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Development of a wireless power transmission system for embedded passive sensors using LF RFID technology

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***Abstract*—Wireless power transmission (WPT) can be used to enable full embedding of sensor systems and thus remove the need for wired connections and batteries. In this paper a WPT system based on inductive coupling at 125 kHz is presented. The main design considerations that must be taken into account when designing such a system will be presented. This includes the design of the power transmitter and the power receiver as well as the fabrication of proper antennas. The proposed system architecture has been completely implemented and measurements have been carried out for validation. It is demonstrated that the fabricated system achieves a wireless transmission of 10.4 W at a 5 cm distance with 69 percent efficiency and 7.9 W at 10 cm distance with 30 percent efficiency. In order to facilitate the integration of the wireless system, a new version of the antennas and the PCB have been fabricated. Two different prototypes are built with two different antenna coil thickness's. The obtained results corroborate the importance of the selected wire resistivity, since 5.9 W and 9.5 W are obtained for 0.5 mm and 1 mm thickness respectively at a 5 cm distance. A first prototype has also been fabricated to prove that the WPT electronics can be successfully embedded into the composite.**

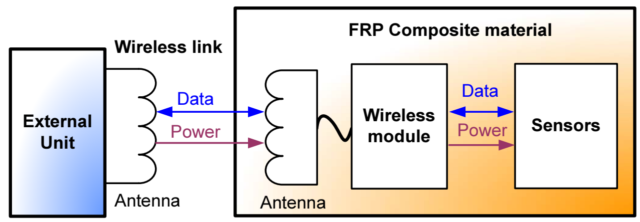

Figure 1. WPT for embedded passive sensors.

Table I
WPT SYSTEM REQUIREMENTS

Requirement	Value	Unit
Transmission distance	10	cm
Antenna size (diam.)	10	cm
Required power	1.5	W

I. Introduction

Wireless power transmission (WPT) is attracting more and more attention during the last years. Especially interesting is the application of WPT for wireless battery charging of consumer electronics. The new standard Qi from the Wireless Power Consortium [1] is trying to achieve a global standardization of this wireless charging technology. Another promising technology is Witricity, which envisages wireless electric power delivered over room scale distances [2]. Some examples of products already commercially available are [3], [4].

Apart from consumer electronics, there are other interesting applications for WPT. It can for instance be used to provide embedded systems with power. There are many applications where a wired connection between some embedded electronics and some external unit is not possible or it has major disadvantages, maybe because it would compromise the system structure. In these cases, WPT can allow a normal operation of the electronics while being fully embedded. Wireless charging of batteries in industrial environments with difficult accessibility could be another good example for applying WPT, since it would avoid having to replace the batteries.

Related to the examples above, the motivation for the research work presented in this paper is the full integration of an optical sensing system into a composite structure for structural health monitoring [5], as illustrated in Fig. 1. In this scenario, WPT by means of inductive coupling at 125 kHz is used to provide the embedded system with enough power. This technology is known from low-frequency (LF) and high-frequency (HF) passive RFID applications [6]. Inductive coupling is also used to extract the sensor data, but this is out of the scope of this paper.

The objective of this research work is to prove that the requirements set in Table I can be achieved. The wireless system must provide an amount of power higher than 1.5 W at a distance that won't be longer than 10 cm and the maximum antenna size was set to 10 cm (diameter).

As a result, this paper is not focused on the integration process of the WPT system into the composite, but on the first WPT system development that has been carried out to evaluate the technology and to test the amount of energy that can be transferred under certain conditions (e.g. antenna size, transmission distance, etc.). Therefore, this paper will firstly introduce some basics about inductive WPT. Afterwards, it will describe the different modules of such a system with the main aspects and guidelines to be taken into consideration during the design phase. The fabricated system will be presented and the obtained results will be discussed. Finally, conclusions and future work have been included.

II. Basics of inductive WPT

There are mainly three methods for wireless power transmission: capacitive coupling, inductive coupling or electromagnetic coupling. The transmission of power by capacitive coupling is

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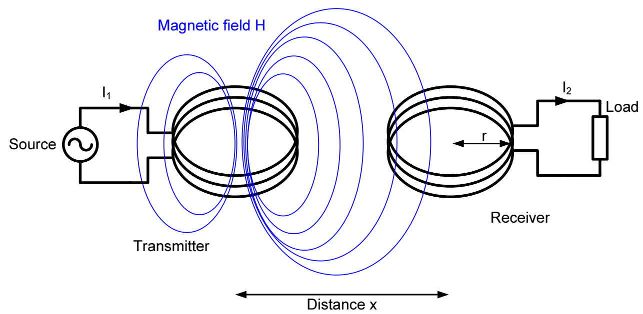

Figure 2. Typical inductive coupling system.

