Dual frequency system for power-demanding measurement in the isolated areas

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Abstract. The paper presents solution for wireless and battery-less measurement in the enclosed areas. The principle is based on previous work, while this paper is focused on high power-demanding applications such as MEMS accelerometers, gas sensors, piezoresistive strain gauges, etc. It can be suitable for continuous wireless and battery-less measurement in isolated systems such as the rotating objects, concrete walls, enclosed barrels, high temperature chambers etc.

It is based on near magnetic field coupling in radiofrequency band. The principle is similar to the RFID, while it is more powerful and the powering and signal transfer is separated by the different frequencies. The antennas are designed for surface mounting.

The system is desired to be used in long-term monitoring of the environment.

Key words

Wireless powering, Battery-less powering, Wireless sensors, Long-term monitoring, Dual frequency operation

1. Introduction

Measurement in the isolated systems is crucial task in many areas of interest. Demand of wireless and battery-less powering can be caused by different reasons. When the powering wires can not be guided to the sensor (e.g. rotating device, homogeneity of the surface …), usually the battery powering take place while this is not suitable for every application. Main disadvantage of the battery powering is the limited lifetime and sometimes an improper environment for the battery (e.g. high temperature). In those cases the wireless powering must be applied.

Wireless powering can be performed for instance using the solar cells, temperature difference cells or vibration harvesting. This paper focuses on the energy from the magnetic field which is injected to the system. This solution is proper only for short distances; typically several centimeters. The principle is similar to the RFID but it is more powerful and allows separated powering and communication.

2. Inductive Coupling

When two or more inductances partly share the magnetic field, the coupling is presented. The voltage transfer between the coils can be calculated using the Faraday's law. The secondary voltage depends on the secondary coils geometry and on the magnetic field distribution of the primary inductance.

A Coupling Coefficient

In terms of the circuit theory the inductance coupling can be described using the mutual inductance or using the coupling coefficient. The coupling coefficient is more suitable because the standard simulation tools can be used for a description of the powering. As well as the voltage transfer also the coupling coefficient is given by the coils geometry and the magnetic field distribution. Most important topology of the inductances is the axial orientation. Coefficients dependency versus the distance is given by the magnetic field intensity distribution and is given by the figure 1. It shows the measurement result of the coupling coefficient between the circular coil and the rectangular surface coil of similar overall dimensions (about 15 cm). This dependency is approximated using the exponential and the $1/x^3$ functions. Character of this dependency is changing approximately at the distance equal to the diameter of the bigger coil (vertical dash line in the picture). This knowledge of the coefficients character can be used for a prediction of the coefficients value for the other coils.

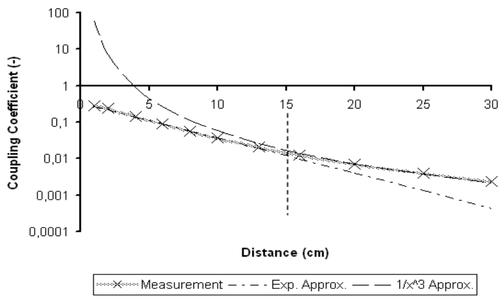

Fig. 1. Approximation by the exponential and $1/x^3$ functions for the coupled coils

The most important parameters of the coupled inductances are the voltage transfer (1) and the input impedance which can be seen on the inductor L_1 (2) [1].

$$\hat{V}_2 = \hat{V}_1 \cdot \frac{k \cdot \hat{Z}_L \cdot \sqrt{\frac{L_2}{L_1}}}{\hat{Z}_L + j\omega L_2 \cdot \left(1-k^2\right)} \tag{1}$$

$$\hat{Z}_{in} = \frac{\hat{V}_1}{\hat{I}_1} = \frac{j\omega L_1 \cdot \hat{Z}_L + j\omega L_1 \cdot j\omega L_2 \cdot \left(1-k^2\right)}{\hat{Z}_L + j\omega L_2} \tag{2}$$

The impedance depends on the loading impedance Z_L and on the coupling coefficient k.

