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Wireless Electrical Power Transmission Using Spark Gap Tesla Coil (SGTC)

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ABSTRACT

Tesla Coil is mainly designed for transmitting the Electrical Power Wirelessly in the same way as the Radio Waves are transmitted into the air. It is designed by the Greek innovator Nikola Tesla and patented in December 1st 1914. But unfortunately, he didn't complete his paper, investors collapsed his laboratory, filed a case on him & he died of poverty and hungry in 1943. He is the one who invented the wireless system, AC Supply, AC Motor and the first person who generated the hydroelectricity.

Tesla coil is basically an RLC circuit and works in resonant frequency. The SGTC consists of an HT Transformer which produce a high voltage (Ex:5KV,25 mA), the capacitors, basically a Cornell Dubiler 942C20P15K-F capacitors are used or else homemade HV capacitors are also used. The Spark Gap is in parallel to the HV Transformer before the capacitors. The gauge of the primary winding used is more than the secondary as because it is like a step-up transformer. The output high voltage is appeared at the one of the ends of the secondary winding where as other end is grounded. The voltage, frequency is all depends on the spark gap. If the spark gap is more than the output voltage increases.

In this paper we are going to illuminate some light bulbs (Fluorescent tubes, neon bulbs, CFL's) wirelessly. We are also proving that AC (Alternating Current) is not dangerous by passing some KV's of AC voltage into the human body

1. INTRODUCTION

The device we now call a "Tesla coil" is probably the most famous invention of Nikola Tesla. On the planet he submitted in 1914 to US patent & Trademark office, it was called "Apparatus for transmitting electrical energy".

Nikola Tesla was born the 10th of July 1856 in a Serbian village of the Austrian Empire (in today's Croatia) and died the 7th of January 1943 in the United States.

It is not an exaggeration to say he was a visionary who changed the world. With his works on alternative current, including many patents on generators, transformers and turbines, he allowed the widespread proliferation of electricity as a source of power as we know it today. He was also a pioneer in the domain of telecommunications; the Tesla coil can be viewed as one of the very first attempts of a radio antenna. It consisted of circuits that are fundamentally the same as our modern wireless devices.

It has a power of 200 W, which is quite low compared to the coils built by professionals, which often surpass several thousands of Watts. It is nevertheless an appreciable power, given the small budget that was allocated. The construction of Tesla Coil was not an easy task and almost every component had to be rebuilt at least twice & sometimes thrice. This however allowed me to acquire my first experience in the domain of high voltages, which was probably the greatest reward this paper gave us.

2. CONCEPT AND CONSTRUCTION

This work deals with the formulas used to conceive the Tesla coil and also with specific details of practical scope.

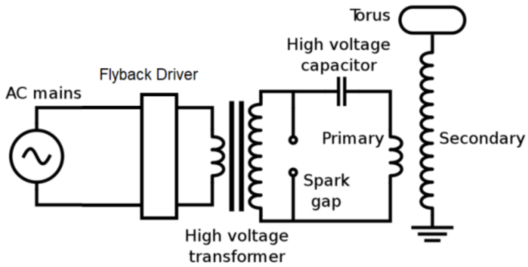


Fig.1 Schematic Diagram of Tesla Coil

A. HV Transformer:

The high voltage transformer is the most important part of a Tesla coil. It is simply an induction transformer. Its role is to charge the primary capacitor at the beginning of each cycle. Apart from its power, its ruggedness is very important as it must withstand terrific operation conditions (a protection filter is sometimes necessary for Fly back Transformer).

Among the most common are the pole pigs, normally used in the electrical grid. These typically provide around 20kV and have no integrated current limitation, which makes them quite deadly if not handled correctly. Obtaining one is quite difficult in Europe.

The other widely-used type of transformer is the neon sign transformer (NST), which is, as its name suggests, generally used to power neon signs. They generally supply between 6 and 15 kV and are current limited often at 30 or 60 mA. They are safer and easier to find than the pole pigs but are more fragile. Notice that newer NST should be avoided, as they are provided with a built-in differential circuit breaker, which will prevent any Tesla coil operation. Indeed, we'll later see that this provokes repeated spikes of current and voltages that will trigger the breaker.

Beside from these two common types, one can also use a fly back transformer or a microwave oven transformer (MOT). Now in this paper we are using the Fly back Transformer.

Fig.2 Flyback Transformer in real life

The power supply of Tesla Coil consists of a single Flyback Transformer, whose characteristics (rms values) are the following:

Voltage (V) = 7000V

Current (I) = 25mA

We can now compute its power P = V I, which will be useful to set the global dimensions of the Tesla coil as well as a rough idea of its sparks' length.

P = 175W

Tesla Coil has thus a relatively low power, which is perhaps not a bad thing for a very first coil. For more power, one can connect several transformers in parallel in order to increase output current.

We'll also need to know the transformer's impedance in order to compute the optimal size of the primary capacitor. Using Ohm's law Z = V /I, one finds:

Z = 280kΩ

B. Primary Circuit:

1 Capacitance:

The role of the primary capacitor is to store a certain quantity of charges (thus of energy) for the coming cycle as well as forming an LC circuit along with the primary inductor.

