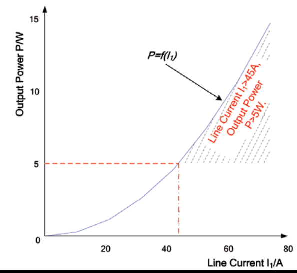
Development and design of a power supply system for intelligent monitoring equipment in smart grids



DESARROLLO Y DISEÑO DE UN SISTEMA DE ALIMENTACIÓN ELÉCTRICA PARA LOS EQUIPOS DE VIGILANCIA INTELIGENTE EN REDES INTELIGENTES

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RESUMEN

- En años recientes se han instalado en las redes inteligentes una amplia variedad de equipos de vigilancia inteligentes distribuidos, equipos que a menudo requieren un suministro de corriente continua de baja potencia. En este artículo se analiza el sistema de alimentación eléctrica utilizado por los equipos de vigilancia inteligente distribuidos de las redes inteligentes. El sistema de alimentación eléctrica capta una reducida potencia de la línea de transmisión o barra colectora, utilizando el principio de inducción electromagnética de Faraday. En primer lugar, la bobina de inducción atravesada por la línea de transmisión o la barra colectora obtiene una reducida potencia en corriente alterna; a continuación se rectifica su tensión en CA y se convierte en tensión de CC, que es pasada a 5 V por un convertidor de CC/CC. Como módulo de corriente de reserva se ha utilizado una batería de litio (BL) para cubrir la zona muerta de la bobina de inducción. Por último, un módulo de gestión de potencia basado en el chip único STC15F2K60S era capaz de optar entre la energía de la bobina de inducción y la del módulo de reserva vigilando la tensión de la batería y la tensión de salida, de manera que la intensidad y la tensión de salida pudieran alimentar al equipo de vigilancia inteligente. Los experimentos han revelado que este sistema de alimentación eléctrica es capaz de suministrar de una forma estable una potencia de 5 W a 5V cuando la corriente de la línea de transmisión o la barra colectora se encuentran en un rango de 0~1000A.
- **Palabras clave:** Redes inteligente, inducción electromagnética, corriente de derivación, equipo de supervisión inteligente.

ABSTRACT

In recent years, a variety of distributed intelligent monitoring equipment has been installed in smart grids, and this equipment often requires low-power DC supply. This paper examines a power supply system which is used by distributed intelligent monitoring equipment in smart grids. The power supply system taps-off low-power from the transmission line or bus bar through the Faraday electromagnetic induction principle. First, the induction coil through which the transmission line or bus bar pass obtains low AC power, then AC voltage is rectified and filtered to a DC voltage which is converted into 5V by a DC/DC converter. A lithium battery (LB) was used as a standby power module to solve the dead zone of the induction coil. Finally, a power management module based on the STC15F2K60S single chip was able to switch between the energy of the induction coil and standby module by monitoring battery voltage and output voltage, so that output voltage and current can supply the intelligent monitoring equipment. Experiments indicated that this power supply system could stably supply 5W power in 5V when the current of the transmission line or the bus bar is in the range of 0~1000A.

Keywords: Smart grids, Electromagnetic induction, Tap-off power, Intelligent monitoring equipment.

1. INTRODUCTION

In recent years, with the rapid development of smart grids all over the world, the SCADA (Supervisory Control and Data Acquisition) system in power grids must monitor grids in real-time through data acquisition, data measurement, intelligent control of power equipment and other functions so as to guarantee the safe and stable operation of the power grid. However, distributed intelligent monitoring equipment in each part of a grid is the information source for the above system. The complex framework of power grids and large distribution networks may cause a lack of available low-power DC supply for the intelligent monitoring equipment. Thus, the power supply of the distributed intelligent monitoring equipment becomes a key problem [1, 2].

