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Smart Meter Electromagnetic Interference Resistance Technology Research

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ABSTRACT: *Wireless smart meters are systems subject to complex electromagnetic interference. To improve their measurement accuracy, this paper proposes a comprehensive EMC solution combining hardware and software, focusing on EMI suppression in three aspects: switch power supply, RF unit, and PCB. The main measures include filtering, grounding, PCB design, isolation technology, software watchdog, median filtering, etc., which effectively reduce EMI impact. Experimental results show that under the given conditions, there is no breakdown or arcing phenomenon, and the measurement accuracy is at the 0.2 level, in compliance with national standards DL/T645-1997, GB/T17215-1998, and DL/T614-1997. The system exhibits good EMC characteristics, which is of significant value for the development of complex electromagnetic environment instruments and meters, such as wireless smart meters.*

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I. INTRODUCTION

With the development of smart meter technology, wireless smart meters are increasingly gaining attention due to their advantages such as wireless data transmission. Their main functional units include GSM/GPRS/Zigbee, radio frequency modules, as well as switch power supplies, power frequency circuits, high-speed digital signal communication interfaces, and various embedded systems such as microcontrollers, DSP, and SOC [1-8]. In their operating environment, factors like power frequency interference, electrostatic interference, switch power supply interference, radio frequency radiation interference, conducted coupling interference, and harmonic interference of digital signals intertwine with each other, affecting the data processing quality of embedded systems in smart meters, the integrity of communication data, and measurement accuracy [8-10]. In this context, a deep analysis of electromagnetic interference in smart meters, along with the adoption of reasonable electromagnetic compatibility measures at various stages of design and implementation based on the signal characteristics of different modules, is of significant importance to improve testing accuracy and data integrity.

II. TYPICAL WIRELESS SMART METER SOLUTION AND THRIE ELECTROMAGNETIC INTERFERENCE ANALYSIS

TYPICAL SOLUTIONS FOR WIRELESS SMART METERS

A typical schematic diagram of a wireless smart meter is shown in Fig 1. In the scheme depicted in Fig 1, the control core adopts a dual-core embedded system structure consisting of DSP + MCU, with the CC2530.

