Contactless Battery Charger for Composite Humidity and Temperature Wireless Sensors

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Abstract – **This paper presents the analysis and design of a DC-DC series resonant power converter used as a contactless battery charger (5V$_{DC}$ – 1A) for a mobile electronic device. The system is enclosed in a sealed spherical pack containing temperature and humidity wireless sensors for real time composting process monitoring.**

Some particular characteristics of the device and its physical dimensions impose a maximum distance between the primary and the secondary transformer windings of 20mm. For transformer type core and windings configuration selection criteria, an experimental characterization of loosely coupled power transformers was evaluated.

Both simulation and experimental results, obtained in a 150kHz laboratory prototype, were used as evidence of the developed theoretical models and analysis.

Keywords **— Loosely coupled transformer, Contactless DC/DC resonant converter, Wireless transmission system.**

I INTRODUCTION

ACOMPANYING the recent emergence and development of electronic portable equipment, contactless electric energy transfer is gaining importance and a lot of research work is being carried out, especially in the area of battery chargers. In these applications, the transformer primary and secondary windings are physically separated by a distance that is usually much less then the dimensions of the cores/coils [1-14]. The existence of a non negligible distance between the primary and the secondary produces, in most cases, the increase of the leakage inductors and the reduction of the magnetizing inductance, resulting in a loosely coupled power transformer with low coupling coefficient.

The ratio between the core dimensions and the distance between transmitter and receiver, as well as the amount of energy to be transferred are important variables to design contactless systems. Physical dimensions of the electric devices are confined to certain limits depending on the application and on the power involved. If the distance between transmitter and receiver exceeds a defined limit, the coupling coefficient may be excessively low, leading to an impracticable efficient transmission, unless some way of improving the coupling factor is found [15-18]. Investigation on this area comprises the development of new circuit combinations, new transformer configurations and modeling and new control processes that may improve the efficiency and performance of the energy transfer.

This paper presents the analysis and design of a contactless DC-DC series resonant power converter aimed as a battery charger (5V$_{DC}$ – 1A output) for an electronic system used to monitoring the temperature and humidity during composting processes. The system is enclosed in a sealed spherical pack using temperature and humidity wireless sensors and also contactless battery charging. Due to the characteristics and physical dimensions of the device a maximum air-gap of 20mm was adopted between primary and secondary transformer windings. Considering the dimension and physical limitations of the system, the amount of power to be transferred and the air-gap dimensions, a transformer model was developed to select the transformer core type and windings configuration that would lead to an acceptable coupling coefficient, and therefore to an improved efficiency. Simulation and experimental results were obtained in a laboratory prototype to verify the theoretical principles.

II CONTACTLESS BATTERY CHARGER

Due to the system characteristics and its dimensions the contactless battery charger will present a primary-secondary spacing length that is of the same order as the core dimensions and will be in the border between near and midrange fields systems. Furthermore, because the secondary inductor must be placed inside the ball its dimensions are limited.

One objective of the compo-ball project is to implement a rechargeable battery inside a ball to supply the electronic circuitry that is also placed in the ball interior. As explained above, the battery charger, being a contactless energy transfer system, will present a transmitter placed outside the ball and a receiver inside it. The transmitter will be composed by a static high frequency series resonant inverter and the transformer primary. The receiver will include the transformer secondary, the diode bridge and the capacitive filter. The control circuit will be placed in the receiver also. The first approach for the system design consisted in the definition of a range of possible distances between the transmitter and receiver. In [19] a similar application without contactless energy transfer system to charge the battery is presented as an alternative unsealed solution.

Considering a ball with an external radius of approximately 50mm, and the aggressive environment where it will be immerged, it was adopted a 10mm thickness to ensure ball robustness. Based in these dimensions, an air gap maximum of

20mm was considered. Several transformer configurations with different core shapes, coils, number of turns and air-gap dimensions were modeled, experimented and simulated. As expected, when using ferrite cores for magnetic flux confining, it was confirmed that the coupling factor was independent of the coils number of turns, depending only in the core geometry and on its magnetic properties, being highly dependent of the air-gap size. For an air-gap of 20mm very low coupling coefficient was obtained, forcing the rise of the transformer primary current magnitude. This last particularity compromises solutions based in the use of ferrite cores due to the inherent saturation of the magnetic cores. A coreless transformer made by two equal spiral concentric inductors, as shown in Fig. 1, was used instead.

