected to the socket is changing. If an intrusive method is used, the user needs to set the load type on the socket every time the load changes, and the user does not need to use non-intrusive means Smart sockets can be identified after setting, avoiding subsequent load control inaccuracies caused by user missed settings or setting errors. Therefore, this research chooses the NILM technology.

The communication channel that interacts with the upper-level equipment adopts a dual-mode method. The high-speed power line carrier technology (HPLC) directly uses the power line for data transmission without additional wiring. The high-speed radio frequency technology (HRF) is used to provide another data channel for the interference of the carrier.

The entire socket adopts dual-core technology, and the part that requires higher computing speed and carries the non-intrusive load identification function is independently completed by an ARM core, and the remaining functions are completed by an SOC core with electrical parameter measurement functions. The SOC core completes real-time sampling, storage, calculation and data processing of input voltage and current signals, load identification and display, and uses HPLC and HRF communication to complete data interaction with upper-level equipment, and cut off the load connected to the product as needed. The original voltage and current data transmission between the NILM circuit and the SOC adopts the SPI communication interface. The SOC is the main and the NILM module is the slave. The SOC sends the original data to the load module in real time. The NILM circuit transmits the load identification result number to the SOC circuit through the serial port. The module needs to supply at least 3.3V, 50mA power to the NILM circuit. The UART port is used for communication between the HPLC and HRF communication circuit and the SOC. The maximum communication rate is 115200bps. The transceiver is isolated by open-drain. At the same time, the SOC provides a pin for resetting the HPLC and HRF circuit. The power module needs to supply at least 12V, 150mA power to the HPLC and HRF circuits. The system structure block is shown in Figure 1.

![Fig.1 System structure block](image-url)
3. Hardware design
In the design, the SOC uses the widely used core RN2025B64 in the field of electric energy measurement, and the realization of the load identification function uses the STM32F412CGU6 of the M4 series of ARM microcontrollers that support multipliers and floating point operations.

3.1. Measuring core processing part
The measurement core circuit mainly includes the current and voltage sampling circuit design and the peripheral circuit design to ensure the normal operation of the SOC core.

3.1.1. Current and voltage sampling
Manganin shunt is used for current sampling. The current signal flowing through the manganin shunt is converted into a proportional voltage signal through conversion, and then after low-pass filtering, the signal enters the voltage sampling pin of the SOC.

Voltage sampling is mainly to consider that the reliability of the circuit will not be affected when the external high voltage impacts. Seven 1% precision 1206 package high withstand voltage resistors are used for voltage division. After the voltage signal is divided, its amplitude is within the input range of the SOC. After low-pass filtering, the signal enters the voltage sampling pin of the SOC. The Current and voltage sampling circuit is shown in Figure 2.

![Current and voltage sampling circuit](image)

3.1.2. HPLC and HRF communication part
It adopts a dual-mode modular design scheme that integrates broadband carrier and micro-power wireless, in which the broadband carrier operating frequency band is 0.7MHz-12MHz, and the micro-power wireless operating frequency band is 470MHz-510MHz. The two communication modes are automatically switched to achieve deep network coverage.

The power supply of the socket to the dual-mode module is 12V±1V, and the load capacity is 250mA. For space considerations, the high-frequency coupling circuit of the dual-mode module is placed on the power board, and the wireless antenna is an external antenna on the function board.

3.1.3. Control part
A relay with magnetic retention function and a derating design method is used to ensure the breaking capacity of the socket. The maximum on-off current is 50A, far exceeding the design requirement which is 20A. At the same time, to ensure the large current flow, a wire is required when making the PCB. Make it thicker and expose the solder pad for external tin hanging treatment. The thickness of the tin is 0.3mm.
The control of the relay is completed by measuring the SOC core. When receiving the load trip and closing command, the operation relay is turned off and closed. The Control part circuit is shown in Figure 3.

3.1.4. Measurement SOC core peripheral circuit design
In addition to the basic minimum system circuit for ensuring core operation, the measuring SOC core also includes peripheral circuits such as infrared transceiver circuits, storage circuits, button detection, and liquid crystal drive circuits.

3.2. Perceptual core processing part
The STM32F412CGU6 type single-core microcomputer is selected in the article, which has a built-in multiplier and floating-point number arithmetic unit. The SPI interface sends the AD sampling data of each cycle from the city power grid to the single-core microcomputer, and the single-core microcomputer sends the identification result to the measuring SOC through the UART serial port after calculation.

