Wireless Power Transmission using Solid State Tesla Coils

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***Abstract*—** Electrical power is crucial to modern systems. From the smallest of sensors and bionic implants to satellites, remote controlled airplanes/cars/robots and oil platforms, it is important to be able to deliver power by means other than wires or transmission lines. The use of wireless power transmission, on a scale larger than used by magnetic induction devices, would allow for systems to operate remotely without the need for relatively large energy storage devices or routine maintenance. It will also be employed in cases where interconnecting wires is inconvenient, hazardous or impossible such as in wet environments, rotating or moving joints as well as powering remote telecommunication equipment.

This paper explores the current wireless power transmission schemes and their practicability. It also delves into theory, design and construction of a method to transmit power through space. To this end, the solid state tesla coil configuration is used as the basis to generate high voltage, high frequency electrical power.

***Keywords*—**Wireless,Tesla coil, Electrical power, Induction.

I. INTRODUCTION

THE idea of transmitting power through the space was conceived over a century ago, with Nikola Tesla's pioneering ideas and experiments perhaps being the most well-known early attempts to do so[1]. His vision was to wirelessly distribute power over large distances using the earth's ionosphere.

Most approaches to wireless power transfer use an electromagnetic (EM) field of some frequency as the means by which the energy is sent. At the high frequency end of the spectrum are optical techniques that use lasers to send power via a collimated beam of light to a remote detector where the received photons are converted to electrical energy.

Efficient transmission over large distances is possible with this approach; however, complicated pointing and tracking mechanisms are needed to maintain proper alignment between moving transmitters and/or receivers. In addition, objects that get between the transmitter and receiver can block the beam, interrupting the power transmission and, depending on the power level, possibly causing harm. At microwave frequencies, a similar approach can be used to efficiently transmit power over large distances using the radiated EM field from appropriate antennas. [2] However, similar caveats about safety and system complexity apply for these radiative approaches.

It is also possible to transmit power using non-radiative fields. As an example, the operation of a transformer can be considered a form of wireless power transfer since it uses the principle of magnetic induction to transfer energy from a primary coil to a secondary coil without a direct electrical connection. Inductive chargers, such as those found commonly in electric toothbrushes, operate on this same principle. However, for these systems to operate efficiently, the primary coil (source) and secondary coil (device) must be located in close proximity and carefully positioned with respect to one another. From a technical point of view, this means the magnetic coupling between the source and device coils must be large for proper operation.

To overcome the above challenges, that is, to transmit somewhat larger distances or have more freedom in positioning the source and device relative to each other, this paper explores the use of a non-radiative approach that uses resonance to enhance the efficiency of the energy transfer.

II. LITERATURE REVIEW

A. Historical Perspective

- In 1864, James C. Maxwell predicted the existence of radio waves by means of mathematical model [3].
- In 1884, John H. Poynting realized that the Poynting Vector would play an important role in quantifying the electromagnetic energy.
- In 1888, bolstered by Maxwell's theory, Heinrich Hertz first succeeded in showing experimental evidence of radio waves by his spark-gap radio transmitter. The prediction and Evidence of the radio wave in the end of 19th century was start of the wireless power transmission.
- Nikola started efforts on wireless transmission in 1891 at his "experimental station" at Colorado [4]. A small incandescent resonant circuit, grounded on one end was successfully lighted.

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Figure 1. Wardenclyffe tower also known as tesla's tower (56.9Meters) at long Island, New York.

- Wardenclyffe tower was designed by Tesla for trans-Atlantic wireless telephony and also for demonstrating wireless electrical power transmission.
- William C. Brown contributed much to the modern development of microwave power transmission which dominates research and development of wireless transmission today(figure 2). In the early 1960s brown invented the rectenna which directly converts microwaves to DC current. Its ability was demonstrated by powering a helicopter solely through microwaves in 1964 [5].

Figure 2 Microwave power transmission laboratory experiment in 1975 by W. Brown.