This is certainly the most difficult component to make on one's own. I had to rebuilt it three time before getting a working and efficient version. The primary capacitor is indeed subject to very rough treatment: it must withstand strong spikes of current (hundreds of amps) and voltage as well as very short charge/discharge times. Moreover, it must boast low dielectric losses at radio frequencies. For performance-related reason, I finally switched to factory capacitors.

Its capacitance must be such as there is resonant amplification in the primary circuit. Let's call Cres this specific value. If the capacitance is lower than Cres the energy available for the rest of the cycle will be lower. The same thing would happen if the capacitance is larger than Cres, but the larger capacitance allows more charge to be stored, which compensates the first problem. We'll see in section 4.2.3 Resonant charge that it might be judicious to make a "bigger" capacitor in order to prevent the amplification from becoming too powerful, which could easily destroy the transformer as well as the capacitor.

Fig.3 Capacitor Bank

By definition, we could find Cres with formula, but we must know the total inductance of the primary circuit. We'll rather use a formula involving the impedance Z. It's important to note that the inductance of the transformer is much greater than the inductance of the primary coil, and the same is true for their impedances; we'll therefore neglect the primary inductor's contribution. The aforementioned formula is the following:

$$C_{res} = \frac{1}{2\pi Z f}$$

The mains current is 50 Hz in Europe and the impedance of our NST is 3.6 · 105 Ω. We thus immediately get:

$$C_{res} = 11.36 \text{ nF}$$

2. Homemade plate-stack capacitors:

Building your own capacitor is a enriching experience but you should keep in mind that its performances will inevitably be lower than those of factory-made capacitors. Using Maxwell's equations, it's possible to find a simple formula giving the capacitance C of a basic capacitor, made of two plate of area A separated by a distance d by a dielectric of permittivity. One can show that.

$$C_{res} = \frac{\varepsilon A}{d}$$

To increase capacitance, one can put several plates in parallel instead of just two. Then, half of the plates are, say, positive while the other half are negative. If this capacitor is made of n plates, there is (n − 1) capacitors in parallel, and its capacitance is thus:

$$C_{res} = (n-1)\frac{\varepsilon A}{d}$$

The choice of the dielectric medium is of prime importance. It must have a high dielectric strength and provide low losses at high frequencies. The dielectric strength is the minimum electric field required to provoke a breakdown of the medium. The dielectric losses come from the fact that a real capacitor also possess a resistive component to its impedance. A fraction of the energy is then lost in the form of heat in the dielectric medium and in the conductors. It is however the dielectric losses that predominates and a loss tangent is defined for each dielectric.

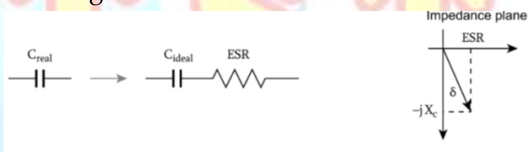


Fig.4 A real capacitor has an internal resistance in addition to its impedance

The resistive component of the capacitors impedance is called equivalent series resistance (ESR) and is measured by connecting a resistor in parallel to capacitor through this formula:

$$ESR = \frac{R_p}{1 + \omega^2 C_p^2 R_p^2}$$

Where:

Rp is the resistance of the parallel resistor,

ω the pulsation of the alternating current,

Cp the capacitance of the ideal capacitor.

The tangent loss is defined as the ratio of the real to imaginary part of the capacitor's impedance (notice the analogy with the Q factor of an oscillator):

$$\tan\delta = \frac{ESR}{X_C}$$

Here is a list of possible dielectrics for high-voltage applications:

Dielectric medium	ϵ_r at 1 MHz	Dielectric strength [kV/mm]	$\tan\delta$ at 1 MHz
LDPE	2.25	18.9 - 26.7	$8 \cdot 10^{-5}$
PP	2.20 - 2.36	24	$2 \cdot 10^{-4}$
PVC	3.00 - 3.30	18 - 50	0.015 - 0.033
Glass	4.7	17.7	0.0036
Neoprene	6.26	15.7 – 26.7	0.038

3. Value of Dielectric Medium:

We can see that the LDPE (low density polyethylene) is a good dielectric for making Tesla coil capacitors, as it has all the required qualities and is easy to find.

When dealing with high voltages, there are certain principles to respect in order to build an enduring cap:

- A shorter distance between the plates will lead to a higher capacitance, but will increase the risk of breakdown as the field will be more intense. There's some sort of minimal distance to respect. For LDPE, I recommend at least 0,15mm per kV (rms) supplied by the transformer.
- It can be demonstrated that the electrical field surrounding spikes tend to be much more intense (spike effect). Therefore, the risk of breakdown will be higher at the corner of the plates. The corners and edges of the plates must be rounded and the surfaces must be clear of any scratch.
- The dielectric medium is likely to have imperfections (microscopic holes, impurities, etc.), which also increases the risk of breakdown. For a given thickness, it is preferable to use multiple thinner layers instead on a single thick one. If one layer was to be damaged, the others will remain intact.
- Corona effect around the plates will gradually attack the adjacent dielectric layers, which is one more reason to prefer multi-layered dielectric. The best protection for a HV capacitor is to be drowned in insulating oil like transformer oil. For a given capacitance, it is also better to build several larger capacitors with thinner dielectric and to connect them in series. This will distribute the voltage on all the sub-capacitors and thus attenuate the Corona effect, which increases the whole capacitor's survivability for a given voltage. It is recommended to put no more than 5 kV (rms) per sub-capacitor.

