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

***Abstract*—The proposed circuit aims to harvest energy from AC powerlines with an ultra-wide input range of 10A-70A of line current. These powerlines serve as an abundant source of energy for many battery reliant IoT devices which are being used excessively in urban environments. A power management circuit is developed to maximize harvested power from these AC powerlines. A buck-boost converter operating in DCM is adopted for impedance matching with independence on operating conditions, ensuring device operation for various ferrite cores and wireless sensors. Maximum Power Point Tracking (MPPT) is implemented to ensure optimal efficiency using the Perturb and Observe (P&O) method. Results show that the designed circuit can regulate output voltage to 3.3V and 5V with a wide open-circuit voltage of 19-89V_{rms}.**

Keywords—Powerline energy harvesting, maximum power point tracking, buck-boost convertor, perturb and observe, ferrite core

I. INTRODUCTION

With the increasing use of IoT devices, it has become more important to find better alternatives to rechargeable batteries currently being used to power these IoT devices. Dependence on battery or any power source limits the applications where these devices can be used for monitoring and data collection purposes. Various designs have been proposed to harvest power from ambient resources including thermal, vibrational, solar, wind, and RF sources [1-5]. Among these ambient resources, AC powerlines are important sources of energy in an urban setting. These AC powerlines can provide abundant energy to nearby IoT devices. Many researchers have investigated different methods to exploit this stable source of energy to power Wireless Sensors [6-10].

Common challenges in powerline energy harvesting are source impedance matching, harvesting core saturation and non-linear nature, frequent line current variations, core geometry design, and positioning and distance of harvesting device from powerline. The power factor issue also arises due to the inductive nature of harvesting core which has been addressed and improved in [11]. The core saturation problem and nonlinearities have been investigated and resolved in [12] and an efficient harvesting device is presented. Source impedance matching is generally implemented using a DC-DC Converter with duty cycle and frequency control [13-15] realized by using Maximum Power Point Tracking [16].

In this paper, we present a power management circuit to harvest energy from railroad powerlines to power Wireless Sensor Networks (WSN). We adopt a specifically designed ferrite core as an electromagnetic harvester to capture energy from railroad powerline magnetic flux. Experimental data show that ferrite core generates open circuit voltage of 19*V*-100*V* for the powerline current ranging from 10*A*-70*A*. For the same range of line current, source impedance ranges from 5kΩ to 7.5kΩ. The power stage has been designed to withstand a wide range of input voltages. A buck-boost converter is adopted to operate in DCM as input impedance in DCM is independent of operating conditions and can be easily controlled. Furthermore, operation in DCM also minimizes DCR losses in the inductor. A current sense IC is used in the output path to sense current. Since the output voltage cannot change across a capacitor instantaneously, any increment in current indicates increase in output power. Maximum Power Point Tracking (MPPT) has been implemented using Perturb & Observe (P&O) to match source impedance. An ultra-low power PIC18LF24K40 MCU has been used to implement MPPT and P&O. The MCU perturbs the current level after every 16 seconds to find Maximum Power Point (MPP). Once the MPP is found, the MCU is put to sleep to minimize power dissipation.

This paper is organized as follows. Section II reviews necessary background knowledge for the ferrite core, MPPT and the techniques used to implement it including P&O and explores most relevant existing Energy Harvesting Circuits. Section III presents the proposed circuit and explains operation of individual blocks. Section IV presents experimental setup and measurement results. Section V then concludes the paper.

II. PRELIMINARIES

A. *Harvesting Core*

A harvesting core is made by winding coil around a ferrite core. Based on Faraday's law of electromagnetic induction, it has been commonly used as a current transformer for measurement purposes and as an energy harvesting device by various researchers [6, 7, 9, 11, 17-20]. The number of turns of the coil and ferrite core geometry determines the potential of the device to harvest electromagnetic power as investigated in [9]. An equivalent model is presented taking nonlinearities into consideration in [21]. A high efficiency design is presented for harvesting core in [12].

