

# Contactless Power and Information Transmission

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**Abstract**—In some applications, contacts between two devices are the first cause of dysfunctions. The aim of this paper is to transfer contactless power energy to add new functions to a tool (e.g., drill machine). A bidirectional communication is also needed. This is realized with an ironless high-frequency transformer for both power and information transmission. Different coil geometries have been studied to reduce mutual inductance between power and information coils. This new solution enables to build low-cost and smart energy transfer systems including communication.

**Index Terms**—Airgap transformer, data transmission, energy transmission, ironless.

## I. INTRODUCTION

FOR professional tools submitted to rough working conditions, like dust and water, it is essential to avoid as much as possible electrical contacts. The aim of this paper is to add new functions on a drill machine, with interchangeable devices supplied by the drill. The communication between the main tool and devices must be bidirectional.

Such devices need to be small with a minimal air gap between the fixed and removable parts. Power transmission is up to 10 W. To be fit for use in the U.S. as well as Europe, the device input voltage can be set between 100–240 Vac. This system contains an ironless transformer (or air transformer) working at high frequency (HF) (Fig. 1).

To simplify the control, a fixed frequency was chosen; hence, no adaptation to load variations is possible.

## II. POWER TRANSMISSION

### A. Working Frequency

To design the dc–ac converter, it is first necessary to define a working frequency. For low-power applications, high frequencies can be used, allowing shorter sizes for the transformer. Our application needs high-voltage MOSFETs that are not adapted for very HF (1–10 MHz). Thus, a 150-kHz frequency has been chosen.

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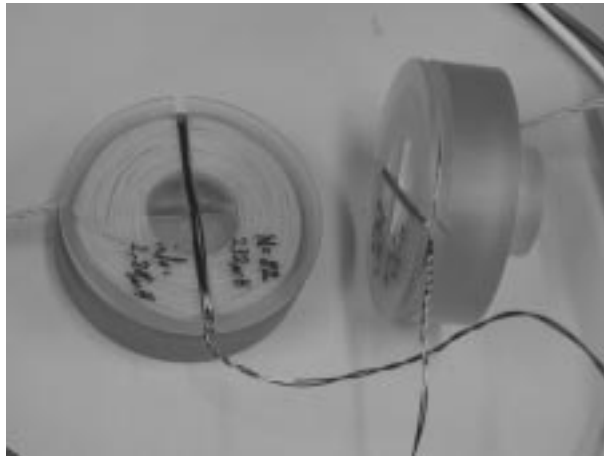


Fig. 1. Photograph of the transformer.

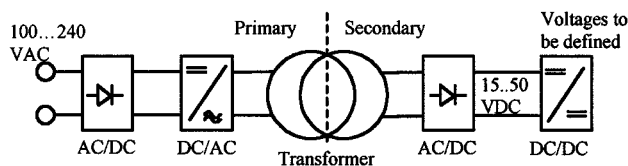


Fig. 2. General system description.

### B. Wires

A skin effect is created with a non-dc current, especially at high frequencies. To eliminate this problem, it is possible to use Litz wires, made of very little diameters and isolated wires. For our working frequency, Litz wires are used when the external diameter is over 0.8 mm.

### C. Design of the Transformer

Fig. 2 shows the general system topology:

The power transmission fixes the transformer secondary current. Taking into account the effect of the secondary ac–dc conversion, the secondary sine mode characteristics are fixed as follows:

$$\hat{U}_2 = 18 \text{ V} \quad \hat{I}_2 = 1.33 \text{ A} \quad P_2 = 12 \text{ W}.$$

The secondary wire section can be calculated with a current density of 3 A/mm<sup>2</sup>

$$S_{Cu2} = \frac{I_2}{J_2} = \frac{1.33}{\sqrt{2} \cdot 3} = 0.316 \text{ mm}^2. \quad (1)$$

The resonant and one transistor converter chosen uses a HF voltage applied to the primary side of the transformer. In function of the used voltage,  $\hat{U}_1$  is comprised within 140–340 Vac peak.

