A Wide Input Power Line Energy Harvesting Circuit for Wireless Sensor Nodes

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2021 IEEE International Symposium on Circuits and Systems (ISCAS) | 978-1-7281-9201-7/20/$31.00 ©2021 IEEE | DOI: 10.1109/ISCAS51556.2021.9401513

***Abstract*— The proposed circuit aims to harvest energy from AC powerlines with a wide current ranging from 10 to 50 A. The proposed system includes a wake-up circuit and is capable of cold-start. A buck-boost converter operating in DCM is adopted for impedance matching, where the impedance is rather independent of the operation conditions. So, the proposed system can be applicable to various types of wireless sensor nodes with different internal impedances. Experimental results show that the proposed system achieves an efficiency of 80.6% under the powerline current of 50 A.**

Keywords— Powerline energy harvesting, current transformer, buck-boost convertor, impedance matching, maximum power point (MPP), wireless sensor network (WSN).

I. Introduction

Massive deployment of wireless IoT (Internet of Things) devices makes replacement or recharge of batteries expensive and impractical for some applications. Energy harvesting is a promising solution, and various designs are proposed to harvest power from ambient resources including thermal, vibrational, solar, wind, and RF sources [1]-[5]. Among these ambient resources, AC powerlines are a stable energy source in an urban environment. Many researchers investigated methods to exploit this stable source of energy to power wireless IoT devices [6]-[14].

Major design challenges of magnetic field energy harvesters for powerline energy harvesting include saturation and nonlinearity of the core, the geometry of the core, and positioning of the harvester, and distance of harvesting devices from the AC power lines [11]-[16]. The power factor is another issue due to the inductive nature of magnetic field energy harvesters [17]. The core saturation and nonlinearity are investigated and an efficient energy harvester is presented in [18]. Design issues for power management circuits for power line energy harvesting include such as impedance matching, underline current and load variations, wake-up circuit, cold-start, and output voltage regulation [12]-[21]. Impedance matching is often achieved by adjusting the duty cycle and the switching frequency of the DC-DC converter [20]-[23] and maximum power point tracking (MPPT) schemes aim to maintain impedance matching under varying operating conditions [4], [24] and [25].

In this paper, we present a power management circuit to harvest energy from railroad powerlines to power wireless sensor networks (WSN). We designed a magnetic field energy harvesting system for railroad power lines, whose current changes a wide range from 10 A to 50 A. Accordingly, the power stage is designed to withstand a wide range of the input current. A buck-boost converter operating in discontinuous conduction mode (DCM) is adopted for impedance matching, as the input impedance is ideally independent of the operating conditions such as input voltage, output voltage and load resistance.

This paper is organized as follows. Section II reviews magnetic field energy harvesters, existing power line energy harvesting circuits, and an oscillator adopted for the proposed circuit. Section III presents the proposed circuit and describes the operation of individual blocks. Section IV presents an experiment setup and measurement results. Section V concludes the paper.

II. Preliminaries

A. Magnetic Field Energy Harvesters

A magnetic field energy harvester (MFEH) shown in Fig. 1 is composed of a winding coil around a ferrite core. It is in essence a current transformer and is used as an energy harvesting device for powerlines [8], [9], [11], [17], [26]-[30]. The number of turns of the coil and the ferrite core geometry determines the potential of the device to harvest electromagnetic power as investigated in [9]. An equivalent circuit model considering nonlinearities is presented in [31], and an efficient magnetic field energy harvester is presented in [18] and [19].

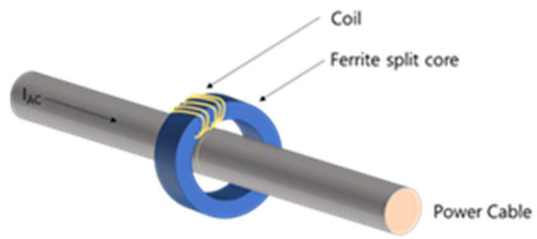


Fig. 1. Magnetic field energy harvester.

