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Wireless Power Transmission Technology for Contactless Recharging and Batteryless Supply

无线电力传输技术用于非接触充电和无电池供应

Leopoldo Angrisani, Guido d'Alessandro, Massimo D'Apuzzo, Mauro D'Arco*

Department of Electrical and Information Technology Engineering, University of Naples Federico II, Naples, 80125, ITALY

mauro.darco@unina.it

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Abstract – **During the last years, three main approaches to transmit power without cable connections have been studied. The first one relies on microwave radiating systems, and its performance is mostly limited by the rectenna device, required to pick-up and DC convert the radiated power. This approach has not pervaded application fields since its hazardousness is still not well assessed. Moreover, it has still to face several technological issues and safety concerns before being eligible for application. The second one refers to optical wireless transmission at long distances, which uses laser and photovoltaic diodes for successful operation. The third approach exploits coupled circuits to transmit power upon short or midrange distances. Its breakthrough is gaining attention in a number of application fields, such as radiofrequency identification, small batteryless home appliances, mobile devices and electrical vehicles recharging, wireless and body sensor networks.**

The paper deals with wireless power transmission technology based on the third approach, and takes into account two classes of applications: contactless recharging and batteryless supply. Contactless recharging involves the possibility of keeping an electrical equipment, and specifically its internal battery, grid disconnected, without giving up to its recharging. Batteryless supply permits the functioning of remote wireless equipment, often deployed in networked architectures, which are more and more valued for their fast installation and easy re-positioning features. For both classes, the benefits that can be achieved by adopting wireless power transmission are also highlighted.

An experimental study is finally carried out. To this end, a typical architecture of a power transmission system relying on resonance-based coupling mechanisms is implemented. The ground electronics of the simple set-up, which uses a relaxation oscillator in the primary circuit and a full-rectifier bridge in the secondary to attain DC power, is described in detail. The obtained results show the efficiency of the power transfer mechanism both for nominal operative conditions and different ones characterized by deliberate mismatches.

Keywords – **Wireless power transmission, Contactless recharging, Batteryless supply, resonance-based coupling.**

I. INTRODUCTION

The idea of wireless power transmission (WPT) dates back to the age of the popular scientist and inventor Nikola Tesla (Smiljan, 1856 – New York, 1943) [1]. This innovative idea was judged visionary at that time, while it has been reconsidered by the scientific community in the last decades. In fact, in the mid '60, pioneering experiments aimed at supplying a light helicopter by means of an electrical source on the ground were successfully carried out [2]. In particular, a microwave link between a power source, consisting of a magnetron connected to a parabolic antenna, and a receiving antenna was set-up: the parabolic antenna granted the focalization of the radiated energy into a collimated beam, while the receiving antenna (rectenna), positioned on-board the helicopter, converted the microwave energy into DC power by means of surface-integrated rectifier diodes [3]. Several other similar experiments followed during the late '60 and all along the '70 attest the extensive efforts to improve the performance of the rectenna. The vacuum tubes were substituted with semiconductor and Schottky diodes, and thin-film technologies, which allowed to realize surface-mounting rectennas characterized by reduced size and weight, were also introduced. However, despite the considerable amount of research and development actions produced in the last decades, the microwave WPT technology has not pervaded relevant application fields.

Optical WPT at long wavelengths technology has been proposed as an alternative. This uses lasers diodes to convert electrical power to a collimated beam at the source side and photovoltaic diodes to retrieve electrical power at the receiving side. Unfortunately, Optical WPT has still to face several technological issues and safety concerns before being eligible for applicative scenarios, hence, as for the microwave WPT technology, at present, its applications are at an experimental stage.

At the contrary, wireless power transmission breakthrough has occurred in applications that use radiofrequency or even lower frequency to transmit energy without cables, often by means of resonant coupled circuits [4]-[7]. The most relevant examples are radio frequency identification (RFID) [8], mobile devices and electrical vehicles recharging [9], battery-less equipment supply, body sensor networks (BSN) deployment, and implantable microelectronic devices, such as cochlear and retinal implants.