At present, the methods of power supply for distributed intelligent monitoring equipment mainly include solar energy, wind energy, storage battery, capacitance coupling, electromagnetic induction and other sources [3, 4]. However, solar and wind energy power supply are limited by light and winds, so their outputs are not stable, and are easily limited by lo-

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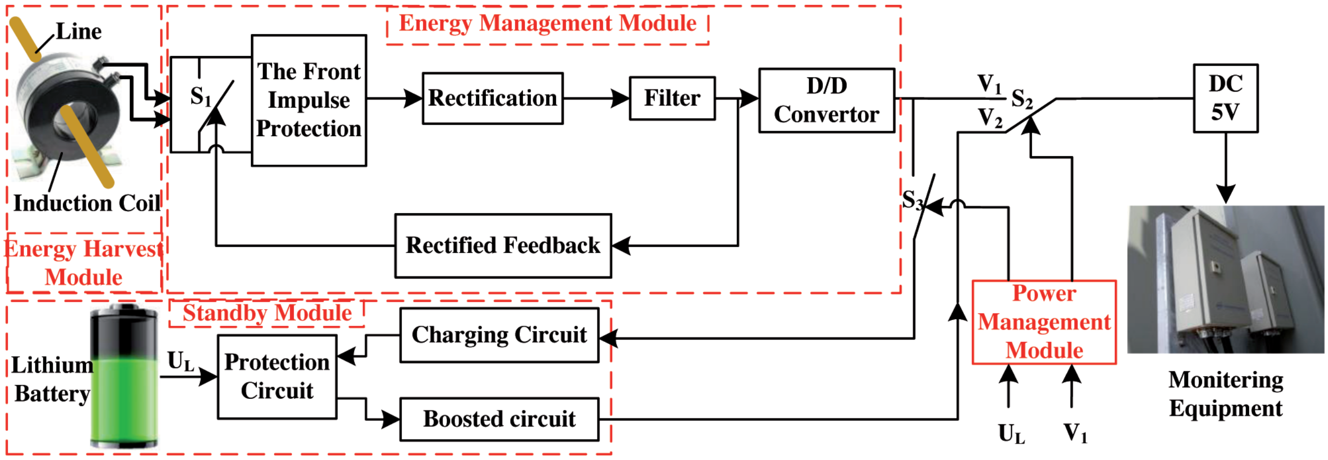

Fig.1: Diagram of the overall plan of the power supply system

cal natural conditions with demanding erection requirements. Thus, they cannot be widely popularized. The output of storage battery power supply [5, 6] is stable although its limited capacity and service life cannot guarantee the long-term operation of the intelligent monitoring equipment. Capacitance coupling power supply [7, 8] is easy to implement and has small influences on primary equipment, but it is easily affected by overvoltage, electromagnetic compatibility and other factors, and so cannot guarantee reliable power distribution for distributed intelligent monitoring equipment. On the basis of the above analysis, electromagnetic induction energy-obtaining power supply is a distributed power supply mode with brighter prospects [9-11].

Electromagnetic induction power supply enjoys certain advantages, including sound insulation performance, small volume and low cost. However, certain pressing problems remain unsolved.

(1) Output power is small, meaning it is difficult to satisfy the power requirements of the monitoring equipment.
(2) Saturation of the iron core is likely to occur in the event of a large primary side current [12, 13].
(3) There is a power supply dead zone. When primary current is small or a power outage occurs, power supply struggles to provide stable output power [14, 15].
(4) In the event of a large primary current, induction coils will generate significant surplus power as well as huge thermal loss [16-20].

With the above in mind, this paper studied an electromagnetic induction power supply system which could satisfy the requirements of distributed intelligent monitoring equipment in smart grids. This power supply system may be applied in the following several typical applications: (1) Power supplies of overhead line condition monitoring systems, such as line wave sensor nodes, data acquisition sensor nodes, environment temperature and humidity sensor nodes and so on; (2) power monitoring devices of transformer substations, such as power supplies of monitoring systems of the switch of reactive power compensation devices in substations; (3) power supplies of cable condition monitoring systems. Starting from the shortcomings of traditional energy-obtaining power supplies, this paper investigated the problems of saturation, dead zone, power and thermal loss respectively. Furthermore, this paper set up an experimental platform to demonstrate the performance of the electromagnetic induction power supply system.

2. POWER SUPPLY SYSTEM

A schematic of the electromagnetic induction power supply system is shown as Fig.1. It is composed of four modules, the energy harvest module, energy management module, standby module and power management module. The energy harvest module adopts a gapped iron core, which efficiently solves the saturation problems. The special circuit design of the energy management module improves power supply whilst simultaneously reducing thermal loss. The standby power supply module is made from a lithium battery and peripheral circuit, which solves the problem of the dead zone. Lastly, the power management module controls the power output of the whole power supply system.