- A physics research group led by Prof. Marin Soljacic at the Massachusetts Institute of Technology (MIT) demonstrated wireless powering of 60W light bulb with 40% efficiency at 2m (7ft) distance using two 6ocm – diameter coils in 2007[6] . Resonant induction was used to transmit power wirelessly. The group is also working to improve the technology. The technology is currently referred to as WiTricity and to carry out this technology forward from the MIT laboratories, WiTricity Corp. was launched [6].

B. Methods of Wireless Transmission of Electrical Power

a. Near Field Techniques

i. Induction.

The principle of mutual induction between two coils can be used to transfer electrical power without any physical contact in between. The simplest example of how mutual induction works is the transformer, where there is no physical contact between the primary and the secondary coils. The transfer of energy takes place due to electromagnetic coupling between the two coils [7].

ii. Evanescent Wave Coupling.

This method uses non-radiative electromagnetic energy resonant tunneling. Since the electromagnetic waves tunnel through the air, energy absorption by air is eliminated and electronic devices are not disrupted. Unlike electromagnetic radiation, it is not considered harmful for the human body.

iii. Air ionization

The concept here is the ionization of air due to the electromagnetic field produced. This technique exists in nature and its implementation requires high fields of about 2.11 MV/m. Richard E. Vollrath, a California inventor has developed an ingenious sand-storm generator, which sends blasts of dust-laden air through copper tubes, generating electricity which can be stored in sphere and used later [8].Example of this technique is seen in nature lightning.

iv. Electrodynamic Induction

This method is also known as "resonant inductive coupling" and it resolves the main problem associated with non-resonant inductive coupling for wireless energy transfer; specifically, the dependence of efficiency on transmission distance. When resonant coupling is used the transmitter and receiver inductors are tuned to a mutual frequency and the drive current is modified from a sinusoidal to a non-sinusoidal transient waveform. Pulse power transfer occurs over multiple cycles. In this way significant power may be transmitted over a distance of up to a few times the size of the transmitter.

v. Electrostatic Induction.

This method is also known as "capacitive coupling". It is an electric field gradient or differential capacitance between two elevated electrodes over a conducting ground plane for wireless energy transmission. It involves high frequency alternating current potential differences transmitted between two plates or nodes.

b. Far Field Techniques

Far Field Energy Transfer is mainly dependent on radiative techniques. Waves are either broadcasted in the form of narrow beam transmission of radio, or light waves. This is solely for high power transfer. Tesla already gave the concept to the world on his paper: "Truly Wireless" in late 1880s-based on the Wardenclyffe Tower that was constructed to transfer the energy for large distance [4].

i. Radio and Microwave

Power transmission via radio waves can be made more directional, allowing longer distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range. A rectenna may be used to convert the microwave energy back into electricity. Rectenna conversion efficiencies exceeding 95% have been realized [9]. Power beaming using microwaves has been proposed for the

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transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered.

ii. Electromagnetic Transmission

Electromagnetic waves can also be used to transfer power without wires. By converting electricity into light, such as a laser beam, then firing this beam at a receiving target, such as a solar cell on a small aircraft, power can be beamed to a single target[10].

LASER Technology uses the same principle as microwave wireless transmission but here energy emission is of high frequency and is coherent. The other great advantage of LASER power transmission is the aperture collection efficiency. The antenna can be made small due to the collimation of the beams. LASER transmission does not get dispersed for long distance but it gets attenuated when it propagates though atmosphere.

C. Need for Wireless Power Transmission

Wireless transmission is employed in cases where instantaneous or continuous energy transfer is needed, but interconnecting wires are inconvenient, hazardous, or impossible (figure 3).

Figure 3 Interconnected wires.

Number of household points receives electricity at the same frequency using single transmitting coil as long as they all are at resonance (figure 4).