In this paper, both contactless recharging and battery-less supply topics are dealt with. Contactless induction mechanisms represent a valuable solution to recharge battery powered vehicles when plugging to the mains reveals troublesome or impossible [10]. Batteryless devices are attractive both from a pragmatic point of view, because of the strategic role they can play in critical logistic scenarios, and from an innovation-oriented point of view, because of the novelty that WPT technology can add to new groundbreaking remote equipment pursuit. In fact, the battery supply is often recognized as a critical aspect of remote equipment functioning, being the periodical battery replacement non-strategic and, sometimes, problematic.

II. CONTACTLESS RECHARGING

Technologies enabling contactless recharge of equipment have been studied for long time and several different solutions have been proposed and developed. A contactless power transfer system permits to avoid the problems that arise when power transmission, such as that required for battery recharging, has to be realized without electrical plugging, or any other locked connection to the energy source. To this end systems exploiting coupled circuits to transmit power within very short distances are typically considered. The coupling is made possible by means of two separated coils at the front-end of a primary and a secondary circuit. The primary coil is energized to produce an induction flow that is concatenated by the secondary coil. At the terminals of the secondary coil the necessary power to recharge the batteries is retrieved from the primary circuit thanks to the coupling mechanism.

The ground electronic is typically designed in order to let the primary circuit evolve according to its own oscillatory mode after having been energized. Such a free-oscillator architecture shows a main advantage with respect to systems in which the primary circuit is driven by a controller, being it capable of continually auto-tuning to the resonant frequency of the system, and thus, of avoiding energy losses caused by changes of the circuit parameters and surrounding environment. At the state of art, this is the most common solution to achieve sufficient power transmission efficiency, which is a key indicator to evaluate the performance of any proposal.

It is worth noting that a relevant contribution to contactless recharging has come from the sector of robotic vehicles, in which vehicles capable of navigating to a recharge station, as soon as low battery is signaled, have been investigated. Specifically, for various applications, vehicles have to be capable of autonomously connecting to the recharging station and waiting until the recharge is fulfilled [11]. This task is highly critical especially for light vehicles, such as unmanned aerial vehicles (UAV), which try to autonomously recharge by landing on auxiliary mobile platforms at ground [12]. Often UAVs undergo fails at recharging because of the difficulties at connecting to the platform, since the vehicles must land in a precise position on the platform to have their own pins in electrical contact to the terminals of the battery recharger.

III. BATTERYLESS SUPPLY

In the recent years batteries technology has become a hot topic that has seen relevant investments and efforts aimed at realizing and delivering long-lasting batteries in order to reduce the replacement frequency. The main efforts in this field have concerned the definition and implementation of energy/power management approaches to be integrated in smart battery systems, similar to those employed in portable computers. Smart batteries include an on-board microcontroller, the firmware of which consists in algorithms that successfully allow to avoid energy misuse at the expense of increased complexity and costs.

Anyway, despite noteworthy advancements have been achieved, at present, the use of embedded batteries is still definitively discouraged in some applications. Generally, this is the case of monitoring applications that use sensors that have to be sealed in plastic enclosures, which limit or make even risky maintenance operations, or that are installed in difficult to reach sites, that make expensive or difficult battery replacement. Also, the case of military applications, in which an ancillary battery-supplied sensor is utilized exclusively to perform periodically checks of the status of a main battery, can be considered. Here the main battery is necessary to power-on weapons that are typically deployed in critical logistic scenarios, where electricity provision is unavailable or unreliable, or that are grid-disconnected for safety even if plugs to the grid are at easy disposal. The ancillary sensors are sometimes supplied by the same battery that assists the weapons: their role is of utmost importance, since a fail of them in signaling a low level battery state would lead to a situation in which the weapons could unexpectedly be unusable.