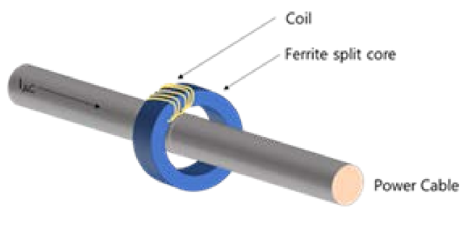

Fig. 1. Harvesting Core

B. *Existing and Relevant Energy Harvesting Circuits for Powerlines*

Zhuang et al. proposed a circuit[6] in which they improved the power available from the core by ensuring that the core is not in the saturation mode. The key idea behind their design is that harvesting core can source maximum power when it is not in saturation. According to their research, instantaneous power can be much greater for a shorter time period than the average power for a greater time period. Thus, their design aims to power the load for a very short period releasing much higher energy. As per their experiment, they were able to extract 792mW of power for the duration of 110ms after charging the capacitor for 190ms from a line current of 10A. In order to ensure that the core doesn't operate in saturation, they adopted a switch to short circuit the core whenever it reaches saturation. They utilized a specialized high permeability core and focus of this work is targets operating mode of the harvesting core. The output voltage is not regulated in this design, hence wireless sensors cannot be powered. Moreover, their design uses Zener Diode for the dissipation of excessive energy wasting the available power which can be utilized.

Torkiat Taithongchai and Ekachai Leelarasmee presented another design in which they were able to harvest 58mW of power at 65A of line current [8]. Their design focused on the energy harvesting circuit without any consideration of harvesting core properties. They adopted a management circuit to dynamically adjust input impedance of the circuit to implement MPPT using a boost DC-DC converter. One shortcoming of this design discussed in their paper, is the dependence on load resistance of the DC-DC boost converter transfer function which inhibits analysis of the full circuit. Also, their design operated from 65A-130A of line current ignoring the lesser line current ranges. Another weakness of this design is that output voltage is not regulated. Instead they used the output voltagefor the feedback control of MPPT. Therefore this circuit can only be used to power rechargeable batteries but not wireless sensors directly.

In another research, Xiangfeng Zeng et al. designed a system to harvest power from 10kV 3-Phase powerline [18]. They proposed the design of a harvesting coil for the compatibility with 3-Phase HVAC powerline. Furthermore, this system consists of commercial off-the-shelve MAX17710 EH IC which limits the power yield to 100mW. Their work lacks consideration for Maximum Power Point Tracking hence extraction of maximum available power is not ensured.

C. MPPT and P&O

Maximum power point tracking (MPPT) is commonly employed in energy harvesting to maximize the power transfer to the load. Some of the frequently used methods to implement MPPT include fractional open circuit voltage (FOCV), incremental conductance (IncCond), and perturb and observe(P&O).

Since the FOCV method uses the relationship between the open circuit voltage of the source and the voltage across the load to determine the MPP, the major disadvantage of this method is that the source must be disconnected from the load leading to the loss of power [22]. Although this can be avoided using pilot cells in the case of PV energy harvesting, such a method is not suitable for harvesting energy using a current transformer.

While the IncCond method is effective at tracking the MPP, it requires two sensors to measure the instantaneous current and voltage of the supply as well as division functionality to calculate the instantaneous and incremental conductance [22]. These extra components and added computation associated with division are not optimal and a MPPT method with less overhead is more appropriate for this application.

The simplicity of the P&O method lends itself to be a good candidate for this application. Under this method, the maximum power point is obtained by perturbing the duty cycle and examining the effect on the power flowing into the load. If the power increases, the duty cycle is further perturbed in the direction that caused the increase in power, otherwise the duty cycle is perturbed in the opposite direction. Furthermore, this method is suitable for applications where rapid changes do not occur and limited computational power is available [22]. The load current based P&O method as described in [23] simplifies P&O by performing MPPT only based on changes in the load current, requiring only a single current sensor and removing the need for multiplication.

III. Proposed Design

The proposed Power Management Circuit (PMC) is designed for powerline energy harvesting with high input voltages up to 100 V and high power of 2 W, and it aims to power WSNs.

A. System Block Diagram

The proposed power management circuit consists of a full bridge rectifier followed by a buck-boost converter and output voltage regulators. The power stage of the circuit is designed to withstand high input voltages up to 100V and relatively high power of 2W. Rectifier Diodes and a DC-DC converter MOSFET diode have been selected with high breakdown voltage. The ultra-low power PIC18LF24K40 MCU controls the circuit and performs MPPT based on the P&O Method. The switching frequency of the converter is set to 15.625 kHz and the MCU operates at 62.5 kHz. The output voltage is regulated at 3.3V and 5V levels to make the circuit compatible with a wide range of commercial off-the-shelf wireless sensors. For this purpose, LT8631 IC, a low power wide-input buck regulator, is configured to provide desired output voltage levels.