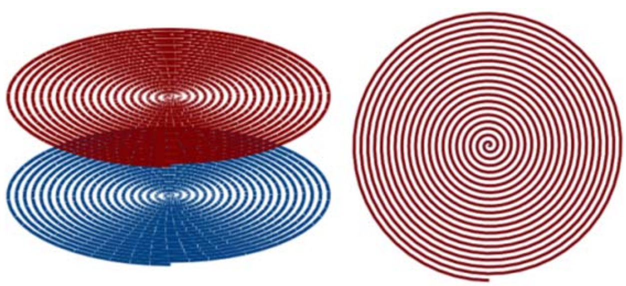

Fig. 1 – Coreless transformer windings configuration, used for contactless battery charging.

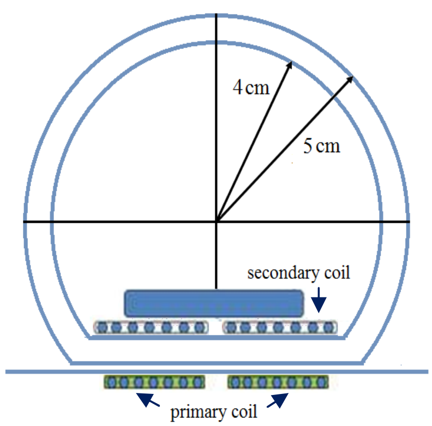

Fig. 2 – Structure of the spherical pack showing the receiver and transmitter spiral planar coils and their physical limitations.

III Transformer Model

In order to calculate and optimize the coupling factor, experimental and theoretical modeling of the transformer was evaluated. To establish the transformer models, one must consider the self and mutual inductances of both primary and secondary coils, as expressed in (1).

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \Psi_1 \\ \Psi_2 \end{bmatrix} = \begin{bmatrix} L_{11} & M \\ M & L_{22} \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{1}$$

The voltages of the primary and secondary coils, as well as their linked magnetic fluxes and their self inductances, are represented respectively by v_{11} and v_{22}, for the first case, Ψ_1 and Ψ_2, for the second, and by L_{11} and L_{22}, for the last. The primary/secondary mutual inductance is represented by M. The corresponding magnetic coupling factor k is defined by equation (2).

$$k = \frac{M}{\sqrt{L_{11}L_{22}}} \tag{2}$$

These results can also be predicted by means of analytic computation using the Neumann mutual induction formula, expressed in (3). In order to theoretically evaluate the induction matrix expressed in (1), only the parametric curves c_1 and c_2, defined geometrically by the paths of both coils, and the magnetic permittivity of vacuum μ_0 ($4\pi\times10^{-7}$ H/m) are required.

$$M = \frac{\mu_0}{4\pi}\int_{c_1}\int_{c_2}\frac{d\boldsymbol{s_1}d\boldsymbol{s_2}}{|\boldsymbol{R_{12}}|} \tag{3}$$

By computing the line integrals defined in **(**3) along both coil paths, taking into account the differential length increments d_{s1} and d_{s2} and their relative distance R_{12}, the mutual inductance is obtained. Notice that the same formula can be used in order to approximately predict L_{11} and L_{22}. In the last example, the paths of integration change to the path of the correspondent coil and this same path slightly deviated by a small distance ε. The limit when ε tends to zero is the mutual inductance between the correspondent coil and itself which corresponds to the self inductance. The optimal ε is the smallest value that does not compromise the convergence of **(**3).

$$\begin{aligned} L_{11} &\cong \frac{\mu_0}{4\pi}\int_{c_1}\int_{c_1+dx_1}\frac{d\boldsymbol{s_1}d\boldsymbol{s_{1'}}}{|\boldsymbol{R_{11'}}|} \;:\; |d\boldsymbol{x_1}| = \varepsilon \\ L_{22} &\cong \frac{\mu_0}{4\pi}\int_{c_2}\int_{c_2+dx_2}\frac{d\boldsymbol{s_2}d\boldsymbol{s_{2'}}}{|\boldsymbol{R_{22'}}|} \;:\; |d\boldsymbol{x_2}| = \varepsilon \end{aligned} \tag{4}$$

Two different prototype pairs of spiral concentric inductor coils were experimentally measured when placed at different distances one from each other.