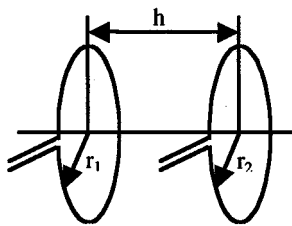


Fig. 3. Basic transformer made of two single turns.

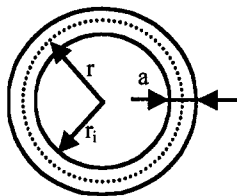


Fig. 4. Definition of a basic turn.

To size the transformer, a software based on the calculation of self and mutual inductances of coils has been developed. The calculation of the inductances is made as follows [1].

First of all, a basic transformer made of two single turns is defined (Fig. 3).

A turn is defined with  $r$  being the mean radius,  $r_i$  being the internal radius,  $a$  being the diameter of the wire, and  $k$  being a ratio defined as

$$k = \frac{r}{a}. \quad (2)$$

To calculate the inductance of a turn, it is necessary to take into account the thickness of the wire. The self-inductance  $L$  becomes

$$L = L_i + L_e \quad (3)$$

where  $L_e$  and  $L_i$  are the external and internal inductances of the turn.

The external inductance is calculated with the Neumann formula [3]

$$L_e = \frac{\mu_0 \mu_{\text{air}}}{4\pi} \cdot \int_{C_1} \int_{C_2} \frac{d\vec{l}_1 \cdot d\vec{l}_2}{|\vec{r}_2 - \vec{r}_1|}. \quad (4)$$

In our application, the development of this equation becomes

$$L_e = \mu_0 \mu_{\text{air}} \cdot \sqrt{r \cdot r_i} \cdot a \cdot \int_0^{\pi/2} \frac{2 \sin^2 \vartheta - 1}{\sqrt{1 - b^2 \cdot \sin^2 \vartheta}} d\vartheta. \quad (5)$$

This integral has to be numerically resolved. Parameters of (5) are defined in Fig. 4, except parameter  $a$ , which depends on the geometry and is defined in (6) as follows:

$$a^2 = \frac{4 \cdot r \cdot r_i}{(r + r_i)^2}. \quad (6)$$

To calculate the internal inductance  $L_i$ , a solution using the magnetic energy density has been tested, but its resolution is complicated and requires a very long calculation time [1]. This problem has been simplified by noting that the quotient of the external inductance with the internal inductance is constant for a constant  $k$  value, independent of the diameter of the wire.

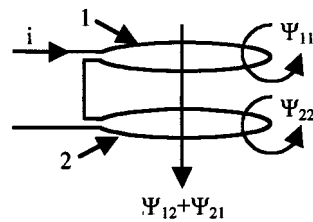


Fig. 5. Flux in a coil made of two turns.

Several values have been calculated to determine a function to find out  $L_i$  from  $L_e$  and  $k$  as follows:

$$L_i = \frac{L_e}{f(k)}. \quad (7)$$

To calculate the mutual inductance  $M$  of two turns, as described in Fig. 3, the Neumann formula [3] may be used, where  $h$  corresponds to the distance between two turns

$$M = \mu_0 \mu_{\text{air}} \cdot \sqrt{r_1 \cdot r_2} \cdot b \cdot \int_0^{\pi/2} \frac{2 \sin^2 \theta - 1}{\sqrt{1 - b^2 \cdot \sin^2 \theta}} d\theta \quad (8)$$

with

$$b^2 = \frac{4 \cdot r_1 \cdot r_2}{(r_1 + r_2)^2 + h^2}. \quad (9)$$

$\Psi$  is the total flux made from current  $i$  through the two turns (Fig. 5)

$$\Psi = \Psi_{11} + \Psi_{22} + \Psi_{12} + \Psi_{21}. \quad (10)$$

With  $n$  turns, (11) is obtained as follows:

$$\Psi = \sum_{i=1}^n \sum_{j=1}^n \Psi_{ij}. \quad (11)$$

The current is the same for all the turns of the same coil. Thus, it is possible to calculate the self-inductance by dividing the total flux by the current