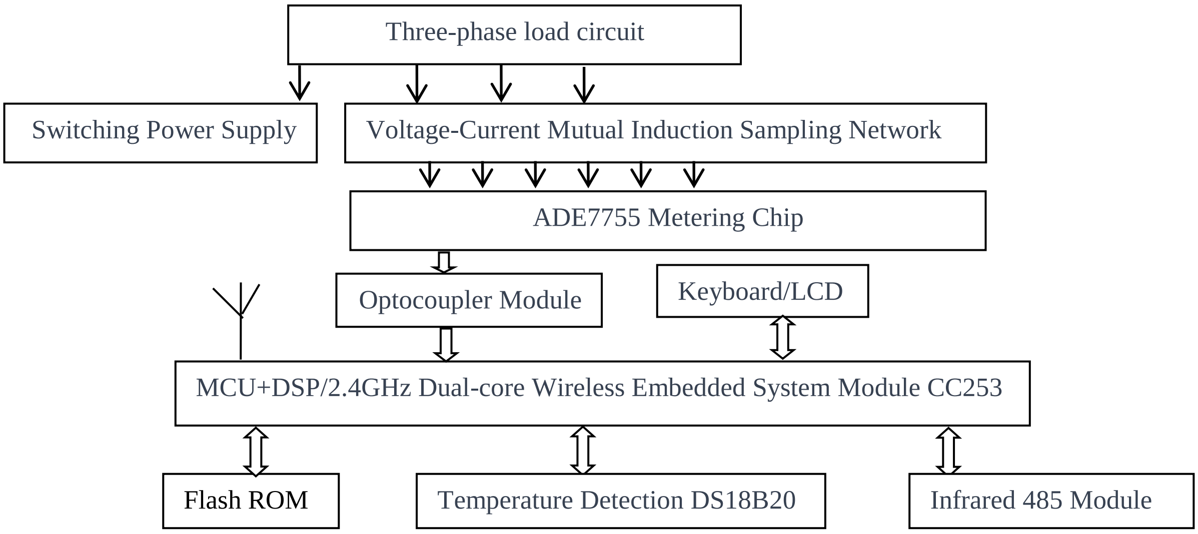

Fig. 1 Typical Wireless Smart Meter Block Diagram

This chip is equipped with an enhanced dual-core structure, consisting of an 8051MCU responsible for control and an AESI28 coprocessor dedicated to DSP operations. Its memory includes 256 KB of Flash ROM, 8 KB of RAM, 8 channels of 12-bit ADC, USART interfaces, and 21 programmable GPIO pins. It also features a built-in 2.4 GHz RF transceiver module, compliant with IEEE 802.15.4 protocol, with adjustable output power ranging from -22 to 3 dBm. It boasts robust DMA capabilities, digitalized RSSI/LQI support, one MAC timer compliant with IEEE 802.15.4 specifications, and hardware support for remote network CSMA/CA functionality. Additionally, it includes one conventional 16-bit timer and two 8-bit timers. The CC2530 operates within a voltage range of 2.0 to 3.6 V, making it suitable for various solutions.

The system can be used for handheld terminal meter reading, RS-485 remote meter reading, and wireless meter reading using Bluetooth or Zigbee, among other applications.

Main Electromagnetic Interference (EMI) in the System and its Characteristics

Electromagnetic interference (EMI) is generally generated by the rapid changes in voltage and current within electronic devices. These interferences can propagate in the form of currents along conducting elements (such as power lines, PCB traces, and cables) to create conducted interference, or they can propagate through space in the form of electromagnetic waves to create radiated interference. In wireless smart meter systems, the input power lines, switch power supplies, and wireless modules are the primary sources of interference [8, 10]. Interference waveform measured with an Agilent spectrum analyzer for the smart meter.

Interference in Switching Power Supplies

In the power frequency power supply, a significant amount of conducted electromagnetic interference (EMI) noise can enter the switching power supply system through the power lines. Depending on the different paths the noise current takes, this noise can be categorized into common-mode noise (u_{CM}) and differential-mode noise (u_{DM}).

(1) Differential-mode (or common-mode) interference is RF noise that exists between any two power supply lines or output lines. In offline switching power supplies, this is typically interference between the live and neutral lines of the AC power supply or between the positive and negative poles of the output lines. The interference voltage acts in series with the input or output voltage of the power supply.

(2) Common-mode interference is interference caused by the RF noise component between any or all power supply lines or output lines and the common ground plane (chassis, enclosure, or ground return line).

$$u_{DM} = u_L - u_N \qquad (1)$$

$$u_{CM} = \frac{u_L - u_N}{2} \qquad (2)$$

In these equations, u_L and u_N represent the noise voltage on the power supply lines L and N.

Additionally, in commonly used flyback-type converters, due to the high operating frequency of the switching transistor, there is significant radiated interference, including electromagnetic interference and electric field interference. The strength of this interference is directly proportional to the product of circuit current (I), the area enclosed by the current loop (S), and the square of the current flow frequency (f). Increasing the switching frequency leads to higher values of d_I/d_t, d_u/d_t, and d_I/d_t, resulting in increased electromagnetic interference (EMI). Switching power supplies typically have three high dI/dt circuits: one is the primary circuit consisting of the DC input filter capacitors, the primary winding of the switching pulse transformer, and the switching transistor; the other is the secondary circuit consisting of the output rectifier diode, output filter capacitors, and the secondary winding of the switching pulse transformer.

RF Interference in Wireless Modules

Wireless transmission is a recent advancement in smart meter performance. Since wireless transmission frequencies are generally above 30 MHz, it can generate RF electric field interference, which acts through both conducted coupling and radiated coupling [11]. The fundamental pathways of radiated interference are illustrated in Fig 2.

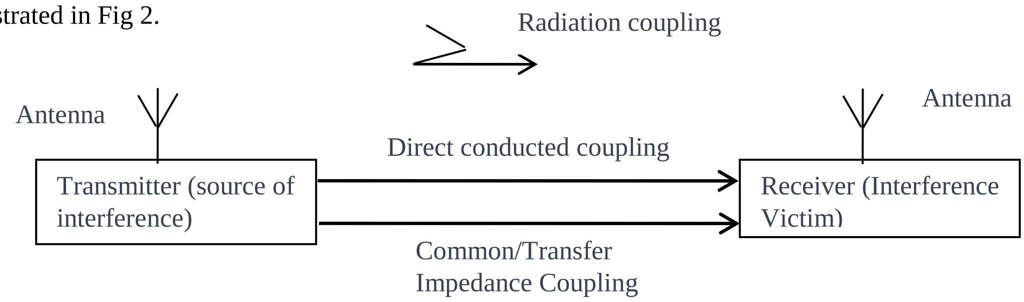

Fig. 2 The basic approaches to mitigate electromagnetic radiation interference

High-frequency circuit radiation and transmission in the RF unit can induce electromagnetic wave-induced noise in the circuit or generate low-frequency components of noise in nonlinear components.