3.2.1. Data input channel design
The data input adopts the SPI interface, and the transfer rate reaches 3M/s. To ensure reliable transfer, combined with the DMA mode of STM32F412CGU6. Measuring SOC as the SPI master, and STM32F412CGU6 as the SPI slave. The UART port is used as a data interface for sensing SOC output to measuring SOC, the default baud rate is 9600bps.
3.2.2. Design of Peripheral Circuit of Perception SOC core
The peripheral circuit of the sensing SOC core includes a crystal oscillator to make it operate normally, and a reset circuit. The crystal oscillator circuit uses a 16M external quartz crystal oscillator, and the reset circuit uses an external RC reset. It also contains a memory circuit using M24512 64k bytes of EEPROM and MX25L25645G 32M bytes of NORFLASH. Program debugging and downloading use standard SWD interfaces.

![Fig. 5 EEPROM circuit](image1)

Fig. 5 EEPROM circuit

![Fig.6 FLASH circuit](image2)

Fig.6 FLASH circuit

4. Software design part
The software system is designed in C language, and the module is packaged according to the object-oriented thinking. The overall architecture is divided into 4 levels: the guidance layer, the scheduling layer, the business layer and the hardware layer. Guidance layer is a collection of codes for realizing software startup work, including guidance modules; scheduling layer is a collection of codes that realize the integrated management of the overall software system, including object management modules, data layer management modules and scheduling modules; hardware layer is a collection of codes that implement MCU driver and device (Flash, UART, etc.) driver, including single-core microcomputer and hardware driver module; business layer is according to the characteristics of the DL/T 698.45-2017 protocol, the basic functions are defined in units of OI (Object Identifier). Manage and implement multiple code collections of the same type or similar functions (OI). Communication link module, 698 protocol module, input and output interface module, record processing module.

4.1. Load identification algorithm design
After decades of development of non-intrusive load identification algorithms, the most common ones in recent research are to design algorithms based on hidden Markov models, deep learning, mixed-integer linear programming, graphic signal processing and other technologies. The requirements are high and it is difficult to implement in embedded systems. And most of the existing studies only focus on the single characteristics of electrical appliances, and it is difficult to distinguish between devices. This article mainly uses multi-dimensional features such as active power, reactive power, and harmonic current to construct a multivariate Gaussian distribution model, and identify electrical appliance through probability distribution, which is suitable for implementation in embedded single-core microcomputers.
Using the clustering method based unsupervised learning algorithm based on transient and steady-state instantaneous quantity curves and other characteristic quantities, through equipment working state collection and sample training, the basic feature library modeling of electrical appliance categories is completed, and achieves energy consumption identification function of electric appliance [7-9]. Based on the superposition and decomposition algorithm of the electricity load of multiple energy consuming appliance based on the classification of electrical appliance, the identification function of different energy consuming devices in different time intervals is realized. It is required that the identification accuracy rate of the electric power consumption state of more than 300W is not less than 95%, and the identification accuracy rate of the electric power consumption state of more than 200W shall not be less than 80%.

Event-based non-intrusive load monitoring and decomposition technology includes three parts: event detection [10-13], feature extraction and load identification [14]. In the aspect of electrical event detection, using the knowledge of time series change point detection, an event sensing method based on sliding window is proposed. The proposed method defines the evaluation function as shown below.

\[ J(k) = \sum_{i=1}^{k-1} (P_i - \frac{1}{k-1} \sum_{r=1}^{k-1} P_r)^2 + \sum_{l=k}^{N} (P_l - \frac{1}{N-k+1} \sum_{r=k}^{N} P_r)^2 \]  

If there is an electrical appliance switching action within the time window taken, the mean value of the active time series will change accordingly, and the evaluation function will take the minimum value at the moment before the state change occurs, and its physical meaning is to split by the change point. The sum of variances corresponding to the two sequence fragments is the smallest. If the evaluation value at a certain moment has achieved a minimum value and the mean value of the electrical characteristics before and after that moment has changed, it can be determined that the state of an electrical appliance in the circuit has changed after that moment. Using this property, the action time of the electrical appliance can be located relatively accurately, and effective event perception can be realized. The event perception effect is shown in Figure 7, the laboratory collected 7-hour power fluctuations on the power line, and the corresponding X-axis position shown in the red circle is the action time of the electrical appliance accurately positioned using the above algorithm.

In terms of feature learning, using the results of event perception, using active-reactive-harmonic three-dimensional features to characterize events, clustering algorithms can be used to complete the correlation analysis between events. You can choose OPTICS clustering algorithm to achieve clustering of perception events. The OPTICS clustering algorithm can retain the clustering structure under different hierarchical conditions, and can easily realize the correlation analysis between events. Figure 8 is the result of feature learning obtained by analyzing actual observation data, kinds of electrical appliances are distributed in different positions according to their characteristics, active power, reactive power, and current harmonic content.
Fig. 8 Feature learning result graph

The event is matched with the known features in the electrical appliance library, and the load identification is carried out.

The specific load algorithm is divided into the following modules
(1) Signal processing module
After acquiring the waveform data from the measuring core, this module processes the waveform data in a certain way to extract effective information. It is mainly to process the analog signal, convert it into meaningful quantities such as voltage and current, and then store the waveform per second to facilitate subsequent processing.

