



# Power Leakage Monitoring and Warning Device for Power Grid Fault Diagnosis: Design and Field Test

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Electrical equipment insulation damage, metal shell conduction on rainy days, and wire short circuits are easy to produce leakage, which form step voltage on the ground and endangers the life and safety of nearby personnel. In addition to the existing leakage protector, a new method is proposed to use leakage energy to obtain energy and early warning. The step voltage generated by the leakage current is collected through the electrode, which is rectified and reduced by the nano power LTC3588, while energy is stored in the supercapacitor for the superheterodyne transmitting module to send the leakage signal to the nearby receiving device. Based on the possibility of the superheterodyne transmitting module sending the leakage signal, it is judged whether leakage occurs here. The experimental results illustrate that when 10 mA leakage occurs in a 220 V wire, the electrode distance is 1.0 m, while the energy extraction device can obtain 360 MW of power for the superheterodyne transmitting module to send the leakage signal.

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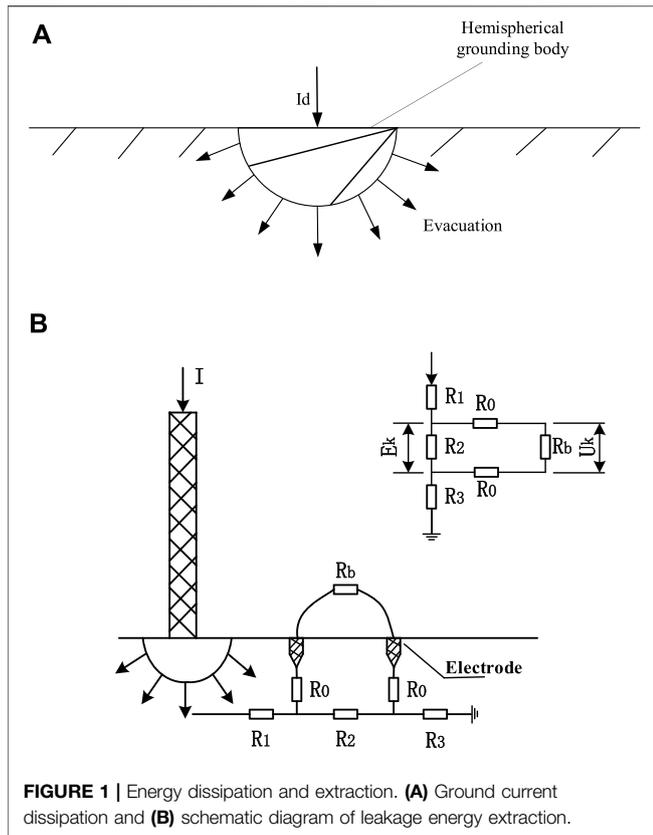
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## INTRODUCTION

The leakage of electrical equipment generates a step voltage on the ground, which causes an electric shock to the human body (Abigail, 2019; Pompodakis et al., 2021; Aliyari et al., 2022). The existing protection measures are to install leakage protectors. However, due to low sensitivity and easy mis-operation of the leakage protector, it causes frequent tripping and affects the reliability of the power supply (Tong et al., 2013; Ndhlablenze and Hlalele, 2020; Cai et al., 2021). Electricity leakage often occurs at bus stops and transmission towers with accumulated water, which results in an electric shock from step voltage and touch voltage (Makhchoune et al., 2022). Therefore, it is indispensable to devise an early leakage warning device to ensure the safety of people's lives. At present, different methods have emerged for the early warning of leakage. Sheng et al. (2014) designed a strategy to obtain the step voltage through a metal rod installed at the bottom of the insulating boot so as to detect the voltage and issue an early warning. The work by Ren et al. (2016) proposed a leakage monitor that is placed on the foot for audible and visual alarm or short circuit protection. In addition, the existing leakage warning devices are all wearable that can only provide protection for the wearer. Thus, it is compulsory to design a general leakage early warning device. The device is installed underground and realizes the self-power supply of the early warning device by collecting leakage energy without installing batteries.

In summary, this study proposes a method of leakage energy extraction and early warning, which uses the leakage current that flows into the Earth to form step voltage power extraction. Through experiments, the influence of the size and laying position of the power extraction electrode on the power extraction is studied. Furthermore, a low-power energy collection circuit is devised to ensure



that the system can start normally in the case of leakage, which realizes the rapid early warning of leakage, while experiments verify the feasibility of this method.