$$L = \frac{\Psi}{i} = \sum_{i=1}^n \sum_{j=1}^n L_{ij}. \quad (12)$$

The way to find out the mutual inductance between two turns is known with (8). It is then easy to obtain the mutual inductance between two parallel coils centered on the same axis. Turns of first coil are noted by  $T1_i$  and turns of the second coil are noted by  $T2_j$ . Equation (13) gives the mutual inductance between coil 1 with  $n1$  turns and coil 2 with  $n2$  turns, where function  $M()$  is given by (8)

$$L_{12} = \sum_{i=1}^{n1} \sum_{j=1}^{n2} M(T1_i, T2_j). \quad (13)$$

The software makes it possible to quickly calculate the characteristics of an air transformer and to easily find out the best one to fulfill size and power requirements. Results obtained are as follows:

turns of primary coil	$N_1 = 82$ ;
turns of secondary coil	$N_2 = 23$ ;
external radius of primary coil	$R_{1\text{max}} = 25$ mm;
external radius of secondary coil	$R_{2\text{max}} = 22$ mm;
primary coil self-inductance	$L_1 = 227$ mH;
secondary coil self-inductance	$L_2 = 24.3$ mH;
mutual inductance	$L_{12} = 19.8$ mH.

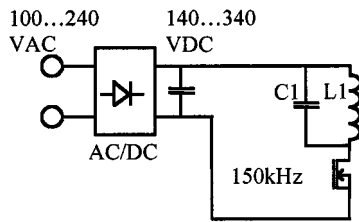


Fig. 6. Flyback converter for primary.

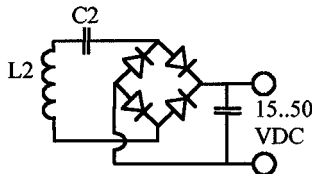


Fig. 7. Secondary with rectifier.

#### D. Design of the Electronic

On the primary, a flyback converter, tuned to the frequency shown in Fig. 6 is used.

Tuning the LC circuit is essential. Though such tuning depends on the load, it is not necessary to adapt the resonant system to it, as the coupling factor is low. The frequency is then defined as follows:

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad (14)$$

with  $f = 150$  kHz and  $L_1 = 227$  mF. Thus,  $C_1 = 5$  nF.

On the secondary, a serial resonant system is placed. To be able to work with a dc current, a rectifier has been added (Fig. 7).

Here also, as in the primary, it is essential to tune the system correctly; with  $L_2 = 24.55$  nH,  $C_2 = 55$  nF

#### E. Measurements

In Fig. 8, the system is supplied by 100 Vac ( $U_1$ ). The consumption of the secondary is 8.4 W ( $P_2$ ), where

1st trace voltage on the secondary;

2nd trace current in the primary;

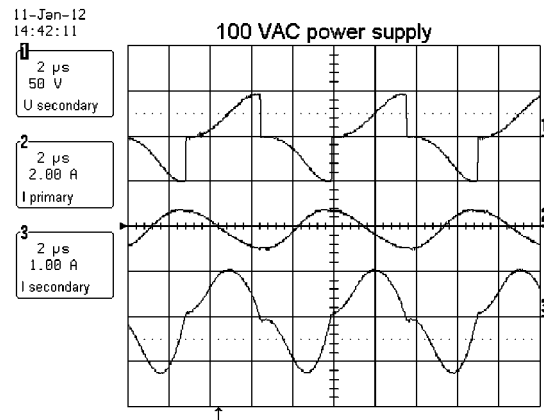
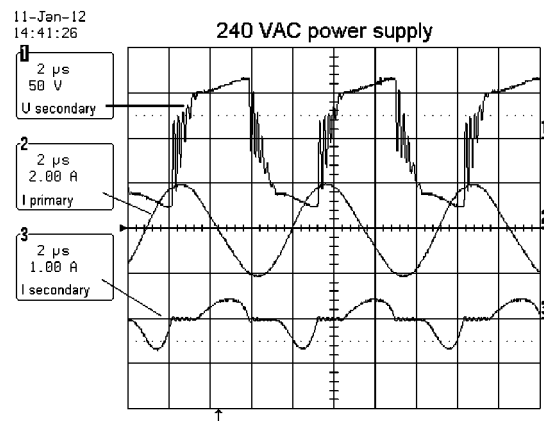
3rd trace current in the secondary.