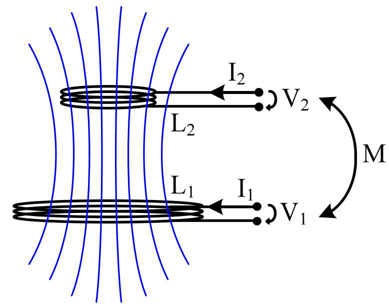

Figure 3. voltage induced by means of inductive coupling.

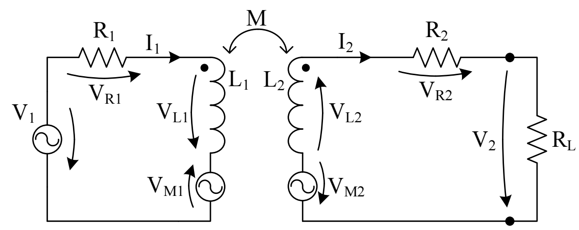

Figure 4. Inductive coupling equivalent circuit.

achieved by means of a capacitor consisting of a transmitting electrode and a receiving electrode [7]. In general, the amount of power that can be transferred is low when compared to an inductive system but it is easier to implement. Electromagnetic coupling is well-known for example from passive RFID systems working at 868 MHz where passive tags are powered at distances up to 10 m [8]. There is also research on how power can be transferred at longer distances (e.g. in the order of km). The most promising technologies in this field are power lasers and microwave transmission.

WPT by means of inductive coupling is the most common operating principle for wireless power transmission. It normally takes place between a transmitting coil and a receiving coil. The current flowing through the transmitting coil will create a magnetic flux around it, as displayed in Fig. 2.

The intensity of the created magnetic field can be calculated by means of (1) and it depends on the number of turns N, the current I flowing through the coil, the radius of the coil r and the distance x at which the field is measured.

$$H(x) = \frac{INr^2}{2\sqrt{(r^2+x^2)^3}} \tag{1}$$

If we analyse this equation for several coil radius we will see that the field intensity remains constant up to a distance approximately equal to the coil radius and afterwards it decreases exponentially. We can also differentiate the previous expression with respect to the transmitting coil radius to find the optimal size for a certain transmission range, which results in $r = \sqrt{2}x$. This means, that for every transmission range, there exists an optimal coil size [6].

If we place another coil near the transmitting coil, as displayed in Fig. 3, part of the generated magnetic flux will also flow through this receiving coil. The amount of flux flowing through the receiving coil depends on several factors such as the size and the coils alignment and is defined by the mutual inductance M.

$$M = \frac{\mu\pi N_1 N_2}{2} \frac{r_1^2 r_2^2}{\sqrt{(r_1^2+x^2)^3}} \tag{2}$$

Apart from the mutual inductance M, the coupling factor K, defined by (3), is also used to define the quality of the coupling between two coils.

$$K = \frac{M}{\sqrt{L_1 L_2}} \tag{3}$$

If we apply a changing current to the transmitting coil, the resulting changing magnetic flux will result in an induced voltage in both the transmitting coil as well as in the receiving coil due to the mutual inductance M, as stated by Faraday's Law. The inductive coupling equivalent circuit is shown by Fig. 4, where V_{M1} and V_{M2} are the voltages induced by coils L_2 and $L1$ respectively and $R1$ and R_2 are L_1 and L_2 coils resistances respectively.

The induced voltages can be calculated by means of (4) and (5):

$$V_1 = V_{R1} + V_{L1} - V_{M1} = I_1R_1 + j\omega L_1 I_1 - j\omega M I_2 \tag{4}$$

$$V_2 = -V_{R2} - V_{L2} + V_{M2} = -I_2R_2 - j\omega L_2 I_2 + j\omega M I_1 \tag{5}$$

In order to increase the efficiency of the power transmission, both the transmitting and the receiving coils are usually tuned at the same frequency by adding a capacitor. Normally, the transmitting coil is tuned by adding a series capacitor. On the other hand, the receiving coil is usually tuned by adding a parallel capacitor. By doing this, the impedance of the antenna is minimised at the desired frequency, which results in a maximum of current flow through the coil. The resonance frequency can be worked out easily by means of (6). For an exact calculation of the required capacitor the parasitic components of both the inductance and the capacitor should be also be considered.