III. EMC DESIGN FOR WIRELESS SMART METERS

A scientifically sound design is crucial for effectively reducing the impact of EMI, ensuring the accuracy of smart metering data and the integrity of communication signals. Based on the primary sources of EMI in wireless smart meters, the EMC design focuses on several key aspects. The comprehensive design incorporates a combination of hardware and software solutions. The hardware techniques include filtering technology, shielding technology, isolation technology, decoupling technology, and grounding technology. Correspondingly, software techniques include median filtering and watchdog timers [8, 12].

EMI IN SWITCHING POWER SUPPLIES

Particular attention must be paid to the closure of magnetic circuits in inductors and transformers. For instance, ring-shaped or seamless magnetic cores are suitable for storing magnetic energy. If there are slots in the magnetic core, a complete short-circuit ring is required to reduce parasitic leakage magnetic fields. Primary switch noise can propagate to the secondary through the capacitance between coil turns in the isolation transformer, leading to difficult-to-filter common-mode noise currents in the secondary, which can then result in emissions. To address this, the secondary is connected to the primary power line using small capacitors, providing a return path for these common-mode currents. However, safety must be considered, and the total leakage ground current should not exceed the safety standards. This capacitor also aids in the better operation of the secondary filter.

Coil-to-coil shielding (inside the isolation transformer) can more effectively suppress primary switch noise induced on the secondary. The shielding close to the primary coil is usually connected to the primary power line, the shielding close to the secondary coil is often connected to the common output ground, and the intermediate shield is generally connected to the chassis. During the prototype phase, it is best to conduct repeated experiments to find the optimal connection method for coil-to-coil shielding.

Filtering can effectively eliminate conducted electromagnetic interference, preventing electromagnetic interference from propagating through conducting elements. Using filtering methods not only prevents external conducted electromagnetic interference from entering a specific working area through conducting elements but also restricts conducted electromagnetic interference from crossing specific boundaries.

To further improve the EMC performance of switching power supplies, the following measures can be taken:

(1) Add a first-stage line filter coil on the side where the power frequency mains enter the switching power supply.

(2) Use power MOSFET switching transistors with low distributed capacitance to ground.

(3) Use diodes with soft recovery characteristics for active power factor correction (PFC) boost rectifiers, and add ferrite beads in series with the diode pins. Add another ferrite bead in series with the power

output voltage leads and the leads of the filter capacitor.

(4) Install an RC absorption circuit between the source-drain terminals of the power MOSFET switching transistor, and connect small ferrite beads in series with the resistor and capacitor pins. These small ferrite beads can absorb high-frequency energy during the charging process of the RC absorption circuit, particularly during peak current periods.

Wrapping or using ferrite cores on cables can also provide some filtering and absorption effects. Both power line filtering and signal line filtering are crucial in electromagnetic compatibility design. High-frequency filter connectors with good filtering performance and simple installation are generally used. When designing or using signal line filters, the cutoff frequency of the filter should be higher than the signal frequency to be transmitted on the cable.

When designing filters, the following points should be considered:

(1)Conduction Interference Handling: To address conduction interference, particularly above 1 MHz, which is often caused by coupling from radiated emissions, a combination of techniques should be employed to suppress both conducted and radiated emissions. These techniques may include shielding, decoupling, and filtering.

(2)Impedance Matching: The attenuation performance of filter circuits is closely related to the impedance of the radiation source and the load. The greater the impedance mismatch in the filter circuit, the better the attenuation of electromagnetic interference. In most cases, the power input exhibits low impedance, and the input side of the power filter should have high impedance.

(3)Common-Mode and Differential-Mode Interference: Adjusting the parameters of capacitors and inductors used to suppress common-mode and differential-mode interference can modify their common-mode and differential-mode interference suppression characteristics. The leakage current of a filter refers to the current passing between the phase and neutral lines and the ground of the casing. In fact, the leakage current of the filter primarily depends on the common-mode capacitors connected between the phase and ground and the neutral and ground. Larger common-mode capacitance results in lower common-mode impedance and better common-mode interference suppression, but it also leads to higher filter leakage current. However, safety standards dictate that the leakage current should not exceed certain limits.