B. Energy Harvesting Circuits for Powerlines

Zhuang et al. proposed a circuit, in which the core of the MFEH is ensured not in the saturation mode [8]. Noting that instantaneous power can be much larger for a short time period than the average power for a long time period, the circuit aims to power the load for a short period with large energy. After charging the storage capacitor for 190 ms from a powerline current of 10 A, the circuit extracts 792 mW from the power line. In order to avoid saturation of the core of the MFEH, a switch is added to the circuit to short the circuit of the core, when the coil reaches saturation.

Taithongchai and Leelarasmee presented a circuit design to harvest 58 mW from a powerline with 65 A of line current [10]. A boost converter dynamically adjusts the input impedance to implement MPPT, which is based on the feedback of the output voltage. A low-power microcontroller PIC16F690 is used to adjust the duty cycle of the boost converter. One shortcoming of the design is the inability to regulate the output voltage, and so that the circuit may be used to recharge batteries but not to power sensor nodes directly. Also, the circuit is limited to harvest energy only from powerlines with large current ranging from 65 A to 130 A.

Zeng et al. presented an MFEH for 3-Phase 10 kV powerlines [27]. The system uses an off-the-shelf MAX17710 energy harvesting IC, which limits the maximum input voltage to 6 V, therefore resulting in a limit of the harvested power of the system.

C. Oscillator

The oscillator shown in Fig. 2 generates a switching frequency with a fixed duty cycle and is adopted for the proposed design [23]. The frequency and the duty cycle of the oscillator can be approximated as (1) and (2), respectively, if $R_2 >> R_1$. The switching frequency and duty cycle can be tuned with R_1, R_2 and C_1, and in practice, R_1 or R_2 can be a variable resistor. The output voltage V_{GATE} drives the gate of a MOSFET in a buck-boost converter for the proposed design.

$$f \approx \frac{1}{(R_1+R_2)C_1 ln2} \tag{1}$$

$$D \approx \frac{R_1}{R_2} \tag{2}$$

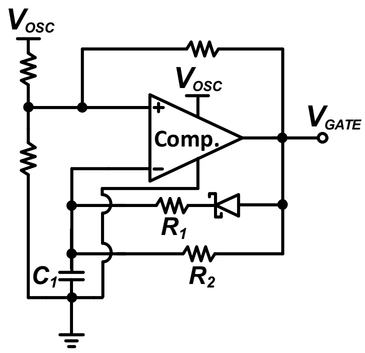


Fig. 2. Oscillator.

III. Proposed Design

The proposed power management circuit (PMC) aims to cover a wide range of powerline current from 10 A to 50 A, and harvest energy from such AC power lines to power wireless sensor nodes.

A. Block Diagram

Fig. 3 shows the block diagram of the proposed circuit for powerline energy harvesting. As an MFEH starts to harvest power from a powerline, the rectifier charges the wake-up circuit to activate the oscillator (OSC), which in turn activates the buck-boost converter. A buck-boost converter provides impedance matching to extract the maximum power. The voltage regulator regulates the output voltage to 3.3 V to power the load, i.e., sensors.

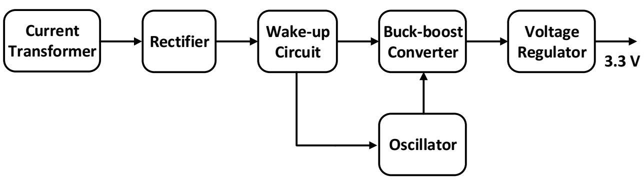


Fig. 3. System Block Diagram.

B. Buck-boost Converter

To extract maximum power from an MFEH, the converter needs to match the internal impedance of the MFEH along with the rectifier. The input impedance of the buck-boost converter operating in discontinuous conduction mode (DCM) is as follows [23].

$$R_{IN} = \frac{2L}{D^2 T_S} \tag{3}$$

where L is the inductance, D is the duty cycle, and T_S is the switching period of the converter. (3) shows that the input impedance of a buck-boost converter in DCM is independent of the operating conditions such as input and output voltages and load resistance. So, our circuit adopts a buck-boost converter in DCM. Once the inductor size and the switching frequency are decided, the duty cycle D can adjust the input impedance of the buck-boost converter to match the impedance of the MFEH along with the rectifier, so that maximum power could be extracted from the energy harvester.