In Fig. 9, only the power supply value is modified and is now 240 Vac. Traces are the same as in Fig. 8.

### III. INFORMATION TRANSMISSION

#### A. Coil Geometries

At first, the solution considered was to use the same coil for both power and information transmission, but using higher frequencies for the information. As the transformer has a limited bandpass, using frequencies higher than approximately 20 MHz is impossible. Using frequencies lower than 20 MHz would

Fig. 8. Signals of the transformer with  $U_1 = 100$  Vac and  $P_2 = 8.4$  W.Fig. 9. Signals of the transformer with  $U_1 = 240$  Vac and  $P_2 = 8.4$  W.

result in a very noisy information signal because of the high harmonics level induced by the power transmission.

Therefore, other solutions using several coils with different geometrical forms have been studied. They suppress the electromagnetic fluxes coming from the power transmission. The mutual inductance is now reduced to the minimum.

Also, the tolerance to positioning has then been analyzed. The goal is to keep moving data transmission from primary to secondary. The “half” geometry coil in Fig. 10 is specially made for unidirectional translations. The “quarter” geometry coil presented in Fig. 11 allows a smaller misalignment, but on both axes. In Fig. 12, the “circle” geometry coil is used where a free rotation is needed.

#### B. Simulation Results

To transfer information as well as possible, the aim is to improve mutual coupling between primary and secondary data coils while reducing mutual coupling between the primary power coil and secondary data coil. It must also be designed for misalignment.

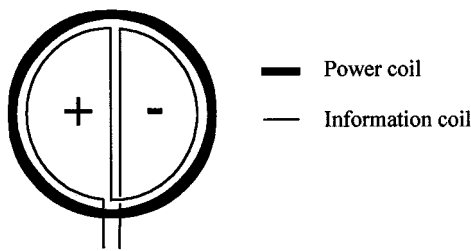


Fig. 10. One axis tolerance, called “half geometry.”

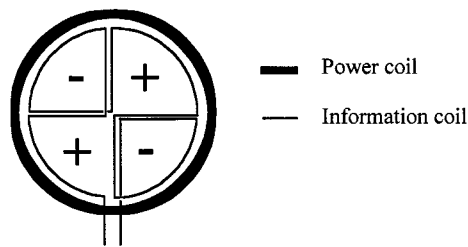


Fig. 11. Two axis tolerance, called “quarter geometry.”

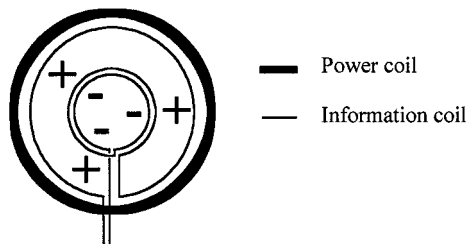


Fig. 12. Rotation allowed, called “circle geometry.”

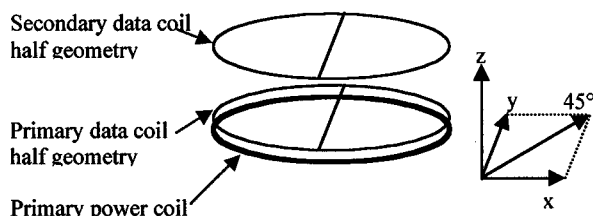


Fig. 13. Scheme of the coils and axis used for simulation.