I knew however that construction defects would result in a lower real capacitance. The targeted capacitance was set a bit "too high" in order to attain a real capacitance close to the resonant value, computed at equation. Indeed, the overlapping area is slightly inferior to the predicted values because, first, the corners are rounded, and second, the overlapping is not perfect. Moreover, the capacitor has a tendency to "inflate" because of the lightness of the materials, and the compression with the two PVC plates was imperfect also. Finally, its measured capacitance was

$$C_{mes} = (33 \pm 0.01)\text{nF}$$

To connect the plates, I had first used aluminum tape, but this solution would have made sense only if the stack was immersed in oil. These sheets are indeed very thin and creases form easily, which made the surfaces very rough. When I lighted Tesla Coil the first time, sparks were springing everywhere... on this band of aluminum tape because of Corona effect. It eventually broke because of the high currents.

Another means of connection was thus to be found, and I reused the design from the first version: a screw thread passing through holes drilled in the plates. This time, the holes were much smaller for the electrical connection to be tight. However, I was doubtful on this conception as the risk of sparks between the plates and the thread (of different polarity) was high, so insulating tape was put on the edges. Doubts were justified: after a few seconds, a bright light appeared in the capacitor with a strong smell of burned plastic: the capacitor was dead.

4. Cornell-Dubilier 942C capacitors:

Despite the "homemade" caps working well, I wanted to build a spare capacitor (just in case), made of industrial caps. When I mounted it on Tesla Coil, it turned out its performance were slightly better, so I decided to keep them as the permanent primary caps.

High voltage industrial capacitors are much more complex than the basic plate-stack design we just considered, and some additional criteria must be taken into account. For Tesla coils, they should have the following qualities:

- Polypropylene capacitor, with metal foil-type electrodes.
- Withstand very short charge/discharge times (high dV/dt).
- Withstand high rms currents (at least 10-15 amps) and strong current spikes (several hundreds of amps).
- Self-healing ability.

As the Cornell Dubilier are best for the Tesla Coil but as they are expensive and lack of availability, we are using Paper Capacitors which have approximately same as the specifications of Dubilier capacitors.

5. Charge at Resonance:

Let's talk briefly about the "good" capacitance of the primary capacitor. In the previous section, we had chosen its capacity so a resonant amplification occurs at 50 Hz. This ensures all the energy of the transformer is used, as the impedances of the transformer and the primary circuit are identical. This choice is risky however, as in case of spark gap fault, voltage and current rise to enormous values in a few tens of seconds, which can destroy the caps as well as the transformer.

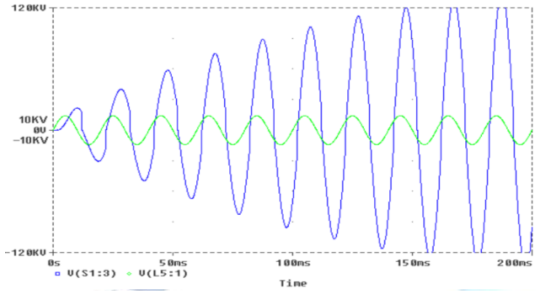


Fig.5 Plot of the voltage output of the transformer (green) and the voltage across the capacitor (blue) over time with a static spark gap.

The resonant amplification in the primary circuit is a very important phenomenon for good Tesla coil performances, but it must remain under control so as not to damage the components. This is why it is strongly recommended to place security devices around sensitive components.

In this philosophy, a security spark gap is generally placed at the lead of the primary capacitor. The NST protection filter is a bit more complex and we'll talk about it later.

It is also recommended to use a non-resonant-sized capacitor, in other words, whose capacitance will not lead to a brutal resonant amplification. This larger-than-resonance (LTR) value depends on the type of spark gap used. For a static spark gap, typical values for the LTR capacitance range from 1.5 to 2 times the resonant capacitance. Kevin Wilson recommends the value of 1.618 times the resonant value, as this value (an estimation of the golden ratio), will ensure no common integer multiples. Following this approach, the LTR capacitance of Tesla Coil will be around:

$$C_{LTR} = 33\text{nF}$$

The capacitance of Tesla Coil primary caps is approximately 1.35 times the resonant value, which is perhaps a bit close to the resonant value. But the various protection measures seem to be working well as no sensitive component has been damaged.

As mentioned earlier, such an increase in the primary capacity has almost no consequences on the global performances of a Tesla Coil. Richard Burnett has shown that, with a static spark gap, the delivered power depends much more on the spark gap spacing than on the primary capacity.

6. Inductance:

The role of the primary inductor is to generate a magnetic field to be injected into the secondary circuit as well as forming an LC circuit with the primary capacitor. This component must be able to transport heavy current without excessive losses. The resonance tuning is traditionally made on this component as we'll see later.