First, the energy harvest module utilizes the electromagnetic induction principle to obtain energy from the transmission line or bus bar, then the obtained energy is converted into stable DC output V_1 by the energy management module, and the lithium battery standby power supply module provides DC output V_2. The power management module monitors U_L, V_1 and V_2. A proposed algorithm determines whether the switch S_3 is close, and also determines the reasonable switching between power supplies of V_1 and V_2 by the switch S_2. The system can provide a stable DC 5V power supply for the monitoring equipment.

3. HARWARE DESIGN OF POWER SUPPLY SYSTEM

3.1. ENERGY HARVEST MODULE

The energy harvest module is a core-through transformer made of a specially-made iron core and winding, and the num-

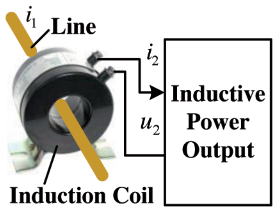

Fig. 2: Diagram of the principle of induction energy-obtaining

ber of turns in the primary winding is equal to one. According to Faraday's law of induction, the diagram of induction energy-obtaining is shown as Fig. 2.

According to the transformer principle, the relationship between the primary side and secondary side current of a mutual inductor can be expressed as,

$$N_1 i_1 = N_2 i_2 \quad (1)$$

Where N_1 represents the number of turns in the primary winding, N_2 represents the number of turns in the secondary winding, i_1 represents the effective current of the power line, i_2 represents the induction current of the induction coil.

The relationship between the secondary side induced electromotive force and the iron core magnetic flux of energy-obtaining module can be expressed as,

$$e_2 = -N_2 d\Phi / dt \quad (2)$$

Where e_2 represents the secondary side induced electromotive force, Φ represents the flux linkage.

When current in the power line is AC, $i_1 = \sqrt{2}\, I_1 sin(\omega t)$, and the effective value of induced electromotive force can be expressed as,

$$E_2 = 2\sqrt{2}\pi\mu_0\mu_r\lambda S N_2 f I_1 / l \quad (3)$$

Where f represents the frequency, S represents the sectional of iron core, λ represents the lamination coefficient of the iron core, μ_r represents the relative permeability of the iron core, and l represents the length of the equivalent magnetic circuit.

Thus, according to the computational formula of electrical power $p=ui$, it can be known that the effective value of the secondary output power of the induction coil can be expressed as,

$$P_2 = 4.44\mu_0\mu_r\lambda S f I_1^2 / l \quad (4)$$

Where P_2 *represents* the secondary output power of the induction coil.

It is known from Formula (3) and Formula (4) that E_2 is proportional to μ_r, N_2 and S while inversely proportional to l; and P_2 is proportional to S and μ_r while inversely proportional to l. In addition, adding an iron core air gap can effectively solve magnetic saturation.

3.2. ENERGY MANAGEMENT MODULE

The function of the energy management module is to convert AC output from the energy harvest module into the required DC input, composed of front-end surge protection, rectified filter, rectified feedback and DC/DC convertor. This is the core of energy conversion of the whole energy-obtaining power supply and its structure is shown as Fig. 3.

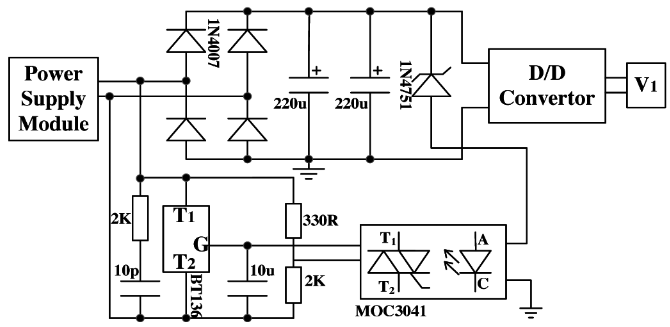

Fig. 3: Circuits of the energy management module

In the electrical power system, once it suffers from an instantaneous short circuit, a large short current will occur in the transmission line of the power supply, which may reach thousands of amperes. The serious consequences are as follows. On the one hand, the electrical power system is suffering a short-time over current shock, which may damage the service life of the equipment and even trigger power failure accidents. On the other hand, magnetic elements for detection or energy-obtaining, for example the current mutual inductor and energy-obtaining mutual inductor, may generate a saturation phenomenon, which could cause waveform distortion of output voltage and overvoltage. In this way, overvoltage can damage the post-stage circuit. Therefore, protection elements must be added to the energy management module.

