Design and Construction of a Tesla Transformer by using Microwave Oven Transfer for Experimentation

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Abstract
This paper has focused on the step-by-step design of a high frequency medium size (1-3 kW) air-cored resonance transformer commonly called tesla coil, that can be easily used for measurements and general research. Therefore, the task is to minimize the number of stochastic and unknown parameters influencing the device functionality and pointing out pros and cons of each solution. The physical dimension of the tesla transformer has been chosen due to cost effectiveness and availability of the regarding components. This design has mainly two units' viz., a power supply and tesla coil. The power supply which fed the Tesla coil having voltage rating 12kV and current rating 120mA has been designed by using three microwave oven components. These components are assembled as dual MOTs voltage doubler circuit and necessary simulation has been carried out by using MicroSim Schematics for the verification of performance.
Keywords: Microwave Oven , Transformer, Multi mini Capacitors, MicroSim Schematics, Toroid, Tesla Coil CAD.

1. INTRODUCTION

The Tesla transformer is a fascinating device capable of creating spectacular effects: by generating high-voltage pulses with several megavolts of amplitudes, it emits electrical discharges [2] that easily extend for several meters and remind natural lightning.The tesla transformer is very familiar for more than a century to the scientific research and also used in several applications. A significant amount of papers, articles and books have been written about its theory of operation and its practical construction. Still, nearly every university high-voltage laboratory and technology museum strives to own a tesla transformer, because some of the effects involved with operation are pretty unique to this kind of device and the theory underneath them still deserves a certain amount of research to be fully explained and justified.

On January 1999 the construction of a medium-sized Tesla transformer was started at the High Voltage Institute of the Helsinki University of Technology (HUT). The Tesla transformer to be built was named "Thor", after the God from the Nordic mythology who was capable of emitting lightning from its powerful hammer. A series resonant converter with constant on time control for capacitor charging applications are described in [3]. Inductance calculations for Radio Coils and Resistance and Self-Capacitance of Single-Layer Solenoids Wireless Engineering are broadly explained in [4, 5]. A wide research results are published on about the tesla coils and the failure of lumped- element circuit in [6]. Modeling of resonant air core transformers including resistive losses and synthesis of multiple resonance networks are carried out in [7, 10]. Testing of insulating materials and its applications at high frequencies and high voltage are investigated in [11, 12]. Also different applications of tesla transformers are highly focused in [13-19]. Different kinds of discharges such as lightning discharge, positive discharge and negative discharge are explained in [20-22] respectively.

2. DESIGN SPECIFICATION AND CONFIGURATION

The general design procedure of a tesla coil is only partly influenced by the power supply choice. The supply voltage value affects clearances and engineering techniques used during the practical construction phases and a tesla coil of chosen size will usually require a minimum power to obtain a satisfactory performance. In several phases of the design, some of the parameters have been chosen according to empirical evidence, without a theoretical justification.

2.1. Power supply design

The Neon Sign Transformer (NST) is the ideal choice for a power supply. They are of relatively high-voltage (up to 15kV) and more common ones are 6kV to 15kV at around 30mA. Furthermore, they also have attractive features such as internal current limiting, effortless paralleling (for increased current), and comes in many different voltages and currents. However, for some people (especially for those on a tight budget), NSTs might be very difficult to obtain, or find cheaply. As such, an alternative power supply has been used. For this purpose two MOTs (these are big transformers found in Microwave Oven) have been used. These are much easier to obtain (in old Microwave Ovens) and are usually available at a very low cost. However, unlike NST, they are usually of a low voltage (typically 2000V AC+) but at a huge current (300-1000mA). 2kV is too low to reliably fire a spark gap, and the huge current will overheat most spark gaps. Furthermore, MOTs are not as well current limited as NSTs. But these problems have been solved by employing a very useful engineering technique known as Dual MOTs voltage doublers circuit (Fig. 1).The opearation is rather simple. On the first half of the AC cycle, the diodes are forward biased and the doubler capacitors are charged up. On the next half of the cycle [1], the current reverses, and the diodes are reverse biased, and behave like an open-circuit. The secondaries of the MOTs are now in series with the charged capacitors. Thus, the sum of all four potentials is now across the diodes, making a 12kVDC (roughly, depending on MOTs) pulse up to several hundred milliamperes to the tesla coil tank circuit through the chokes. The chokes and bypass capacitors (not mentioned in Fig. 1) form an RC low-pass filter to prevent any RF feedback from the tesla coil. This circuit has been used without any filter and smoothing component, but with excellent results.

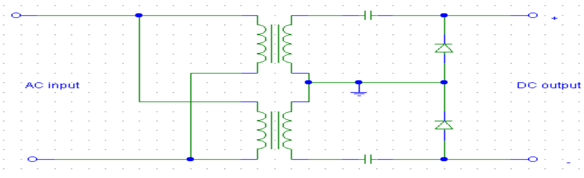

Fig. 1. Dual MOTs voltage doublers circuit.

