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An indoor power line based magnetic field energy harvester for self-powered wireless sensors in smart home applications

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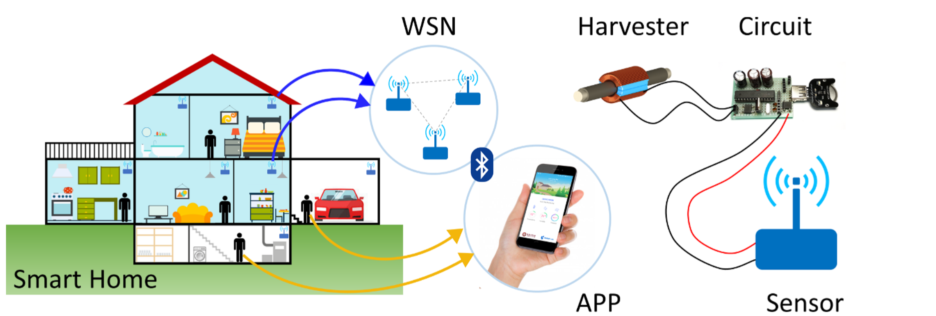
HIGHLIGHTS

- An indoor power line based magnetic field energy harvester for is presented.
- Easily clamping over power line without cutting or disturbing the power supply.
- Advanced PMC for reducing power consumption and storing harvested energy.
- Self-powered smart home monitoring system was successfully demonstrated.
- Software interface for mobile and web platform acquire and display WSN information.

GRAPHICAL ABSTRACT



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ABSTRACT

In smart home system (SHS), various IoT sensors are widely used for monitoring and security purposes. In order to detect fires, heat, potential disasters in early stage, and ensure the safety of electricity, real-time online condition monitoring of indoor power line is necessary. However, these monitoring sensors depend on batteries, either replaceable or rechargeable, which are less economical, have limited life time, are environmentally hazardous, and complex to replace. Herein, we present an indoor power line based magnetic field energy harvester (IPLEH), as a sustainable and maintenance free power supply for self-powered wireless monitoring sensors in smart home applications. The proposed IPLEH harvests energy from the magnetic field induced by a current carrying conductor without electrically contacting the conductor, that are easily available in indoor power line system. The IPLEH device consists of ferrite split-core which can be easily installed on the existing power lines without cutting or disturbing the power supply. The experiment results show that the proposed IPLEH can deliver an average power density of 14.67 $mWcm^{-3}$ (average power of 105.24 mW under the optimum load resistance of 230 Ω). In addition, different sensors applications such as temperature, humidity, human motion, and plant health, which are driven by the IPLEH, are successfully demonstrated. The wide applicability of the IPLEH and the experimental results are promising for the development of sustainable energy harvesters, that can be practically implemented in self-powered wireless monitoring systems for residential, commercial and industrial buildings.

1. Introduction

Autonomous sensors and wireless sensors networks (WSNs) have attracted much attention in the Internet of Things (IoT) industry as well as in the smart home system (SHS) [1–5] for the purpose of monitoring, control and automation. In residential, commercial, and industrial buildings, lots of electrical wiring required for lighting, power distribution, heating, and communication networks. Although, safety

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regulations are implemented during the electrical installation, many undesired circumstances such as short-circuit, firing, etc. occurs because of overload, heating, temperature variation, aging effects, etc. To detects the potential disasters in early stage, continuous monitoring of power line is essential. Different IoT based wireless sensors such as power consumption, temperature, light, gas, and so on, are being used for the monitoring [6–10]. A study on the smart home market shows that the SHS market will be worth $53.45 billion by 2022, which shows the importance and growing tendency of the SHS [11]. According to the CISCO Internet Business Solutions Group, the IoT has already become a distinct entity as more devices than humans are connected to the internet [12]. A study shows that, the number of IoT-connected devices will exceed 45 billion by 2020 [13]. The use of SHS provides a comfortable, safe, relatively low power and convenient lifestyle by enabling intercommunication between household appliances such as lights, heating, ventilation, and air conditioning (HVAC) systems, TVs, computers, entertainment systems, and security systems. However, most of these sensors are powered by either replaceable or rechargeable batteries. The major issues involved in the use of those batteries are their limited life time, environmentally hazardous nature, high cost, and complex replacement procedures. Therefore, there have been many attempts to harvest energy from ambient environment, in order to enhance the battery-life and finally develop self-powered wireless autonomous sensors. Different energy harvesting technologies have been reported for wireless monitoring sensors, including radio-frequency [14–16], light [17], piezoelectric [18,19], electrostatic [20], electromagnetic [21–26], triboelectric [27], and thermoelectric [28,29] mechanisms. But for the indoor sensor application, there is no physical source of energy such as wind, light, thermal, etc. This limitation creates challenges to harvest energy in indoor environment. Therefore, for indoor energy harvesting, one of the promising source is magnetic field from the indoor power lines in the electrical system installed in home, buildings and factories. Every current carrying conductor creates the time-variant magnetic field around it which can be a sustainable source of magnetic field energy and harvesting that energy can leads to the development of self-powered sensors [21–23,30–36]. The output performance of the different magnetic field energy harvesters related to indoor and outdoor power lines, are shown in Table 1. In indoor electrical system in building, industries, and factories, the current carrying power lines are easily available, which creates the magnetic field around it. In case of residential building, current carrying power cords are available at along with home appliances, extension power cords and wall power outlet. Those all current carrying power lines are the good source of magnetic energy which can be harvested for driving variety of sensors and monitoring devices. Variety of design, principle and methods such as transformer based have been implemented for harvesting magnetic energy from power line both in indoor and overhead lines. To our knowledge, most of the previous magnetic energy harvesters were either bulky in design, complicate in usability and installation which makes the practical application more complicated. Also, the harvester is not feasible for typical two-wire power lines in indoor electrical system. Another challenge is the design of the harvester, which must have capability to install on the existing indoor electrical system. This research is mainly focused on solving these challenges in order to develop self-powered wireless monitoring sensors for indoor smart home applications.