Overvoltage protection of the energy management module is achieved through a parallel voltage dependent resistor and bi-direction TVS diode. The absorptive capacity of the voltage dependent resistor is large but its response time is long, while the response time of the bi-direction TVS diode is fast but its absorptive capacity is small. Combining the advantages of both, the protection circuit can effectively reduce the amplitude of overvoltage.

To realize the balance between supply and demand, rectified feedback is added and thermal loss is reduced. The AC voltage output from the energy harvest module passes through diode rectification and capacitor filtering successively and 1N4751 and MOC3041 series circuits are used to detect the voltages at both ends of the filter capacitor. The value of the capacitor with 220 uF is acquired from a large number of trials. If the voltage is over 31V, MOC3041 works and triggers T1 on. If the energy harvest module output appears to short circuit and no induction power output occurs, capacitance will power the load and voltages at both ends of the capacitor decrease. In the next power frequency period, voltages at both ends of the filter capacitor are detected again. Once they are less than 31V, MOC3041 breaks and the energy harvest module again obtains energy. At the same time, the capacitor is charged. In this way, circulation is kept and power can be obtained according to the requirements of the load, which avoids the energy management module overheating due to excessive energy.

The structure of the DC/DC convertor [21] is shown as Fig.4.

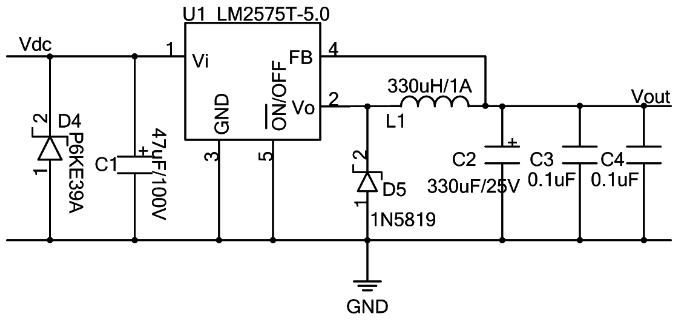

Fig. 4: Implementation circuit of DC/DC convertor

LM2575T 5.0 is adopted to convert high DC voltage into DC 5V. Its starting voltage is as low as 7V, with over 75% conversion efficiency and 5W maximum output power.

3.3 POWER MANAGEMENT MODULE

The power management module is the bridge between the energy harvest module and standby module. The power management module uses the STC15F2K60S single chip U3 as its controller and includes relay K_1, transistor Q_2, a resistor-capacitor and other elements, as shown in Fig.5. Its working process is as follows. Firstly, the built-in sampling circuit U_3 collects the terminal voltage of the battery, U_L. The output of the energy management module with load is V_1. If the energy output from the energy management module is adequate, U_3 outputs a high level through P2_0 to make Q_2 on, K_1 coil has electricity and normally open contact is on. At this time, the energy harvest module powers a load and selects an appropriate moment to power the battery. If the energy output from the energy management module is not adequate, U_3 outputs a low level through P2_0 to make Q_2 off, K_1 coil lose power and normally closed contact is on. In this situation, the standby module powers the load. The power supply of U3 is provided by the standby module. This coordination mechanism can guarantee that the power supply system can provide uninterrupted power for the monitoring equipment.