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

A last parameter to be considered is the quality factor, which is used to characterise the resonance circuit and is defined by (7):

$$Q = \frac{f_{res}}{B} \tag{7}$$

where B represents the bandwidth.

For RLC resonance circuits the expression can be easily worked out by means of (8):

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{8}$$

High values of the quality factor mean that a higher induced voltage and therefore a higher transmission efficiency can be achieved. However, a too high quality factor may lead to problems to keep the system tuned, since the bandwidth decreases accordingly. Moreover, over-voltages that can appear in the receiving and transmitting coils should also be considered when designing the system; above all, when selecting the components, which must be able to handle such high voltages.

III. System architecture

A. Transmitter

The power amplifier is the core of the power transmitter. Especially interesting for wireless power transmission at LF frequencies are class-D amplifiers with full or half-bridge architectures. In this work, a half-bridge architecture has been used.

Figure 5 illustrates the half-bridge architecture. It is mainly based on two transistors which operate as switches. The combination of the squared input signal and the inverter makes that only one of the transistors is active in every signal half-period. When the transistor T_1 is ON, the power supply voltage is applied to the load and current flows through it. On the other hand, when the transistor T_2 is active, there is no voltage applied to the load and therefore no current flowing through it. Theoretically, the efficiency of such amplifiers is 100 %, which means that all the power consumed by the amplifier is delivered to the load.

The main difference when compared to the full-bridge architecture is that this one features four transistors, which makes it possible to have power on the load in every transition of the input signal and not only during one of the halves. As a result, full-bridge amplifiers achieve four times more power than the half-bridge version with the same input power at the cost of having more components. There are other possibilities such as class-E amplifiers, but this architecture was found more difficult to keep tuned when connecting the load by means of inductive coupling. The reason for this is that the inductive coupling acts as a transformator, which means that the load is somehow transferred to the transmitter. The class-E architecture operation greatly depends on the load value.

It is also important to select transistors that can operate at the desired frequency and also that can handle the foreseen voltages and power levels. Of course, the insertion losses should be as low as possible. Another important point to be taken into consideration when designing the transmitter are the over-voltages that will take place. In our case, voltages up to 400 V were measured, which means for example that the selected capacitors should be able to deal with such voltage levels.

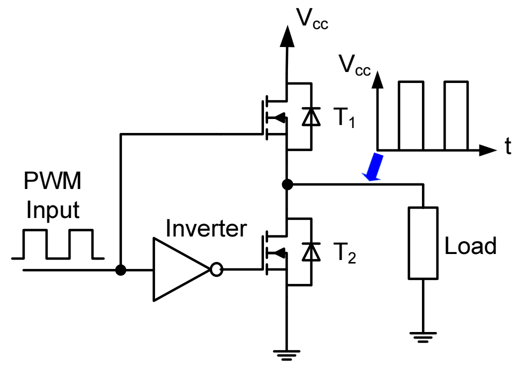

Figure 5. Half-bridge architecture.

B. Antennas

A key element in the wireless power transmission system are the antennas, which will define the transmission range and the efficiency of the power transmission. As explained in the previous section, the optimal size for a defined transmission range is $r = \sqrt{2}x$. As defined in Table I, the maximum transmission distance for the targeted application is 10 cm. Taking these values into consideration, we decided to build antennas with 10 cm diameter as a good trade-off between transmitted power and antenna size.

Apart from the antenna size, an important design issue is the wire used to build the coil. It is very important to select wires with low AC and DC resistances, which define the resistance against DC and AC currents respectively. These resistances can result in power losses, as illustrated in Fig. 4 by means of R_1 and R_2. Furthermore, they can lead to an increase of the temperature in the coil, which will also lead to an increase of the resistance.

Before presenting the fabricated antennas, it is interesting to describe two effects that can influence the performance of inductively coupled systems: the skin effect and the proximity effect. These effects can increase the AC resistance of coil wires and thus reduce the system performance.