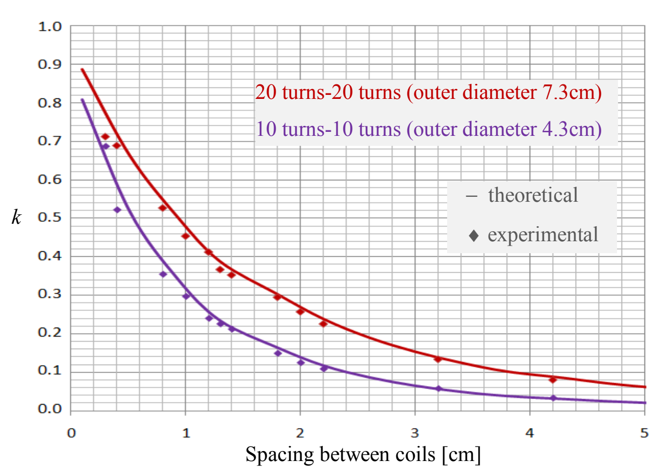

Fig. 3 – Magnetic coupling factor dependence with distance for concentric spiral coils.

The experimental process consisted in evaluating the resultant coupling factor by means of the analysis of the measured primary and secondary inductances, where respectively the secondary and primary coils were open and short-circuited.

The inductances and the correspondent magnetic coupling factor of the transformer coils were also evaluated theoretically and compared with the results obtained experimentally. The comparison is resumed in Fig. 3 and Tab. 1.

Tab. 1– Self inductances of the experimental set.

coil pair		experimental	theoretical
10 turns/ 10 turns	L_{11}	2.69 µH	2.8 µH
	L_{22}	2.64 µH	
20 turns/ 20 turns	L_{11}	13.7 µH	14.7 µH
	L_{22}	13.2 µH	

Both methods present consistent results with small discrepancies that are no greater than 7% for distances inferior to 10mm and even smaller for larger distances.

As a rule of the tomb, it can be considered that the magnetic coupling factor for spiral concentric coils decays to values below 0.04 as the distance between coils tends to the coil diameter.

The fact that poor coupling factor is evident in contactless power transfer for distances of the same order of the coil diameter obliges the use of particular electronic converters that are able to compensate the loss of the primary generated useful magnetic flux. In order to better understand how this compensating process is achieved, an equivalent model of the transformer is considered, as illustrated in Fig. 4.

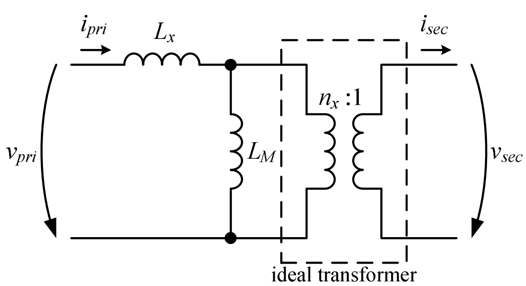

Fig. 4 – Equivalent three parameter transformer model.

For consistency between the model represented by (1)-(2) and the one shown in Fig. 4, the subsequent relations must be accomplished.

$$L_x = (1-k^2)L_{11}; \quad L_M = k^2 L_{11}; \quad n_x = k\sqrt{\frac{L_{11}}{L_{22}}} \tag{5}$$

A simple analysis of the transformer model shown in Fig. 4 allows concluding that the fictitious leakage inductance L_x is the one responsible for the useful magnetic flux loss and therefore for the power transfer reduction. The next section discusses an elegant solution to overcome this drawback by means of using a resonant electronic converter.

IV CONVERTER STRUCTURE

Using a series resonant electronic converter, as the one illustrated in Fig. 5, it is possible to compensate the voltage drop caused by the transformer leakage inductance L_x if the converter switching frequency is near to the resonant frequency of the L_x and C pair. Assuming the last condition, the total voltage drop along the series of L_x and C can be neglected and, as a result, the total inverter voltage is sensed at the ideal transformer primary side. The parameters exhibited in Fig. 5 can now be calculated accordingly to the ones obtained for the pairs of coils analyzed in III.

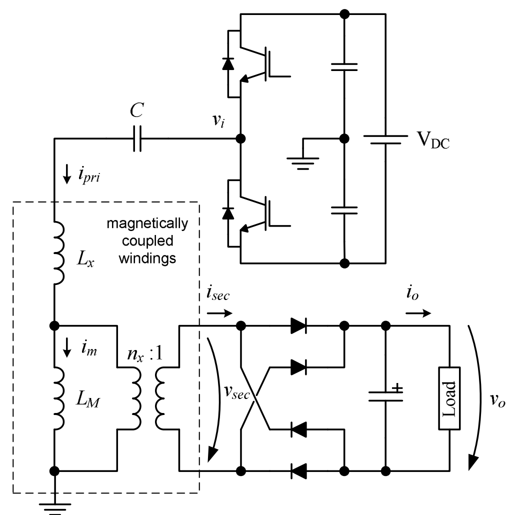

Fig. 5 – Resonant converter.