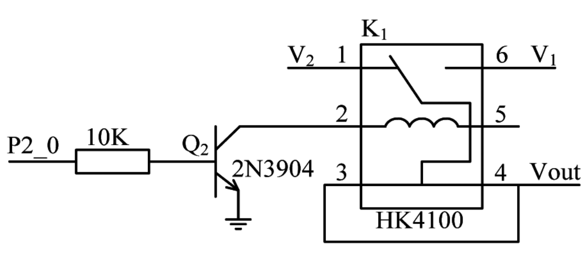

Fig. 5: Simplified circuit diagram of the power management module

3.4 STANDBY MODULE

The standby module includes one piece of lithium ion battery, a protection circuit, a charging circuit and a discharging circuit. In the event of an overly small line current or line outage, the standby module powers the intelligent monitoring equipment. The lithium ion battery uses a 18650 iron phosphate rechargeable lithium battery of 2.6Ah, which delivers stable performance and large discharge power and can be used circularly. We choose the lithium battery because it has the following advantages compared with other forms of energy storage: (1) its useful life is longer, with a charging number of more than 1000, and hence can be used with the energy harvest module for years; (2) the capacity of the unit volume is large but in a small size, and thus is suitable for the miniaturization demands of our power supply system and will allow flexible installation use in the future; (3) environmental pollution caused by lithium batteries is less, and its price is relatively cheap, which has economic benefits; and (4) the battery has a large number of applications in other related systems, and shows excellent performance in complex environments. The battery therefore meets the requirements set. The protection circuit of the lithium battery uses a combination of S8261 and FS8205, with overshoot, over discharge, over current and short-circuit protection. The discharging circuit uses RT9266, with typical output parameters of 5V1A. The charging circuit uses TP4056 [22], which includes a typical AC constant-current and constant-voltage charging mode and allows the specific charging circuit to be charged and set, up to a maximum of 1.2A, as shown in Fig.6.

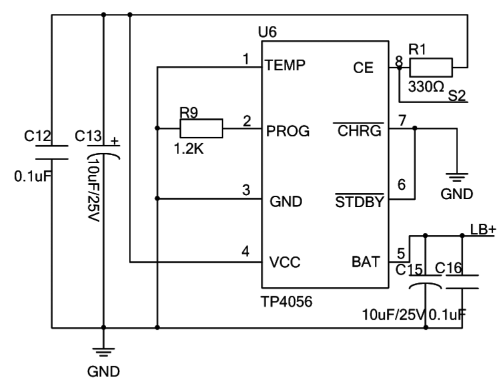

Fig. 6: Charging circuit of the lithium battery

The charging circuit uses TP4056 as the core, supplemented by a small number of peripheral components, to realize the abundant function as follows:

1) Constant-current and constant-voltage charging mode.

When the input voltage is greater than the power low voltage detection threshold and TP4056 enables a input high level, the chip starts charging the battery. If the battery voltage drops below 3V, the circuit uses a small current to pre-charge the battery. When the battery voltage exceeds 3V, the circuit uses a constant-current mode to charge the battery, with the charging current determined by the resistor R_{PROG} between the PROG pin and GND. When the battery voltage is close to 4.2V, the charging current decreases, and TP4056 will enter a constant-voltage charge mode. When the charging current is reduced to the termination threshold of the charge, the charging cycle will be ended.

2) The charging current can be set.

The charging current is determined by the resistor R_{PROG} connected between the PROG pin and GND. The resistor R_9 used in this paper is 1.2kΩ.

3) Under-voltage protection.

The internal under-voltage lockout circuit of TP4056 monitors the input voltage, and before the V_{CC} rises above the under-voltage lockout threshold, the charging circuit remains on shutdown mode.

4. CONTROL STRATEGIES OF ENERGY HARVEST POWER SUPPLY

To realize the reliability of power supplies between the energy management module (EMM) and the standby module, this paper designed the control strategies for the energy harvest power supply, which is based on the hardware design of the power management module outlined in Section 3.3. The process flow is shown as Fig.7.

The intelligent monitoring equipment is most often powered by the energy harvest module. When the system is started it attempts to power itself through the energy harvest module. Output voltage V_1 and battery voltage U_L are detected. When $V_1 \geq 4.8V$, it is determined that energy harvest power is adequate. The energy harvest module powers the monitoring equipment and tries to charge the battery according to U_L. When $V_1 \leq 4.8V$, it is determined that energy harvest power is inadequate. In this case, the lithium battery (LB) powers the monitoring equipment. The above operation and cycle is repeated every two minutes.

In the above, V_L is the external voltage value of the lithium battery, which is tested by the power management module. V_L = 3.8V is the threshold voltage of the lithium battery for the deciding when the standby module will charge the lithium battery. When the energy output mode of the power supply system is the power management module, once $V_L \leq 3.8V$, the charging circuit charges the lithium battery. This decision-making system efficiently controls the duration of charging times for the lithium battery, increasing its useful life.