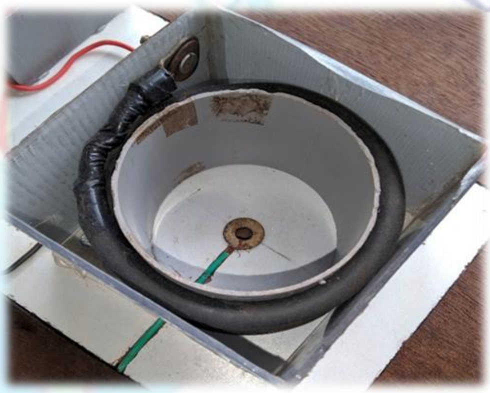


Fig.6 Photo of Tesla Coil's primary Coil

The primary winding has been tapped to 5.2 turns and has a measured self-inductance of

$$L_{mes} = (0.00218 \pm 0.01)\text{mH}$$

This very approximative value has been measured on a small LCR bridge. A more precise device could be used but the tuning is made via a trial-and-error method, so knowing the exact inductance is not of prime importance.

Different geometries are possible for the primary coil. We'll look at the most common one before examining more thoroughly the case of Zeus. Note that the formula giving the self-inductances for each of them are approximative and are just used to have a rough idea of the number of turns required to achieve proper tuning.

i) Helical geometry:

The inductor looks like a solenoid with widely spaced turns. Such geometry will cause quite high coupling between the primary and secondary circuits, which is not always a good thing as we discussed in Influence of the coupling. Apart from the over coupling problem, having a high primary increases the risk of arcing between the top load and the primary, which is potentially catastrophic. Indeed, enormous voltages are applied to a circuit that is not designed to handle them, which can lead to destruction of the primary capacitors or/and the transformer if not properly protected. To solve this issue, the base of the secondary coil can be raised above the primary. This design has not proven very efficient however

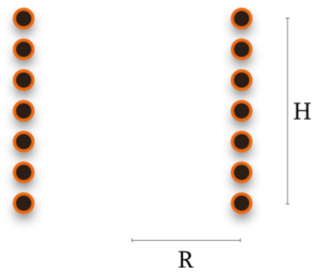


Fig.7 Schematic of Helical Coil

If we call R the radius of the helix, H its height (both in centimeters) and N its number of turns, an empirical formula yielding its inductance L in microhenry's is

$$L_{helic} = \frac{0.374(NR)^2}{9R + 10H}$$

ii) Archimedes' spiral geometry:

This geometry naturally leads to a weaker coupling and reduces the risk of arcing in the primary: it is therefore preferred on powerful coils. It is however rather common in lower power coils for its ease of construction. Increasing the coupling is possible by lowering the secondary coil into the primary. Zeus' primary inductor has this shape.

Fig.8 Schematic of Archimedes Spiral Coil

Let W be the spiral's width given by W = Rmax − Rmin and R its mean radius, i.e., R = (Rmax + Rmin)/2, both expressed in centimeters. If the coil has N turns, an empirical formula yielding its inductance L in microhenry's is:

$$L_{flat} = \frac{0.374(NR)^2}{8R + 11H}$$

iii) Hybrid geometry:

This conical configuration is a sort of compromise. It allows a fair coupling between the two circuits and is rather safe as well. It's the most common configuration for low power coils. A posteriori, I think such a geometry would have been a better choice for Zeus, despite being more difficult to built

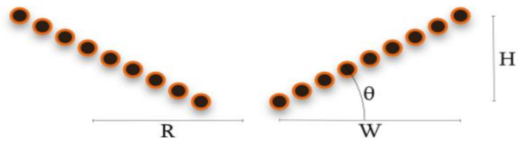


Fig.9 Schematic of Hybrid Coil

By defining the parameters H, W, R and N as previously, the self-inductance is computed by doing an average of the values Lhelic and Lflat weighted by the angle θ of the cone with the horizontal plane.

$$L_{Hybrid} = \sqrt{L_{Helic} \cos^2\theta + L_{flat} \sin^2\theta}$$

iv) In Case of this Paper:

The Primary of the Tesla Coil uses the Spiral Geometry wounded 5.2 turn. Its radius of 3.03 inches and the height of coil is 1.57 inch. From here

$$L_{Helic} = \frac{0.374(5.2 \times 3.03)^2}{(9 \times 3) + (10 \times 1.57)} = 0.00218mH$$

This is close to the measured value. It must be kept in mind however that the primary's real inductance will be slightly higher than this value, as the latter neglects the wirings used to connect the components. These wirings indeed form a closed loop which contains some ferromagnetic materials (screws, bolts, etc.). This extra inductance is somewhat wasted as its magnetic field is far from the secondary and will not contribute to its resonance.

Some details must be taken into account in order to keep this parasitic inductance as low as possible. Avoid loops in the wiring and make it as short as possible. It is also recommended to avoid placing wires parallel to each other to avoid induced currents.

v) Skin Effect:

To minimize energy losses, the resistance of the primary circuit must be made as low as possible. This implies the use of good conductors as well as a large conduction area. It is easy to imagine the practical limitations of this idea. For example, if we wanted to make a spiral from a 12-meter rod of 1.2cm diameter made of massive copper (this is roughly the dimension of Zeus' primary inductor). This spiral would weight 12 kg and would require advanced machinery to be bend. And the cost would be terrific.

