

Desaturation Controller for a Magnetic Core

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Abstract— The proposed powerline energy harvesting circuit aims to prevent saturation of a magnetic core, resulting increase of the harvested energy. The proposed magnetic field energy harvester (MFEH) has two secondary coils, the original one to harvest energy from the primary powerline and the additional one to desaturate the magnetic core. When the magnetic core is saturated by the magnetic field generated by the powerline, current starts to flow through the additional coil to desaturate the core. The desaturation controller is composed of a current sensor and a microcontroller unit (MCU) with associated switches. Experimental results show that the proposed circuit harvests 42.7 mW under powerline current of 25 A in rms. The circuit increases the amount of harvested power by 5.2 mW or 13.7 % through desaturation of the core.

Keywords— Powerline energy harvesting, current transformer, magnetic field energy harvester, magnetic core saturation.

I. INTRODUCTION

Nowadays, massive deployment of wireless IoT (Internet of Things) devices makes replacing or recharging of batteries expensive or impractical. Energy harvesting is a promising solution, and intensive research was performed to harvest power from various ambient resources including thermal, vibrational, solar, wind, RF sources, and powerlines [1]-[5]. AC powerlines are a stable energy source in urban and rural environments. Many researchers investigated methods to harvest energy from powerlines, often to power wireless IoT devices [6]-[9].

The performance of a magnetic field energy harvester (MFEH) for a powerline depends on several parameters including geometry, saturation, and nonlinearity of the core, position of the harvester, and the distance from the powerline [10]-[12]. Impact of the saturation and nonlinearity of magnetic cores is investigated in [13]. Design issues for power management circuits for powerline energy harvesting are impedance matching under powerline current and load variations, wake-up circuit, cold-start, and output voltage regulation. The duty cycle or the switching frequency of a DC-DC converter is often adjusted for impedance matching [5], [14]-[16], and maximum power point tracking (MPPT) aims to maintain impedance matching under varying operating conditions [1].

In this paper, we present a powerline energy harvesting circuit with a desaturation controller to reduce saturation of the magnetic core. In addition to the original secondary coil for the power stage, an additional secondary coil, called desaturation coil in this paper, is added to the MFEH. The direction of the powerline current sensed by a current sensor is applied to a microcontroller unit (MCU), which sets the direction of the desaturation coil current opposite to the direction of the powerline current. So, the magnitude of the

excessive magnetic field strength is decreased to reduce saturation of the magnetic core so that more energy can be harvested. The MCU and the controller for the desaturation are powered externally for the proposed circuit, but they can be powered by the harvested energy.

This paper is organized as follows. Section II reviews magnetic field energy harvesters, magnetic core saturation, existing desaturation techniques and negative voltage converter. Section III presents the proposed circuit and explains its operation. Section IV presents an experiment setup and measurement results. Section V concludes the paper.

II. PRELIMINARIES

A. Magnetic Field Energy Harvester (MFEH)

An MFEH shown in Fig. 1 is composed of a winding coil around a ferrite core. In essence, it is a current transformer and commonly used for powerline energy harvesting [5]. The number of turns of the coil and the geometry of the ferrite core determine the performance of the MFEH to harvest electromagnetic power as investigated in [10].

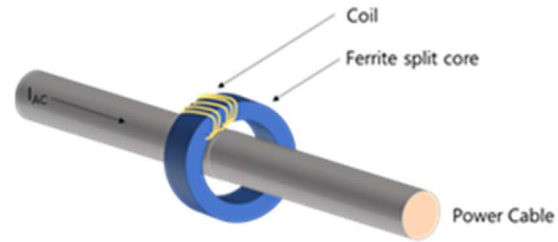


Fig. 1. Magnetic field energy harvester.

Fig. 2 shows an equivalent circuit model of a typical MFEH. The number of turns on the primary side is 1 and so represented as a wire. L_{Eff} is the effective inductance, L_{Leak} the leakage inductance, and R_{Wire} the wire resistance of the coil. When the magnetic core is saturated, L_{Eff} drops significantly, which causes a large amount of current to flow through L_{Eff} , resulting small current through the load or a small amount of energy harvested.