### Design Principle of Leakage Energy Extraction

The leakage energy and the early warning device collects the step voltage generated by the leakage current to supply power to itself. When the transmission pole tower leaks electricity, the charged body is in direct contact with the ground. Due to the existence of soil resistance, when the leakage current naturally flows from the electrode to the surrounding soil, a pressure drop will be generated in the soil and a certain surface potential distribution will be formed, while the hemispherical area will generate a uniformly distributed voltage drop (Roy and Kundu, 2021), which is depicted in **Figure 1A**.

The leakage energy extraction and early warning device are used as conductors to form a circuit with the Earth. Among them, two electrodes are buried at different potential points while a step potential  $E_k$  is formed between the electrodes (Kim et al., 2019; Sunjerga et al., 2019). According to the step voltage principle, current will be generated to supply power for the leakage energy extraction and early warning devices to realize passive self-start. Furthermore, the schematic diagram of leakage energy extraction is shown in **Figure 1B**. In addition, the contact resistance  $R_0$  between the two electrodes and the soil is connected in series with the leakage energy extraction and early warning device  $R_b$ .

Currently, the actual voltage between the electrodes (i.e., the step voltage  $U_k$ ) is written as follows:

$$U_k = \frac{R_b}{R_b + 2R_0} E_k. \tag{1}$$

## DESIGN OF THE LEAKAGE ENERGY EXTRACTION AND EARLY WARNING DEVICE

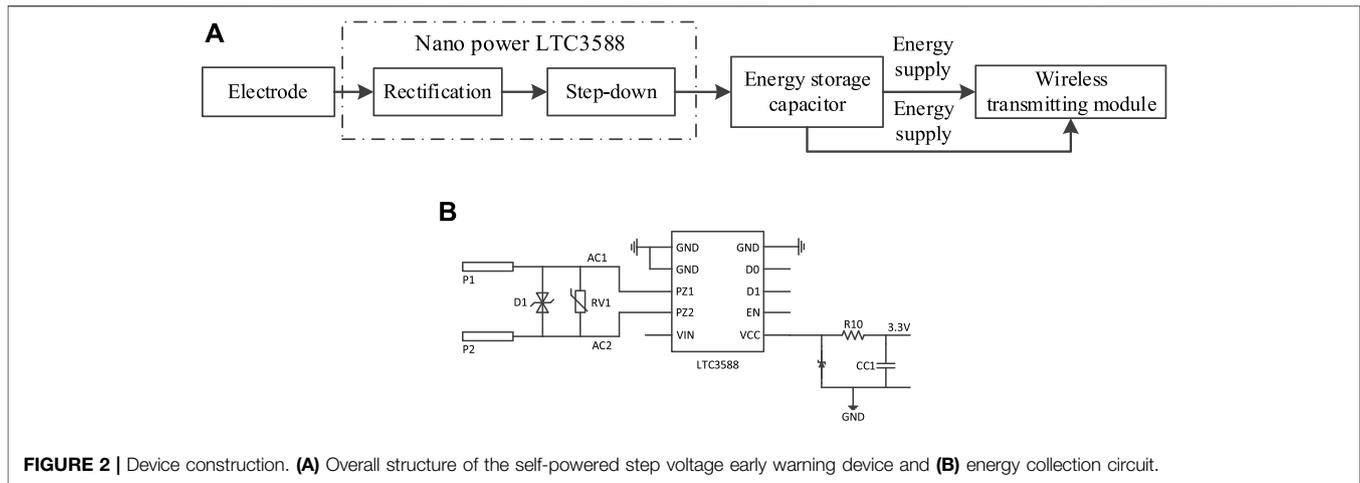
### Overall Structure of the Leakage Energy Extraction and Early Warning Device

The leakage signal obtained from the electrode is an AC signal, while the leakage current is generally less than 50 mA with a small output power. It is inevitable to select the rectifier and DC/DC (direct current-direct current) step-down module with low power consumption to output stable DC. After storage, a stable DC is used for the wireless transmitting module to send a leakage signal, upon which the wireless transmitting module selects the superheterodyne module with extraordinarily low power consumption. In particular, the overall structure of the leakage energy extraction and early warning device is depicted in **Figure 2A**.

