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100 μW Coreless Flyback Converter for microbial fuel cells energy harvesting

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Abstract—The microbial fuel cells (MFCs) are emerging energy harvesters that are promising for the autonomous supply of seafloors remote sensors. Regarding the low voltage and power level delivered by MFC an electrical interface is required to condition the sensors needs. The flyback in discontinuous conduction mode appears to be the best candidate to extract the maximum power delivered by the MFC, to electrically isolate the sensor from the source and to boost the voltage to the one required by the energy buffering. Our work highlighted the significant impact of the magnetic core loss of coupled inductances on the power efficiency decrease, mainly due to the hysteresis and magnetic saturation even at μ -scale energy transfer. In this paper, we propose to remove the magnetic core to suppress these previously mentioned losses. The low density harvested power (100 μW for 10th cm^2 electrodes) and low-size constraint i.e. m^2 -scale in seafloors remote sensors application allow to use 0.5 m^2 air-core inductance. By plugging a 20- cm^2 MFC delivering a maximum power of 90 μW at 0.3 V, the proposed air-core based flyback achieved 60% efficiency experimentally. This figure correctly matches simulations in which a model of the coreless coupled inductances, extracted from experimental characterizations, is used. This work is the first to validate the concept of a flyback with coreless coupled inductances harvesting 10th of μW s.

Keywords— Energy harvesting; Coreless transformer; Coupled coils; Flyback converter; Impedance matching; Microbial fuel cell

I. INTRODUCTION

During the last two decades, there has been a growing interest in a high amount of energy sources around the sensors that could potentially replace chemical batteries and power sensor nodes, making them autonomous. Most researchers currently focus on thermal, solar and vibrational energy sources since they propose relatively good energy debit [1]. Recently, attention has been paid to microbial fuel cells (MFCs), an emerging and innovative way to scavenge energy from waste materials around a sensor. In substance, microbial fuel cells convert chemical energy from a large range of carbonate substrates (such as oolitic aragonite, crushed marble, or coral skeletons) into useful electrical energy [2,3] thanks to bacteria catalysis properties. The main drawbacks of this energy source are the low kinetics of oxydoreduction reaction (around 100 μW for 20 cm^2 -scale) and its low oxydoreduction potential generated (lower than 0.6 V) which is usually not sufficient to directly reach the operating voltage range of a sensor node.

In order to maximize the harvested power, store the energy and use it to supply the sensor nodes, an electrical harvesting interface is required as others sources. This interface allows increasing the voltage up to usable tension, 2 V in this paper, and adapting its input impedance to MFC one, thus extracting the maximum possible power from the cell. The use of a flyback converter in discontinuous mode ensures this adaptation as well as an isolation between the source and the energy buffering which allow to apprehend MFCs parallel/series connections.

The main flyback losses observed in previous work [4] are due to the magnetic losses in the magnetic core. Using a coreless transformer eliminate the magnetic losses and allow to not be constrained by the switching frequency boundary imposed by the saturation. However, at equivalent size the coreless transformers are several orders of magnitude less inductive than transformers with magnetic core. The size needed to provide an equivalent transformer makes it totally unsuitable in most cases. However, the MFC has a poor power density ($\mu\text{W}/\text{cm}^2$) then the tens of cm^2 required for the electrode can be shared with an air transformer as shown in Fig.1. However cuts need to be made in the conductive electrodes perpendicularly to the generated eddy current in order not to reduce the effective quality factor of the coupled coils.

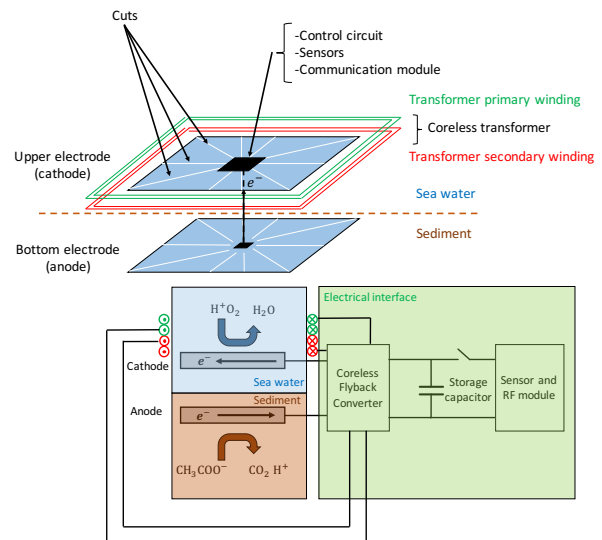


Fig. 1. Prototype and schematics of the biofuel cell and its coreless interface.