Nonetheless, the use of batteries is connected to environmental issues, which represent a further reason to discourage battery exploitation. Used batteries are special wastes that have to be properly treated in order to perform recycling and reduce their environmental impact.

Recently, wireless sensor networks harvested by ambient energy (WSN-HEAP) have also been proposed. The underneath technology, at the state-of-art, is utilized in systems characterized by low power consumption. These typically deploy an extra back-up battery to support power peaks or intervene in case of any other power unavailability, thus granting the regular operation. But, back-up batteries suffer of deterioration, require cyclic checks, and need occasionally replacements; therefore, HEAP technologies do not represent a definite solution to the aforementioned problems.

WPT technology can be considered a viable solution to avoid the use of batteries in systems for which plugging to the grid is not convenient. As for contactless recharging applications resonant-based WPT systems can supply remote equipment by exploiting the magnetic coupling between a set of conductive coils. Several interesting experiments show that remote equipment such as sensors can reliably operate without batteries for collecting and transmitting measurement data to a central collector.

IV. RESONANT COUPLED CIRCUITS

For both contactless recharging and batteryless supply an inductive coupling can be exploited to perform wireless power transmission satisfying a wide range of power requirements. In detail, induction systems rely on the magnetic component of a quasi-evanescent but not radiating field. In fact, the induction mechanism is the prevalent magnetic phenomenon observed in the presence of low frequency field variations, whereas it becomes very feeble at radio frequencies [13].

The coupling is usually realized by means of coils, loops or windings. The operating frequencies can be between 10 kHz and 1 MHz, which are typical of circuits including coil inductors. The distance at which the power can be transmitted is a function of several parameters, some of which are related to the geometry, mutual position, and consistency of the coils (radius, mutual distance, alignment, number of turns), others depend on the circuitry parameters such as inductance and capacitance values.

The power transmission actually occurs when a load is connected to the terminals of the coil to form a closed secondary circuit. The transmitted power could include both an active and a reactive component even if the load is a mere resistor. The convenience for a resonance condition can be thus also explained, observing that, to obtain the maximum power transfer, the secondary circuit has to be arranged in order to annul the whole reactance or susceptance. To this end the series or parallel insertion of a capacitor between the coil and the load shows to be effective. It can be shown that series insertion allows to annul the reactance of the secondary circuit; it is thus suggested to feed high impedance loads working with low level currents. Parallel configurations annul the susceptance of the circuit and are suitable to feed low resistance loads working with high currents.

In several applications, especially when the coils are not immobilized, the auto and mutual inductance parameters can change. In these cases, it is necessary to implement suitable control strategies to preserve efficiency in the power transfer.

The most commonly adopted solutions avoid the implementation of control strategies by deploying a relaxation oscillator in the primary circuit [14]-[16]. These types of oscillators are capable of continually auto-tuning the frequency of the system in order to maximize the power transfer efficiency without neither requiring active driving of the frequency nor variable capacitors in the secondary circuit. For other solutions in which the primary circuit is driven by a sinusoidal current source, any tuning mismatch of the secondary circuit would lead to efficiency losses in the power transfer.

In the next Section a typical system architecture, based on the use of a Royer oscillator is considered [17]-[19]. The circuit is directly introduced throughout a description and its functioning is described by means of simulations.

For these applications an empirical design is usually preferred by engineers, since theoretical approaches aimed at estimating the power transmission efficiency, such as the couple-mode theory or reflected load theory (RLT), show some drawbacks. In particular CMT is only applicable to coils with high quality factors and large coupling distance, while an analysis by RLT can be rather delicate.

V. TYPICAL SYSTEM ARCHITECTURE

A typical system architecture includes a primary circuit which is magnetically coupled to a secondary one to be remotely energized. The primary circuit is essentially a relaxation oscillator made up of a resonant tank, realized connecting a capacitor Cr and a centered-tapped coil Lr.