1) Skin effect and proximity effect: The skin effect describes the property by which alternating currents flowing through a conductor tend to concentrate on its surface. This means that the current density gets smaller as the depth gets higher. As a result, the resistivity of the inductor increases.

The skin depth δ defines the depth up to which the main amount of current is concentrated and can be worked out by means of (9) [9].

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma}} \tag{9}$$

The increase in the resistance can also be worked out by means of (10) [9].

Figure 6. Fabricated solenoid coils.

Table II
RESULTS

	Diameter	Turns	Inductivity	
			Theoretical	Measured
Tx. coil	10 cm	15	38,3 μH	42,9 μH
Rx. coil	10 cm	8	11,9 μH	14,3 μH

$$R_{skin} \approx \frac{1}{2\pi r\delta\sigma} \tag{10}$$

The proximity effect describes the property by which the alternating magnetic field generated by a conductor will alter the current density distribution in adjacent conductors. This happens because of the induced eddy currents. The result of this density distribution change is also an increase in the conductor resistivity.

It is important to take these two effects into account, since a lower conductivity in the antenna will decrease the efficiency of the wireless power transmission system. Furthermore, it must not be forgotten that the influence of these effects increases with the frequency of operation.

2) Fabricated antennas: For the present system we decided to build solenoid antenna coils, as shown in Fig.6. In order to reduce the effect of the skin and proximity effects, enamelled copper litz wires with 1 mm thickness have been used to build the coils. This way, the conductor is made up of many parallel individually isolated wires. The reduction of the radius for the wires will have a positive effect on the proximity effect. Moreover, the increase of the overall surface will also have a positive effect on the skin effect.

In order to work out the inductivity of a solenoid coil the Wheeler formula can be used [10]:

$$L = \mu_0 \frac{\pi r^2 N^2}{h + 0.9r} \tag{11}$$

where h represents the height of the coil.

Although this is an approximated expression, it can be used for a first rough design of the system. Both fabricated coils have been characterised and results are summarised in Table II. It can be seen that the calculated inductivity matches well the measured one.

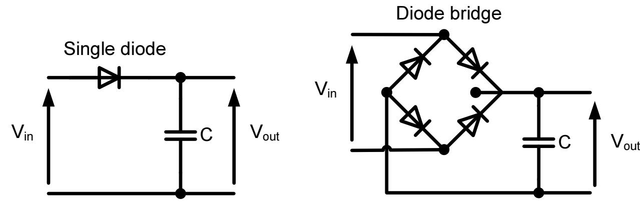

Figure 7. Voltage rectifiers.

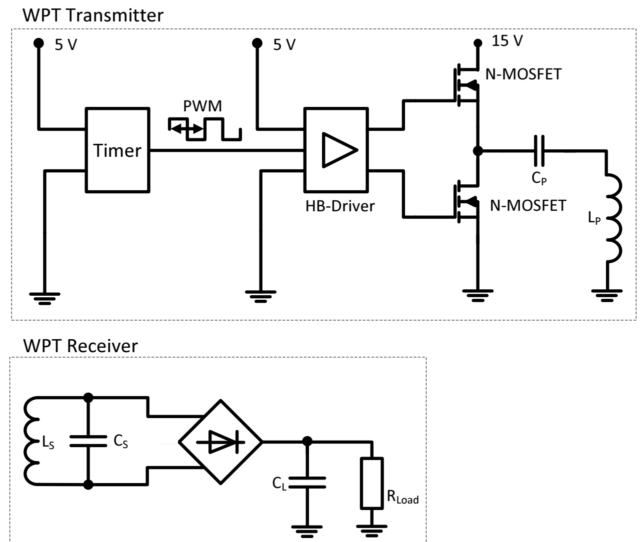

Figure 8. System block diagram.

C. Receiver

The receiver gathers the energy transmitted by the transmitter by means of its antenna coil tuned at the desired frequency (125 kHz in this case) and converts it into DC power. In order to transform the received AC signal into DC voltage rectifiers are used. They are normally based on a single diode architecture (half-wave rectification) or diode bridge architecture (full-wave rectification). Both architectures are shown in Fig. 7. The main difference between both is that the latter features a lower AC ripple in the output signal and achieves a higher efficiency because it uses both input signal half waves.

