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Experimental Results on Magnetic Cores for Magnetic Induction-Based Energy Harvesting

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Abstract- In this work it is presented an energy harvesting system based on disperse magnetic energy produced by electric current across power line of a power distribution network in order to supply energy for devices in a wireless sensor network. The system is based on toroidal cores tested and validated with different materials and dimensions (five based on ferrite, seven based on nanocrystalline, seven based on iron powder) aiming harvesting optimal power device. From principles of magnetic ferromagnetic materials, it is discussed the magnetic field theory to obtain energy for supplying power to devices. It was implemented a prototype consisting of a test bench capable of emulating power-line high currents and of a power conditioning circuit. Test procedures were executed in three parts. The first was to determine the magnetic parameters (*e.g.* relative permeability and magnetic curve) of each harvester using a circuit able to measure core permeability in order to obtain B x H cycle. The second was to test a proposed power conditioning circuit composed of an AC/DC rectifier and a voltage regulator. The third, the experimental results were compared with theoretical ones. The obtained experimental results have been in agreement with theory, showing that the energy harvesting system is capable of supplying up to 315.6 mW from ferrite based core, 54mW from nanocrystalline based cores and 0.77mW from iron powder based ones, by capturing magnetic dispersion produced by a 15A current in the power line, which can be applied to various low power devices, mainly in wireless sensor network for data acquisition and control parameters of the power line itself.

I. Introduction

Nowadays, a high development of low power electronic devices and wireless communication technologies are observed, providing, for example, a growing use of wireless communication networks. Specifically, Wireless Sensor Networks (WSN) is getting attention of researchers. In general, WSNs are powered by batteries, but their maintenance services depend, in general, on the location of the sensor nodes, which can be difficult or impossible to achieve. In this way, battery-less node devices are welcome. Lately, there is a clear tendency in harvesting energy from environment in order to achieve either battery-less devices or somehow devices with integrated battery charger. Energy Harvesting is the process of capturing small amounts of energy from energy sources available in environment, for example: thermal, solar, mechanical, etc. A possible energy-source takes place around power lines of power distribution network, namely, magnetic field based induction. In this way, it is possible to harvesting energy to, for example, supply sensor nodes to monitoring environment variables near the power lines.

In an example of application, [1] describes an approach of several existing technologies for energy harvesting applied in sensor nodes and, from the evaluated technologies, the energy harvested by magnetic field using magnetic cores has been demonstrated the most promising achieving 250mW.

In [2] it was proposed an inductive harvester for use in locations where there is a magnetic field around inaccessible conductors and experimental results have shown that it can provide 300 μW with a magnetic flux density of 18 μT.

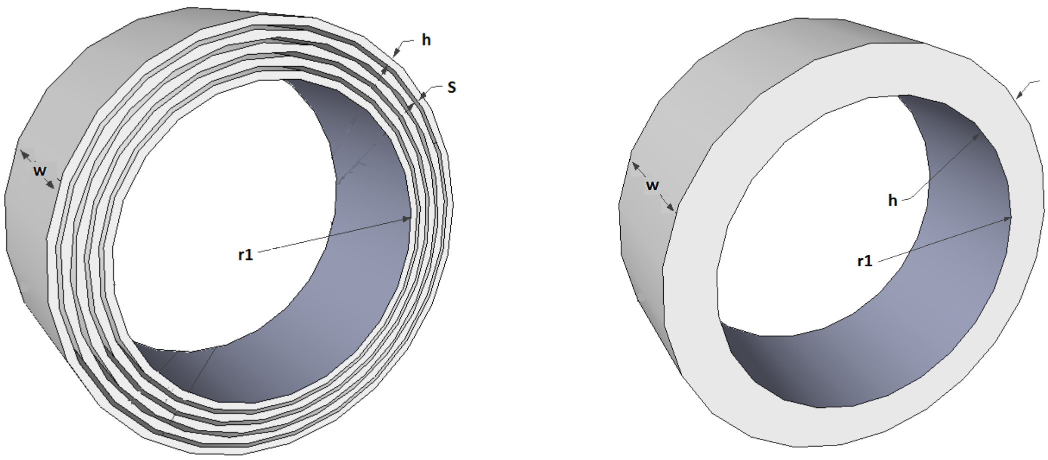
In [3] it was proposes a micro magnetic-induction based harvester for low-power devices which a tiny core consisting of five blades was capable of applying 10mW in a load of 50Ω.

In [4] it was performed some experiments that have shown that the dimensions, shape and materials forming the magnetic cores interfere in the process of harvesting energy from magnetic field.

In this work it is presented an energy harvesting system based on disperse magnetic energy produced by electric current around power line of a power distribution network which can be applied to supply energy for devices in a wireless sensor network. The main results are from the comparative analyze among experiments carried out with different magnetic cores: five of ferrite, seven of nanocrystalline e three of iron powder.

