Combined RF-Ultrasonic Wireless Powering System for Sensor Applications in Harsh Environment

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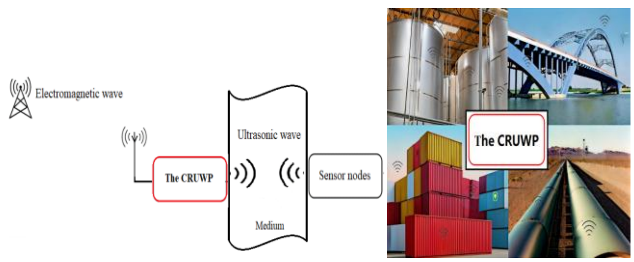
***Abstract*—Sensors are vital tools in monitoring operating conditions and collecting data in scientific studies and engineering works. However powering sensors for a long term in harsh environments where physical access is difficult like enclosed oil pipes, sealed containers and underwater isn't straightforward. To solve this problem, a novel hybrid power supply technique is proposed, combining the advantages of radio frequency and ultrasonic power transmission. By harnessing the penetration capabilities of ultrasound and the long-distance wireless transmission benefits of electromagnetic waves, the proposed a combined RF and ultrasonic wireless powering (CRUWP) system to power sensors deployed in harsh environments. This article builds a system model and introduces 90% efficient time-sharing energy management scheme for coupled circuits to address the power density mismatch between RF and ultrasonic energy transmission. Furthermore, the power budget analysis is presented for the hybrid power supply scheme, showcasing its capability to deliver 1 mW output power to the load.**

Keywords—Wireless power transmission, Hybrid power systems, Power control.

I. Introduction

In recent years, there has been an increasing use of low-power devices, such as sensors and implantable devices, for various applications such as hydrology, biology, environmental monitoring, construction, and mechanics[1][2]. These devices are often deployed in harsh environments, including those that are underwater, underground, or within infra-structures, and are sometimes enclosed in metal cavities such as steel bridges, metal pipes, and shipping containers[3]. Batteries are the main source of power for those sensors however batteries have limited lifetime. Replacing batteries in those scenarios could become very challenging due to the high cost of access and physical infeasibility[4].

One possible solution to this challenge is wireless power transfer (WPT), which can replace the need for batteries and cables. Various methods of WPT, such as microwave energy transfer, inductive coupling, and capacitive coupling have been reported in the past decade[5][6][7]. However, these methods have been found to be ineffective for powering sensors within enclosed metal cavities due to the screening effect of metal, which prevents RF energy transmission, inductive and capacitive coupling from penetrating the metal enclosure[8].To address this issue, a new combined RF/Ultrasonic wireless powering (CRUWP) system is proposed in this work. The CRUWP system combines radio frequency energy transfer (RFET) with ultrasonic energy transfer (UET) to establish an wireless energy. transfer path in both the air and metal. The RF link provides reliable and flexible energy transfer, while the UET link overcomes the limitations of energy transfer in metals. The system structure is shown in Fig. 1(a). The proposed HWPT system, with a focus on versatility and convenience, endeavours to fulfil commercial power limitations while maintaining a compact form factor. Fig. 1(b) shows the potential application.



(a) (b)

Fig. 1. Illustration of the HWPT system, which harvest electromagnetic energy and emits the energy as ultrasonic waves (a) and its potential application scenarios in closed metal sealed containers, steel bridges, shipping containers and oil pipelines (b).

In this paper, we will study the feasibility of this system with an aim to provide real-time wireless power transfer to sensors located within enclosed metal cavities, operating with a power supply of approximately 1 mW which is a typical power for majority sensor node required. We will investigate link budgets for both RF and ultrasound transmissions and efficiency of key modules in the system. Potential work to optimise the system will be given in the end.

II. The HWPT System

A. System architecture and the power transfer model

The proposed hybrid wireless power transmission system architecture comprises three distinct components, namely the RFET link, UET link, and hybrid energy converter (HEC). The RFET link acts as the intermediary between the RF transmitter and the HEC, while the UET link facilitates power transfer between the HEC and the sensor applications. Energy transfer within the RFET link occurs via the antenna, while the UET link employs a piezoelectric transducer to transfer energy. A visual representation of the entire system architecture is provided in Fig. 2.

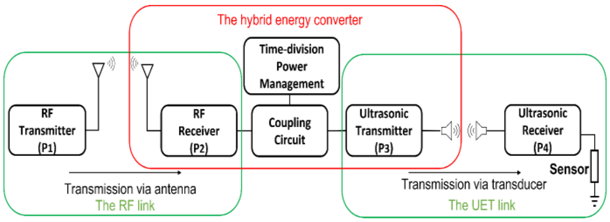


Fig. 2. The hybrid wireless power transfer structure. The green blocks are RF energy harvesting frame and ultrasonic energy transfer frame, where the P1 and P2 are the power from transmitter and receiver of antenna, and P3 and P4 are the power from transmitter and receiver of transducer.