A capacitor is added after the rectifier which acts as a filter and smooths the rectified signal to have an almost constant DC signal. The higher the ripple of the rectified signal is, the higher is the capacitance needed to filter the signal.

IV. FABRICATED WPT SYSTEM

The block digram of the fabricated system is shown in Fig. 8. The timer is used to generate the squared signal at 125 kHz that will switch the power amplifier transistors ON and OFF. The Half-Bridge (HB) driver takes care of generating the inverted signals to control both transistors. The fabricated transmission coil is tuned at 125 kHz by adding the serial capacitor C_p.

In the receiving part the receiving coil is tuned at 125 kHz by adding a parallel capacitor C_s. The signal rectification is done by means of a bridge rectifier and the corresponding AC

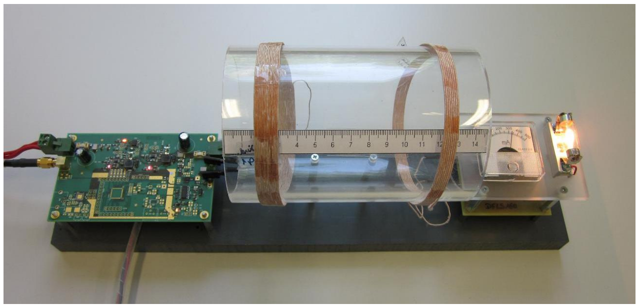

Figure 9. Measurement set-up.

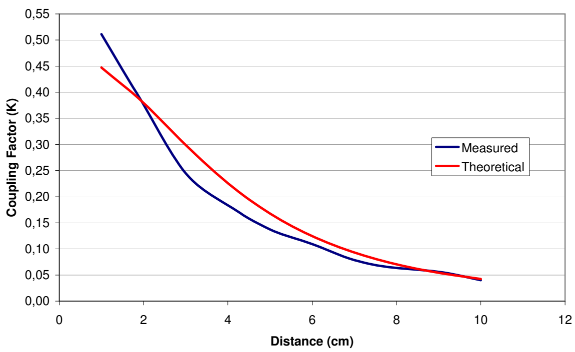

Figure 10. Measured coupling factor.

filtering capacitor C_L. The output power is measured at the load R_L.

The fabricated system is illustrated in Fig 9. The transmitter is placed on the left and the receiver on the right, together with an ammeter and a light bulb to illustrate the transmission of power. For the results presented in the next section both were removed and replaced with a power resistance.

V. Results

Firstly the coupling factor between antenna coils is measured to characterise the quality of the inductive coupling. Theoretically the coupling factor K can be worked out by means of (12):

$$K = \frac{V_2}{V_1}\sqrt{\frac{L_1}{L_2}} \qquad (12)$$

The obtained results for the coupling factor both theoretical and measured are compared in Fig.10. It can be seen that the theoretical calculated coupling factor matches well the measured values. As it could be foreseen, the coupling factor decreases as the distance increases with values between 0.5 and 0.05 for distances between 1 cm and 10 cm respectively.

In Fig.11 the output power obtained for different load values at a distance of 10 cm is displayed. It can be seen that the highest amount of power is transmitted for a load of about 150 Ω. In this case, almost 8 W of power are transferred. The results obtained by means of a simulation tool are also displayed. The difference between simulation and measurement is mainly due to the non-ideality of the different real components.

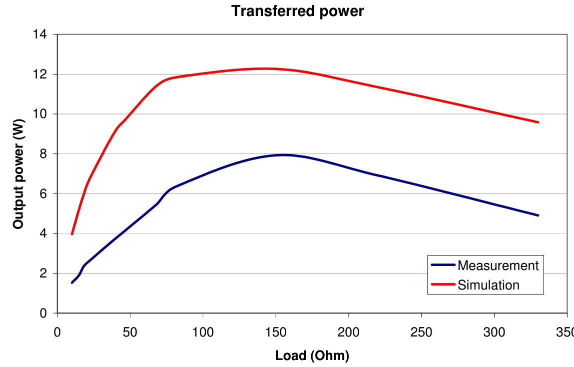

Figure 11. Measured output power.