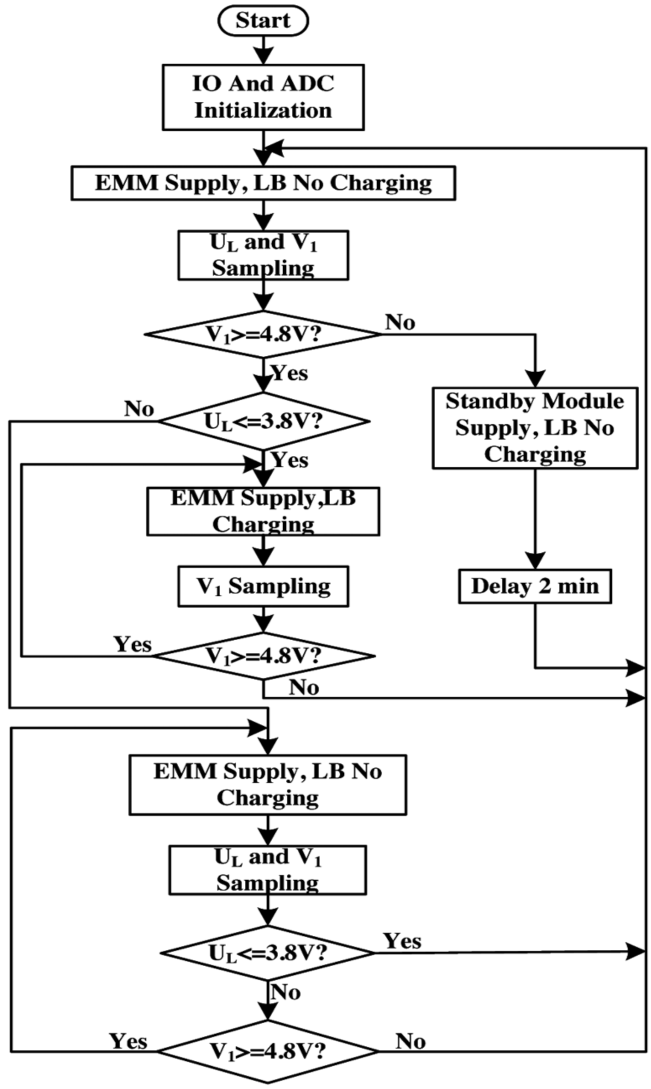

Fig. 7: Process flow diagram of power management

5. EXPERIMENTAL TEST AND RESULTS ANALYSIS

This paper designs the power supply system based on the electromagnetic induction principle for intelligent monitoring equipment. To verify its performance and adaptability in the power distribution network, this paper carried out an experimental study on the power supply system.

5.1 CONSTRUCTION OF THE EXPERIMENTAL PLATFORM

To simulate the large current environment in the power distribution network, we set up an experimental platform in the laboratory, as shown in Fig.8. The power input of this experimental platform was 220V AC commercial power and the voltage was transformed to T1 by an autotransformer. The output voltage was loaded to slide-wire rheostat R1 and the secondary side of current transformer T2. The primary side of current transformer T2 was cascaded with splitter R2 and the simulated copper bus bar. Output voltage through T1 could vary the current in the bus bar between 0~1000A.

5.2 TEST RESULTS AND ANALYSIS

5.2.1 Experiment on the energy harvest module

This experimental platform could supply a large controllable current with a current range between 0~1000A and fur-

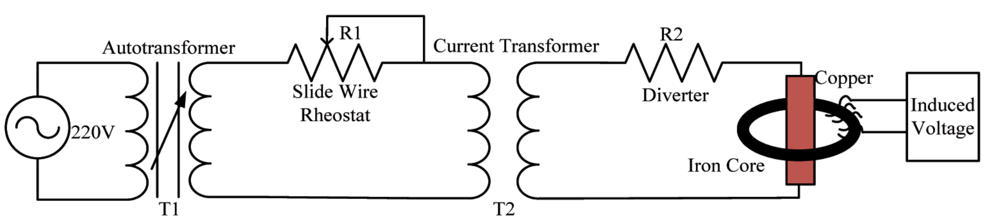

Fig. 8: Schematic diagram of the simulated experimental platform

ther verify the output performance of the energy harvest module. Fig.9 shows the output power curve of the energy harvest module (load at output terminal is 60Ω resistance). The curve indicates that when primary current is over 45A, the output power of the energy harvest module can reach 5W.