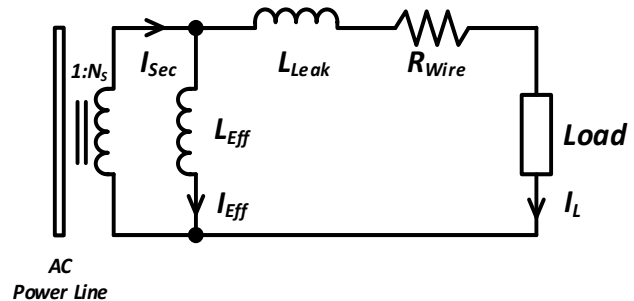


Fig. 2. Equivalent circuit of an MFEH.

B. Magnetic Core Saturation

Fig. 3 shows a typical B-H curve of a magnetic core. As the magnitude of the magnetic field strength $\vec{H}$ increases, the magnitude of the magnetic flux density $\vec{B}$ increases linearly initially, but it becomes saturated due to saturation of the magnetic core. The induced current $\vec{I}_S$ on the secondary side is as follows.

$$\vec{I}_S \propto \left| \frac{d\vec{\Phi}}{dt} \right| = S \left| \frac{d\vec{B}}{dt} \right| \quad (1)$$

where $\vec{\Phi}$ is magnetic flux, and S is the area of the cross-section through which the magnetic flux passes. When the magnetic core is saturated, $\frac{d\vec{B}}{dt} \approx 0$ and hence $\vec{I}_S \approx 0$, resulting little energy being harvested. The B-H curve is determined by the material properties of the magnetic core.

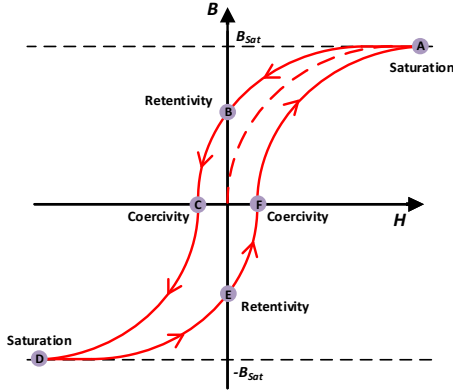


Fig. 3. Typical B-H curve of a magnetic core.

The B-H relationship is linearized and expressed as an arctangent function as show in (2) [17].

$$B(t) = B_{Sat} \frac{2}{\pi} \tan^{-1}(\beta H(t)) \quad (2)$$

where β is a constant representing sensitivity of the core in the linear region and determined by the material property of the magnetic core. A linearized B-H curve is shown in Fig. 4. It is divided into three regions, one linear region and two saturation regions. The proposed method is to monitor if $\vec{B}$ enters the saturation region based on the linearized model. If it does, it activates the desaturation coil to reduce $\vec{H}$, resulting $\vec{B}$ moving back to the linear region.

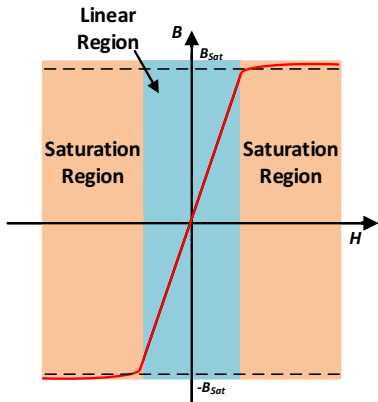


Fig. 4. Linearized B-H curve of a magnetic core.

Fig. 5 shows typical waveforms of the powerline current $\vec{I}_p$ and the induced current $\vec{I}_S$. The induced current $\vec{I}_S$ follows derivative of $\vec{I}_p$ initially. When $\vec{I}_p$ reaches a certain value, the magnetic core becomes saturated, and hence $\vec{I}_S$ drops sharply

and reaches near zero eventually. The status of the magnetic core, saturated or not, can be identified roughly by sensing the induced current $\vec{I}_S$. The method is rather simple and adopted for the proposed circuit.