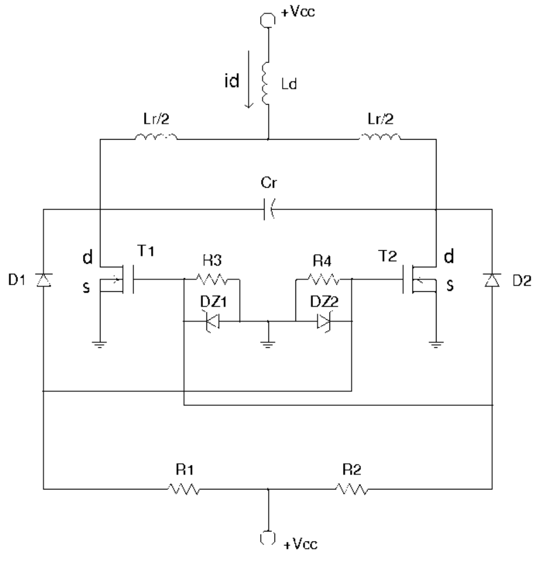

Fig.1, Schematic of a Royer oscillator made up of two identical conducting branches, each one consisting of a MOSFET transistor, a diode and a resistor.

The secondary circuit has a front-end made up of a second coil connected to a capacitor to form an identical resonant tank.

To illustrate in details the functioning of such a system, a very simplified schematic of the primary circuit is given in

Fig. 1. The circuit is made up of two identical conducting branches, each one consisting of a MOSFET transistor, a diode and a resistor, i.e. R1=R2, R3=R4, D1=D2, DZ1=DZ2, and T1=T2. The layout does not show the snubber circuits necessary for power MOSFETs protection during switching on and off transients.

In branch number 1, the current is withdrawn by the DC supply, Vcc, through resistor R1, and flows towards ground either through the diode D1 and the cascaded transistor T1, if transistor T1 is switched-on, or else through Zener diode DZ2. Equally, in branch number 2, the current is withdrawn by the same supply through resistor R2 and goes to ground either through diode D2 and the cascaded transistor T2, if transistor T2 is switched-on, or through Zener diode DZ1.

It is worth noting that, at turn on, being the circuit symmetrical, there should be no voltage difference between the terminals of the resonant LrCr tank connected to the transistors drains. But, in the practice the weak asymmetries and background noise in the tank start progressively mounting current and voltages oscillations. The asymmetries and noise act in conjunction with a positive reaction, obtained by cross-connecting the gate terminal of each transistor to the anode terminal of the diode that probes the conducting state of the other transistor in the opposite branch.

To help the injection and sustainment of the oscillations in the tank, a supplementary path for the current is arranged in the circuit by linking through a choke inductor the central tap that separates the two halves of the Lr coil to the DC supply. To limit the peak currents the inductance of the choke is chosen much greater than that of the coil forming the resonant tank.

At steady state the transistors work in push-pull mode by switching on and off upon the polarity alternation of the sinusoidal voltage across the capacitor Cr.

The circuit functioning can be simulated for several different configurations. As an example, for a configuration characterized by R1=R2=33 Ω, R3=R4=10 kΩ, Ld=1 mH, Lr=1 µH, Cr=350 nF, the current waveforms in the transistor T1, Zener diode DZ1, and inductor Lr evolve to the steady state conditions illustrated in Fig.2.

VI. MEASUREMENT RESULTS

A prototype of the power transmission system described in the previous section has been realized to conduct an experimental study. The prototype utilizes a couple of twin coils made up of five circular copper windings and characterized by a diameter equal to 14 cm.