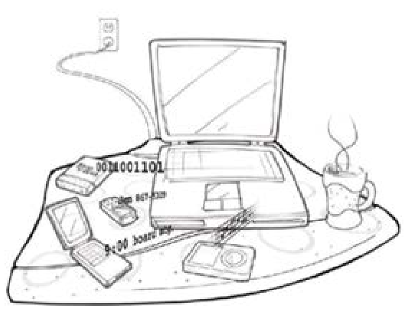

Figure 4 Household points receiving electricity from one coil

D. Technology Benefits and Applications

The interest in highly resonant wireless power transfer comes from many markets and application sectors. There are several motivations for using such technology, and these often fall into one or more of the following categories:

- Make devices more convenient and thus more desirable to purchasers, by eliminating the need for a power cord or battery replacement.
- Make devices more reliable by eliminating the most failure prone component in most electronic systems—the cords and connectors [10].
- Make devices more environmentally sound by eliminating the need for disposable batteries. Companies make about 40 billion disposable batteries each year, and wireless electricity could do away with that [11]. Using grid power is much less expensive and more environmentally sound than manufacturing, transporting, and using batteries based on traditional electro-chemistries.
- Reduce system cost by leveraging the ability to power multiple devices from a single source resonator.
- Charging will likely become possible for mobile devices from different manufacturers via wireless charging pads in public spaces such as cafés, airports, taxis, offices, and restaurants.
- LED (light emitting diode) lights can be directly powered with wireless electricity, eliminating the need for batteries in under-cabinet task lighting, and enabling architectural lighting designers to create products that seemingly float in mid-air, with no power cord[12].
- The unmanned planes or robots (where wires cannot be involved viz: oceans, volcanic mountains etc.) which are run by the wireless power over an area, as they could fly for months at a time, could be used for research.

E. Solid State Tesla Coil (SSTC)

It is an air-cored resonant transformer capable of generating extremely high voltages. Its construction is relatively straightforward. The key concept of a Tesla Coil is its resonant property, where a Resistor-Inductor-Capacitor (RLC) resonant circuit is energized at its resonant frequency, developing very high voltages [13].

A Tesla Coil consists of two concentric coils which are not electrically connected to each other. The Primary Coil usually consists of a few turns of heavy wire, and has a shape ranging from a solenoid to a flat spiral. This coil is usually connected to some capacitor, forming the Primary LC circuit. The secondary circuit consists of a long coil of wire, usually having several hundreds to thousands of turns wound on a pipe, and placed concentrically in the middle of the coil [14]. The control circuit consists of solid state devices.

III. SYSTEM DESIGN.

A solid state tesla coil usually has these key components:

- Power source.
- Switching circuit. The circuits that make the tesla coil work at the correct frequency and duty cycle.
- Primary coil. The primary coil (figure 5) is powered by the control circuitry and generates the magnetic field that the secondary use to create the high voltage. It is the few turns of thick wire at the base of the secondary coil.

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- Secondary coil .The secondary coil (figure 5) is a long cylinder. It is PVC pipe covered by an enameled wire. One side is connected to ground; high voltage comes through the other side.
- The Top load: The top load is the metallic object at the top of the secondary coil. It provides a capacitance to the Tesla coil.

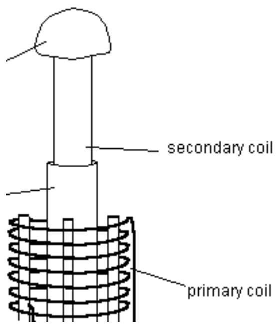

Figure 5 Secondary and primary coils.