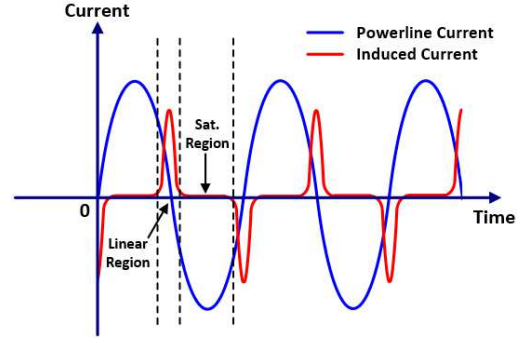


Fig. 5. Waveforms of powerline and induced currents.

C. Exsiting Desaturation Techniques

Paul et al. analyzed Si steel, Ni steel, and nano crystalline for the material of the MFEH core and proposed an MFEH with dual core [6]. Two cores made of different materials are integrated together. The inner core is made of Si steel due to its high B_{Sat} , and hence the core remains in the linear region mostly. The outer core is made of Ni steel due to its high permeability and low core loss. However, this design does not address the fundamental problem of core saturation, as large powerline current can reach the saturation region.

Zhuang et al. proposed a powerline energy harvesting system with a desaturation coil for the magnetic core [7]. An additional secondary coil is wound to the magnetic coil, controlled by an MCU, and a battery powers the MCU. When the magnetic core is saturated due to the excessive strength of the magnetic field generated by the powerline current, a DC current in the opposite direction to the powerline current flows through the additional coil to reduce net magnetic field strength, and therefore achieve desaturation of the magnetic core. With the desaturation coil, the harvested power of the proposed circuit increases by a factor of 45%, and the circuit can harvest 283 mW, on average, under AC current of 10 A in rms at 50 Hz. One shortcoming of the circuit is that the activation time period of the desaturation controller is fixed. So, it is applicable only for a fixed power line current, and the line current usually varies.

D. Negative Voltage Converter

A negative voltage converter (NVC) shown in Fig. 6 is more efficient than a full-bridge rectifier, even with Schottky diodes, and hence adopted for the proposed circuit [3]. During the positive (negative) cycle of the input voltage, the PMOS M_1 (M_2) and NMOS M_4 (M_3) conduct, so that the current flows from node A (B) to the load. The diode D_1 prevents the current from flowing in the reverse even if the load voltage is higher than the input voltage.

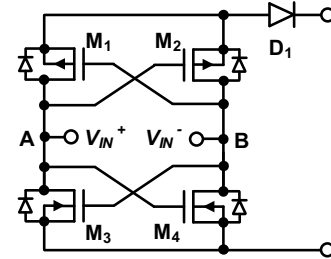


Fig. 6. Negative voltage converter.

This section describes the proposed circuit, in which a desaturation controller is the core building block.

A. Block Diagram

Fig. 7 shows the block diagram of the proposed powerline energy harvesting circuit. The inductor L_1 is the original secondary coil, and L_2 is the additional secondary desaturation coil. A current sensor senses the induced current I_S and feeds the info to the MCU. When the magnitude of I_S reduces to the predetermined point, the magnetic core is saturated. The MCU turns on the relevant switches to flow I_D through L_2 . The direction of I_D is set to the opposite to the direction of I_P . The magnetic core is desaturated to operate in the linear region. To demonstrate operation of the proposed circuit, the power for the desaturation controller and the current I_D is supplied externally. The power can be supplied from the harvested energy for real applications.