(4)Filter Installation: Power filter installation should be located near the entry point of the power lines. Integrating the power filter with the interface is preferable. For metal-shielded enclosures, independent power shielded filter units are a good choice and should be installed at the entry point of the power lines. Ensure that the filter housing has good electrical contact with the equipment chassis (ground) for optimal filtering performance. For example, making modifications to the AC power input circuit of a switching power supply can improve its EMI characteristics.

KEY PRINCIPLES FOR DESIGNING PRINTED CIRCUIT BOARDS(PCB)

PCB is a convergence point for various types of interference, and it is essential to carefully design the PCB for wireless smart meters. The key principles include: [13-14]

(1) Use miniature components and multi-layer printed circuit boards (PCBs). Multi-layer PCBs allow for compacted wiring spaces, provide excellent high-frequency characteristics, and facilitate EMC (Electromagnetic Compatibility) design. In multi-layer PCBs, it's important to separate the power plane from the ground plane. One of the most critical ways to reduce electromagnetic radiation interference or enhance resistance to radio frequency (RF) interference is to decrease the current frequency of high-frequency interference sources, effectively reducing the frequency of interfering electromagnetic waves. The higher the frequency of loop currents, the more severe the EMC radiation, with electromagnetic radiation field strength increasing proportionally with the square of the current frequency.

(2) Minimize the loop area of high-speed signal lines and clock signal lines on the PCB. Keep traces as short as possible and place signal lines close to the ground return path. When simultaneously using high-speed, medium-speed, and low-speed logic circuits, design high-speed circuits at the entrance of the PCB. Ensure that signal lines and signal return lines are as close as possible. Use curved traces and avoid sharp bends in the circuit layout. Pay attention to impedance matching for high-speed input/output signal lines to reduce and eliminate signal reflections. Maintain distance between input and output lines of filters to avoid parallel routing that might affect filtering effectiveness.

(3) Follow PCB layering principles, similar to those used for arranging printed circuits and routing traces. The component side should have a ground plane underneath it. Critical power planes should be adjacent to their corresponding ground planes, and neighboring layers should not carry critical signals across regions. All signal layers, especially high-speed and clock signal layers, should be adjacent to ground planes, and efforts should be made to avoid placing two signal layers adjacent to each other. The choice of the number of PCB layers should consider the shielding and isolation requirements for critical signals. Determine the required number of PCB layers first and then, considering the cost of manufacturing the PCB, adding ground and power

layers is one of the best strategies for EMC design.

(4) Consider the sequencing of PCB routing during the design process. Routes for power, ground, clock, and signal lines should be short, direct, wide, and uniform. Avoid right angles and abrupt changes in routing. Eliminate "zig-zag" patterns and use rounded traces instead of sharp ones wherever possible. Widen power and ground traces as much as possible. Keep power and ground traces close to each other. Separate the routing of analog circuits from digital circuits, and ensure that power circuit routing and control circuit routing are distinct.

(5) When individual power or ground layers cannot form a continuous plane, use multiple grid connections to create a ground grid network. This effectively reduces the area of current loops, decreases common impedance, and increases distributed capacitance between signal layers and ground layers.

(6) Minimize the path for high-frequency signal currents passing through inductors. At higher frequencies, the inductive reactance of leads is generally greater than their resistance, making the leads behave like inductors. Series-connected inductors can cause electromagnetic radiation. Most electromagnetic radiation is caused by high-frequency current loops on the device being tested, with the worst-case scenario being an open-loop antenna configuration. To address this, reduce the length and size of leads for high-frequency signal currents, and eliminate any abnormal antenna-like structures, such as discontinuous traces or excessively long component pins. To avoid excessively long ground lines (close to $\lambda/4$), use a multi-point, near-grounding wiring approach, aiming for low high-frequency impedance in ground lines. One of the most important methods for reducing radiation interference or improving resistance to RF radiation interference is to minimize the area of high-frequency current loops. Wiring should aim to reduce the antenna effect of cables and minimize the dipole antenna effect. For cross-routed input/output signal lines, use cables with good shielding performance, and for internal conductors, use multi-strand twisted pairs to cancel out spatial fields. The shielding layer can serve as ground.