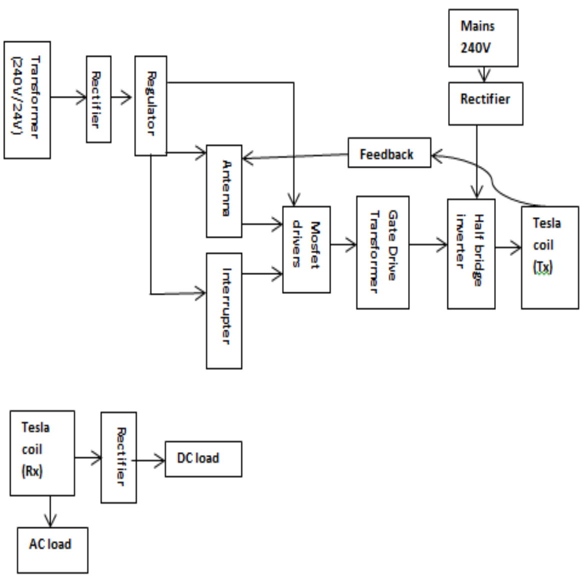

Figure 6 Functional block diagram

It shows how the system modules relate to one another.

A. System Modules

- Two power supplies are provided-One that powers the tesla coil switching circuit and the other the primary coil (Figure 6).
- The Interrupter (Figure 7) turns turn the Tesla coil on and off at a certain frequency. This doubles as a power control if the duty cycle of the circuit is varied.

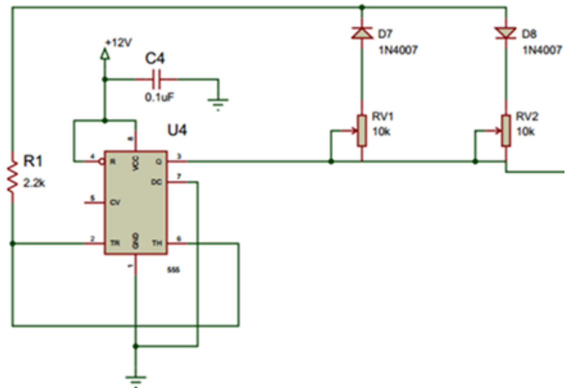

Figure 7 The Interrupter

- Antenna section. It is the feedback mechanism (figure 8). This part of the circuit is designed to capture feedback from the secondary coil to keep the circuit resonating. The antenna could be any straight piece of wire connected to the circuit. The other end is left unconnected.

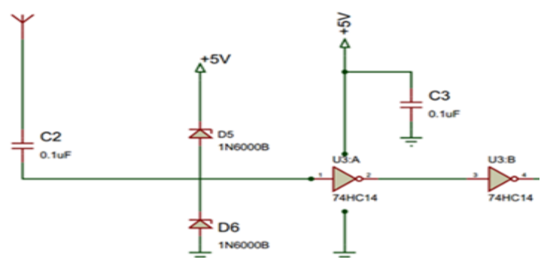

Figure 8 Antenna section

A solid state Tesla coil works by switching the primary coil at a resonant frequency. This frequency varies due to the height of the coil, the top load, and the environment [14]. Thus, a fixed frequency oscillator is not ideal.

The used driver changes its frequency based on what the antenna receives from the Tesla coil. Antenna feedback is designed to capture feedback from the secondary to keep the circuit resonating. Because we use feedback to provide the signal to the half bridge, the coil is always in tune. Using schottky diodes (diodes with a low forward voltage drop, and hence, fast) to clamp the signal to ground and +Vcc, to ensure the drive is not destroyed; a square signal to the driver input is obtained.

- Gate drive. This part of the circuit combines and amplifies the interrupter and feedback signals to drive the gate drive transformer (figure 9). The circuit works by generating a square wave from the respective outputs of the inverting and non-inverting MOSFET drivers and they operate in phase.

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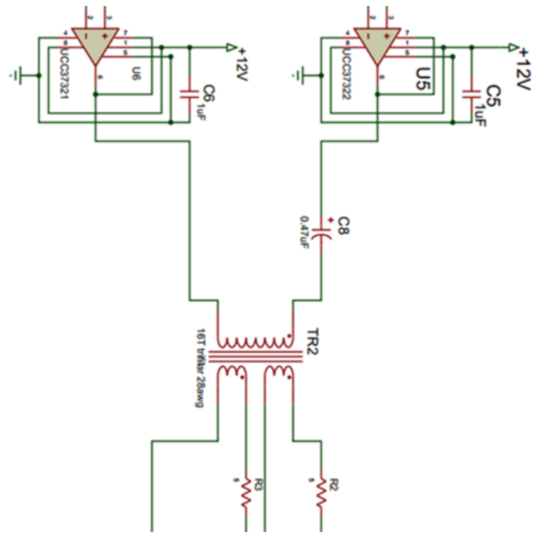

Figure 9 Gate drive

- Gate drive transformer. Isolates the switching circuit (figure 10).