With a three-dimensional (3-D) finite-element software (FLUX3D),<sup>1</sup> simulated values of the induced voltage of the secondary data coil, caused by the primary power or data coil, have been obtained for different positions of the secondary data coil (Fig. 13). The initial position ( $x = 0$ ,  $y = 0$ , and  $z = 0$ ) corresponds to the three coils centered and a distance of 1 mm between the two data coils. A sine current at 150 kHz runs into the primary power coil, of which the peak value is 1.8 A. At the same time, a sine current at 4 MHz runs into the primary data coil, of which the peak current is 0.1 A.

Figs. 14 and 15 show the peak induced voltage on the secondary data coil for different movement directions. Peak value of a sine cannot be negative. In this case, negative values correspond to an out-of-phase of 180° compared to the current in the primary and are shown to better the understanding of the diagrams.

<sup>1</sup>FLUX3D, ver. 7.40, CEDRAT Inc., Meylan, France, 2000.

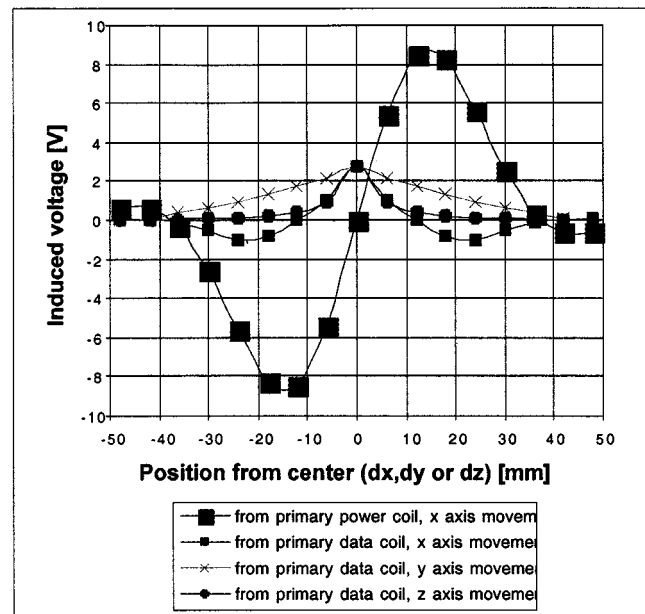


Fig. 14. Induced voltage on the secondary data coil for the “half” geometry.

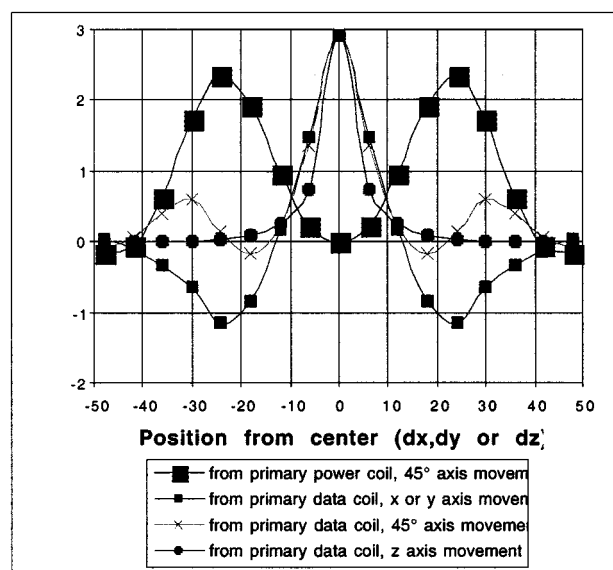


Fig. 15. Induced voltage on the secondary data coil for the “quarter” geometry.

### C. “Half” Geometry

The induced voltage from the power coil is nil for any movements on the  $y$ - or  $z$ -axes, but increases a lot for  $x$ -axis movements. For the secondary data coil, large movements are possible on the  $y$ -axis (half of the value at 20 mm), but movements on the  $x$ - or  $z$ -axes are limited. This is the best geometry for a unidirectional misalignment.