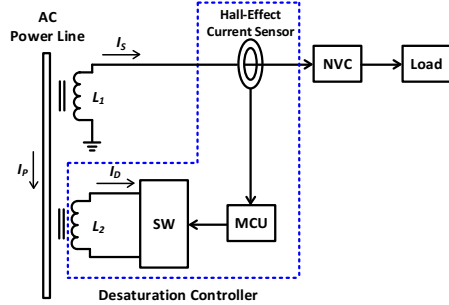


Fig. 7. Block diagram of the circuit.

B. Circuit Diagram

Fig. 8 shows the schematic diagram of the proposed circuit. When the magnitude of the induced current I_S is greater than 0.5 mA, the core is considered as not saturated. The two switch signals S_1 and S_2 are low, which turn off all the transistors $M_5 - M_8$. The current I_D through L_2 is zero. When the induced current is less than 0.5 mA, the core is saturated. The signal S_1 (S_2) becomes high if I_S is positive (negative). M_5 and M_8 (M_6 and M_7) are turned on to set I_D opposite of I_P . The net magnetic flux density $\overrightarrow{B_{net}}$ is obtained as follows.

$$\overrightarrow{B_{net}} = \overrightarrow{|B_{L1}|} - \overrightarrow{|B_{L2}|} \quad (3)$$

The resistors R_1 and R_2 are used to limit the magnitude of the desaturation current I_D .

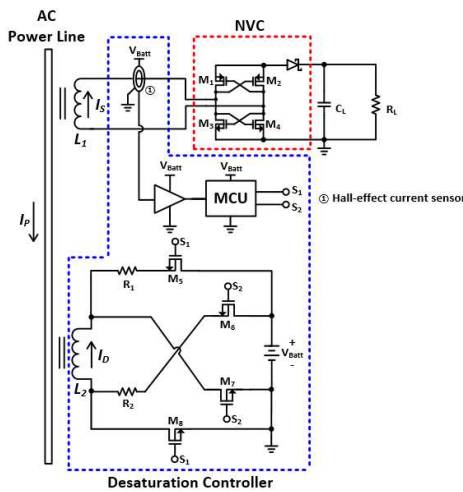


Fig. 8. Proposed powerline EH circuit with core desaturation.

A. Prototype and Experiment Setup

Fig. 9 shows a PCB prototype and experiment setup of the proposed circuit. The size of the PCB prototype is 51 mm by 110 mm. The MCU is Microchip Technology PIC16LF18446 on a development board DM164137, and the current sensor is TI TMCS1101. The powerline current is 25 A in rms with 50 Hz. The number of winding turns for both L_1 and L_2 is 100. Hereafter, all the current values are in rms unless stated otherwise.

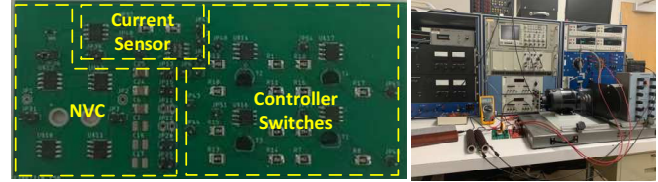


Fig. 9. (a) PCB prototype (b) experiment setup.

B. Secondary Current in Different Regions

Fig. 10 shows the waveforms of the induced current I_S obtained under the powerline current I_P of 20 A and 25 A without the proposed desaturation controller. The load resistance R_L is set to 1 k Ω for both measurements. The waveform of I_S is sinusoidal with little distortion under $I_P = 20$ A, implying the magnetic core operates in the linear region. As I_P increases to 25 A, the core enters the saturation region for certain time periods. The induced current I_S drops sharply even though the powerline current increases. It results in reduction of the amount of power harvested.

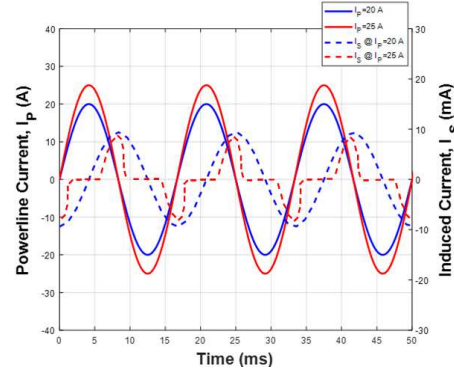


Fig. 10. Waveforms of the induced current I_S under the powerline current of 20 A and 25 A.