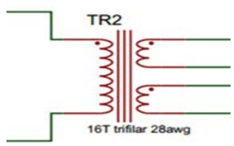

Figure 10 Gate drive

- Half bridge Inverter. These are two MOSFET that alternate switching on and off to produce alternating current (figure 11). This is done at a high voltage, mainly so that power can be pumped through the primary coil. This causes a magnetic field to be formed that excites the secondary coil (resonator).

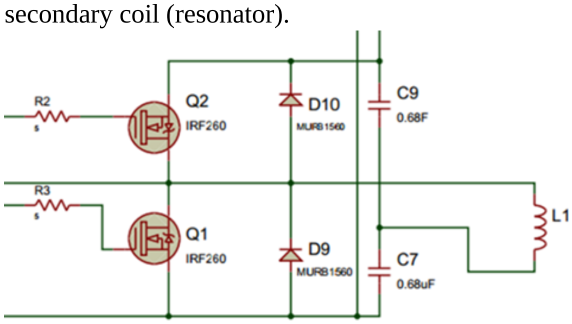

Figure 11 Half bridge Inverter

- Two tesla coils; Transmitter and receiver.

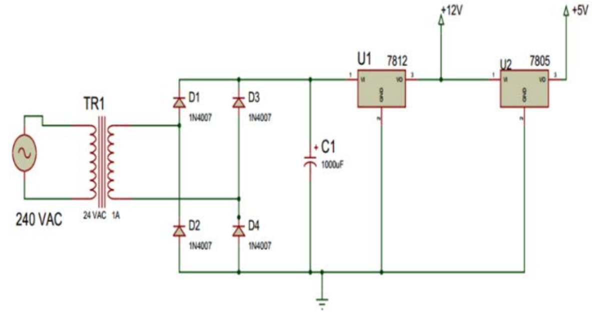

Figure 12 Power supply to control circuit

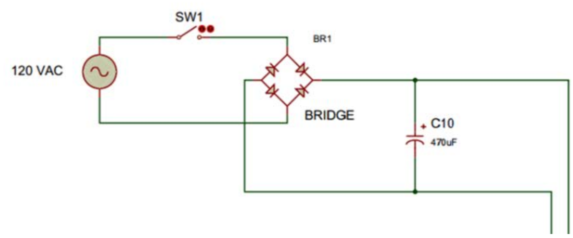

Figure 13 Power supply to the half bridge

B. Tesla Coil Design.

The inductance of a coil can be estimated using equation 1:

$$L_{solenoid} = \frac{\mu_o N^2 \pi a^2}{b}[Henry] \qquad (1)$$

Where μ_o is the permeability of free space and a and b are expressed in meters. N is the number of turns.

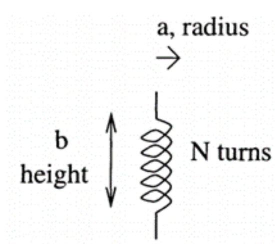

Figure 14 Cartoon of a solenoid Inductor with marked dimensions.

where 'a' is the radius of the coil and 'b' the height of the coil.

a. Wheeler's Formula

The Wheeler's formula was used to estimate the inductance of the Tesla coil.

$$L_{solenoid} = \frac{a^2 N^2}{9a + 10b}[\mu H] \qquad (2)$$

Note that a and b are expressed in inches.

b. Estimating Capacitance

Medhurst Capacitance

$$C_o \approx 2Ha[pF] \qquad (3)$$

Where a is radius of the solenoid in centimeters and H is a factor based on the Medhurst table [15].