B Equivalent Circuit

For an understanding the effects in the circuit it is helpful to derive an equivalent circuit of the coupled inductances. Figure 2 shows the equivalent circuit of one pair of the coupled inductances L_1, L_2 from the figure 3 (e.g. L_1, $L_{2pow.}$). Derivation of this circuit can be realized by observing the circuit behavior under the loading impedance change [1, 4].

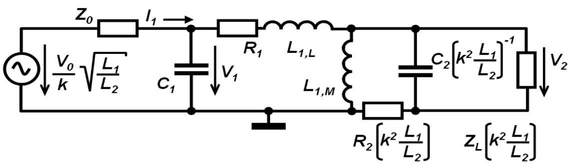

Fig. 2. Equivalent circuit respecting the parasitic properties of the inductances [1]

3. Resonance Behavior

It is evident from the Fig. 2, that the circuit exhibits some resonant behavior. Omitting the parasitic effects, the parallel resonance frequency f_{rp0} can be expressed by the (3). The inductance L_e is a parallel combination of the $L_{1,L}$ and $L_{1,M}$. Parallel capacitance C_p is the transformed secondary side capacitance.

$$f_{rp0} = \frac{1}{2 \cdot \pi \sqrt{L_e C_p}} = \frac{1}{2 \cdot \pi \sqrt{L_2 \cdot C_2 \cdot \left(1 - k^2\right)}} \qquad (3)$$

The voltage transfer in resonance can exceed the nominal transfer (1) (up to over thousands of percents). This effect is crucial part of the powering strategy because the voltage level on the load must be high enough for rectification.

The current flowing to the primary inductance is also depending on the loading impedance. Thus the signal transfer from the sensing probe can be realized using the current measurement in the primary inductance. This is basic principle of the passive RFID systems.

Unfortunately this concept can be realized only for very power-modest circuits because if the secondary side is loaded, the signal transfer is ineffective.

4. Powering Strategy

When the power consumption is too big, the simple RFID powering scheme can not be applied. It is important to separate the powering and the communication line.

One possibility is to implement some power management and divide the operation into three phases. In the first phase the circuit is collecting the energy. When there is enough energy the measurement can be performed and the last phase is the signal transfer. This concept is sometimes useful but has disadvantage that the measurement can not be continual and sometimes the capacitor for energy storage must be too big.

Other possibility is to divide the powering and communication by the frequencies bands. Figure 3 shows modified RFID principle, where the powering and communication is has its own receiving inductance and the frequencies can be selected to be different.

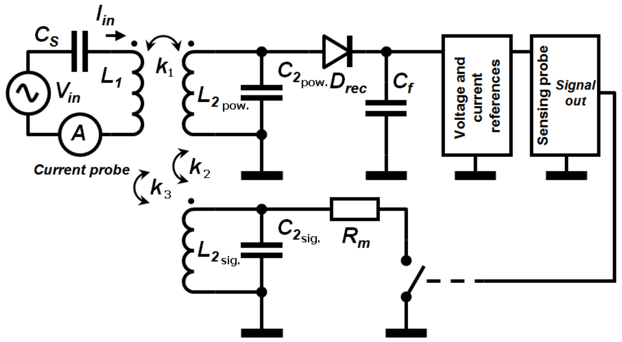

Fig. 3. Simplified powering and communication scheme with separated lines

The inductance L_{2pow} is powering the electronics and the inductance L_{2sig} serves for the signal transfer. The coupling k_2 between the L_{2pow}, L_{2sig} is parasitic and should be minimal in order to keep the lines separated. Signal transfer from the sensing probe is sensed using the current probe on the inductance L_1. For each position of the switch it is different also the input current at given frequency because the modulating resistor R_m changes the quality factor. Loading impedance represented by the sensing probe is stable and on different frequency. Current change on the input is thus caused mainly by the switch.

5. Receiving inductances

The goal of this paper is to maximize the powering ability and keep the possibility of passive signal transfer. The crucial devices for this are the secondary inductances. Figure 4 presents two possible configurations.