Considering the previously discussed 20-20 turns winding pair, the converter parameters, for a 20mm spacing, result as follows: L_x=12.8µH, L_M=0.89µH and n_x=0.26. The value of the resonant capacitance C=100nF was designed for a resonant frequency near 140kHz. The experimental results, obtained in the built prototype, are analyzed in the following section.

V SIMULATION AND EXPERIMENTAL RESULTS

The reliability of the proposed analysis was verified by means of simulation and experimental evidence. A laboratorial prototype similar to the Fig. 5 resonant converter, exhibiting the same parameters as the ones obtained for the 20-20 turns measured windings, was built. The simulation results are present in Fig. 6 and the corresponding experimental results are shown in Fig. 7.

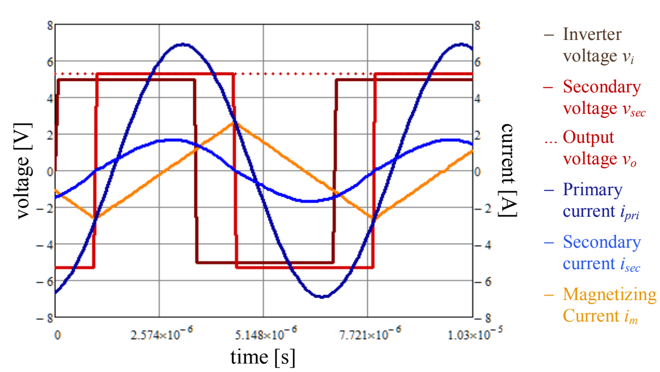

Fig. 6 – Simulation results of the resonant converter operating at full load

The inverter was operated with a DC supplying voltage of 5V. The switching frequency was adjusted slightly above resonance (145.7kHz) in order to obtain a $5V_{DC}$ output voltage for full load test conditions (1A–5Ω).

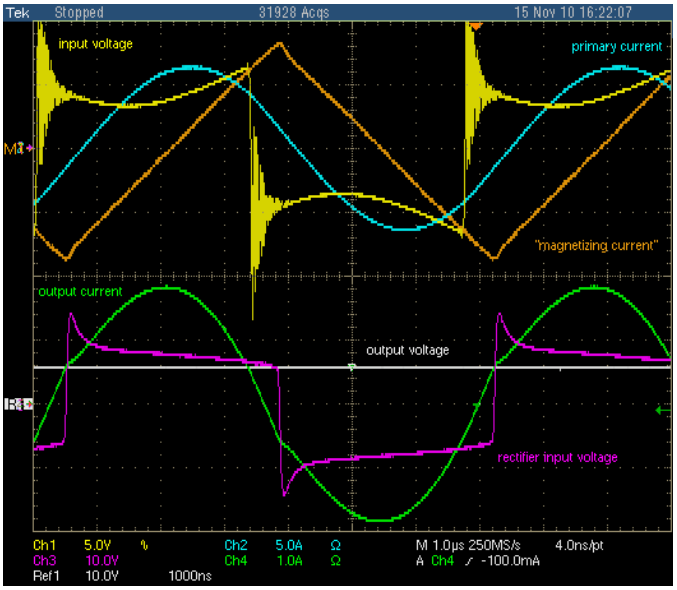

Fig. 7 – Experimental results with 20mm spacing and full-load operation. Ch1-Yellow trace → Inverter voltage; Ch2 - Blue trace → primary current; Ch3 - Magenta trace → Secondary voltage; Ch4 - Green trace → Secondary output current; Ref1 - White Trace → Output DC voltage.

In what concerns the consistency of the adopted models and theoretical assumptions, simulation and experimental results are evidence of its correctness and applicability in poor coupled contactless power transmission systems.

VI CONCLUSION

Contactless power transmission systems that distance a length that is of the same magnitude as the one of the windings diameter exhibit poor coupling factors, severely degrading the linked magnetic flux. Analytic calculations can be evaluated in order to infer about the windings geometry resultant self inductances and magnetic coupling factor.

For full series resonant compensation of the transformer leakage inductances using one single side capacitance only, three parameter equivalent transformer model is recommended for the resonant converter design.

Several spiral inductors were built and experimented. A fully working laboratorial prototype was build, operating at a frequency near 150kHz. As desired, for a primary secondary winding spacing of 20mm, a 5W output power was achieved at full load operation. The obtained coupling factor verifies the developed theoretical model and is approximately 0.26. Due to skin effect and in order to reduce the coil AC resistance, the primary inductor was assembled with ten 0.315mm diameter twisted wires. The current flowing in the primary is about 7A and the resonant capacitor voltage has a maximum magnitude of 70V.

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