(7) Use low-impedance ground connections (ground plane) between integrated circuit chips. The impedance between supply pins of different integrated circuit chips should be kept as low as possible, and high-frequency bypass capacitors should be connected between the supply pins and ground for integrated circuit chips.

(8) Keep traces as far away as possible from sources of interference. Consider the use of ferrite materials in the layout and reserve space for bead and chip filter components for future adjustments. Implement RC decoupling filter circuits in signal input circuits to eliminate signal transmission interference caused by long traces.

CIRCUIT ISOLATION

In switch-mode power supplies, isolating components can cut off the propagation path of noise interference, thus suppressing noise interference. Circuit isolation primarily involves isolating digital circuits, isolating analog circuits, and isolating digital-to-analog interfaces. For isolating the analog part of switch-mode power supplies, linear isolators (such as optocouplers) are generally used to isolate DC signals, while transformers are used to isolate AC signals. For isolating digital circuits and digital I/O (Input/Output) in data communication, optocouplers or pulse transformers can be employed.

SHIELDIN AGAINST RADIO FREQUENCY(RF) AND OTHER INTERFERENCE

Shielding can effectively suppress electromagnetic interference that propagates through space, known as radiated electromagnetic interference. The purpose of using shielding is twofold: to limit the radiated electromagnetic energy from exiting a specific area and to prevent external radiated electromagnetic energy from entering a specific area. Shielding mechanisms can be categorized into electric field shielding, magnetic field shielding, and electromagnetic field shielding. When designing shielding, the following principles are typically followed:

(1) Begin by determining the electromagnetic environment, which includes factors such as the type, intensity, frequency, and distance from the radiation source to the shielding structure.

(2) Based on the requirements for electromagnetic shielding and the nature of the electromagnetic field, select the appropriate electromagnetic shielding material's conductivity, permeability, and thickness.

(3) Determine the sensitivity of the receiver and the shielding requirements.

(4)Once the electromagnetic shielding material is chosen, proceed with the design of the electromagnetic shielding structure. For electric field shielding, high-conductivity materials like copper are commonly used. For magnetic field shielding, especially at low frequencies, materials with appropriate thickness and high permeability are chosen to meet the electromagnetic shielding requirements.

(5) When transparency is required for the shielding enclosure, metal mesh shielding can be used. Metal mesh shielding is less effective than solid metal shielding and is generally not used in a double-layer configuration.

(6) If a single-layer electromagnetic shield is insufficient to meet the shielding requirements, multiple

layers of shielding can be employed to achieve better shielding effectiveness.

SOFTWARE-BASED EMC TECHNIQUES

Using software-based interference mitigation techniques is also an effective method for suppressing interference. This can involve adding filtering programs like median filtering to microcontroller programs. The basic steps of median filtering are as follows: replace the value of a point in a data sequence with the median value of neighboring data points in that sequence. To do this, arrange the data sequence in ascending order, denoted as $x_{i1} \leq x_{i2} \leq \ldots, \leq x_{in}$, where n is the number of data points. The median value y is then determined as the middle value in the sorted sequence.

$$y = Med\{x_{i1}, x_{i2}, \ldots, x_{in}\} = \begin{cases} x_i(\frac{n}{2}+1) & \text{n为奇数} \\ \frac{1}{2}[x_{i\frac{n}{2}} + x_i(\frac{n}{2}+1)] & \text{n为偶数} \end{cases} \quad (3)$$

In the formula, when considering a point's neighborhood values as a window, in one-dimensional situations, the median filter typically employs a sliding window containing an odd number of data points.

Additionally, software-based anti-interference techniques can also include methods to reestablish normal program execution when the program becomes chaotic or disrupted.

INSTRUCTION REDUNDANCY

When the CPU experiences interference and encounters errors, the program may deviate from its normal execution sequence and "wander" to execute instructions at an erroneous address. To mitigate this, it is common practice to insert several NOP instructions after multi-byte instructions (e.g., 2-byte or 3-byte instructions). This helps prevent subsequent instructions from being misinterpreted as operands, automatically guiding the program back to its normal sequence. Additionally, for instructions that play a crucial role in the program flow (e.g., interrupt return RETI, long call LCALL, long jump LJMP), it is advisable to precede them with two empty operation instructions to prevent program misdirection and ensure the execution of these critical instructions.

