Wireless Energy Transfer using Magnetic Resonance

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Abstract—In 1899, Nikola Tesla, who had devised a type of resonant transformer called the Tesla coil, achieved a major breakthrough in his work by transmitting 100 million volts of electric power wirelessly over a distance of 26 miles to light up a bank of 200 light bulbs and run one electric motor. Tesla claimed to have achieved 95% efficiency, but the technology had to be shelved because the effects of transmitting such high voltages in electric arcs would have been disastrous to humans and electrical equipment in the vicinity. This technology has been languishing in obscurity for a number of years, but the advent of portable devices such as mobiles, laptops, smartphones, MP3 players, etc warrants another look at the technology.

We propose the use of a new technology, based on strongly coupled magnetic resonance. It consists of a transmitter, a current carrying copper coil, which acts as an electromagnetic resonator and a receiver, another copper coil of similar dimensions to which the device to be powered is attached. The transmitter emits a non-radiative magnetic field resonating at MHz frequencies, and the receiving unit resonates in that field. The resonant nature of the process ensures a strong interaction between the sending and receiving unit, while interaction with rest of the environment is weak.

Keywords – wireless energy transfer; near field; evanescent wave, magnetic resonance; self-resonance

I. A BRIEF HISTORY

In 1891, Nikola Tesla invented a type of resonant transformer called the Tesla coil, which was used to generate very high voltage, low current, and high frequency alternating electricity. He experimented with a large variety of coils and configurations, one of which is as:

![Fig. 1. Basic configuration of Tesla coil.](image)

Referring to Fig. 1, the capacitor 1C forms two resonant circuits: one with the primary coil 1P, and another with the secondary coil 1S. The voltage is supplied by the Neon sign transformer 1T.

The spark gap 1SG consists of two electrodes separated by a gap, filled with an inert gas. When high enough voltage is applied across it, a spark forms, ionizing the gas, and allowing conduction.

As the voltage across the gap 1SG increases, the charge across the capacitor 1C also increases. When the gap sparks, the capacitor discharges into the primary and the secondary. Thus, the voltage “bounces” back and forth at an extremely high rate. When the rate of discharge between the capacitor 1C and primary 1P, matches that of the capacitor and secondary 1S, the two circuits are said to be "in resonance". The voltage rises to such high levels that it is discharged through the discharge terminal in the form of an electric arc.

Tesla used these coils to conduct numerous innovative experiments. In 1899, he achieved a major breakthrough in his work at Colorado by transmitting 100 million volts of electric power wirelessly over a distance of 26 miles to light up a bank of 200 light bulbs and run one electric motor. He claimed to have achieved 95% efficiency. The method he used to wirelessly transmit electricity was the employment of the earth's own resonance with its specific vibrational frequency to conduct AC electricity via a large electric oscillator at about 7.8 Hz.

However, there were several safety hazards that were needed to be considered. A Tesla Coil produces high voltage electric arcs. These arcs cause permanent damage to electrical devices on contact. Many devices can also be damaged without being directly struck by the arc, due to the sheer amount of voltage being transferred. Tesla coils also destroy hearing aids and cardiac pacemakers in their vicinity. For all the above reasons, this technology has been languishing in obscurity and not much research has been carried out in the field of wireless energy transfer.
However, the advent of a number of portable entertainment and communications devices warrants another look at this technology. We propose the use of a technology, which uses the phenomenon of electromagnetic resonance for energy transfer. The idea is to use two copper coils, one at the transmitting end connected to the power supply, and the other at the receiving end, which is strongly coupled to the magnetic field of the first. For strong coupling to take place, the receiving coil must be within the near field region of the transmitting coil.

II. NEAR FIELD INDUCTIVE COUPLING

Unlike the previously used far field electromagnetic waves, we propose the use of near field inductive coupling through magnetic resonance. A near field is the region around the source of electromagnetic radiation within a radius \( r << \lambda \), where \( \lambda \) is the wavelength of the transmitted wave. The total energy per unit area at a distance \( r \) from the transmitter is proportional to \( 1/r^2 \). Since the receiver is within a very small radius of the transmitter, most of the transmitted energy appears at the receiving end. Thus, losses are less.

Another advantage of using near fields is that energy is available to the receiver only if the energy is tapped, and this is sensed by the transmitter by means of answering electromagnetic near fields emanated by the receiver. This is different from the far field, which draws energy constantly from the transmitter, whether it is immediately received, or not. This non-radiative energy transfer is mediated through evanescent waves.

The theoretical realization of the scheme, Fig. 2, consists of two self-resonant coils. One coil (the source coil \( 2S \)) is coupled inductively to an oscillating circuit; the other (the device coil \( 2D \)) is coupled inductively to a resistive load.

\[ \begin{align*}
\text{2A} & \quad \text{2S} & \quad \text{K} & \quad \text{2D} & \quad \text{2B}
\end{align*} \]

Fig. 2. Theoretical model for self-resonant coils.

\( 2A \) is a single copper loop of radius 25 cm that is part of the driving circuit, which outputs a sine wave with frequency 1 MHz. \( 2D \) is a loop of wire attached to the load (light bulb). The various \( K \)'s represent direct coupling constants between the objects indicated by the arrows. The direct coupling constants between \( 2B \) and \( 2A \) and between \( 2B \) and \( 2S \) are negligible.