Fortunately, we can make use of a propriety of high-frequency currents. The skin effect is the fact that, at high frequencies, the current flow mainly on a thin layer near the outer surface of the conductor. We'll see how this justifies the use of hollow copper tubing (as plumbing pipes), much easier to handle.

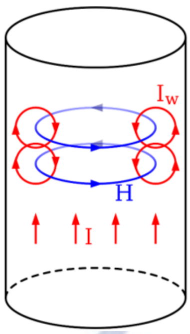


Fig.10 Alternating current I creates an alternating magnetic field H, which will generate eddy currents Iw.

Skin effect is easily explained by magnetic induction. When an alternating current flows in a conductor, it will generate a magnetic field around it, which is also alternating. Lenz' law then says that these variations of magnetic field will lead to the apparition of an emf that will tend to attenuate these variations.

Eddy currents will therefore appear, which will oppose the main current in the center of the cylinder but not near its edges. When current I goes in the opposite direction, so will H and Iw and the previous discussion holds for both directions.

It can be shown that the current density J(d) in a cylindrical conductor follows an 1/e law from the edges to the center:

$$J(d) = J_s e^{-d/\delta}$$

Where:

d is the depth (i.e., The distance from the surface),

JS the current at the conductor's surface, JS ≡ J(d = 0),

δ is the "skin depth", a parameter depending on the material.

Taking d = δ in (4.11), we see that δ represents the depth at which the current density is only 0.37 (1/e) times the density in the surface. Computing the skin depth is complicated in the general case. However, with a good conductor and at reasonable frequencies (< 1018 Hz), the following formula is a very good approximation.

$$\delta = \sqrt{\frac{2\varrho}{\mu\omega}}$$

Where:

ϱ is the resistivity of the conductor (1.7 x 10−8 Ωm for copper)

μ is magnetic permeability (1.26 x 10−6 H/m for copper)

ω the angular speed of the current, equal to 2πf.

C. Spark Gap:

The function of the spark gap is to close the primary LC circuit when the capacitor is sufficiently charged, thus allowing free oscillations inside the circuit. This is a component of prime importance in a Tesla coil because its closing/opening frequency will have a considerable influence on the final output.

An ideal spark gap must fire just when the voltage across the capacitor is maximal and re-open just when it falls down to zero. But this is of course not the case in a true spark gap, it sometimes does not fire when it should or continues to fire when the voltage has already diminished; we'll see which factors will make a spark gap efficient.

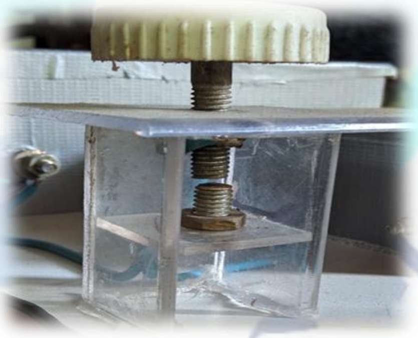


Fig.11 Spark gap used in the Tesla Coil paper

1. Two types of spark gaps:

i) Static:

In a static spark gap, there's two or more electrodes spaced by a given distance. When the potential difference between them rises above some critical value, the air is ionized and thus becomes conducting. This closes this gap, allowing current to flow.

The critical intensity of the electrical field above which air breakdown occurs depends on many parameters (humidity, temperature, air composition, etc.) and it is difficult to predict it in the general case; gas breakdown itself is a very complex phenomenon. The generally admitted value, which is nothing more than an order of magnitude, is EC = 3 · 105 V/m [38]. Using this value in the spark gap design will not yield expected results. Indeed, apart from factors related to air itself, the geometry of the electrodes will influence the intensity of the field for a given potential difference as well.

It's much more efficient to build an adjustable spark gap and to find the optimal distance afterwards, by trial-and-error. This is done by first setting the distance to an obviously too short value, lighting the coil and observing the result. Next, spacing the gap a little bit and trying again until the arcs at the top load are the longest.

If the electrodes are too close, the gap will fire while the capacitor is not full, which will considerably diminish the coil performances. If they are too distant, the spark will simply not fire and the coil doesn't work. The latter case is much more dangerous as we discussed Charge at resonance. If the primary circuit is correctly conceived however, the security gap will take over and will bypass the fragile components.

Static spark gaps are easy to construct but generally have poorer performance than their rotating counterpart. They have a tendency to fire erratically and to carry on firing when voltage has diminished. Moreover, the path of ionized air has a certain resistance.

ii) Rotative:

On this kind of spark gap, it's no longer the voltage that closes the circuit. Here, we have basically a conducting rod that spins rapidly between electrodes. When the rod is at its closest distance from the electrodes, current flows via small paths of ionized air. When the rod offsets from this position, current flow stops, which re-opens the gap.

There are many ways to built such a rotative gap (several rods, several pairs of electrodes, synchronous or asynchronous motor, etc.).