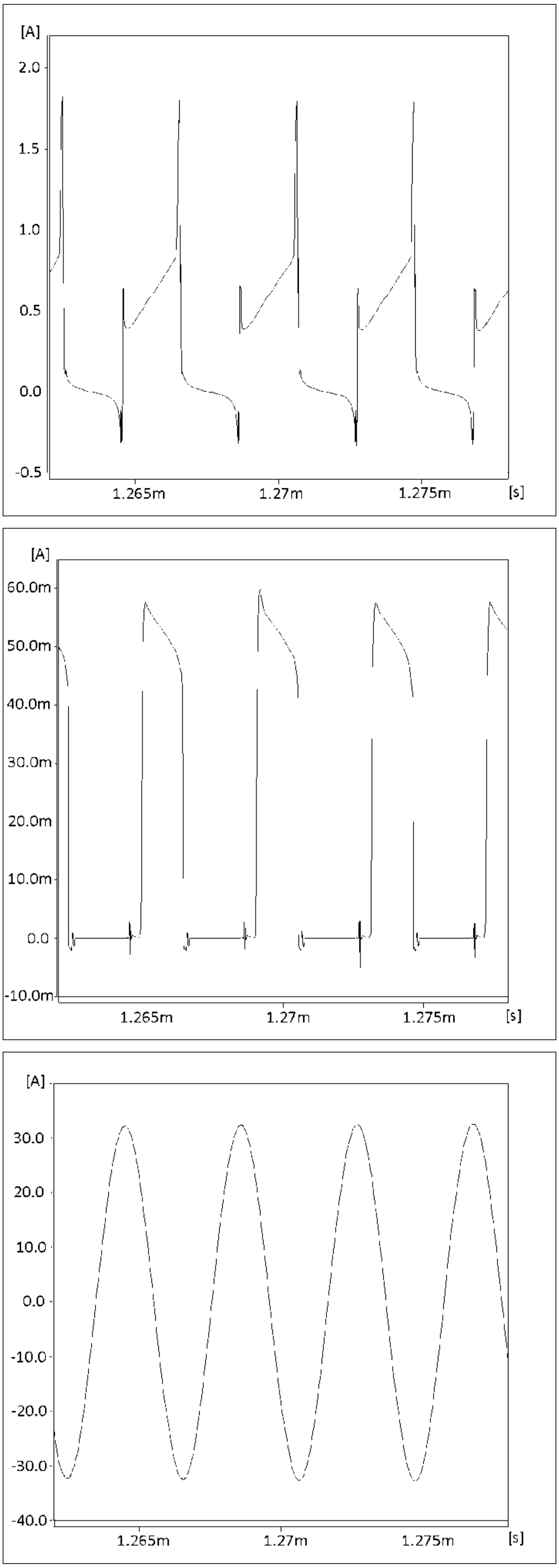

Fig.2, From top to bottom, the current waveforms for: MOSFET transistor T1, Zener diode D1, and inductor Lr.

For test purposes a measuring station consisting of a power supply, multimeters, a digital oscilloscope, and variable power resistors with slide-type wirewound, has also been set up. The power resistors connected to the secondary circuit have been utilized as loads during the tests. The experimental set-up is shown in Fig.3. Different scenarios have been explored in order to highlight how the transmitted power depends on the distance and mutual position of the coils, and on the load value.

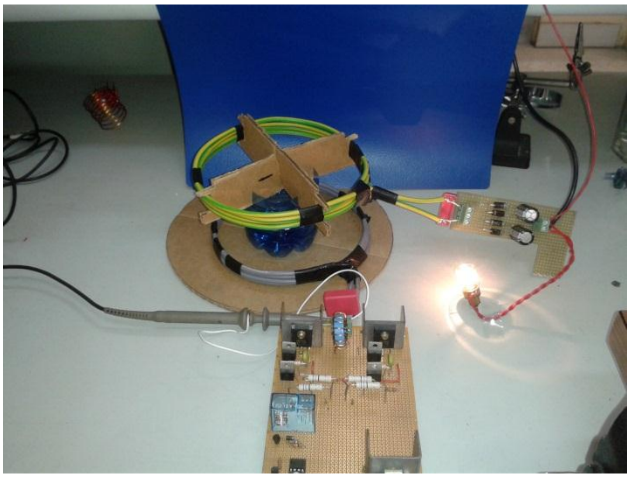

Fig.3 –. Prototype of the power transmission system utilized for the experimental study.