Furthermore, leakage energy extraction and early warning devices are composed of electrodes, nano power LTC3588, an energy storage capacitor, and a superheterodyne transmitting module. The optimized design and laying position of the electrode can maximize the energy of the step voltage. Moreover, a low-loss full bridge rectifier and an efficient step-down converter are integrated with the nanopower LTC3588 chip. In special cases, the full-bridge rectifier converts the AC charge generated by the leakage current into fluctuating DC energy. The step-down converter effectively transfers the internally stored charge to the output (Wang et al., 2015; Zhao and Yang, 2017), while the supercapacitor stores the energy after step-down and voltage stabilization, which drives the superheterodyne transmitter module to send the leakage signal at the same time.

### Leakage Energy Circuit Design

The electric leakage energy extraction (Liu et al., 2021) circuit utilizes the step voltage formed by the leakage of the piece of equipment on the ground to obtain energy (Chen et al., 2021). Moreover, the step voltage obtained by the electrode is generally up to 36 V, but the output current is generally tens of milliamps with milliwatt-level output power. There are losses of various factors in the energy collection circuit; a leakage energy collection circuit with low power consumption plays a vital role in design and research. It is worth noting that the voltage obtained by the electrode is AC and unstable, which changes according to the change of external leakage, while the energy required by the superheterodyne emission module is a stable DC voltage (i.e., generally 2–3.6 V). Therefore, in order to enable the superheterodyne transmitter module to obtain energy continuously and stably from the electrodes, a low-power AC/



**FIGURE 2 |** Device construction. **(A)** Overall structure of the self-powered step voltage early warning device and **(B)** energy collection circuit.

DC conversion circuit needs to be used to convert the alternating current into stable DC. Then, stable DC is stored in the supercapacitor and continuously and stably supplied to the superheterodyne transmitting module.

In this article, a leakage energy extraction circuit based on the nano power LTC3588 energy collection chip is designed, as shown in **Figure 2B**. The input terminals are PZ1 and PZ2, which are used to connect electrodes P1 and P2. In addition, the output VCC is connected to the supercapacitor CC1 to store charge, upon which the super capacitor is 0.47F and 5.5 V. When current leakage occurs, the electrodes connected at both ends of PZ1 and PZ2 collect the step voltage generated by leakage. After rectification and step-down by the nano power LTC3588 circuit, it outputs a stable DC voltage of 3.3 V, which is stored on the supercapacitor and supplies power to the superheterodyne transmitting module.

### AC/DC and Step-Down Modules

The nano power LTC3588 energy collection chip is adopted, which integrates a low-loss full-bridge rectifier and a high-efficiency step-down converter. The nano power LTC3588 will enter the sleep state in the regulation mode. In this state, the input and output quiescent currents are quite small. The step-down converter is turned on and off as required to meet the regulation effect, while the output voltage is set to 3.3 V. Consequently, the nano power LTC3588 converts the AC collected by the electrode into stable DC through a low-loss full bridge rectifier, while the high-efficiency step-down converter reduces DC higher than 3.3 to 3.3 V for subsequent circuits.

In order to prevent the single-phase grounding of the transmission line and the impact of the 220 V on the energy harvesting circuit, there is no doubt that the pressure-sensitive resistor  $R_{V1}$  needs to be placed in front of the nano power LTC3588. When the voltage exceeds the threshold voltage, it will be instantly turned on and will absorb the excess current to protect the subsequent circuit since the design is based on leakage energy extraction and an early warning device that is calculated according to the step voltage of 36 V of a human electric shock. In order to prevent circuit damage caused by the voltage taken by the electrode being greater than 36 V, it is essential to add  $D_1$  in front of the

rectifier bridge and a 36 V bidirectional  $T_{VS}$ . Furthermore, when the voltage is greater than 36 V, it can achieve transient suppression, that is, the high impedance between the two poles becomes low impedance with surge power being absorbed so that the voltage clamp between the two poles is at a predetermined value, which can effectively protect the circuit from surge pulse damage.