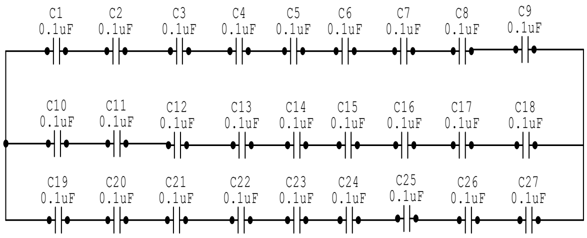

Fig. 2. Multi-mini Capacitors (MMC).

2.2. Multi-mini capacitor design

Capacitance values for the primary usually vary between 0.01 µF and 0.05 µF. The capacitor choice influences both the primary resonance frequency and the maximum available pulsed power for the tesla coil. The film-foil polypropylene capacitors[3] protected by polyester wrap and epoxy end seals are the best choice for Multi Mini Capacitors (MMC) because they have very low dielectric losses which is suitable for continuous use in high AC voltage. Also they can withstand fast rise time pulses and have excellent high frequency performance. Each capacitor has voltage rating 1.6kV and capacitance 0.1µF. For 12kV supply an MMC has been designed which has three strings (each string with 9 capacitors in series) in parallel. The final MMC (Fig. 2) has voltage rating 14.4 kV and the equivaent capacitance (0.033µF) is given by equations (1) and (2).

$$C_{series} = \frac{C}{n_1} \tag{1}$$

$$Cparallel = n_2 C \tag{2}$$

Where; n_1 is the number of capacitors in series and n_2 is the number of strings in parallel, and C equals C_1, C_2, ………,C_n..

2.3. Secondary coil design

The secondary diameter and height (D/H) ratio has been chosen as 1:4.23. The desired secondary coil height is 55cm and to maintain the D/H ratio suitable coil diameter is 13cm. The 26 SWG (diameter of 0.457mm) magnet wire is used for secondary coiling through out 55cm. Since, no spacing between the turns, thus total number of turns are above 1100. The secondary inductance is given by Wheeler's [4] emperical equation (3).

$$L_s = \frac{R_s^2 N^2}{2540 \ (9R_s + 10H)} \tag{3}$$

Where; L_s is secondary inductance (mH), *Rs* is secondary radius (cm), *H* is secondary height (cm), *N* is number of turns.

The secondary self capacitance is estimated by a formula due to Medhurst [5] is given in equation (4).

$$C_s = KD \tag{4}$$

Where; C_s is secondary self capacitance (pF), D is secondary diameter (cm), K is a constant depending on the D/H ratio.

The self- resonance frequency of the secondary without top load is given in equation (5).

$$F_s = \frac{1}{2\Pi\sqrt{L_s C_s}} \tag{5}$$

Where; F_s is self-resonance frequency of the secondary (kHz), L_s is secondary inductance (mH), C_s is secondary capacitance (pF).

2.4. Toroid design

The selected top terminal [6] is a toroid with an outer diameter d_1 and a cross-section diameter d_2 (Fig. 3). The toroid capacitance is calculated from the following emperical equation (6).

$$C_{top} = 2.3(1.2781 - \frac{d_2}{d_1})\sqrt{0.1217 d_2 (d_1 - d_2)} \tag{6}$$

Where, C_{top} is toroid capacitance (pF), d_1 is toroid outer diameter (cm), d_2 is toroid cross-section diameter .

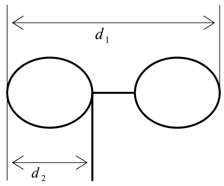

Fig.3.Toroid with outer diameter d_1 and cross-section diameter d_2.

2.5. Flat primary coil design

The shape of the primary coil has been chosen as flat spiral, for simplicity of its manufacturing and because it allows to maximizing its distance from the top of the secondary coil.As the secondary coil is supposed to be freely movable inside the primary coil, the inside diameter of the primary turn must be equal to the secondary outer diameter plus some clearance.Optimal performance can be achieved if secondary and primary circuits have got the same resonance frequency. Given that the value selected for the primary capacitor is 0.033µF. Thus, the primary inductance is given by equation (7).

$$L_p = \frac{1}{C_p}\left(\frac{1}{2\Pi f_s}\right)^2 \tag{7}$$

The flat spiral primary is also best for higher power levels. With this type of coils distance to the toroid is maximum level and minimizes the chance that sparks hit the primary. The Fig. 4 shows a cross section view with winding width (W) and average radius (R) of the flat spiral primary coil.