### D. “Quarter” Geometry

There is no induced voltage for any single  $x$ ,  $y$ , or  $z$  movement and a limited voltage for a 45° ( $x$  and  $y$ ) movement. Near the center, mutual inductance between the two data coils is quite the same as for the “half” geometry, but decreases a bit more rapidly as the misalignment is on the  $y$ - or the  $z$ -axes. The advantage of this geometry is to tolerate more misalignment on

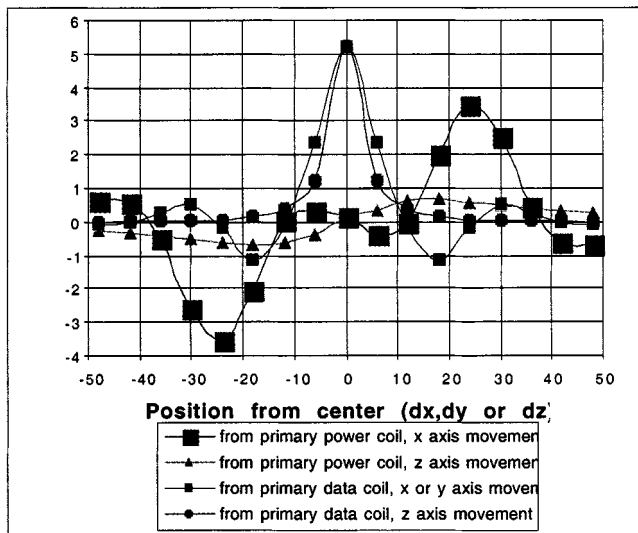


Fig. 16. Induced voltage on the secondary data coil for the “circle” geometry.

both  $x$ - and  $y$ -axes than the “half” geometry. Due to several uses of this system, such as displacement of the secondary on several primary (automotive system), rotative table, parking place for battery charge of cars, etc., the misalignment value of 50 mm has been chosen (the medium radius of the coil  $r = 20$  mm). With this high value, the whole spectrum of possibilities is studied.

#### E. “Circle” Geometry

This geometry has been made specially for a free rotation of the secondary part. The size and number of turns of the small diameter coil have to be adapted to cancel the mutual flux between power and data coils. Mutual flux between primary power or the data coil and secondary data coil is then identical for any rotation of the secondary. Near the center, the data transmission is even better with this geometry than with the two others and the  $x$ -,  $y$ -, or  $z$ -axis tolerance is quite big (approximately 8 mm is still valid) (Fig. 16). This geometry is the best for any movement, except if the movement is only on one axis.

A case that often happens for such a power transmission is when a vehicle (or wagon) moves on a track. The primary is made of an alignment of coils along the way in order to supply the secondary permanently. An industrial example exists with the project called “Serpentine.” This is a vehicle between public transportation and a taxi. The primary is built on the road and the vehicle is driven automatically on this track [7]–[10]. In this case, we have a movement of the secondary in only one direction, but this displacement is more than a simple misalignment. The use of the “half” geometry coils for data allows a continuous transmission when the vehicle is moving on the track, from one coil to the next one. Fig. 17 shows a scheme of this case.

This may easily occur if the primary is made of several coils and the secondary moves from one coil to the other. Some industrial assemblies use this solution. Fig. 17 shows a scheme of this case.

Fig. 18 represents the values of magnetic fluxes of the “quarter” geometry, calculated with 3-D finite-element software.

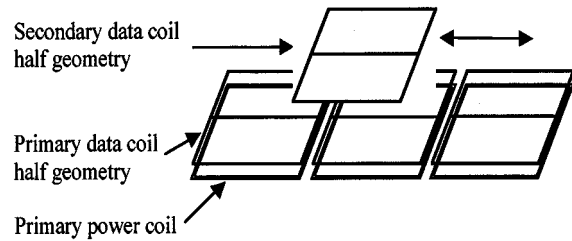


Fig. 17. Scheme of a secondary moving on a track made of an alignment of coils.