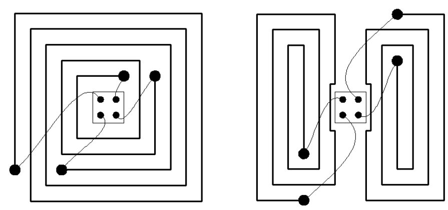

Fig. 4. Two possible configurations of powering and signal inductances, powered device is in the center

The overall geometry of the antennas is given by demand of application. It is presumed the surface mounting, thus the rectangular surface antennas were tested. In the center there is situated the sensor and the electronics. Two basic concepts of location were tested whereat the total surface of the antennas is equal. Power and signal-transfer ability for both configurations are presented on the figures 5 and figure 6.

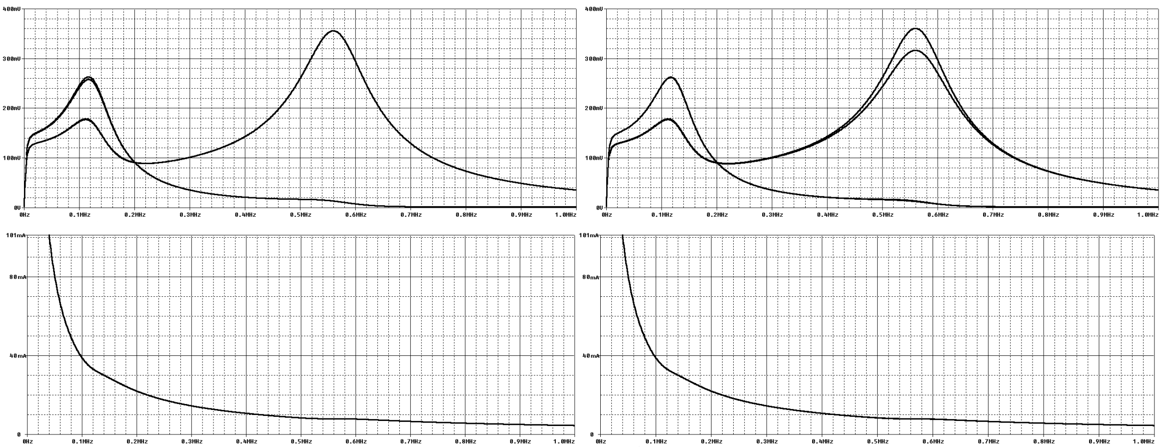

Fig. 5. Simulation results for concentric configuration of the antennas (according the figure 4, left)

6. Simulation results

A Properties of the antennas

Presented results were simulated according the figure 3. The transmitting antenna L_1 is always simple winded circular coil of winding number 10, diameter 15 cm and inductance 39 μH. Coupling coefficients k_1 and k_3 were measured and it is 0.25.

Receiving antennas $L_{2pow.}$, $L_{2sig.}$ are squared and were performed on the cuprextit board. They are of different dimension for different configurations to keep the total surface equal.

The axial configuration of the antennas has following properties. The powering inductance has winding number 8, diameter 10 cm, inductance 14 μH. Signal inductance has winding number 8, diameter 8 cm, inductance 10.6 μH. Coupling k_2 between the inductances was measured to be 0.44.

The configuration side-by-side has different parameters for the simulation. The powering inductance and the signal inductance are same, it has winding number 21, diameter 9 x 4.5 cm, inductance 21 μH. Coupling between the inductances was measured to be 0.024.

B Estimation of the results

The figures 5 and 6 show the AC analyses of the voltages and currents on the antennas. It is for the input voltage 1 V and different loading resistance (1 kΩ, 10 MΩ) on the signal antenna (simulation of the modulating switch). The load on the powering antenna is stable 10 kΩ. The pictures present voltage on the powering antenna (up) and current of the transmitting antenna L_1 (down). The left figures are for the modulation switch on the lower frequency antenna and the right figures are for the high frequency modulation. Crucial features to be estimated are the stability of the powering voltage, good response of the input current on the loading impedance change.

Because of big coupling coefficient between the receiving antennas for the axial configuration the modulating switch is affecting the powering line and the powering thus stops to be effective. Also the current change is negligible in this configuration.