II. Basic Magnetic Field Theory

In this section, a mathematical modeling for the magnetic flux on each magnetic and insulated blades was made considering nanocrystalline cores, which are laminated, and ferrite and iron powder cores, but these are solid. Figures 1 (a) and (b) show a drawing of nanocrystalline cores and ferrite and iron powder ones, respectively. The cores provide magnetic paths for concentrating the magnetic flux generated by the current flowing in the internal conductor (not shown in the figures) which passes in the central of the cores.



(a) (b)

Figure 1. Perspective drawing of cores: (a) Nanocrystalline, (b) ferrite and iron powder.

It can be demonstrated from the basic expression of magnetic flux, $\phi = \int BdA$, that:

$$\phi_L = \frac{\mu_m I \sin(\omega t)}{2\pi} w \int_{r_L}^{r_f} \frac{dr}{r} \qquad (1)$$

which follows:

$$\phi_L = \frac{\mu_m Isen(\omega t) w}{2\pi} \ln\left(\frac{r_L + h}{r_L}\right) \qquad (2)$$

where ϕ_L : magnetic flux of the magnetic L-th blade of the core (where $0 < L < N_L$, N_L = number of core blades) and r_L is the radius of the L-th blade.

Similarly, now considering the insulating blades, it is obtained:

$$\phi_P = \frac{\mu_0 Isen(\omega t) w}{2\pi} \ln\left(\frac{r_P + S}{r_P}\right) \qquad (3)$$

where ϕ_P: magnetic flux of the magnetic P-th blade of the core (where $0 < P < N_{L-1}$) and r_P is the radius of the P-th blade.

Considering now that is a coin wounds around the core with N_2 turns. In this way, the output voltage of coin terminals, according to Faraday's Law, is expressed as:

$$V_S = -N_2 \frac{d\phi_T}{dt} \qquad (4)$$

where ϕ_T is the total magnetic flux. ϕ_T can be obtained by the summation of the magnetic flux through the magnetic and insulating blades:

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$$\frac{d\phi_T}{dt} = \sum_{L=1}^{L=n} \frac{d\phi_L}{dt} + \sum_{P=1}^{P=n-1} \frac{d\phi_P}{dt} \qquad (5)$$

where:

$$\frac{d\phi_L}{dt} = \frac{\mu_m I \omega \cos(\omega t) w}{2\pi} \ln\left(\frac{r_L + h}{r_L}\right) \qquad (6)$$

$$\frac{d\phi_P}{dt} = \frac{\mu_0 I \omega \cos(\omega t) w}{2\pi} \ln\left(\frac{r_P + S}{r_P}\right) \qquad (7)$$

To obtain theoretical results, it was considered as parameters the core dimensions: *w*, *h*, *S*, and *r1* (internal radius), as shown in Figure 1.

III. Experimental Study

In order to obtain experimental data and validate the theoretical analyzes, it was developed a pilot plant capable of emulating the line current of a power distribution system, as shown in Figure 2. This plant consists of a bench containing ten load resistors of 220Ω (200W). The nominal voltage is $220V_{RMS}$. To switch the load currents, it was used switches. To evaluate each core considering different materials and dimensions, the primary conductor is surrounded by the core, as seen in Figure 2. The secondary coin is connected to a simple power conditioner circuit (PCC).

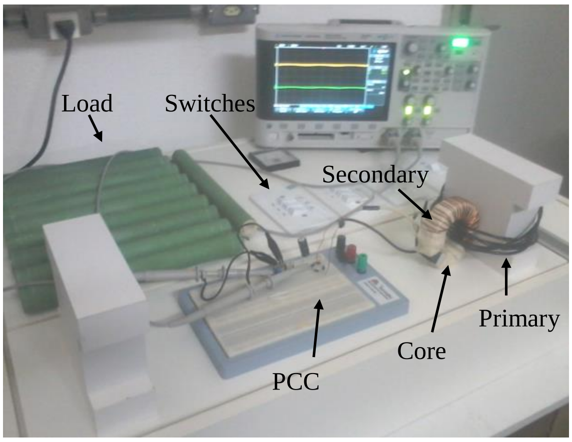

Figure 2. Test Bench.

The proposed PCC comprises a simple rectifier/filter scheme and a variable resistor as load, as seen in Figure 3.