It is noteworthy that when both the UET link and RFET link operate with high efficiency, the power density of the UET link significantly surpasses that of the RFET link. Specifically, the HWPT power received by the receive antenna is lower than the driving power required for the piezoelectric transducer. Therefore, considering the constraints imposed by power and size, careful consideration must be given to the design of the power management circuit to accommodate these distinct characteristics. The primary challenge in developing the proposed hybrid wireless power transmission system lies in devising an appropriate coupling circuit for the RF link and UET link, taking into account their mismatched power densities. In addition, due to the limited power input of the RF link, the incorporation of a highly efficient power management system is crucial.

B. *Coupling circuit*

To achieve the coupling of RF link and UET link efficiently, a hybrid energy converter as shown in Fig. 3 is designed. The purpose of the coupling circuit is to harvest radio frequency (RF) energy within a range of 1mW to 200 mW for a certain period and produce ultrasonic energy output between 500 mW and 1000 mW within a shorter period. To enhance the versatility of this circuit for various applications, it is designed to adapt to different transmission distances and media by matching antennas of different frequencies as well as transducers of varying frequencies. The coupling circuit is adjustable, allowing for the optimization of the RF antenna frequency and ultrasonic energy transducer frequency within a range of 1 MHz to 2.5 GHz and 10 kHz to 1 MHz, respectively.

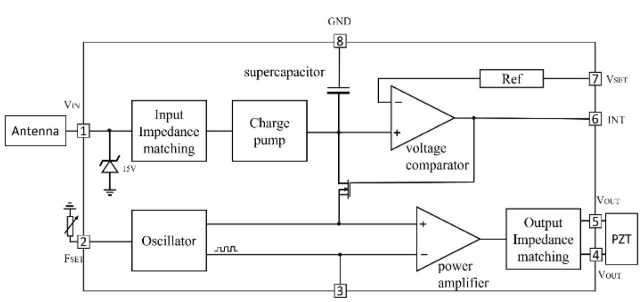


Fig. 3. The coupling circuit collects electromagnetic waves through the antenna and emits ultrasonic waves through the PZT. The converter mainly includes matching network, charge pump, oscillator and energy management.

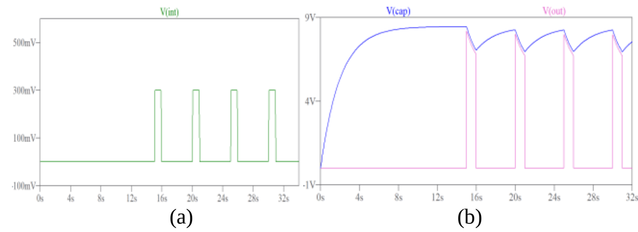


Fig. 4 The interrupt signal from the power management circuit (a). Capacitor voltage and output voltage result based on interrupt control (b). When the interrupt signal is high level, the load is cut in and energy from capacitor put in load. While the interrupt signal is low level, the load is cut off and energy recharges to capacitor.

In order to enhance the output power of the transducer, we propose a time-division coupling power management method. This method involves the use of an efficient energy management circuit to separately operate the RF and ultrasonic energy transmission links at different times. By accumulating RF energy, the power of the ultrasonic energy can be transmitted repeatedly, which can improve the efficiency of the ultrasonic energy transmission. Fig. 4 depicts the timing diagram of the proposed hybrid energy coupling (HEC) system. The voltage output required to drive the transducer is controlled by an interrupt signal that is determined by the capacitor voltage accumulated through the harvested RF energy. To minimize losses, the interrupt signal threshold is set to 0.3 V, as illustrated in Fig. 4(a). The capacitor voltage can be adjusted through the use of a voltage comparator. Based on this, the simulation outcomes for the charge and discharge voltage, as well as the output voltage of the capacitor, are depicted in Fig. 4(b).

III. Simulation Results

To determine the maximum power transfer of the hybrid system, a transfer model can be employed while accounting for link loss. This involves measuring and simulating the power input and output of the system, and subsequently calculating the difference after considering losses from the RF link, UET link, and coupling circuit. Analyzing this relationship enables the identification and optimization of the maximum power transfer point for the specific application.