Table III
Output power

Distance	10 cm	5 cm	Unit
Power	7.9	10.4	W
Efficiency	30	69	%

The optimal value of 150 Ω for the load can be explained if we analyse the real part of the resonance circuit impedance, which is given by (13):

$$Re(Z) = \frac{R_C^2 R_L + R_C R_L^2 + R_L(\omega L)^2 + R_C(-\frac{1}{\omega C})^2}{(R_C + R_L)^2 + (\omega L - \frac{1}{\omega C})^2} \qquad (13)$$

where R_C and R_L are the parasitic resistance of both the inductance and the capacitor in the receiver resonance circuit. We will obtain that the real part of the impedance is 151 Ω, which is the value for which a maximum transfer of power between the resonance circuit and the load takes place.

Finally Table III presents the obtained results for both the output power and the efficiency at two different distances: 5 cm and 10 cm.

It can be seen that the developed system achieves an output power of 10.4 W with 69 % efficiency at 5 cm distance and 7.9 W with 30 % efficiency at 10 cm distance. The efficiency has been calculated by means of (14) as the relationship between the power provided to the system and the power delivered to the load.

$$\eta(\%) = 100\frac{P_{out}}{P_{DC}} = 100\frac{\frac{V_{out}^2}{R_L}}{I_{DC}V_{DC}} \qquad (14)$$

VI. New prototypes to enable integration

Although the obtained results are good and fulfill the requirements previously set in Table I, the antennas are still too big for integration into the composite structure, mainly because of their height. For this reason, a new prototype was built using a new flat antenna design as well as a new PCB for the electronics.

Furthermore, a thinner cable was used (0.5 mm thickness) and the antenna diameter was reduced to 7 cm in order to save space and facilitate the integration. The fabricated prototype and the built measurement set up are shown in Fig. 12.

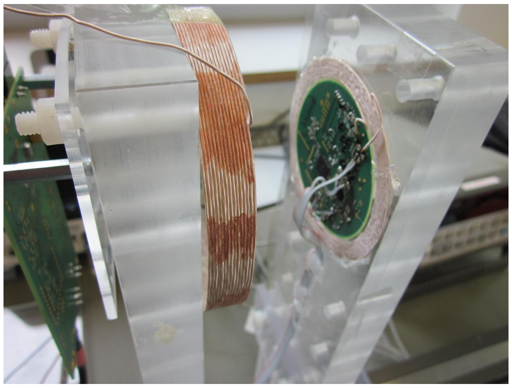

Figure 12. Measurement set-up with new prototypes.

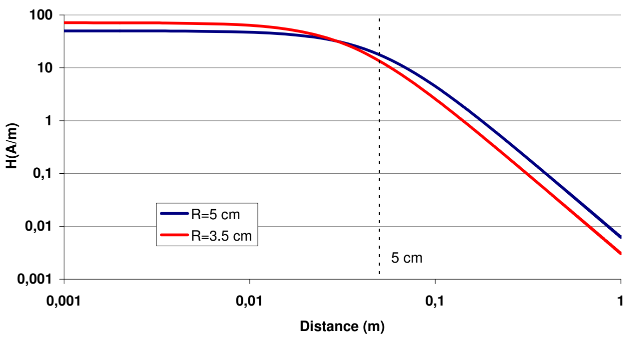

Figure 13. Magnetic field for the two different coil radius.

Table IV compares the results obtained with the previous prototype with the ones obtained with this new prototype. Because of the new reduced diameter, the measurements were conducted only at a distance of 5 cm.

It was found that the power was reduced from 10.4 W to 5.9 W and the efficiency from 69 % to 23.9 %. There are two main reasons to explain this decrease in the amount of transmitted power. On the one hand, the thinner cable will present a higher resistivity, which will increase the power losses and thus reduce the system efficiency. On the other hand, the new antenna presents a reduced diameter. In order to check the influence of this factor, Fig. 13 illustrates the magnetic field intensity of two coils with 7 cm and 10 cm diameter. For this calculation (1) has been used, leaving the current I and the number of turns N constant. It can be seen that for a distance of 5 cm the smaller coil achieves a lower magnetic field, which will of course contribute to a lower amount of transmitted power.

Another experiment was carried out to check the influence of the wire thickness. This time, a new antenna with 7 cm diameter was built but using again the thicker wire (1 mm thickness) used in the first prototypes. The three antennas used so far for the power receiver are displayed in Fig. 14. The results are shown in Table IV and compared to the previous ones.