C. Wake-up Circuit

When the MFEH starts to generate power from a powerline, it charges capacitor C_1 through R_1 of the wake-up circuit in Fig. 4. The capacitor voltage V_{OSC} provides power to the oscillator. When the voltage reaches 3 V, the oscillator starts to oscillate, which activates the buck-boost converter. When the MFEH does not generate power, the V_{OSC} approaches to 0. Hence, the oscillator becomes inactive to save the power dissipation of the converter. The breakdown voltage of the diode D_1 is 5 V, which regulates the maximum capacitor voltage V_{OSC}.

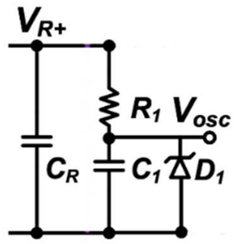


Fig. 4. Wake-up Circuit.

The proposed system is capable of cold start. Suppose that the capacitor C_1 is drained completely, and all the blocks in Fig. 3 are deactivated. As the MFEH generates induced voltage out of the powerline, the full-bridge rectifier composed of passive diodes charges the capacitor C_1. When the capacitor voltage V_{OSC} reaches 3 V, it activates the oscillator and hence the buck-boost converter.

A complete circuit diagram of the proposed PMC is shown in Fig. 5. The MFEH, noted as the current transformer, generates an AC voltage harvested from the powerline current. The full-bridge rectifier is implemented with Schottky diodes for high efficiency. The inductor L_1 of the converter is 15 mH and the capacitor C_O is 1 F. Based on simulation results, the input impedance of the buck-boost converter is set to 2 kΩ to match the source impedance of the current transformer followed by the rectifier and the wake-up circuit. The voltage regulator provides regulated 3.3 V DC for the load such as sensors, and it is an off-the-shelf IC Analog LT8608.

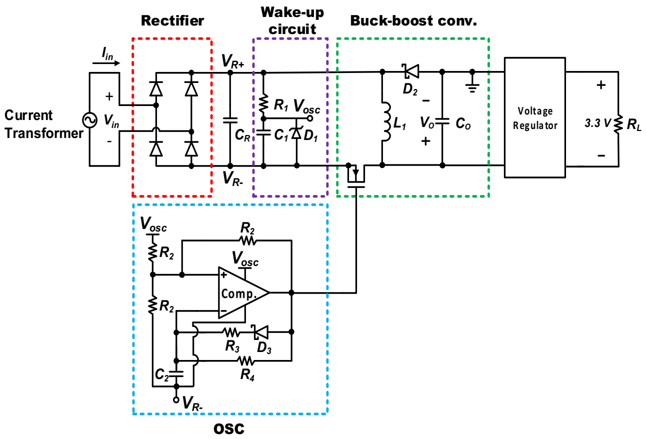


Fig. 5. Proposed Power Management Circuit.

IV. Experimental Results

A. *Prototype and Experiment Setup*

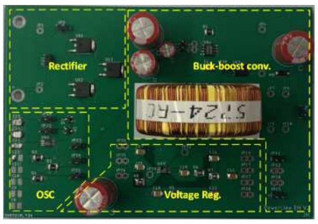
The MFEH or current transformer is shown in Fig. 6. The size of the ferrite core is 59 mm by 49 mm. The powerline current of the MFEH ranges from 10 A to 50 A for our experiments.

(a) Core

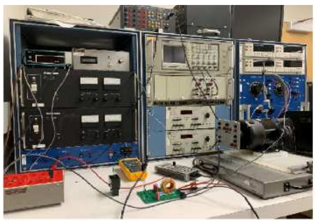
(b) With a case

Fig. 6. Magnetic Field Energy Harvester.

Fig. 7 shows a prototype of the proposed PMC and the experiment setup. The size of the PCB is 91 mm by 132 mm.



(a) Prototype



(b) Experiment setup

Fig. 7. Prototype and Experiment Setup.

B. *Power and Efficiency*

The proposed PMC with the MFEH is experimented with the powerline current of 10 A, 30 A and 50 A with a frequency of 60 Hz.