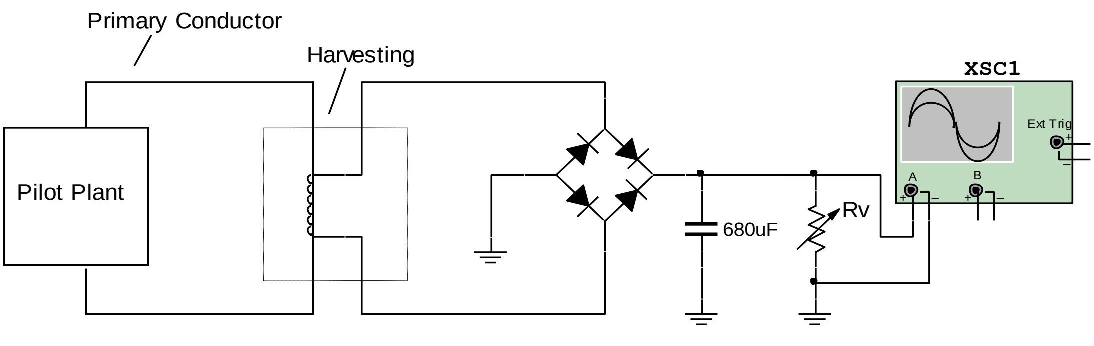

Figure 3. Power conditioning circuit.

IV. Experimental Results

After performing several experiments with the 15 magnetic cores (5 of ferrite, 7 of nanocrystalline, and 3 of iron powder) and considering the load R_V ranging from 10Ω to 2kΩ, it was possible to obtain the maximum power and maximum DC voltage for each core. The results are depicted in Figure 4, Figure 5 and Figure 6 for ferrite cores (cores F4, F3, F2, F1.1, F1), nanocrystalline cores (cores NC1, NC1.1, NC2, NC3, NC3.1, NC4 and NC4.1), and iron powder cores (cores P3, P4.1 and PE) , respectively.

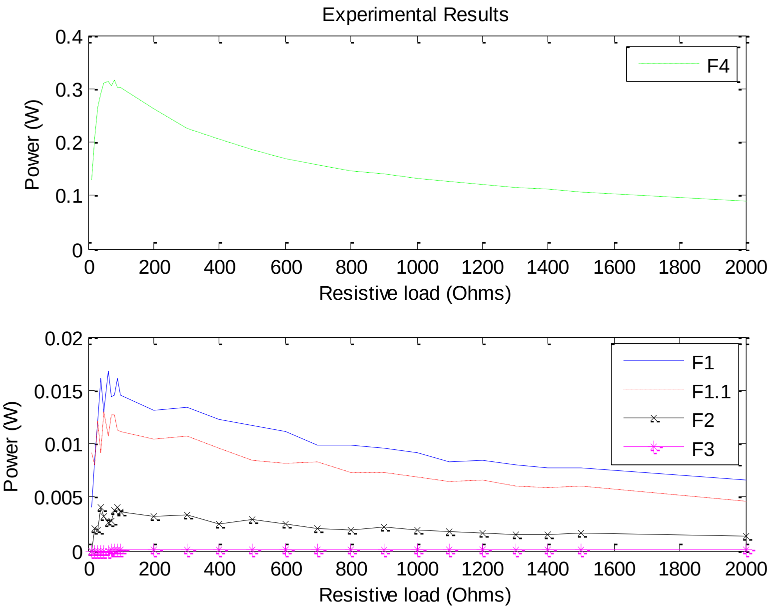

Figure 4. Power levels obtained by variation of *Rv* considering ferrite cores.

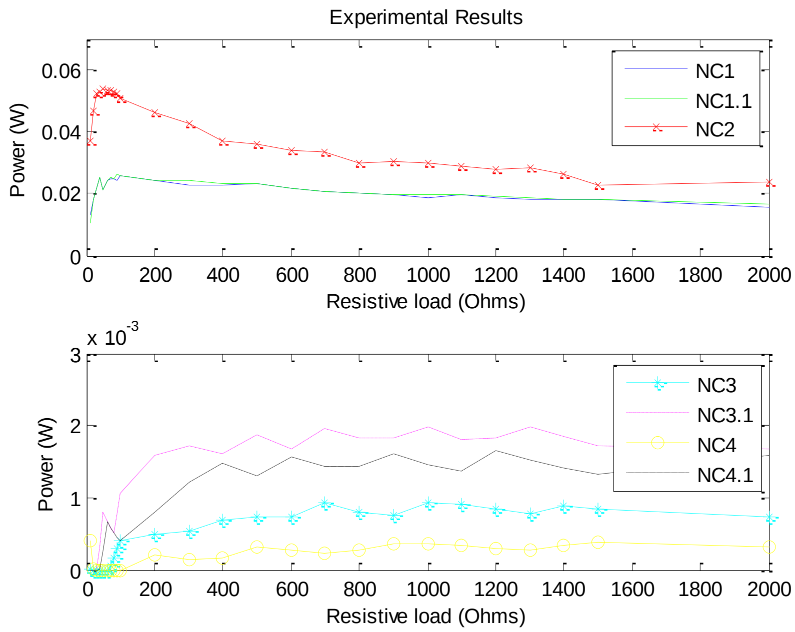

Figure 5. Power levels obtained by variation of *Rv* considering nanocrystalline cores.