This kind of spark gap is more precise and yields better results, but is more difficult to build and adjust. Indeed, it must be built in such a way so the rod passes in front of the electrodes just when the voltage difference across the capacitor is maximum.

iii) Details of Construction:

The Tesla Coil uses the static spark gap. As mentioned earlier, they tend to remain open after the voltage has diminished. This happens because the path of ionized air demands a much lower voltage to live on than it requires to be created.

In order to improve its performances, the gap has to be quenched, that means to be forced open. Here's a few strategies for that.

One is to force a large, continuous flow of air inside the spark gap, in order to chase the ionized air. Sucking the air is also possible (for example, with vacuum cleaner parts) and gives good results as well.

Blowing air into the gap has many benefits. This not only quenches the gap but also cools it. Because the critical breakdown field decreases with temperature and the high current crossing the spark gap will indeed increases its temperature, the spark gap will fire at a lower voltage after a few seconds (and the sound of the spark gap becomes notably more high-pitched), hindering the coils performances. Thus, cooling the gap will prevent such problems.

It is also possible to use more than two electrodes. The single arc will then be divided into so many smaller arcs, which will quench more easily. The drawback of this configuration is that all these sub-arcs will act like series resistors: all of them will dissipate energy in the form of light, heat and noise. The Richard-Quick design makes use of several copper tubes disposed in parallel. I used this model for Tesla Coils gap.

The spark gap has to deal with enormous current, with transient spikes of nearly 300 amperes. This leads to the apparition of strong corrosion on the electrodes, which will also hinder the coils performances. It is necessary to regularly clean/sand them.

D. Secondary circuit:

1. Coil:

The function of the secondary coil is to bring an inductive component to the secondary LC circuit and to collect the energy of the primary coil.

This inductor is an air-cored solenoid, generally having between 800 and 1500 closely wound adjacent turns. In the Tesla coil the secondary coil is made of enameled copper "magnet wire" with a diameter of SWG 36 which is wound around a PVC pipe of 2-inch external diameter. The coil is 11.21 inch tall.

To calculate the number of turns that have been wound, this quick formula will avoid a certain fastidious work:

$$N = \frac{H}{d}$$

where H is the height of the coil and d the diameter of the wire used. In our case, the number of turns is 1440 turns (more or less a few turns). It is quite low, but the diameter of the coil is rather large in comparison of the coil's power; this will provide a fair self-inductance while limiting parasitic capacity.

Another important parameter is the length l we need to make the entire coil. It is given by

$$l = 2\pi N r$$

where r is the radius of the coil. Zeus' coil has thus necessitated 248 meters of wire. One can show that the self-inductance L in henrys of a adjacent-turns solenoid is given by

$$L = \mu \frac{N^2 A}{H}$$

where μ represents the magnetic permeability of the medium (≈ 1.257 · 10−6 N/A2 for air, very close to the value of the void), N the number of turns of the solenoid, H its total height, and A the area of a turn. Injecting Zeus' coil values, we get

$$L_{th} = 18.62mH$$

Fig.12 Secondary Coil used in the Tesla Coil paper

i) Characteristics of Secondary Coil:

A. Resistance:

During the first tries of Tesla Coil, I had placed the secondary coil lower in the primary spiral in order to increase coupling. This didn't yield the expected results: arcing between the primary and secondary occurred, which damaged the coil at several points, I thus put the secondary coil back in its initial position. Fortunately, the coil hasn't been sectioned. The only noticeable consequence was an increase of the coil's resistance, increasing from 20 to 25 Ohms.

However, this value was measured with a classical ohmmeter, i.e. with a direct current. But what will flow in the coil is high-frequency alternating current. A more precise measure would include effects such as skin effect and proximity effect. The method proposed by Fraga, Prado's and Chen takes these effects into account and has been proven to be precise for solenoids. The JAVATC simulator yielded the following value ("Fraga AC resistance"):

$$R_{ac} = 49.8\Omega$$

Fig.13 Results of inadequate space between the coils: arcing between the two occurred, burning the secondary coil at several points.

B. Inductance and capacitance at resonance:

The inductance calculated at and measured are again valid for low frequencies only. The self-inductance of the secondary coil driven at resonance is slightly different, because of the non-uniform repartition of current and because the length of the coil is comparable to the wavelength of the signal it will carry [43]. Once again, a more precise formula must be used. The JAVATC simulator gave the following value ("Effective series inductance"):

$$L_{res} = 18.62mH$$

ii) Q-Factor:

We can now compute the Q factor of the coil, established in the last chapter. To get a coherent result, we'll use the previous values for R, L and C (with top load capacitance added). We thus get:

$$Q = R^{-1}\sqrt{\frac{L}{C}}$$

$$Q = 476$$

Which is a rather good value, that will indicate low losses in the secondary LC circuit. It is difficult to surpass 500 with common conductors.