In this paper, we present an indoor power line based magnetic field energy harvester, to harvest the time-variant magnetic field around the power conductor line in indoor electrical system. The harvester can provide continuous electrical power for a variety of monitoring sensors, microprocessors, and wireless communication modules in the SHS. Finite-element-method (FEM) simulations are performed to understand and analyze the distribution of the magnetic flux density, thus improving the harvester design. The harvester power successfully drives variety of monitoring sensors such as temperature, humidity, motion, and pressure along with wireless communication with Bluetooth. The power harvested during sleep mode of sensors can be accumulated and stored in storage units such as capacitors and rechargeable batteries, which can then supply the required power to sensor nodes during the active mode even though there is no current flow in the power conductor. Therefore, the combination of a continuously harvesting generator and storage unit facilitates the development of a self-powered WSN system and IoT devices for the SHS. This effort clearly demonstrates the potential of IPLEH as small-sized, cost-effective, sustainable, and maintenance-free energy harvester in the aim to provide electrical power sources for continuous monitoring sensors in smart home system.

2. Results and discussion

2.1. Harvester device configuration

The schematic structure of the proposed IPLEH is shown in Fig. 1a. The miniaturized energy harvester device consists of a ferrite split-core (two C-shaped ferrite cores). The ferrite core has an outer diameter of 22 mm, inner diameter of 13 mm, and height of 29 mm. The IPLEH is capable of installing it over the current-carrying conductor with a polyvinyl chloride (PVC) insulation at the outer layer, as shown in Fig. 1a, such that both of the coils will cut the magnetic field lines generated by the conductor. Because of the split-core nature, the harvester device can be easily wrapped around the existing current-carrying conductor without cutting the wire or power-cut because of its split-core structure. This is important for the installation of the monitoring sensor without cutting the power conductor or interrupting the power supply. This split-structure of the harvester device is important because, if the core is a single solid structure, it needs to be installed during the installation of the conductor, or the conductor cable needs to be cut, which will interrupt the continuous power supply.

2.2. Theoretical analysis

To attain a quantitative understanding of the theoretical modelling of the IPLEH, we started with a coil near a current-carrying conductor, as shown in Fig. 2a. The quantity of the induced ac voltage in the coil resembles the total power available at the output of the harvester. According to electromagnetic theory, the magnetic flux density B_s due to a current-carrying conductor with an infinite length, at a radial distance r from the center axis of the conductor, is given by

Table 1
Comparison of the output performance of magnetic field energy harvester.

Refs.	Coil turns	Core material	Core structure	Volume (cm^3)	Average power (mW)	Average power density (mW/cm^3)	Line current (A)
[21]	3000	Ferrite	Rectangular	58 × 50 × 39	57.4 (calculated)	0.507	9
[22]	280	Mu-metal	C-core	1.79	10	5.58 (calculated)	13.5
[23]	2000	FeSiB	C-core	2.89	63.72 (peak)	22.01 (peak)	10
[31]	8000	Ferrite	Bow-Tie	180	0.812	0.0018	–
[35]	400	Ferrite	Helical	Ø50 × 150	0.612	0.0021	50
[36]	40,000	Cast Iron	Solenoid	981	0.3	1.8	400
This Work	1600	Ferrite	C-core	7.17	105	14.67	65.3