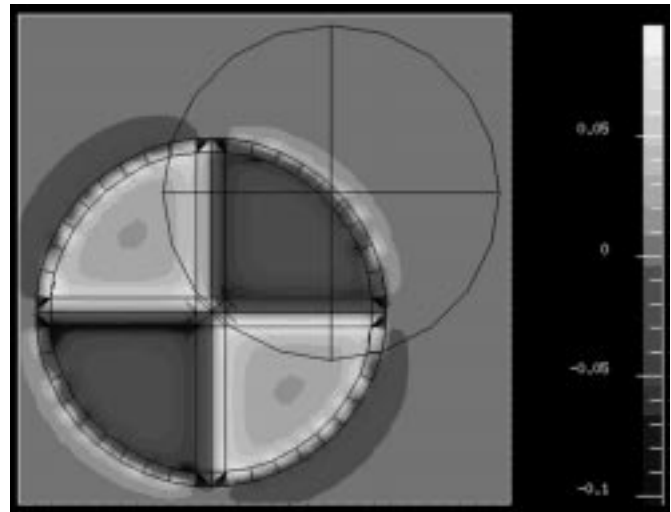


Fig. 18. Magnetic flux calculation with 3-D finite-element software.

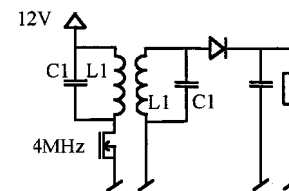


Fig. 19. Simplified electronic scheme of information transmission.

#### F. Electronic

The same principle as for power is used to transmit information with a carrier wave at 4 MHz. Fig. 19 shows a simplified electronic scheme.

Resonant systems on both sides have to be tuned in order to reach the maximal signal on the secondary, using a current as small as possible on the primary coil. As the communication is bidirectional and the same coil is used for both the transmitter and receiver, the same resonant system is used. Capacity calculated with (14) gives good results for both directions.

With this principle, it is easy to communicate with the RS232 protocol in half-duplex mode up to 19 200 b/s. Other protocols may also be possible. However, this principle cannot be used for direct transmission protocols such as factory instrumentation protocol (FIP) because of the noise created by the power transmission. Such principle is well adapted for HF (4 MHz) modulated signals.

Data transfer higher than 250 kHz can be reached by reducing position tolerances between the fixed and removable parts.

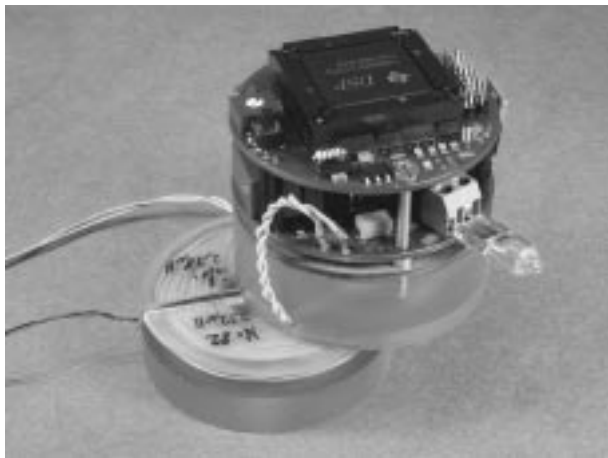


Fig. 20. Photograph of the secondary part of the transformer.

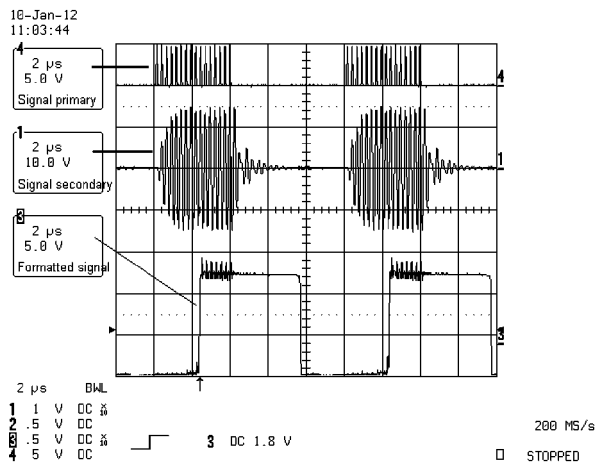


Fig. 21. 200-kHz data transmission.