INTERCEPTION TECHNOLOGY

Interception, in this context, refers to redirecting a program that has deviated from its normal execution sequence to a designated location. When dealing with program "wandering," a software trap can be set (used to reset the program to the entry address 0000H) to prevent the program from going astray. To achieve this, one should first design the interception trap program instructions. Next, these traps should be placed in appropriate program segments to guide the program back to the normal entry point before addressing any errors. Typically, software traps are implemented by adding the following instructions to a non-program section in ROM.

```
NOP; No Operation
NOP; No Operation
LJMP 0000H; Long jump to the entry address 0000H.
```

SOFTWARE "WATCHDOG" TECHNOLOGY

When a program goes into a temporary infinite loop due to erratic behavior, software traps become ineffective, and the system becomes completely unresponsive. In such situations, you can employ software watchdog technology. The software "watchdog" is a timing mechanism with a period slightly longer than the time it takes for the CPU's main program to complete one normal loop. During the execution of the main program, the watchdog timer needs to be reset periodically, essentially refreshing the timer's time constant. Consequently, when the program goes astray and fails to refresh the timer as expected, it triggers a timer interrupt. This timer interrupt can be used to automatically reset the system.

IV. SYSTEM TESTING

The experimental system for verifying EMC effectiveness is shown in Fig 3, and the test results are presented in Table 1.

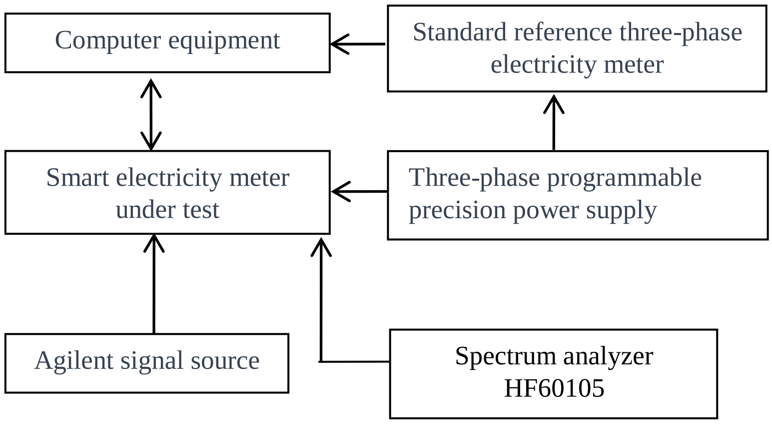

Fig.3 Test system diagram

The main test conditions are as follows:

(1)6.5 kV impulse voltage with a pulse width of 1/20 μs.

(2)4 kV 1/20μs pulse open-circuit voltage/short-circuit current.

(3)Rapid instantaneous multiple pulse test under 6 kV for 30 seconds.

(4)8 kV electrostatic discharge 10 times (with a 60-second interval between each) without breakdown or arcing phenomena.

(5)Normal data bit error rate under 2.4 GHz RF communication.Current magnitudes selected are $0.1I_b$, $0.5I_b$, and I_b,I_{max} respectively.

Table(1).Relative error in smart meter parameter testing

Range	Voltageactive	current	power	reactive power	power factor
$0.1I_b$	0.18	0.23	0.116	-0.192	0.56
$0.5I_b$	0.23	0.26	0.079	-0.152	0.52
I_b	0.20	0.20	0.104	0.094	0.47
I_{max}	0.22	0.24	0.124	0.184	0.58

Note: 'I_b' is used to test the standard current, generally set to 15 A.

As shown in Table (1), the maximum error values for each parameter are provided. This demonstrates that the designed meter accuracy class fully meets the 0.2-grade accuracy, satisfying the requirements of standards DL/T645—1997, GB/T17215-1998, and DL/T614-1997.

V. CONCLUSION

We have comprehensively considered the EMI (Electromagnetic Interference) in the wireless smart meter, addressing the main sources of interference from the switching power supply, RF unit, and PCB layout. This comprehensive EMC (Electromagnetic Compatibility) design includes techniques such as filtering, shielding, grounding, watchdog, isolation, and the application of median filtering algorithms.

The system has undergone practical testing involving various parameters, including high-voltage pulse interference. Under experimental conditions, there were no breakdowns or arc phenomena. This effectively reduces the impact of EMI and ensures that the system accuracy meets the requirements of the DL/T645-1997, GB/T17215-1998, and DL/T614-1997 standards at the 0.2 level. This is beneficial for the rapid and widespread adoption of wireless smart technology and holds significant importance for the development of intelligent instruments operating in complex electromagnetic environments.

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