Power versus distance measurements have been obtained taking the ratio between the square value of the rectified voltage measured across the load and the load resistance. Measurements have been performed for different distances between the primary and secondary coil, keeping the coils parallel to each other and with their center aligned. In the experiments the secondary coil was connected to a resistive load, characterized by low resistance (20 Ω). Table 1 shows the transmitted power for different values of the distance between the coils, ranging from 1 up to 24 cm.

TABLE 1, POWER TRANSMITTED TO A SECONDARY CIRCUIT LOADED BY A 20 Ω RESISTOR VERSUS DISTANCE BETWEEN COILS.

Distance [cm]	Power [W]
1	61.25
3	45.00
4	31.25
8	8.45
16	0.45
24	0.05

Moreover, power transmission efficiency has been determined by taking the ratio between the power absorbed by the primary circuit and that delivered to the load; the values obtained in the experiment are given in Table 2.

TABLE 2, POWER TRANSMISSION FFICIENCY VERSUS DISTANCE BETWEEN COILS.

Distance [cm]	Efficiency
1	0.8507
3	0.7500
4	0.6510
8	0.3912
16	0.0250
24	0.0052

Successively, the experiments have been repeated in the presence of a higher resistance load (200 Ω). The transmitted power for the same distances considered above is given in Table 3. Due to a minor loading effect on the resonant tank at the secondary side, the typical behavior of a resonant circuit can be observed. The transmitted power shows a maximum equal to 6.48 W at a distance equal to 8 cm, in correspondence of which the efficiency of the power transmission system is 32%.

TABLE 3, POWER TRANSMITTED TO A 200 Ω RESISTOR VERSUS DISTANCE BETWEEN COILS.

Distance [cm]	Power [W]
1	5.6785
3	5.7800
4	5.7460
8	6.4800
16	1.4450
32	0.0288

Actually, it is the load resistance that is responsible of the power demand of the remote equipment. While in the presence of high power demands the transmitted power definitely decreases upon the distance, a finite short distance between the coils can be tolerated or even planned for light power demands.

The distance between the coils, together with the capacitance, inductance and resistance parameters, also affects the operating frequency of the system. In fact, altering the geometry of the system determines changes of the auto and mutual inductances of the coupled circuits. The oscillatory architecture anyway automatically settles to an operating frequency that grants the maximum power transmission for that configuration. Table 4 gives the operating frequency versus distance between coils. In this experiments it can be observed that the relative inductance increment seen at the primary circuit, which is caused by less flux cancellation, consequent to the lengthened distance between it and the secondary coil, makes the operating frequency decrease from 168 kHz down to 122.9 kHz.

TABLE 4, OPERATING FREQUENCY AS A FUNCTION OF THE DISTANCE BETWEEN COILS. MEASUREMENTS HAVE BEEN PERFORMED WHEN THE SECONDARY CIRCUIT IS LOADED BY A 200 Ω RESISTOR.

Distance [cm]	Frequency [kHz]
1	168.00
3	165.00
4	143.00
8	130.00
16	122.80
32	122.90

Keeping the two coils perfectly parallel at a distance between the respective planes equal to 12 cm with their own orthogonal axes parallel to each other but misaligned, the effects of coils misalignments have also been investigated (Fig.4). Starting from perfect axial alignment conditions, the secondary coil has been gradually moved away in order to have its axis parallel but at a distance from the axis of the primary coil. The distance between the axes orthogonal to the planes hosting the coils states the alignment mismatch. Table 5 gives the power transmitted to the secondary coil loaded by a 200 Ω resistor for misalignments ranging from 0 to 16 cm.