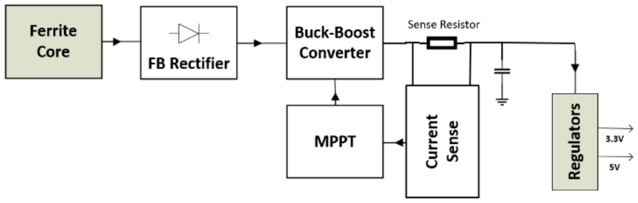

Fig. 2. System Block Diagram

B. Power Stage

The power stage consists of a full bridge rectifier consisting of Schottky diodes followed by a buck-boost converter designed to work in discontinuous conduction mode. Schottky diodes offer low forward drop voltage at high current densities. They are also better suited for fast switching frequencies due to negligible reverse recovery current leading to minimal switching losses. A MOSFET with maximum V_{DS} of 200V was selected since it would be exposed to higher voltages in this circuit, . The emulated input impedance of the buck-Boost converter in DCM is given in (1)

$$R_{IN} = \frac{2L}{D^2 T_s} \quad (1)$$

where L is the inductance, D is the duty cycle, and T_S is the switching period of the converter. The input impedance of an ideal buck-boost converter in DCM is independent of the operating conditions, such as input and output voltages and load resistance. This is a major advantage of a buck-boost converter in DCM and is the main reason for the adoption of such a converter. The switching period T_S is 64*ms* while the inductor is rated at 400uH. The duty cycle D is controlled to adjust the emulated impedance of the proposed system. An inverting buck-boost converter is adopted for impedance matching for the proposed circuit.

The control parameter for the Duty Cycle D is output power. A sense resistor of very low resistance (75mΩ) has been used in the output current path to sense power. Output power can be estimated by assuming the output voltage for one perturbation constant. Voltage drop across the sense resistor is then amplified using MAX9934 which is a current sense amplifier.

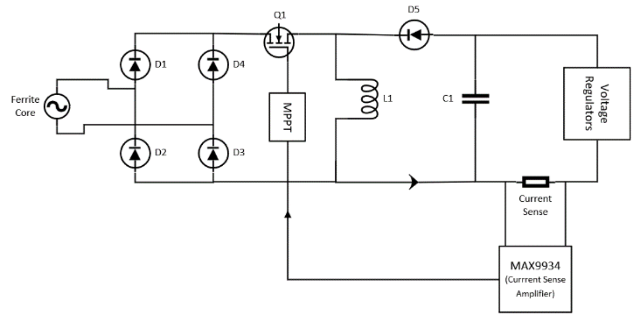

Fig. 3. Power Stage and Current-sense Feedback Control

C. *Maximum Power Point Tracking using P&O*

For the PMC to be independent of the specific current transformer used as input, the buck-boost convertor must be able to match a range of possible internal resistances presented by the transformer. Therefore, MPPT can be used in this case not to track the MPP over time but rather to track the MPP for various current transformers. Consequently, the load current based P&O method for MPPT was chosen for this application due to its low overhead.

The P&O algorithm, as shown in Fig. 4, is modeled as a finite state machine consisting of a total of three states. States 0 and 1 are responsible for perturbing the duty cycle and form the core of the P&O algorithm. The transitions between state 0 and state 1 are based on the comparison between the present load current and the load current before the perturbation. In order to make the transitions more robust to load current ripple, an ADC is used to sample 128 individual current values which are averaged using simple addition and shift operations.

In steady state operation, P&O algorithms generally result in oscillations around the MPP that do not contribute to MPPT. Therefore, when such oscillations are detected by observing a buffer of the previous twelve states, the MCU enters an idle mode implemented using Microchip's XLP technology. In this idle mode, the CPU clock is switched off while the peripherals continue to run, removing the dynamic power consumption of the CPU [24]. The idle state is exited using a 16 second timer interrupt which re-enables the CPU clock and allows the system to resume MPPT.