A. *Coupling efficiency*

The voltage comparator and oscillator were simulated using to ADG6412 and LTC6906 from Analog Devices, Inc. in LTspice respectively, based on the coupling circuit depicted in Fig. 3. To fulfil the design requirements of wide voltage, the voltage range of ADG6412 was set to ±15 V. Similarly, to meet the wide output frequency requirements, the output frequency of LTC6906 was adjustable from 10 kHz to 1000 kHz. As previously stated, electromagnetic waves possess low-density energy, while ultrasonic waves possess high-density energy. Therefore, a time-division energy management and control approach was employed.

The energy accumulated in the capacitor for a long time is automatically released through the power management circuit, and high-density energy is released to the ultrasonic drive circuit in a short time. The increase gain is determined by the ratio of the accumulation time to the discharge time. To enable the

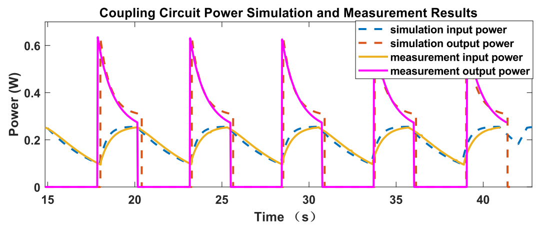


Fig. 5 The relationship between input power and output power for coupling circuit. The input power of the test is taken as a positive value, and the results show that the output power can be boosted from 0.3 to 0.6W at an input power of 0.1 to 0.25 W. The efficiency is about 90%.

testing process, the simulation employed a 3-second charging time and a 2-second discharging time, with the resulting simulation outcomes and measurement illustrated in the Fig. 5.

The ratio of power boost is determined between charging time and discharging time and the capacitance. The storage capacitor in this test is 50 millifarads. The charging time is 3 seconds and the discharging time is 2 seconds. The simulation average efficiency of coupling circuit is 90.7%. The actual test result shows that the efficiency is 90%.

B. Power budget

Utilizing the coupling efficiency of 90% and the RF energy transmission model and the acoustic energy transmission model, we can establish the relationship between the input power and the transmission distance under the condition of maximum power transmission, considering an output power of 1 mW. Fig. 6 shows a case of a power budget model. This model is based on the relationship between transmit power and transmission distance when perfectly matched. It can guide and predict applications. Considering the RF energy limitation and safety, the input power of the model only considered lower than 55 dBm.

C. Discussion

The proposed transmission model facilitates the determination of the relationship between input power (P1) and output power (P4) required to achieve a 1 mW output for sensors via hybrid wireless power transfer systems. The test results of the coupling circuit exhibit a high degree of consistency with the simulation results, with errors attributed to the impedance matching network in the test circuit. Although the RF link and UET link are ideal models, primary transmission loss can be calculated. The coupling circuit, de-signed with a broad input range, can increase input power to achieve the desired output power level, thereby meeting diverse application requirements as shown as Fig. 6. However, it is essential to note that the presented results only account for input power levels that comply with RF public radiated power limitations. Subsequent research will involve comprehensive system-level evaluations of the RF link and UET link, followed by a detailed comparative analysis of the proposed hybrid energy transfer model. These future studies will provide a deeper understanding of the overall system performance and guide the development of more robust and efficient wireless power transfer solutions for sensor applications.

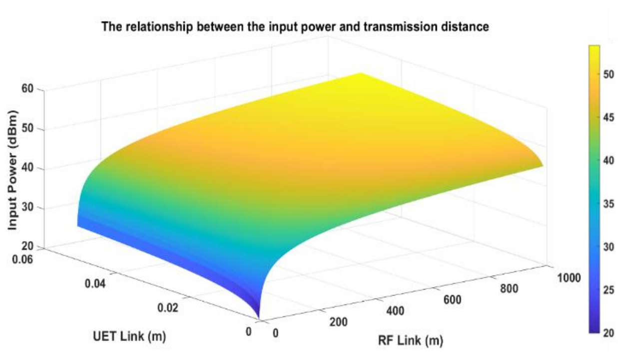


Fig. 6 The power budget (for 1 mW output) of system for different transmission distance with RF link and UET link. The gain of antenna is 30dBi and work at 2.4 GHz, transducer is PZT-5 (the radius is 9mm) and the UET link medium is low-carbon steel.

IV. Conclusions

This article presents a novel power supply scheme for powering sensors in harsh environments via a hybrid wireless energy transfer system. A coupling circuit with a wide voltage input is designed to enable the selection of different input power levels based on the application environment. The proposed coupling circuit demonstrates a high efficiency of up to 90%. This design significantly expands the range of potential input power sources, enabling greater flexibility in powering sensors across diverse environments. The results presented in this article provide a foundation for further research into wireless power transfer for sensor systems and networks, with the potential to greatly enhance the performance and reliability of sensor device.

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