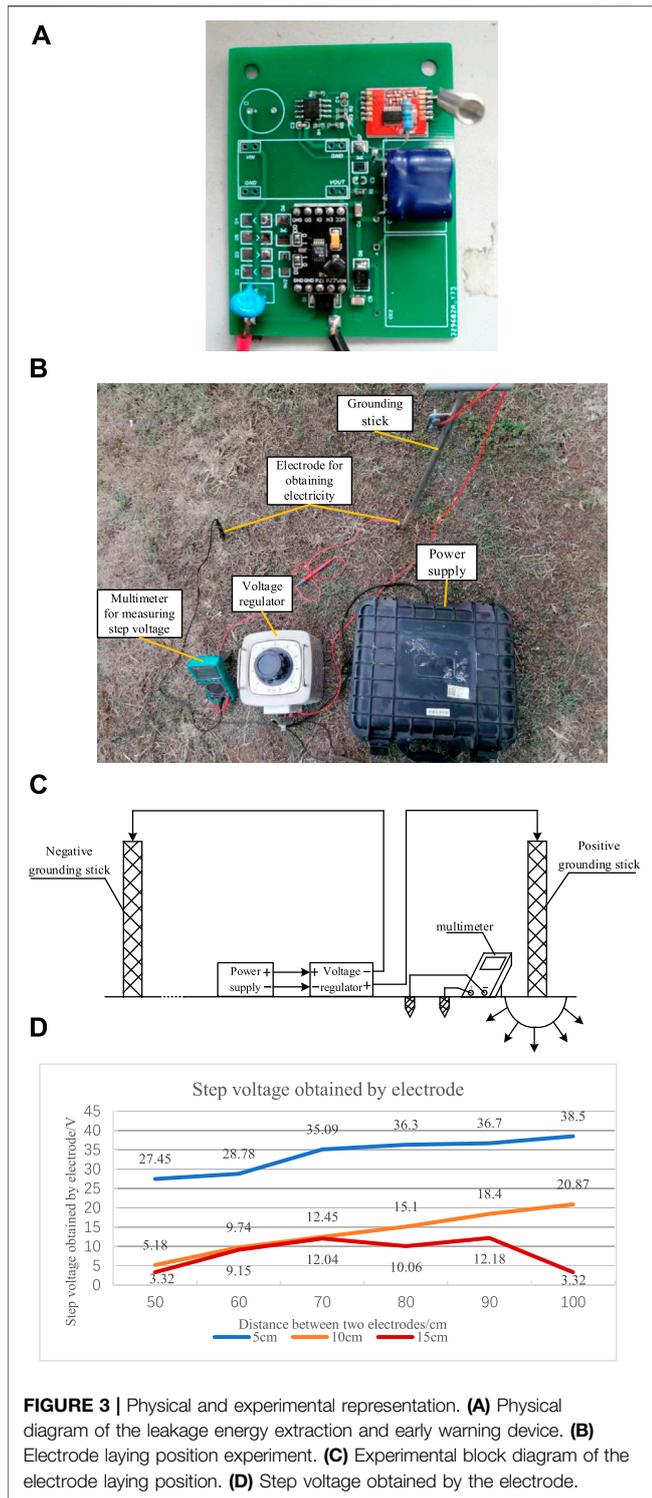
### Design of the Energy Storage Circuit

The storage unit used in the leakage energy extraction circuit is a supercapacitor, which is generally the Faraday level, with a large capacity and slow self-discharge rate. Furthermore, the self-discharge starts at 5 V while the discharge energy is about 1 V after 10 hours. Moreover, it is relatively simple to use and does not need a special charging and discharging circuit.

Since the output voltage of the nano power LTC3588 energy collection module is set to 3.3 V, a supercapacitor of 0.47 F and 5.5 V is selected. A 5  $\Omega$  current limiting resistor is connected in series in front of the super capacitor, while a 3.37 V varistor diode is connected in parallel. When the working voltage of the super capacitor is greater than the breakdown voltage of the voltage regulator, the charging current will flow directly from the varistor diode, upon which the voltage of the capacitor will not increase to avoid the overvoltage of the super capacitor. The disadvantage of this method is that the pressure-sensitive diode and current limiting resistor will produce more energy loss, which will result in the heating of the pressure-sensitive diode.