To measure the maximum power delivered by the MFEH, we attached a variable resistor at the output of the MFEH, while all other circuit blocks, including the rectifier, the converter and the oscillator, are removed. We measured the maximum power P_{Max} delivered to the resistor with an optimal resistance value. To measure the efficiency of the PMC, we attached a variable resistor directly at the output of the buck-boost converter without the voltage regulator and measured the maximum power $P_{Max,buck\text{-}boost}$ with the optimal load resistance value. The efficiency of the proposed PMC is defined as follows.

$$\eta = \frac{P_{Max,buck-boost}}{P_{Max}} \times 100(\%) \qquad (4)$$

1) Powerline current of 10 A

Fig. 8 shows the power P_{Max} delivered to the load resistor by our MFEH with the rectifier under the powerline current of 10 A. The measurement results show that the peak power of 7.96 mW is achieved for the resistance of 2 kΩ, implying the resistance that is required for the input impedance of the buck-boost converter. The power P_{Max} is sensitive to the resistor value, which indicates that impedance matching is necessary for the proposed powerline energy harvesting system.

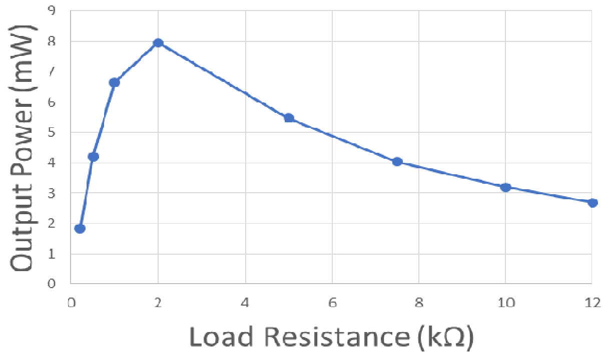


Fig. 8. Output Power vs. Load Resistance of the Magnetic Field Energy Harvester for Powerline Current of 10 A.

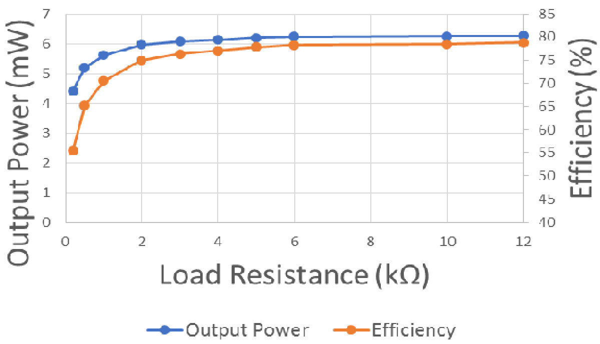


Fig. 9. Output power and Efficiency vs. Load R of the PMC for Powerline Current of 10 A.

To emulate the optimal resistance of 2 kΩ, the duty cycle *D* of the buck-boost converter with a 15 mH inductor is set to 21% under the switching frequency of 3 kHz. A variable load resistor is attached in parallel with the capacitor C_O. Fig. 9 shows the power delivered to the load resistor and its efficiency of the proposed PMC. The output power is somewhat constant for load resistor greater than 2 kΩ. It verifies that the input impedance of the buck-boost converter in DCM is rather insensitive to its load resistance. The peak output power and efficiency of the buck-boost converter are 6.2 mW and 77.89%, respectively, under the load resistance of 5 kΩ.

2) Powerline current of 30 A

The same measurements are performed for the powerline current of 30 A. Fig. 10 shows the power delivered to the load resistor by the MFEH. The peak power of 70.21 mW is achieved with the load resistance of 2 kΩ. It implies the source impedance of the MFEH is independent of the powerline current. As the current increases three times, the power would be nine times for an ideal MFEH as a current transformer, but the actual increase is slightly less than that mainly due to the increased loss of the MFEH.

Fig. 11 plots the output power and the efficiency of the PMC. The peak output power and the peak efficiency are 55.69 mW and 79.32%, respectively, under the load resistance of 5 kΩ. As expected, the efficiency increases as the powerline current increases, but the optimal resistance remains the same.