This paper proposes to replace the classical magnetic core transformer with an air core transformer in a flyback converter interface for MFC. The first section presents briefly the harvesting system. In a second section, we present the design and optimization of a well-purposed coreless transformer. In the last section, simulations and experimental results are shown and discussed.

II. HARVESTING SYSTEM MODEL AND ANALYSIS

A. Electrical characterization of the MFC and MPP

The static behavior of the MFC has first been studied in [4]. It has hence been proven that there is a large voltage range where the behavior of the MFC can be considered linear. Thus, in this range, the MFC can be assimilated with a voltage source ($V_s = 0.6V$) in series with a resistance R_s . If the cell is less than 1 m^2 the MFC resistance R_s can be estimated by $R_s = 2.6/S$, with S the electrodes surface in m^2 . Based on these considerations, we can conclude that the maximum power PMPP extracted from a MFC can accurately be given by (1). The associated working point is called maximum power point (MPP) and is reached when the output voltage of the cell is equal to $\frac{V_s}{2}$.

$$P_{MPP} = \frac{V_s^2}{4 \cdot 2.6} [W/m^2] \quad (1)$$

B. Transformer model and characterisation

In magnetic core transformers, the use of a ferromagnetic core increases the magnetizing inductor, since the magnetic permeability of the water is decades lower than the classical magnetic material one (table 1).

TABLE I. MAGNETIC PERMEABILITY

Ferrite	Air	Water
$> 100 \mu H/m$	$1.25 \mu H./m$	$1.25 \mu H/m$

Consequently, for the same topology the magnetizing inductor L_m is more than several decades lower for air-coupled coils (3). In order to have a sufficiently high magnetizing inductor while keeping a good coupling, substantially large coils has been used. The well known equivalent model of a coreless transformer taken from [5] is shown in Fig. 2. C_{p1} and C_{p2} are the parasitic inter-winding capacitances crated by the electrostatic coupling between the wires. R_1 , R_2 , represent respectively the coper losses, L_{e1} , L_{e2} , are the leakage inductances and the parasitic of the primary and secondary. L_m is the magnetizing inductance of the coreless transformer. R_{s1} and R_{s2} have been added in order to take in account the skin effect in the transformer.

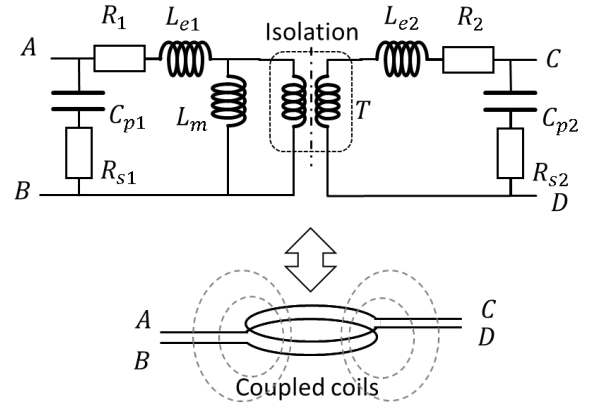


Fig. 2. Equivalent model of a coreless transformer

The coupling factor k can be calculated using (2).

$$k = \frac{L_m}{L_m + L_{e1}} \quad (2)$$

In order to design the coreless transformer, considering a perfectly circular shape and perfectly coupled coils the values of the equivalent model can be estimated using (3).

$$L_m + L_{e1} = N^2 \mu_0 R \left(\ln \left(\frac{8R}{a} \right) - 2 \right) \quad (3)$$

Where N is the number of turns, a is the wire radius and R is the wire diameter (5).

$$R_1 = R_2 = \frac{2R\rho}{a^2} \quad (4)$$

Where the copper resistivity is $\rho = 1.68 \cdot 10^{-8} \Omega \cdot m$.