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The Spherical top load capacitance was estimated using the formula:

$$C = 4\pi\varepsilon_O R \qquad (4)$$

where R is radius in meters, and ε_O permittivity of free space.

IV. RESULTS & DISCUSSION

The transmitter Tesla coil (figure 16) consisted of 10 primary turns while the secondary consisted of 530 turns made of 14AWG (1.63mm) enameled copper wire and 23AWG (0.51mm) enameled copper wire respectively.

The receiver Tesla coil (figure 17) consisted of 250 primary turns while the secondary consisted of 50 turns all made of 23AWG (0.51mm) enameled copper wire respectively.

The receiver circuit (figure 15) consisted of nine concentric led lamps and power control circuit.

The control circuit (figure 14) consisted of sub-circuits that make the tesla coil work at the correct frequency and duty cycle.

The transmitter primary was fed with 20v ac power at 50Hz; the output was 1060v ac power at 73 KHz. The theoretical resonant frequency was calculated to be 67.4 KHz. The deviation in the actual resonance frequency from the theoretical resonance frequency is due to the imperfections in designing the Tesla coil. Parasitic capacitance and inductance also contributed to this difference.

Nine Led lamps were light at a distance of 1 meter. It had a typical efficiency was 40% for a distance of 1m.Losses in the control circuit and the half bridge were major constraints.

Power transmission was maximum when a common ground was used between the transmitter and the receiver.

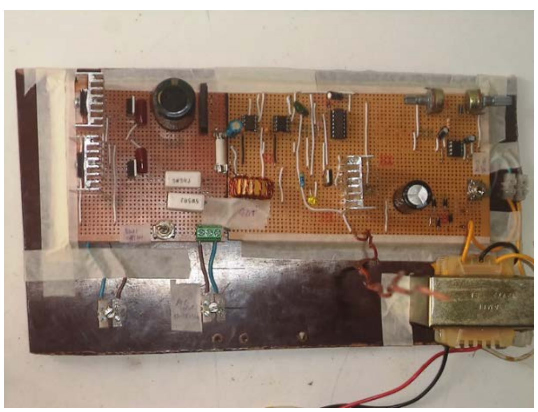

Figure 13 Control Circuit

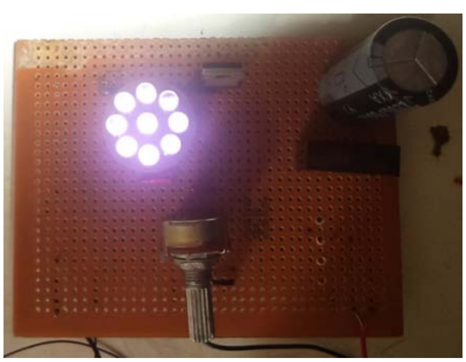

Figure 15 Receiving Circuit

Figure 16 Transmitter Tesla coil

Figure 17 Receiver Tesla coil

V. CONCLUSION.

The main objective of this paper was to demonstrate wireless power transmission using solid state tesla coils. Tesla coils are remarkable devices able to generate high voltage, high frequency waveforms with little control circuitry. Most of the builders of Tesla coils are interested in producing electric arcs and visible effects suitable for displays and general amusement, not in producing power supplies and power effects units which may have significant practical importance. The paper has demonstrated that tesla coils can be designed for wireless power transmission.

Further improvements to be made on the design include:

- Design of a full wave inverter to power the Tesla coils. This will minimize the losses since full wave inverters do not exhibit the losses prevalent in half wave rectifiers.
- A better feedback mechanism can be adopted instead of using a wire. A small current-transformer on the secondary coil can be used, instead, to obtain feedback. This is constructed by wrapping around 50 turns of wire on a small ferrite core with the secondary wire going through this ring on the ground side. Care must be taking to ensure the right phasing.

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