It can be seen that the transmitted power gets increased to 9.5 W, which is much closer to the first obtained 10.4 W. This small decrease in the transmitted power will probably be due to the smaller antenna size, as previously shown in Fig. 13 and also due to the new antenna shape and position. It must be pointed out that this time the antenna has been placed around the PCB, which will for sure influence the magnetic flux flowing through the antenna coil.

Table IV
COMPARISON DIFFERENT ANTENNAS

	Required	**Solenoid**	**Flat**		**Unit**
			V1	V2	
Antenna diam.	< 10	10	7	7	cm
Wire thickness	—	1	0.5	1	mm
Power	> 1.5	10.4	5.9	9.5	W
Efficiency	—	69	23.9	39.5	%

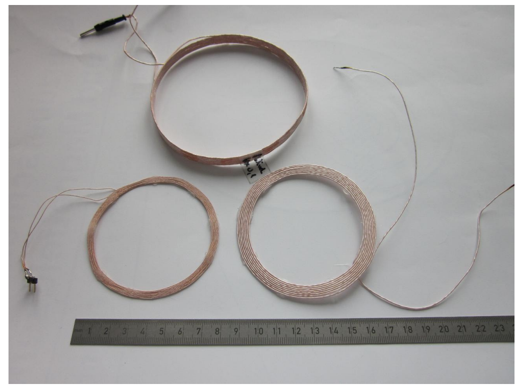

Figure 14. On the top, the solenoid antenna with 10 cm diameter and 1 mm thickness. On the bottom the flat antennas with 7 cm diameter and 0.5 mm (left) and 1 mm (right) thickness's.

VII. CONCLUSIONS AND FUTURE WORK

WPT technology can remove the need for wired connections and batteries and thus allow a full integration of electronics into different structures. This paper has presented the development of a WPT system envisaged to provide sensors embedded in composite structures with enough power by means of inductive coupling technology at 125 kHz. The main system requirement was defined as 1.5 W wireless power transmission at a maximum distance of 10 cm with an antenna size (diameter) smaller than 10 cm.

After explaining some basics about inductive coupling and the involved effects and phenomena, the paper has given some guidelines for designing the power transmitter, the receiver and the corresponding transmitting and receiving antenna coils. A first version of the WPT system has been fabricated as a “proof of concept” and it has been demonstrated that the targeted amount of transmitted power is feasible: 10.4 W at a 5 cm distance with 69 % efficiency and 7.9 W at 10 cm distance with 30 % efficiency have been obtained.

Nevertheless, as this first fabricated system was not suitable for embedding into the composite, mainly because of the antenna shape and size, a new flat and smaller antenna as well as a new PCB was fabricated for the power receiver.

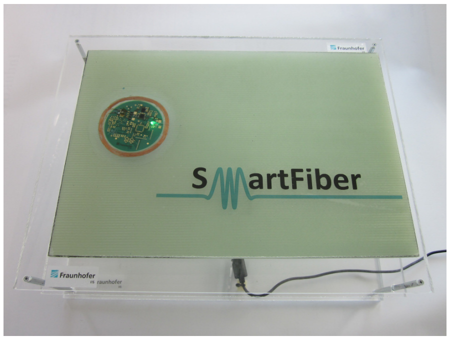

Figure 15. Demonstrator presented at the HMI Messe 2012 in Hanover. The power transmitter is placed below the FRP plate.

The antennas have been demonstrated to play a key role in the system performance. Two versions were fabricated, one with a 0.5 mm wire thickness and another with 1 mm. It was found that the thicker antenna achieved 9.5 W at 5 cm distance, whereas the thinner one achieved 5.9 W. This was due to the increase in the wired resistance and the consequent power losses.

Our future work includes the integration of the electronics and the antenna into composite samples to evaluate the influence of the material on the wireless system performance. Furthermore, the effects the composite fabrication process may have on the electronics must be studied (e.g. temperature, pressure, etc.). Some prototypes have actually already been successfully integrated in glass fibre-reinforced plastic (FRP) material, as displayed in Fig. 15. This demonstrator was built in collaboration with other project partners (Ghent University in Belgium and Airborne Technology Centre in The Netherlands) to show that WPT electronics can be successfully fully embedded into the composite.

Acknowledgements

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