C. Impedance matching using a flyback

The linearized input impedance of a flyback in discontinuous conduction mode can be expressed as

$$R_{IN} = \frac{2(L_{e1} + L_m)f}{D^2} \quad (5)$$

With D the duty cycle of the flyback control voltage, L_1 the primary inductance of the flyback transformer and f the switching frequency of the flyback.

The losses introduced by the electrical converter can be split up into:

- Magnetic losses in the transformer core
- Conduction losses in the transformer, diode and MOSFET.
- Switching losses in the diode and MOSFET.

The energy stored in the primary leakage inductor is lost as it cannot be transferred to the secondary windings, the power loss can be approximated with

$$P_{leakage} = \frac{L_{e1}}{2f} \frac{(0.3D)^2}{(L_{e1} + L_m)^2} \quad (6)$$

The conduction losses in the transformer and the MOSFET are theoretically given by:

$$P_{conduction} = (R_1 + R_{ds(on)})I_{1rms}^2 + R_2I_{2rms}^2 \quad (7)$$

Without the resistive elements the root mean square currents can be approximated by:

$$\begin{cases} I_{rms1} = \frac{0.3D^2}{fL\sqrt{3}} \\ I_{rms2} = \frac{2(0.15D)^2}{fL\sqrt{3}} \end{cases} \quad (8)$$

The losses induced by the gate capacitance of the transistor can be expressed by:

$$P_{switch} = C_{gate}V_g^2f \quad (9)$$

III. CORELESS TRANSFORMER DESIGN AND MODELING

A. Design of the transformer

The MOSFET (FDV301N) and the diode (BAT54) used in the experimental setup (Fig. 3) has been simulated with Spice equivalent models given by the manufacturers.

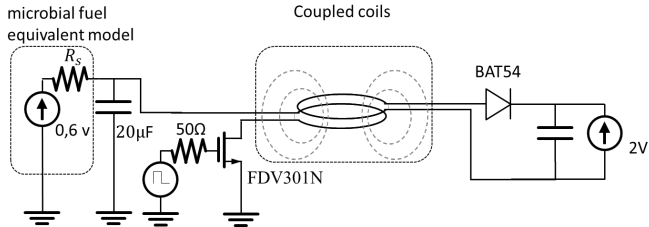


Fig. 3. Experimental coreless transformer based flyback

In order to keep the command losses P_{switch} below $2\mu W$ a switching frequency of 5 kHz is used. As seen on equation (5) a significantly smaller duty cycle is used in order to keep R_{IN} equal to R_s . In order to have a pulse width higher than 5 % the primary inductance have to be superior to $325\mu H$. To have around half meter square area a 60cm diameter transformer is used.

To see the impact of the number of turns chosen, the elements of the equivalent model of the transformer have been calculated and the associated converter simulated, as shown on Fig 4 an optimum is reached around 17 turns.

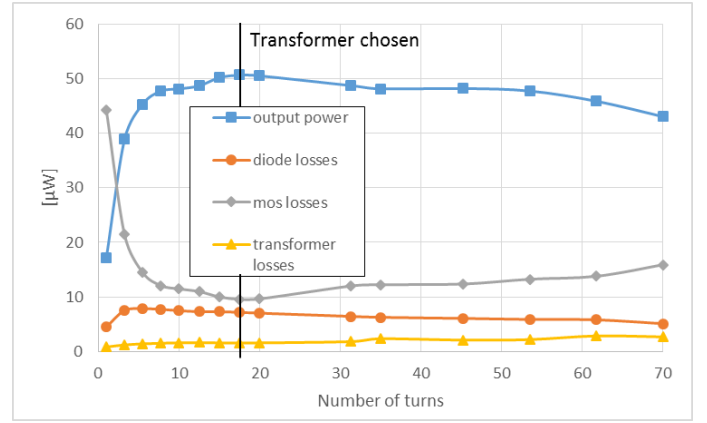


Fig. 4. Simulated power delivered by the coreless transformer and the losses created in the proposed interface

B. Characterization of the coreless transformer used

Our air-core transformer has been characterized using an impedance analyzer. Using a gradient algorithm, we found the set of parameters that could fit the equivalent model with the experimental data. Those parameters are given in Table II.