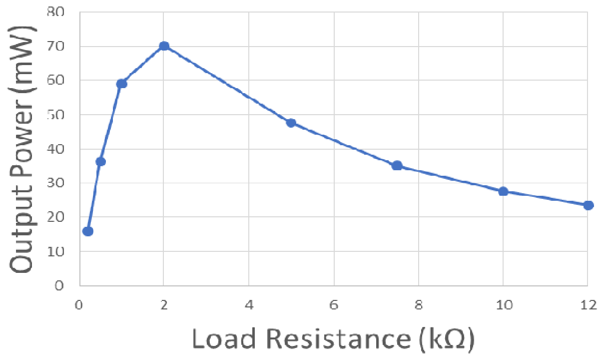


Fig. 10. Output Power vs. Load Resistance of the Magnetic Field Energy Harvester for Powerline Current of 30 A.

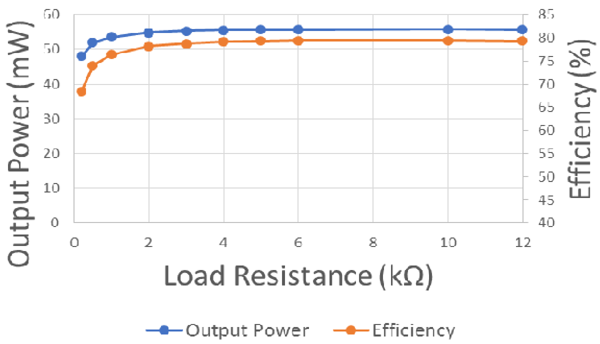


Fig. 11. Output power and Efficiency vs. Load R of the PMC for Powerline Current of 30 A.

3) Powerline current of 50 A

The measurements are repeated for 50 A. Fig. 12 shows the peak power of 193.34 mW is achieved for the MFEH at the load resistance of 2 kΩ. Again, it verifies the source impedance of the MFEH is independent of the powerline current. As the current increases five times compared with the case of 10 A, the harvested power increase is 5.66 mW from 199 mW, which is twenty-five times the harvested power with the case of 10 A, implying further increased loss of the MFEH.

Fig. 13 plots the output power and the efficiency of the PMC. The peak output power and the efficiency of the PMC are 156.6 mW and 80.99%, respectively, under the load resistance of 5 kΩ. The efficiency increases slightly compared with that of 30 A.

Fig. 12. Output Power vs. Load Resistance of the Magnetic Field Energy Harvester for Powerline Current of 50 A.

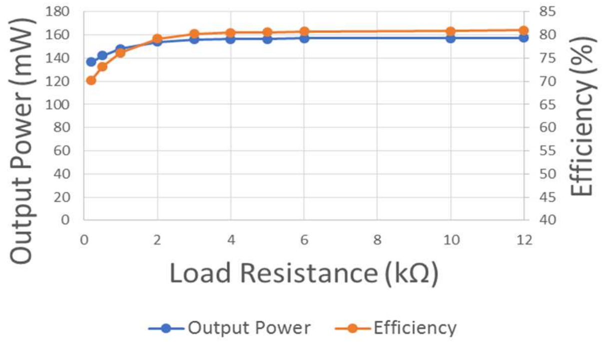


Fig. 13. Output power and Efficiency vs. Load R of the PMC for Powerline Current of 50 A.

In order to power the wireless sensor nodes with a stable output voltage, the proposed circuit adopts a voltage regulator IC Analog LT8608. Corresponding to different applications with different needs of supply voltage, LT8608 can regulate the output voltage to 1.8V, 3.3 V, 5V and 12V. For the proposed circuit, with a recommended configuration from the datasheet, when the output voltage of the buck-boost converter is between 3.9 V to 42 V, LT8608 can regulate it to 3.3 V.

V. Conclusions

An AC power line energy harvesting circuit is presented in this paper. The proposed system adopts an MFEH to extract energy from AC powerlines and adopts a buck-boost converter operating in DCM for impedance matching. A wake-up circuit is adopted so that the circuit is capable of cold-start. The proposed PMC is designed to operate for a wide powerline current. The measurement results also indicate that the source impedance of the MFEH remains constant even under a wide range of the powerline current.

Acknowledgment

This research was supported in part by the National Science Foundation Award number 1704176.

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