Note that it is also possible to measure the Q factor experimentally following the procedure detailed in ref.

iii) Quarter-Wave Antenna:

We saw in section Quarter-wave antenna how we could apply this model to the Tesla coil. In the next section, we'll calculate the resonant frequency f of the secondary coil to be 3.19·105 Hz. The corresponding wavelength is λ = c/f (where c is the speed of propagation of the wave: here, c ≈ 2.998 x 108 m/s), i.e., approximately 1477 m. In other words,

$$\frac{\lambda}{4} = 369$$

As the total length of the wire in Tesla Coil secondary coil is around 248 meters, we can conclude it is correctly tuned like a quarter-wave antenna. But as mentioned earlier, this is not necessary, that is why we performed such rough calculations.

iv) Construction:

This component is not especially difficult to build but requires a lot of patience. The 800 turns have been wound entirely by hand and took a few days. Precautions had to be taken in order to prevent sweat from infiltrating the coil.

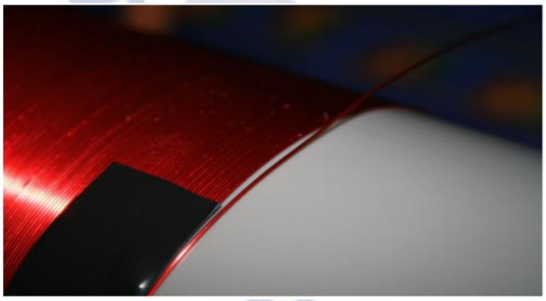


Fig.14 Picture while winding Secondary Coil

The very high voltages involved can cause arcing between turns if the coupling is set too high xi. It is common to apply an insulating resin on the coil, which will reinforce the insulation already provided by the polyurethane covering the magnet wire. I couldn't find such a resin so I instead applied liberal amounts of insulating spray (the same used in the capacitors).

There's an important empirical rule about the ratio between the height H and the diameter D of the coil. It has been observed that the best performances are attained with an H/D ratio between 3 and 5. Tesla coil is thus conformed with a ratio of 4.

E. Top Load or Torus:

The top load acts like the upper "plate" of the capacitor formed by the top load and the ground. It adds capacity to the secondary LC circuit and offers a surface from which arcs can form. It is possible, actually, to run a Tesla coil without a top load, but performances in terms of arc length are often poor, as most of the energy is dissipated between the secondary coil turns instead of feeding the sparks.

The are many different possibilities regarding the shape of the top load, the most common ones being the sphere and the toroid. Computing its capacitance is difficult in the general case (a collection of empirical formulas is given in ref). The JAVATC program gave the next value:

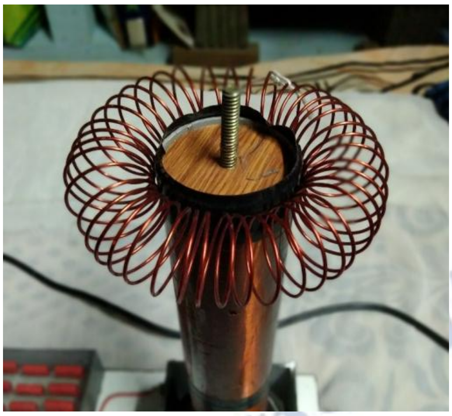
$$C_s = 10.34pF$$

1. Influence of Geometry:

The top load is perhaps the most important component when determining the final arc length (except the transformer of course). There is a lot of discussion about its optimal size.

In a general way, a larger top load will have a larger capacitance. Regarding formula specifying the voltage gain, one could think it is desirable to keep the secondary capacitance as low as possible, as Vout decreases when Cs increases. However, if the top load capacitance is low (or nonexistent), the majority (resp. the totality) of the secondary capacitance will be located in the secondary coil itself. Then, the energy of the secondary circuit is mainly dissipated as heat between the turns instead of feeding the sparks. Hence an optimal capacitance exists.

Be it toroidal of spheric, the curvature radius of the load will increase with its size. And the larger the curvature radius is in a certain zone, the weaker the electric field will be. Fewer spark will be able to form, and the available energy for each of them will be greater. This will result in less numerous but longer sparks. It is even possible to make the top load big (and smooth) enough so not a single arc can form. Conversely, if the curvature radius is smaller, the electrical field will be intense in many zones, allowing more sparks to be formed; these will be shorter as the available energy will have to be distributed between all these arcs. There is thus also an optimal size to the top load.



2. Schematic of Top Load or Torus

The toroidal geometry is often preferred instead of the spherical. If the top load is a sphere, the near electrical field will be more uniform, which will result in more numerous, shorter sparks. But with a toroidal geometry, the electrical field is more intense on the outer edge of the toroid: there will be fewer sparks but longer on average, most of the arising from this outer edge.

State of the surface: Another important parameter influencing the final arc length is the roughness of the top load surface. If the surface has asperities, the electric field near these will be much more intense. It can indeed be shown from Maxwell's equations (Gauss' law to be precise) that the electrical field is more intense near zones of strong curvature. This fact is called the spike effect. If one wishes to get longer sparks, it will be judicious to have a smooth top load ; to reduce the number of breakout points and thus of sparks

Addition of a breaking point: In order to force sparks to be generated at a single point (and thus having longer arcs), it is possible to add a breaking point to the top load. By spike effect, this will ensure the electrical field is comparatively much stronger near this zone. It has been suggested that the breakout point should be a ball instead of a spike. This will allow the spark base to "glide" on it, giving more time for the spark to develop. Because of the higher temperature of the ionized air path, it will indeed have a tendency to rise.