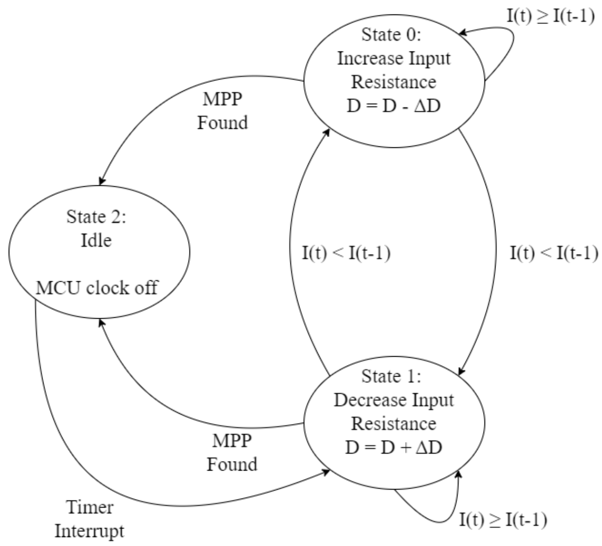

Fig. 4. P&O State Transition Diagram

IV. Experimental Results

A. *Prototype and Experiment Setup*

The proposed power management circuit is prototyped using commercial off-the-shelf discreet components and is shown in Fig. 5.

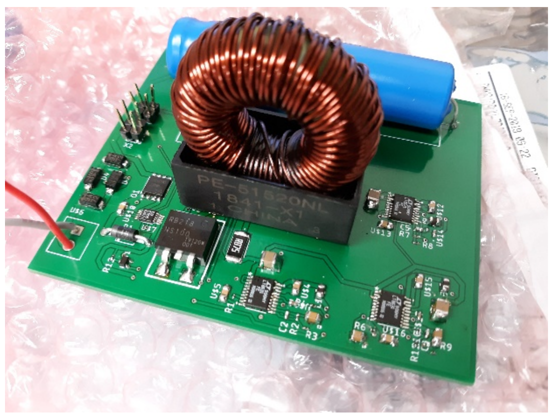

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Fig. 5. Prototype

The circuit was tested for MPPT operation using a $10V_{pk}$ Sine waveform generator at 60 Hz with a resistor in series acting as source impedance.

B. *Power and Efficiency*

Under a specific source impedance, a resistor is directly connected equal to source impedance and maximum power available is measured. Then the circuit is operated for MPP under 100Ω of load resistance and power is measured. The two powers are compared and plotted against source impedance (Fig. 6). Our system is able to harvest power with an efficiency of about 58% regardless of the load connected and source impedence. Moreover, our system successfully harvests a consistent amount of power under various loading conditions against a directly attached load (Fig. 7).

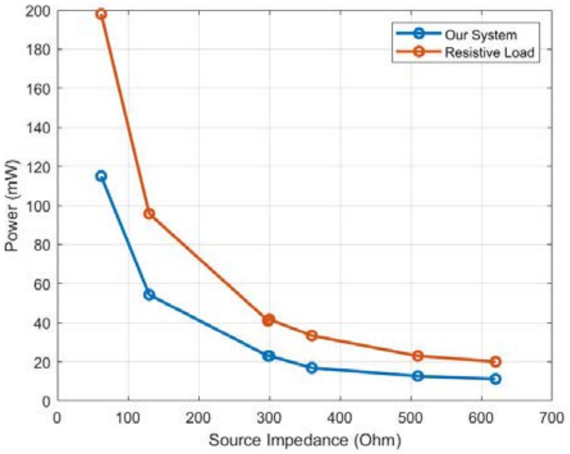

Fig. 6. Power extraction under changing load

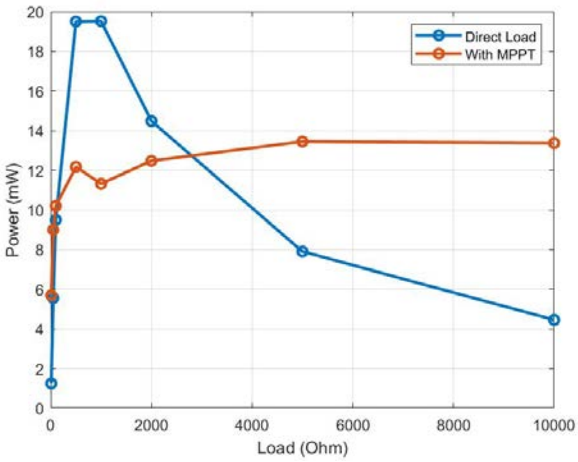

Fig. 7. Power extraction under changing load

MPPT performance was verified by performing a duty cycle sweep against power with a source impedence of 62 Ohms. Maximum power delivered to load is 115mW at 24% duty cycle with a series impedance of 62 ohms (Fig.8).