Fig. 20 shows the secondary part of the transformer. Power and data are transmitted and a bulb is used to create a 10-W ballast.

G. Measurements

Fig. 21 shows a transmission of bits at 200 kHz with 4-MHz carrier frequency through “half” geometry data coil. Coils are correctly centered so that there is no influence of the power transmission, where

- 1st trace voltage on the primary;
- 2nd trace induced voltage on the secondary;
- 3rd trace formatted signal received by the controller.

IV. CONCLUSION

A complete integrated system using an air transformer to transmit power (10 W) and information (19 200 b/s) has been built and tested. It makes it possible to add specialized functions on tools with power supply and information exchange contactless transmission. With such devices, systems become extremely robust in an aggressive environment.

The presented system has been designed for 10 W on the secondary and 100 Vac on the primary. According to the thermal behavior of the system in the chosen application, higher power transmission could be reached.

REFERENCES

- [1] M. Perrottet, “Transmission Électromagnétique rotative d’Énergie et d’information sans contact,” Ph.D. dissertation, EPFL, Lausanne, Switzerland, 2000.
- [2] M. Jufer, “Traité d’électricité EPFL,” in *Electromécanique*. Lausanne, Switzerland: Presses Polytech. Univ. Romandes, 1995, vol. IX.
- [3] F. Gardiol, “Traité d’électricité EPFL,” in *Electromagnétisme*. Lausanne, Switzerland: Presses Polytech. Univ. Romandes, 1996, vol. III.
- [4] J.-D. Chatelain and R. et Dessoulavy, “Traité d’électricité EPFL,” in *Electronique*. Lausanne, Switzerland: Presses Polytech. Univ. Romandes, 1995, vol. VIII.
- [5] N. Macabrey, “Alimentation et guidage linéaire sans contact,” Ph.D. dissertation, EPFL, Lausanne, Switzerland, 1998.
- [6] M. Jufer, L. Cardoletti, P. Germano, B. Arnet, and M. Perrottet, “Inductively powered automatic vehicles—Serpentine,” in *15th Int. Electrical Vehicle Symp. and Exhibition*, Brussel, Belgium, Sept./Oct. 29–30, 1998, pp. 403–404.
- [7] M. Jufer, L. Cardoletti, P. Germano, B. Arnet, M. Perrottet, and N. Macabrey, “Induction contactless energy transmission system for an electric vehicle,” in *Int. Conf. Electrical Machines*, vol. II, Vigo, Spain, Sept. 10–12, 1996, pp. 343–347.
- [8] B. Saugy, R. Nieth, O. Graf, A. Gutscher, and B. Cardis, “Road electrification for automated public transport,” in *15th Int. Electric Vehicle Symp. and Exhibition*, Brussels, Belgium, Sept./Oct. 29–30, 1998, pp. 399–400.
- [9] P. Germano, N. Macabrey, and M. Jufer, “Contactless power transmission: Linear positioning of the moving element,” presented at the 8th Eur. Conf. Power Electronics and Applications, Lausanne, France, Sept. 7–9, 1999.
- [10] M. Jufer and P. Germano, “Contactless power transmission: Frequency tuning by a maximum power tracking method,” in *7th Eur. Conf. Power Electronics and Applications*, vol. IV, Trondheim, Norway, Sept. 8–10, 1997, pp. 693–697.



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He was involved with several projects dedicated to motor control. A major project he was involved with was the realization of an autonomous artificial respirator working without external battery or supply. His research interests are in the field of the air transformer design used for energy and information transmission.

He was also involved with the Serpentine project in order to build a new automatic car system in Lausanne, Switzerland.



**Marc Perrottet** was born in Gumezens, Switzerland, in 1967. He received the Diploma in microengineering and the Ph.D. degree from the Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, in 1992 and 2000, respectively. His doctoral dissertation concerned contactless power and information transmission for rotating devices.

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