TABLE II. TRANSFORMERS PARAMETERS.

Parameters	Coreless transformer	Classical Transformer [4].	Units
	Parameters values	Parameters values	
R_1	1.2	0.35	Ω
R_2	1.2	0.35 Ω	Ω
L_{e1}	30	0.155	μH
L_{e2}	30	0.155	μH
C_1	391	3	pF
C_2	391	3	pF
L_m	642	18000	μH
R_{s1}	49.5	Not measured	Ω
R_{s2}	49.5	Not measured	Ω
R_p	$+\infty$	6	K Ω
k	0.955	0.99	

IV. EXPERIMENTAL VALIDATION AND SIMULATION

The experimental setup used in order to realize the measurements is shown in Fig. 5. The experiment has been made with a 20 cm² MFC mimicked by a Thevenin generator, ($V_{in} = 0.6$, $R_s = 1.3$ k Ω). Theoretically, the maximum power calculated using (1), is equal to 69.2 μW . Experimentally, with a 2 V output voltage, 43.2 μW has been transferred at 5 kHz, 13% lower than the expected performance Fig.4. If the power needed for the command of the MOSPHET (1.8 μW) is removed global efficiency achieved is = 60 % which is close to the 70% achieved by the BQ25570 of Texas instrument for the same input voltage.

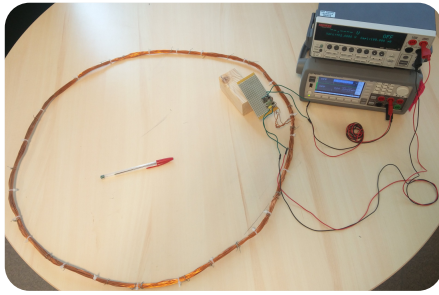


Fig. 5. Experimental setup

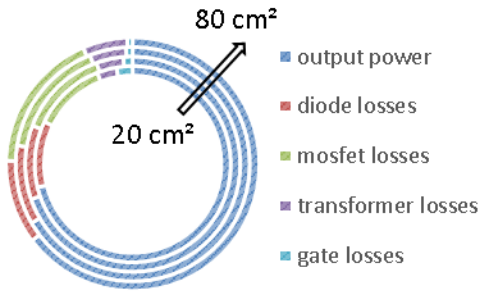


Fig. 6. Distribution obtained by simulation of the power extracted from the MFC for different electrodes surfaces, 5KHz but optimised duty cycle .

From Fig.6, we can notice that, with larger electrodes, the losses in the transformer and in the MOSFET increase. Indeed, the currents increase, leading to higher losses. The losses induced by the command of the transistor remain the same as long as the same component is used.

As seen in Table II, the coreless transformer presents a 28 times lower magnetizing inductor value and a leakage inductor 200 times higher. On the one hand the low magnetizing inductor is compensated by the reduction of the duty cycle, however the ringing phenomenon is amplified for both sides of the transformer. The magnetizing inductor being lower and the duty cycle smaller, the current peak is significantly increased from 1.2mA for the classical transformer to 6.2mA for the coupled coils. The winding being 3.5 times more resistive and the RMS current 2 times higher, the conduction losses are also increased. Theoretically these losses are increased from $0.6\mu\text{W}$ for the classical transformer to $3.8\mu\text{W}$ for the coupled coils.

On the other hand, the coupled coils are completely removing the magnetic core losses. The current passing through the transformer is not limited by the saturation of the transformer, the surface of the MFC can be increased without having to adapt the transformer. The duty cycle being extremely low a transformer with multiple primary and only one secondary could be used. Such a structure would minimize the number of components and copper used.

V. CONCLUSION

In this paper, we designed and realized for the first time a coreless transformer based electrical harvesting interface for microbial biofuel cells. We proved, using simulations and experimental measurements, the consistency of the proposed concept. The use of an air core allows to remove the magnetic losses and to get rid of the saturation constraint. In order to keep the consumption of the converter and its control module a low frequency is used. This first prototype achieved 60% efficiency for an output power of $43\mu\text{W}$.

Investigations have to be made regarding the magnetic field interactions with the water. The subsequently low amount of energy transferred imposes a specific design of the flyback structure, from the transformer to the active components through the snubbers.

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