For side-by-side configuration the performance of the powering is stable and nearly independent on the situation on the signal line. This configuration must be preferred in order to maximize the modulation depth. This ensures possibility of sensing the signal for long distances and simultaneously provides enough energy for powering

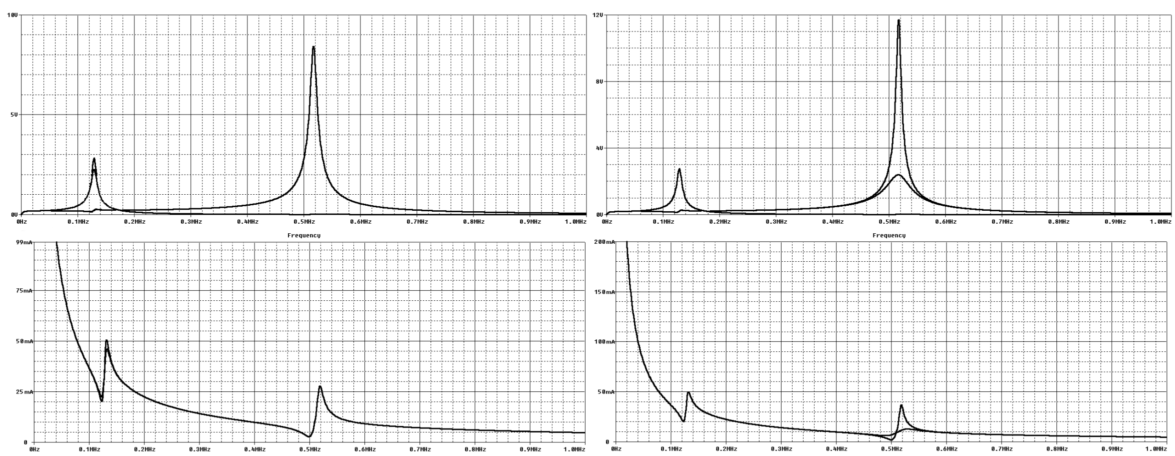

Fig. 6. Simulation results for configuration of the antennas side by side (according the figure 4, right)

7. Circuit realization

Circuit from the figure 3 was realized using the discrete devices and tested with the side by side configuration of the antennas. As the sensor for measurement it was tested the accelerometer ADXL 203 and strain gauges [2].

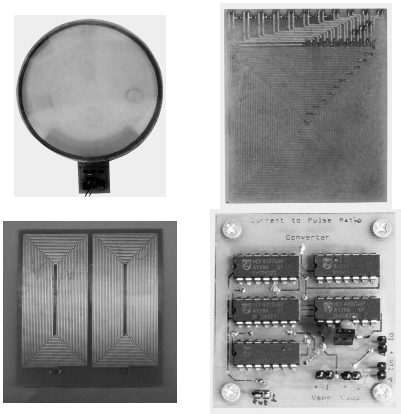

Fig. 7. Realization of the sensing probe using the discrete devices (right, down) and transmitting and receiving antennas

The measurement was effective up to distances of 10 cm. Accuracy of the measurement was limited by the simplicity of the realized converter and it was about 15%. Nowadays the integrated circuit is prepared. It will be finished in March 2011. The expected performance is 15 cm distance ability and the accuracy better then 5%.

8. Conclusion

The paper presented wireless powering solution for measurement in the isolated areas which can be used for long-term monitoring of contamination of physical damage in barrels, concrete walls etc.

It is provided by the near magnetic field and the signal transfer principle is similar to the RFID systems. There are presented possibilities of maximizing the power transfer in order to perform high power measurement (high relatively to the RFID systems). The paper focused on dual frequency solution – one frequency for powering other for the signal transfer. There are two possible configurations of the antennas. The side-by-side configuration appears to be the best solution.

Functionality of the system was tested on the circuit consisting of discrete devices and which is able to measure with the accelerometer ADXL203 and the strain gauges. The measurement was effective up to distances of 10 cm. Nowadays the integrated circuit is prepared. It will be finished in March 2011. The expected performance is 15 cm distance ability and the accuracy better then 5%.

As the transmitting antenna (L_1) was used simple-winded circular coil and the receiving antennas were performed on the cuprextit board and attached to the circuit.

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