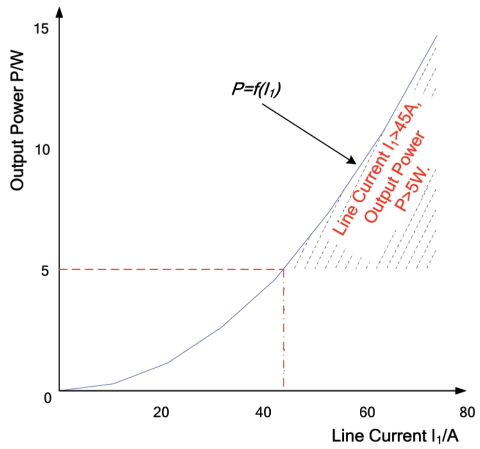

Fig. 9: Power current curve of the energy-obtaining module

Table 1 shows the output voltage, load resistance and output power of the energy harvest module after the power management module. No standby module is used in the experiment. The data indicate that when primary current is I_1=10A, the energy harvest module can output 4.92V. This current is called the wake-up current although the power at this time is very small. With the increase in primary current, the output power of the energy harvest module gradually increases. When primary current is I_1=75A, the output power can reach 5W. This current is called the starting current of 5W output power.

Primary Current I_1 (A)	Output Voltage U_2(V)	Load Resistance R (Ω)	Output Power P_2 (W)
0	0	15.0	0
10	4.92	631	0.04
20	4.89	53.8	0.45
30	4.90	20.4	1.18
40	4.90	10.5	2.29
50	4.89	7.5	3.19
60	4.87	5.5	4.31
70	4.86	4.8	4.92
80	4.86	4.7	5.02
100	4.85	4.7	5.00
300	4.87	4.7	5.05
500	4.87	4.7	5.05
1000	4.86	4.7	5.00

Table 1. Data of output power of the energy management module

5.2.2 Performance experiments on the standby module

After output protection and boost to 5V for the standby module, the output of the controller is limited to 5V 600mA. The energy harvest power supply do not contact with the energy harvest module. The energy management module converts the output to the standby module and the output successively connects with pure resistance R between 100Ω and 4.5Ω. The output voltage is measured and the output power is calculated, as shown in Table 2.

Load Resistance R/Ω	Output Voltage V_2/V	Power P/W
100	5.05	0.255
80	5.05	0.319
60	5.06	0.427
40	5.10	0.650
20	5.03	1.265
10	5.05	2.55
8	5.04	3.175
6	5.03	4.217
5	5.05	5.10
4.9	5.04	5.184
4.8	5.03	5.271
4.7	5.03	5.383
4.6	5.02	5.478
4.5	5.03	5.622

Table 2. Output V2 of standby module

As can be seen from Table 2, the standby module, which contains a lithium battery (with output voltage of 3.7V) and is managed by the power management module, can output 5V stably under different pure resistive loads.

5.2.3 Switching performance of the power management module

After the energy harvest power supply is fully in place, primary current varies between 0~70A. Power output is connected with a pure resistant load of R=10Ω. With the changes in primary current, the output voltage and their sources in the test are shown in Table 3.

Primary Current I_1/A	Power Supply
10	Standby Module V_2
20	Standby Module V_2
30	Standby Module V_2
40	Standby Module V_2
50	Energy Management Module V_1
60	Energy Management Module V_1
70	Energy Management Module V_1