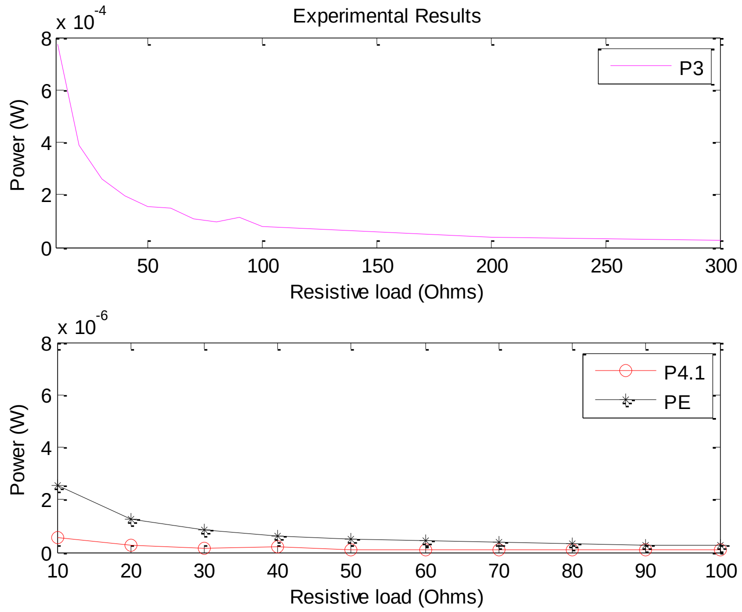

Figure 6. Power levels obtained by variation of *Rv* considering iron powder cores.

Considering the power obtained from different cores, the best obtained results were: ferrite core F4, following by the nanocrystalline core NC2, and iron powder core P3, as shown in Figure 7. Table 1 shows the values of voltage, load current, RMS voltage, and peak voltage measured at the terminals of the secondary coin, before the PCC and the value of Rv at the instant of maximum power.

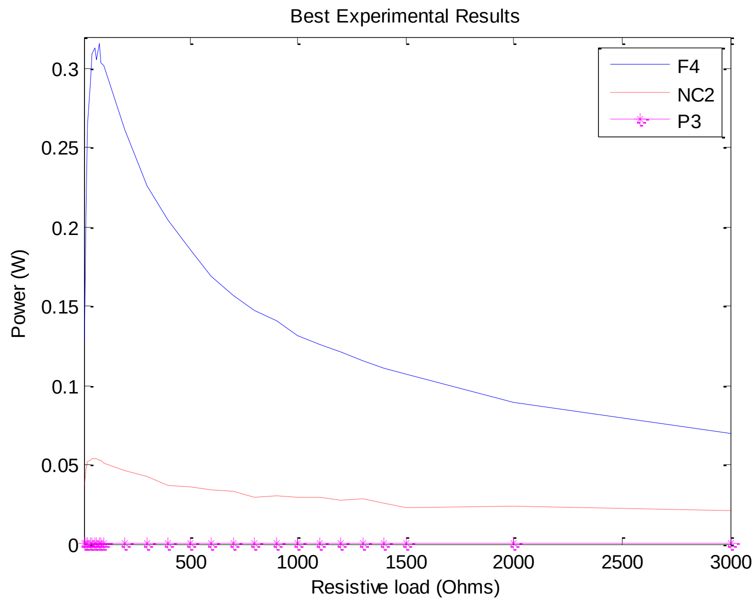

Figure 7. Best obtained results.

Material		Best Results					
		V (rms)	V (peak)	V (load)	I (load)	P (load)	Rv (load)
		[V]			[mA]	[mW]	[Ω]
Ferrite	F4	5,47	7,23	5,025	62,8	315,6	80
Nanocrystalline	NC2	2,03	3,43	1,64	32,9	54	50
Iron Powder	P3	0,084	0,179	0,0889	8,8	0,77	10

Table 1. Experimental best results.

V. Conclusions

For the experimental results, it was possible to obtain 315.6 mW of power, 5 Vcc and 80Ω from ferrite core, 54mW, 1.64Vcc, 50Ω from nanocrystalline core and 0.77mW, 88.9mV, 10Ω from iron powder, considering $15A_{RMS}$ current on the primary conductor. Finally, it is concluded that use of ferrite based energy harvesting system is more feasible for power supply to low-power devices and it was found that using nanocrystalline core, the saturated point is very small, although having a high relative magnetic permeability.

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