### Design of the Early Warning Circuit

In particular, the superheterodyne transmitting module utilizes the output voltage of the leakage energy extraction circuit as the power supply. When the superheterodyne transmitting module transmits the leakage signal to the receiving equipment, it indicates that leakage occurs here. Moreover, when the receiving equipment does not receive the leakage signal, it indicates that the leakage does not occur here so as to realize the early warning function of leakage. Because the energy generated by the leakage is at the milliwatt level, the superheterodyne transmitting module and superheterodyne receiving module are selected.



The superheterodyne transmitting module has a voltage range of 2.0–3.6 V together with a transmitting power of 15 MW, which has a sleep and fast wake-up power supply, zero standby power consumption, and a transmission distance of 15 m. Furthermore, the superheterodyne receiving device can be installed at the site where the transmission tower is 7 m above the ground. In case of

**TABLE 1 |** Step voltage obtained by the electrode.

Distance from the electrode to the leakage point/cm	Distance between two electrodes/cm					
	50	60	70	80	90	100
5	27.45	28.78	35.09	36.3	36.7	38.5
10	5.18	9.74	12.45	15.1	18.4	20.87
15	3.32	9.15	12.04	10.06	12.18	3.32

electric leakage, the superheterodyne receiving device receives the leakage signal for audible and visual early warning to avoid electric shock to personnel close to the area, which locates the leakage point at the same time.

### EXPERIMENT AND VERIFICATION

The physical diagram based on the leakage energy extraction and early warning device is revealed in **Figure 3A**. The leakage energy extraction and early warning circuit includes a nano power LTC3588 energy collection circuit, supercapacitor, and superheterodyne emission module. The nano power LTC3588 energy collection circuit converts the collected AC voltage into a stable DC voltage, which is stored in the supercapacitor. Then, it supplies power to the superheterodyne transmitting module to continuously transmit the leakage signal and realize leakage early warning.

#### Experimental Environment and Results of the Electrode Laying Position

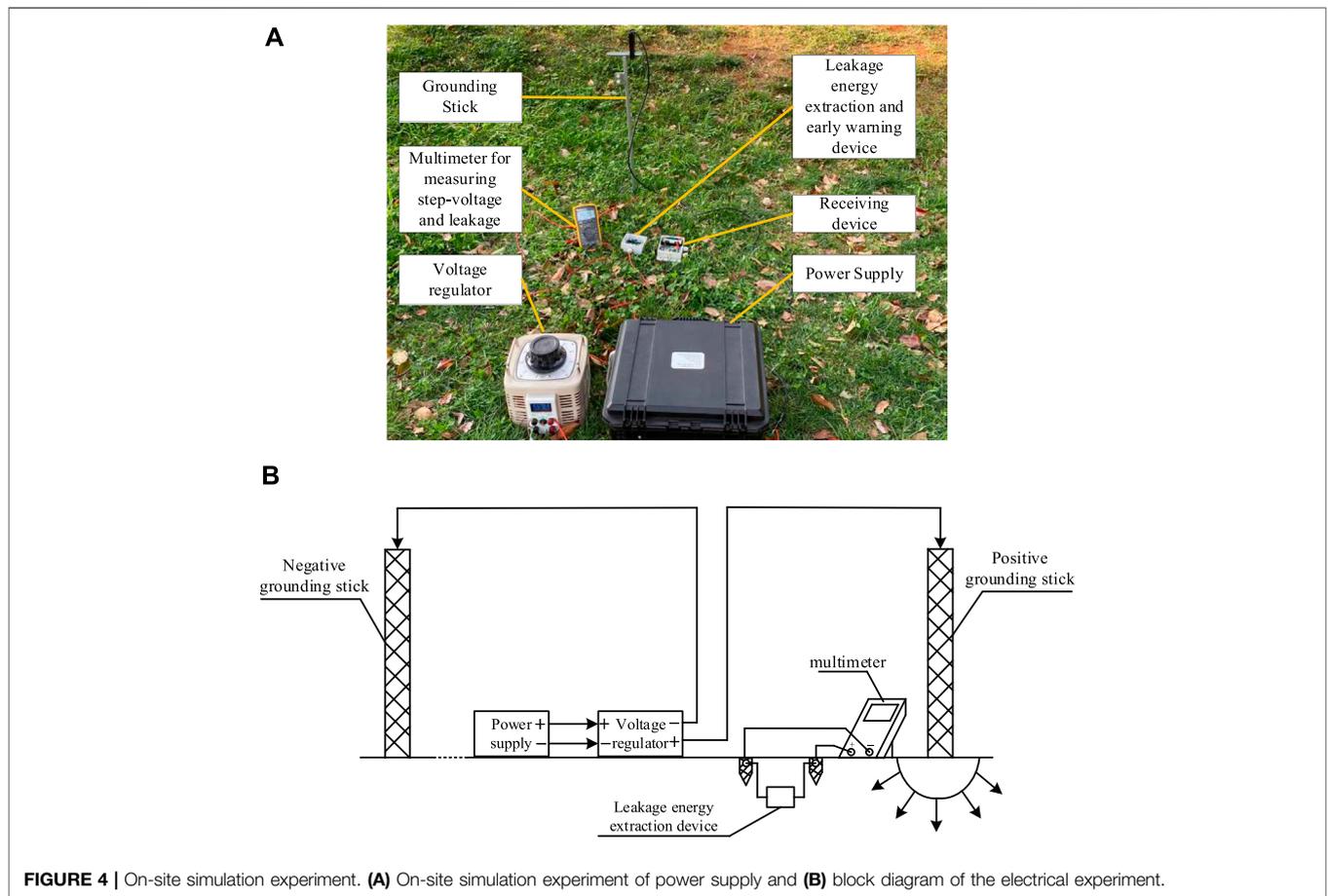
The field simulation experiment is shown in **Figure 3B**. The 220 V power supply is input to the voltage regulator, which adjusts the voltage to 220 V and inputs it to the grounding stick. Furthermore, the leakage is injected into the ground through the grounding stick to simulate the grounding fault of a 220 V transmission line. The experimental block diagram of the electrode laying position is represented in **Figure 3C**.