Fig. 11 compares the waveforms of the induced current I_S with and without the desaturation controller with the load resistance R_L of 1.3 k Ω and 0.9 k Ω , respectively, under the powerline current I_P of 25 A. It is evident that the rms value of I_S increases with the desaturation controller, implying increase of the harvested power.

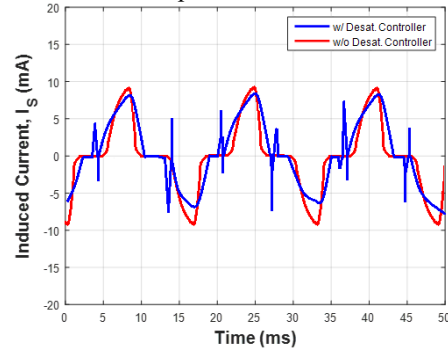


Fig. 11. Waveforms of the induced current I_S with and without the desaturation controller under the powerline current of 25 A.

The ultimate goal of the proposed desaturation controller is to increase the amount of power harvested. We measured the power delivered to the load resistor R_L for the proposed circuit with and without the desaturation controller. The current sensor is bypassed for “without” the desaturation controller and all the parts for the desaturation controller are disconnected. Fig. 12 shows the power delivered to the load or output power, in which R_L ranges from 0.1 k Ω to 3 k Ω . As R_L increases the output power increases initially for both with and without the controller. The power starts to decrease after it hits the peak power. The peak power *without* the desaturation controller is 37.5 mW for $R_L = 0.9$ k Ω . The peak output power *with* the desaturation controller is 65.8 mW for $R_L = 1.2$ k Ω . The desaturation controller increases the peak power by 75.5%. Note that the optimal load resistance R_L for peak power is 1.2 k Ω *with* the desaturation controller and reduced to 0.9 k Ω *without* the controller. It implies saturation of the magnetic core reduces the effective source impedance of the magnetic field energy harvester.

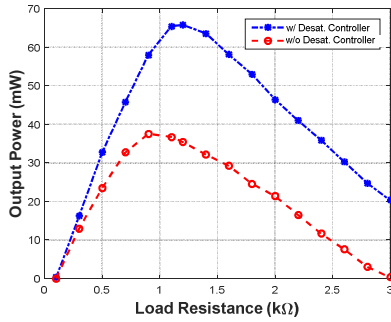


Fig. 12. Output power vs. load resistance with/without the desaturation controller.

The desaturation controller dissipates power, which is a loss. Hence, the amount of the harvested power is reduced by the amount of power dissipated by the controller. Table I lists a breakdown of the power dissipation of the controller at the peak output power.

TABLE I
POWER DISSIPATION BREAKDOWN

Parts	Power Dissipation (mW)
Current Sensor TI TMCS1101	2.81
Microcontroller PIC16LF18446	0.54
Two MOSFET switches	1.59
One current-limiting resistor	18.2
TOTAL	23.14

The desaturation controller dissipates 23.14 mW in total. Therefore, the peak harvested power with the controller is 42.66 mW (= 65.8 mW - 23.14 mW), implying the proposed circuit increases the amount of harvested power by 13.8 %.

V. CONCLUSION

A powerline energy harvesting circuit with a desaturation controller is presented in this paper. The proposed circuit adopts an MFEH with a desaturation coil to compensate the saturation effect of the magnetic core. The proposed circuit increases the harvested power by 5.2 mW or 13.8% compared

with a circuit *without* the controller under the powerline current of 25 A. For the proposed circuit, the current I_D for desaturation is fixed, resulting its effectiveness is limited for a certain range of the primary current. A powerline energy harvesting circuit with an adaptive desaturation controller is left for future work.

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