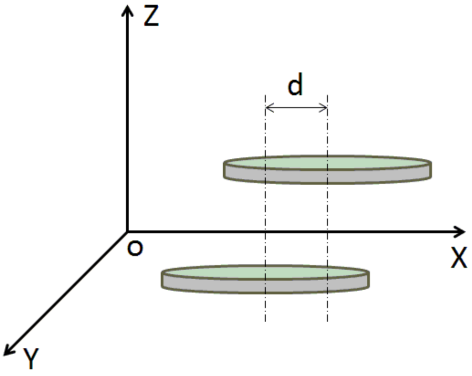

Fig.4, Parallel coils with their own orthogonal axes parallel to each other but misaligned by *d* cm.

Finally, orthogonal coils positions, have been considered to verify if WPT can take advantage by deploying more primary coils in vertical walls surrounding a platform hosting the secondary coil. Table 6 shows the transmitted power versus distance for a system made up of one vertical coil and one horizontal coil. The edge of the vertical coil is tangent to the horizontal platform hosting the secondary coil, i.e. the center of the vertical coil is at 7 cm height upon the horizontal platform; the orthogonal axes of the two coils are kept coplanar. At a distance equal to -7 cm the vertical coil is positioned in the plane that also contains the axis of the horizontal coil.

TABLE 5, EFFECTS OF MISALIGNMENT ON THE POWER TRANSMISSION SYSTEM.

Distance [cm]	Power [W]
0	6.4800
1	6.4800
2	6.1250
4	3.9200
8	1.6200
10	0.7200
12	0.2450
16	0.0098

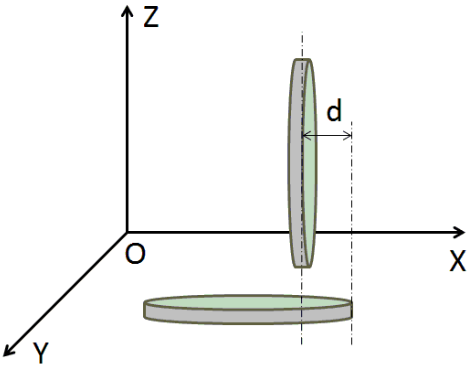

Fig.5, Schematic of the geometry characterized by orthogonal coils.

TABLE 6, EFFECTS OF ORTHOGONALLY POSITIONING OF THE PRIMARY AND SECONDARY COIL.

Distance [cm]	Power [W]
-7	1.0513
-6	1.4965
-5	1.8050
-4	2.1632
-3	2.4865
-2	3.0258
0	3.6450
2	3.1250
3	2.3544
4	1.4112
5	0.8192
6	0.2813
7	0.0085

VII. CONCLUSION

The role of the wireless power transmission technology based on resonant coupled coils has been discussed with reference to two classes of applications. It has been shown that both contactless recharging and batteryless supply can take advantage from this technology.

Contactless recharging involves the possibility of keeping grid disconnected an electrical equipment, or more precisely its internal battery, without giving up to its recharging, letting for example robotic vehicles to autonomously and reliably afford recharge when low battery state is signaled.

Batteryless supply can support the functioning of remote wireless equipment, often deployed in networked architectures, that have become more and more widespread due to their fast installation and easy re-positioning. Batteryless supply represents a much robust solution with respect to ambient energy harvesting or scavenging proposals to avoid back-up batteries. Nonetheless, the perspective of less used batteries needing proper treatment for recycling or disposal, confers additional interest to this approach.

A power transfer system that relies on a resonance-based coupling mechanism and is capable of supporting contactless recharging and batteryless supply has also been discussed. The typical architecture of a system exploiting a relaxation oscillator in the primary circuit has been set up to conduct an experimental study. The results of several tests show the efficiency of the power transfer mechanism both for nominal operative conditions as well as for different ones characterized by deliberate mismatches.

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