Table 3. Power switching features

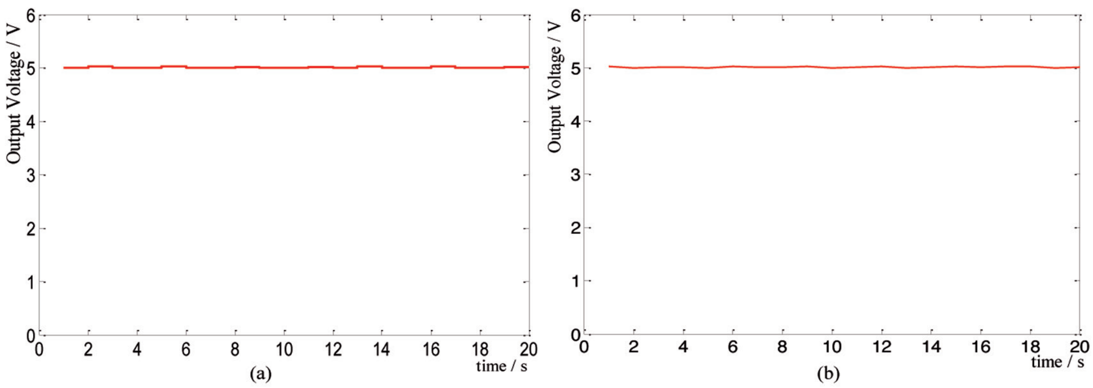

Fig. 10: Pure impedance load waveform of the energy harvest module. (a) Primary Current 20A. (b) Primary Current 70A.

Under lithium battery power, the standby module stably outputs power of DC5V5W. In the event of adequate output power, the energy management module could power the lithium battery and smoothly switch with the standby module under the control of the power management module with a switching time of less than 10ms.

5.2.4 Output waveform of the power supply

An oscillometer is used to measure the voltage waveform at both ends of current R and the effective value of voltage is recorded. When primary currents are 20A and 70A respectively, the corresponding voltage waveforms are shown as Fig.10 (a) and Fig.10 (b). The output waveform of the power is smooth on the whole, with a ripple wave less than 5%, which satisfies the requirements of common electronic equipment.

Figure 10 shows that when primary current is 20A and 70A respectively, the system outputs a stable and approximate linear voltage waveform, and the output voltage can be viewed as a DC voltage. In Figure 10(a), primary current is 20A, the supply power of the system is switched to standby module at this time, and the output voltage is 5V. The standby module can continuously provide stable power for intelligent monitoring equipment. In Figure 10(b), the primary current is 70A, the supply power of the system is switched to the energy harvest module at this time, and the output voltage is 5V. The energy harvest module can also continuously provide stable power for intelligent monitoring equipment. In conclusion, under the different power supply modules, the power supply system can supply reliable 5V power.

Throughout the duration of all experiments and tests, there is no obvious saturation or heating phenomenon in the iron core of the energy harvest module, conforming to the design requirements.

5.3 PERFORMANCE COMPARISONS

This power supply system can meet the performance of the system design after a series of experiments and testing. Its performance was compared with similar power supply solutions as shown in table 4.

In Table 4, due to the good switching performance and the high reliability of the power supply system, the system can adapt to the operating conditions of various power lines and provide stable, reliable and secure energy for the intelligent monitoring equipment. Thus, the design performance of the equipment can be easily realized.

6. CONCLUSION

This paper studies and develops a power supply system for distributed intelligent monitoring equipment in smart grids. A specific iron core is adopted in the power supply and energy conversion circuits are used to regulate suitable output voltage and power. Furthermore, a switchover standby power supply mechanism is adopted. All these guarantee the reliability of the power supply system for the distributed intelligent monitoring equipment. A large number of experiments indicate that this power supply system could provide DC5V5W for intelligent monitoring equipment within a current effective value of 0~1000A, with a comprehensive ripple wave of less than 5%. There is no obvious saturation or heating phenomenon in the

Power Supply Solutions / Performance	Battery Only (Results in this paper)	Self-power Only Supply[23]	Self-power Supply + Battery[24]	Self-power Supply + Battery (Results in this paper)
Output Voltage (V)	3.7 or 5	3.3 or 5	5	5
Output Power	10 mW	2.5W	2.5W	5W
Time of Supply Electricity	2 Years	Uncertainty	About 3 Years	About 5 Years
Switching Performance (A)	None	70	110	50
Reliability	High	Low	High	Higher
System Application	Narrow	General	Wide	Wider

Table 4. Performance comparison

iron core of the energy harvest module. It solves coil saturation and power supply dead zone that is encountered in traditional energy harvest modules. At the same time, it improves the output power of power supply to 5W. In addition, when the power line is running above 50A, the energy harvest module can supply enough energy, and the power supply system can switch quickly (<10ms) to the standby module below 50A. The work of this paper improves the performance of such power systems significantly. The system has been applied in the power supplies of sensor and communication modules in a switch cabinet contact temperature monitoring system. At present, the system is operating normally.

APPRECIATION

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