III. EVANESCENT WAVE COUPLING

An evanescent wave is a damped wave, whose power exponentially decays with an increase in distance. Evanescence basically means 'tending to vanish'. The wave is most intense within a distance of one-third wavelength from an electromagnetic source.

Evanescent wave coupling is accomplished by placing two or more electromagnetic elements close together so that the evanescent field generated by one element does not decay much before it reaches the other element.

Referring to Fig. 3, in evanescent wave coupling, both the transmitter and receiver emit evanescent waves of the same frequency. However, they are traveling in opposite directions. This forms a standing wave, which facilitates efficient transfer of energy between the transmitter and receiver. Initially, the energy is being transmitted from the transmitter to the receiver. As the receiver utilizes this energy, the standing wave collapses. This process repeats itself and the energy is transferred in bursts.

IV. TRANSMITTER CIRCUITRY:

Referring to Fig. 4, the transmitter circuit consists of:

Clock generator \( 4CG \):

Any resonant circuit and an amplifier can be used as a clock generator. The resonant circuit can be simple like an RC oscillator or a more complex arrangement like a quartz piezo-electric oscillator. The amplifier feeds a portion of signal back to the oscillator to maintain oscillations.

Phase shift network \( 4PH \):

[7] mentions the use of a phase shift network to convert the low frequency input A.C.
signal to a high frequency directional ultrasound wave. We plan to use a similar phase shift network to increase the input frequency. This will limit the wavelength of the transmitted waves to the near-field region.

The phase shift network in Fig. 5 generates a phase difference between the clock signal 4CG and the VCO 5V output 5Va. The leading edge of the clock signal sets Latch 1 5L1, while the leading edge of the VCO output 5Va turns off the output of Latch 1. The pulse width of Latch 1 is thus proportional to the phase difference between the clock generator input 4CG and VCO output 5Va. The phase detector output of Latch 1 is then smoothed by a low pass filter, which is then passed the error amplifier, which then adjusts the VCO such that the phase detector output is equal to the phase control input.

V. RECEIVER CIRCUITRY

Referring to Fig. 6, the receiver control electronics circuitry 6R is equipped with a voltage regulator, which is unique to each receiving device 6D, which regulates the voltage to a specified value.

VI. CHOICE OF COIL

Ideal inductors would have zero resistance and zero capacitance. But practical inductors have ‘parasitic’ resistance and capacitance. The first self-resonant frequency of an inductor is the lowest frequency at which an inductor resonates with its self-capacitance. At this frequency, the effective inductance is zero since it is canceled by its counterpart.

To calculate the self-resonant frequency of the coil, we use an adaptation of the formula for helical antennas found in the section on slow wave structures in [16].

\[ F = \frac{29.85 \times (H/D)^{1/5}}{N \times D} \]

Where, \( F = \) self resonant frequency in MHz of an ‘isolated’ coil
\( H = \) coil height in meters
\( D = \) coil diameter in meters
\( N = \) total number of turns

The constraint is that this formula is only valid for \((H/D) < 1\), which was a part of the initial assumptions of the derivation of the formula.

We choose a coil with height and diameter such that its self-resonant frequency is at least two times its operating frequency. For an operating of 1MHz, the self-resonant frequency should be 2MHz. If the ratio \(H/D\) is kept at 0.5, then for a coil with 100 turns, the diameter works out to be approximately 13cm.

VII. FEASIBILITY

The system can use transmit and receive high-Q resonant antennas, preferably of a small size to allow them to be fit in a small handheld device. Efficient power transfer may be carried out between two antennas by storing energy in the near field of the transmitting antenna, rather than sending the energy into free space in the form of a travelling electromagnetic wave. The receiver antenna should be smaller for purposes of packaging. The system can transmit 25W of power at an efficiency of 25% over a distance of 1.5m.

VIII. APPLICATIONS

The main application of this lies in the wireless charging of all portable devices including cell phones, music players, laptops, and so on. In fact, we can also power light bulbs, compact fluorescent lamps (CFL’s), electric fans, television sets etc. The devices that need to be charged can be broadly classified into two types: Those which will be relatively stationary with respect to their environments, like television sets, desktop computers, fans etc. and those which are mobile, and will be charged whenever they are near a transmitting source, like cell phones, lap tops, game controllers etc.
We envision the creation of wireless electricity ‘livespots’, where one can walk in and charge any device wirelessly. To make such livespots feasible, we contemplate the creation of separate charging zones in commercial establishments like cafés, restaurants, and malls similar to smoking or Wi-Fi zones.

In an office, all computers can be powered by an overhead transmitter, thus eliminating the tangles of power cords that exist now.

We can also get rid of separate chargers for different equipments, and bring a level of standardization and convenience.

With the proliferation of this technology, we foresee a day when wireless electricity will be so ubiquitous that governments can provide transmitters at regular intervals so that most citizens can harness it.

VI. DRAWBACKS

In a world without wires, ‘energy theft’ will become a possibility. However, since we are using near field magnetic resonance, which works at a distance up to 10 meters, the chances of this happening are rather unlikely.

Also, there will be a need for standardization of equipment. Retrofitting old equipment with receivers or purchasing new equipment will be expensive.

Public awareness about the safety of using this technology will have to be created before it becomes widespread.

REFERENCES

[16] S Ramo, J R Whinnery and T D Van Duzer, ‘Fields and waves in Communication Electronics’