The top load position is also subject to some guidelines. If it is too close from the top of the secondary coil, its electrical field will "drown" the last spires, which will result in a lower final voltage. Conversely, if the top load is too high, its electrical field cannot.

F. Resonance Tuning:

Setting the primary and secondary circuits at resonance, i.e., have them share the same resonant frequency, is of prime importance for good operation. The response of an RLC circuit is the strongest when driven at its resonant frequency. In a good RLC circuit, the response intensity falls sharply when the driving frequency drifts from the resonant value.

Let's have a look at this Tesla Coil's case. We compute the secondary resonant frequency with its capacitance Cs and its inductance Ls with the well-known formula.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The secondary capacitance is equal to the coil capacitance plus the top load capacitance, computed by taking into account the non-uniformity of the current distribution. But the non-uniformity of the current distribution. The JAVATC simulator gives a value for the total secondary capacitance (Effective shunt capacitance), Cs = 18.425 pF. Let's also recall the secondary inductance: Ls = 18.62 mH.

We thus get:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$f = \frac{1}{2\pi\sqrt{(18.62 \times 10^{-3}).(33 \times 10^{-12})}}$$

$$f_{res} = 203.04\text{KHz}$$

G. Tuning methods:

The tuning is generally done by adjusting the primary inductance, simply because it's the easiest component to modify. As this inductor has wide turns, it is easy to modify its self-inductance by tapping the final connector at a certain place in the spiral.

The simplest method to achieve this adjustment is by trial-and-error. For this, one begins to tap the primary at a point supposedly close to the resonant one, lights the coil and evaluates arc length. Then the spiral is tapped a quarter of turn forward/backward and one re-evaluates the result. After a few tries one can proceed with smaller steps, and will finally get the tapping point where the arc length is the highest. Normally, this tapping point will indeed set the primary inductance such as both the circuits are at resonance. I used this procedure for Tesla Coil and tapped the primary to 5.2 turns.

This method isn't infallible however. It presupposes that there is one and only one resonant point. This would be true if current and voltage distribution were uniform. And we saw the secondary coil has a distributed capacitance and deals with non-uniform current/voltage distributions. This may lead to the apparition of several secondary resonances (see Fig. 4.35), i.e., local but not necessarily global impedance minima [50]. By proceeding though, the trial-and-error method discussed above, one can think they've reached the true resonant value but actually have a secondary resonance. A more precise method would involve an analysis of the individual response of both the circuits (in the coupled configuration, of course, i.e., without physically separating the circuits) with a signal generator and an oscilloscope. Detailed procedure is given in refs.

Arcs themselves can produce some extra capacitance. It is therefore advised to set the primary resonant frequency slightly lower than the secondary, in order to compensate for this. This is noticeable however only with powerful Tesla coil (which can produce arcs longer than 1m), and should have little influence on Tesla Coil.

H. RF Grounding:

It is the ground at which the bottom of the secondary coil is connected. Its role is to keep the voltage at the base of the coil at zero, but also (more importantly) to act like the second "plate" of the top load-ground capacitor. In this light, it makes the secondary capacitance less dependent of the immediate environment.

The best grounding method is to use a metallic rod stuck into the soil; when this option is not possible, one has to make his own ground. For this purpose, it is possible to use a large metallic plate, placed underneath the Tesla coil. Its total width should be equal to twice the distance between the top load and the base of the secondary coil. The plate used on Zeus is only 1m wide but seems to be sufficient. It is made of 4 panels of 50cm × 50cm bound with aluminum tape and covered by stronger, convectional tape for protection. This allow the plate to be folded, which increases transportability.

Tesla Coil's plate is to be made of plain metal, but it is also possible to use a conducting mesh. This is actually better as it prevents some eddy current from taking place.

But as this is not a high rating Tesla Coil, we just used the normal earth pit (Ground pit) as the ground for the Tesla Coil.

3. RESULTS

The below shown figure is how the Tesla Coil paper looks when it is not powered.

When powered ON by using the Tesla Coil paper we are able to light the fluorescent bulb wirelessly as shown in below figure.

4. CONCLUSION

It is not an exaggeration to say he was a visionary who changed the world. With his works on alternative current, including many patents on generators, transformers and turbines, he allowed the widespread proliferation of electricity as a source of power as we know it today.

He was also a pioneer in the domain of telecommunications; the Tesla coil can be viewed as one of the very first attempts of a radio antenna. It consisted of circuits that are fundamentally the same as our modern wireless devices.

The construction of Tesla Coil was not an easy task and almost every component had to be rebuilt at least twice & sometimes thrice. This however allowed me to acquire my first experience in the domain of high voltages, which was probably the greatest reward this paper gave us.

At the End of the paper, we can conclude that this is a model of the Tesla Coil which is developed by the great *NIKOLA TESLA* to transmit the electrical energy wirelessly. By using this paper, we can light the bulbs (Fluorescent, Neon) wirelessly up to 1.5 meters to 2 meters of distance as this is a model and low power coil, we can't light bulbs for longer distances.

By using this paper, we can learn more about resonance, resonant frequency & how this resonance phenomenon works and more about the resonant transformer.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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