(2) Event monitoring module
Input the sequence obtained by processing, judge whether there is an event according to the change of the sequence according to certain rules, and record the time when the event occurs. When an event occurs and the event ends, complete the extraction of the event feature quantity, use the feature quantity to characterize the event, and quantify the description of the event.

(3) Zero-crossing detection module
Through this module, complete cycle data can be obtained.

(4) Linear interpolation module
There may be signal loss during the communication between the measuring core and the sensing core. The actual cycle frequency is 50 Hz, but the cycle obtained during the sampling process is not necessarily complete. Interpolation processing is required for the acquired points to ensure correctness of the calculation of subsequent feature quantities.

(5) Load matching module
Match the event with the known appliances in the appliance library, associate the event with a specific appliance, and determine which appliance action triggered the event. In addition, it is necessary to complete the matching of on-events and off-events, and find out the rising and falling edges that belong to the same electrical appliance, so as to frame the operating range of the electrical appliance.

(6) Classification and measurement module
Complete the energy consumption measurement of different electrical appliances, and use the average power information of the electrical appliances to calculate the energy consumption under the operating conditions of the electrical appliances.

(7) Status check module
Since the actual operating power is affected by the fluctuation of the voltage amplitude and frequency, it is not a fixed value. Use this module to compare the total active power of the running electrical appliances with the total active power measured by the electric meter at regular intervals, and correct the power measurement error in the load identification stage. Unidentified events are re-identified to improve the accuracy of load identification and energy consumption classification and measurement.

(8) Slowly changing power prediction module
Since some electrical appliances have a slow change of active power for a long time during the turn-on process, there is a certain impact on subsequent electrical identification. When certain active slow-changing electrical appliances are identified, turn on the module, and perform ultra-short-term prediction of the active power change of this kind of active slow-changing electrical appliances in the
on state, and eliminate the influence of the active slow-changing electrical switch on time process on subsequent identification.

(9) Transient impact identification module
Attached to the event monitoring module, when an active transient impact is detected, the impact is recorded and retained as one of the identification features to quickly identify electrical appliances with unique transient features in the feature library.

(10) Edge-Cloud collaboration Module
Communicate with the cloud, feedback the unknown electrical appliances encountered locally to the cloud, and receive auxiliary information from the cloud to help the smart meter complete the scheduled work. The formation of unknown electrical appliances is, on the one hand, discovered by means of events. Unidentified electrical appliances are formed. It is also possible that for some reason, the event is not found, you can compare the power of the identified electrical appliances with the line measurement. Then the difference between the total-power is found. Flow chart of status check as shown in Figure 9, and the overall framework process of load identification is shown in Figure 10.

![Flow chart of status check and Flow chart of the overall framework](image.png)
4.2. Load control algorithm design
The goal of the algorithm of the load control part is to define the conditions for the action of various relays. When the conditions are met, the relay will act.

(1) Unconditional action: refers to the real-time switching of the relay when it receives an immediate action order from the upper-level equipment

(2) Single condition action: refers to the definition of the following individual conditions to switch the relay:
Voltage action conditions: The voltage action threshold can be set, using "hysteresis mode", the relay cut-off voltage is less than the closed voltage. In order to prevent the relay from switching the voltage point again, repeating the action, and damaging the appliance.
Current operating conditions: the same as the voltage processing method.
Appointment operating conditions: according to the agreed time, the relay will switch on and off.
(3) Multi-condition action: refers to the combination of various conditions of the "single condition" action to form multiple conditions.

Encode various action conditions and set the priority. When multiple conditions are set, the action priority is executed in the order of unconditional, multiple conditions, and single condition. In the case of single condition, each condition is in parallel relationship, cut off priority of the action is higher than the closing action.

The program flow chart is shown as in Fig. 11.

5. Structural design part
The system uses "86 panel" structural parts. The difficulty is to accommodate circuit boards that realize each function in a very small space. This solution divides the circuit boards into multiple pieces according to their functional characteristics. The three-dimensional plug-in method is used as shown in the following Fig. 12. Among them, the dual-mode communication module divides it into two circuit boards to separate the power coupling part of the circuit from the weak current logic circuit to accommodate three-dimensional plug-in connections.
6. Conclusion

The smart socket with load identification and control function designed in the article can be applied to the system to provide accurate control of a certain type of load, and it can also be separated from the system to provide overcurrent and overvoltage protection and electric energy measurement functions. In terms of installation method, it is fully compatible with the 86-size ordinary panel sockets used in residential houses on a large scale. That is to say, the socket can not only be used as the collection and control equipment required by the power supply company to carry out demand-side power management, but also can meet the energy safety needs of users, has certain application value.

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