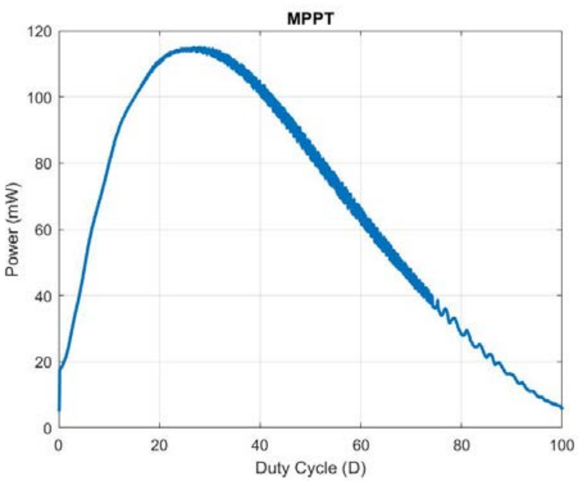

Fig. 8. System Block Diagram

C. Power Losses

The system was analyzed for power losses and efficiency as shown in Fig. 9. System efficiency is about 58% with major losses in the full bridge rectifier.

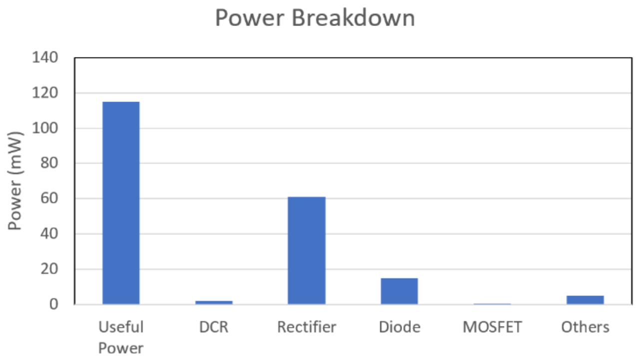

Fig. 9. Power Loss Breakdown

D. Voltage Regulation

Finally, the voltage regulation of the circuit was tested by using a load resistor of 700 ohms which is a typical load of a Wireless Sesnsor Network. Voltage hike and regulation graph is shown in Fig. 10.

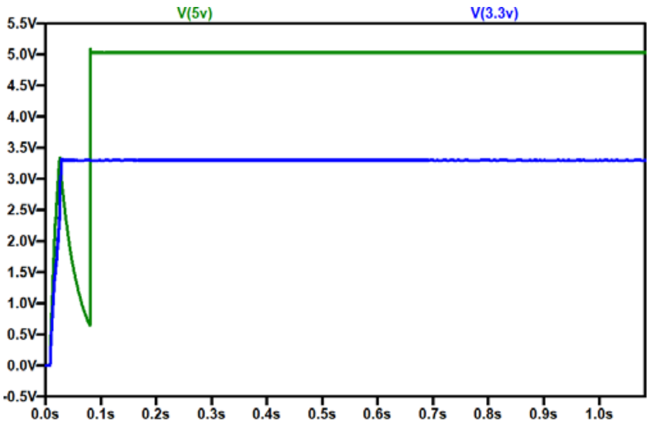

Fig. 10. Voltage Regulation – 3.3 V and 5 V

V. Conclusions

A powerline energy harvesting circuit is presented in this paper. The proposed circuit adopts a buck-boost converter operating in DCM for impedance matching and is controlled by an ultra-low power MCU and a current sense IC. The circuit is designed to operate for wide and high input voltages. Final voltage is regulated at 3.3V and 5V to make it compatible with commercial off-the-shelf wireless sensors. The circuit is experimentally tested and validated for correct operation and hence it can be used to power any WSN using powerline coupling.

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