It is worth noting that the buried depth of the electrode is 15 cm, upon which the electrode is laid 5, 10, and 15 cm away from the leakage point. The step voltage observed based on changing the distance between the electrodes is shown in **Table 1** and **Figure 3D**, which can be applied to determine the best laying position of the electrode.

According to the aforementioned data, when the electrode is inserted into the Earth at a depth of 15 cm, it is 5 cm away from the leakage point together with 100 cm between the two electrodes, upon which the maximum power is obtained.

#### On-Site Simulation Experiment and Results of the Leakage Energy Acquisition and Early Warning Device

For the purpose of verifying the reliability of the designed leakage energy extraction and early warning circuit, the on-site simulation experiment is illustrated in **Figure 4A**, while the



**FIGURE 4 |** On-site simulation experiment. **(A)** On-site simulation experiment of power supply and **(B)** block diagram of the electrical experiment.

**TABLE 2 |** Experimental results of the energy extraction circuit based on LTC3588.

Input current (mA)	Output power	Leakage warning
10	360 mW	Yes
20	573 mW	Yes
30	789 mW	Yes
40	866 mW	Yes
50	1.22 W	Yes

block diagram of the electricity extraction experiment is depicted in **Figure 4B**. The 220 V power supply is input to the voltage regulator that adjusts the voltage to 220 V and inputs it to the grounding stick to simulate the ground fault of the 220 V transmission line. The electrodes of the leakage energy extraction and early warning device are buried 5 cm away from the grounding stick, 100 cm apart, and 15 cm deep. The two ends are connected in parallel with a multimeter to measure the step voltage, which is connected in series with a multimeter to measure the leakage. At this time, whether the indicator light of the receiving device is switched on is observed. If it is on, a leakage warning is carried out while the starting time of the superheterodyne transmitting module is measured. The test results are shown in **Table 2**.

The experimental results show that when 10 mA leakage occurs in a 220-V wire, the electrode distance is 1.0 m. In particular, the energy extraction device can obtain 360 MW power for the superheterodyne transmitting module to send a leakage signal so as to realize early leakage warning, which further verifies the feasibility of this method.

## CONCLUSION

This article provides a leakage energy extraction and early warning device, while the experimental results indicate that the leakage energy extraction and early warning device can obtain 360 MW power, which proves that the leakage energy extraction and early warning device can take energy from weak leakage and work normally, upon which it meets the rapid response of the early leakage warning device for leakage in the low-power mode so as to verify the feasibility of this method.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

QY: conceptualization, writing—reviewing and editing; XX: writing—original draft preparation and investigation; JH: visualization and contributed to the discussion of the topic; JW: supervision.

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