2.6. Rotary spark gap design

The major weakness of a not-triggered static spark gap is the tolerance in its threshold voltage and therefore the amount of uncertainty implied by its operation. On the other end, triggered spark gaps are considerably expensive and their lifetime is limited. As this project aims at exploring the Tesla coil properties independently of the characteristics of the spark gap, spreading of the threshold voltage and timing errors have to be reduced to a minimum. Using a rotary spark gap, the triggering voltage tolerance can be eliminated by setting the electrode clearance to a minimum that guarantees dielectric breakdown in every condition. This type of spark gap has the advantage, that switch off time is low. The distance of the gap may be reduced to an absolute minimum, which in turn lowers the losses. Therefore, an asynchronous rotary spark gap (Fig. 5) has been designed; employing a 500 W, angle grinder running at 11000 rpm (220 VAC, 50 Hz). The rotor is composed by a bakelite disk measuring 15.5 cm in diameter and 7 mm thick. Four double-sided electrodes are mounted on the rotating disk. The entire assembly is dynamically balanced to avoid dangerous oscillations that could damage the rotor. The maximum break rate is thus (11000 / 60) × 4 = 733.33 breaks per second.

2.7. Finalized design

The complete setup of the tesla coil along with asynchronous rotary spark gap and dual MOTs power supply can be compared with the simulation results and may differ a little


Fig.6.Complete setup of Tesla Coil.

bit because all the calculations regarding the tesla coil have been performed using some empirical equations. Here, the complete Tesla coil design specification is depicted in Table 1.

Table 1: Final design specifications

Requirement	Specification
High Voltage Transformer	12 kV, 250mH, MOT
Primary Capacitor	0.033µF, 14.4 kV, MMC
Primary Coil Type	Flat pancake
Primary Coil Conductor Diameter	0.25"
Primary Coil Turn-to-turn Spacing	0.5"
Distance between Primary inner turn and Secondary	0.5"
Total number of Primary Turns	12
Calculated Primary Tap Point for Resonant Frequency	9-10 Turns
Secondary Coil Diameter	130 mm
Secondary Coil Wire Gauge	26 SWG
Secondary Coil Winding length	550 mm
Secondary Coil Aspect Ratio(H/D)	4.23:1
Toroid Dimensions	20"×5"
Toroid Capacitance	22.1pF
Resonant Frequency of Secondary with Toroid	156.8 kHz

3. MEASUREMENT AND SIMULATION RESULTS

3.1. MicroSim schematics

The simulation results also verify the output voltage (12 KVDC) of MOT power supply as shown in Fig. 7. The simulation clarifies that the pulsed DC output is 5.6 times the V_{RMS} output of a single transformer in the unloaded condition [7]. The pulse rate is equal to the line frequency and the current across the resistive load is shown in Fig. 8.

3.2. Secondary coil calculation

The secondary coil calculation can also be made by using a software named Tesla Coil CAD rather than using several emperical equations. The Tesla Coil CAD window is shown in Fig. 9.

3.3. Primary coil calculation

The Tesla Coil CAD window for primary coil calculation is shown in Fig. 10. The window depicted in Fig. 10 shows that the primary will need to be tapped between turn 9 and turn 10 to form resonant circuit at 166.95kHz. The graph of number of turns versus primary coil inductance is shown in Fig. 11.

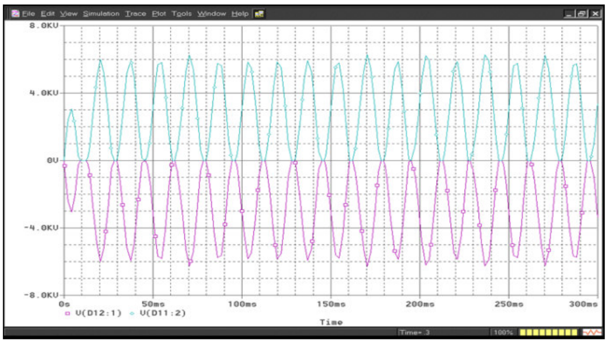

Fig. 7. Simulation result for MOTs secondary voltage.

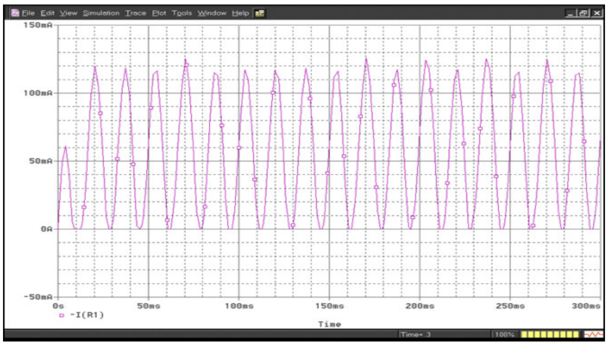

Fig. 8. Simulation for load current.

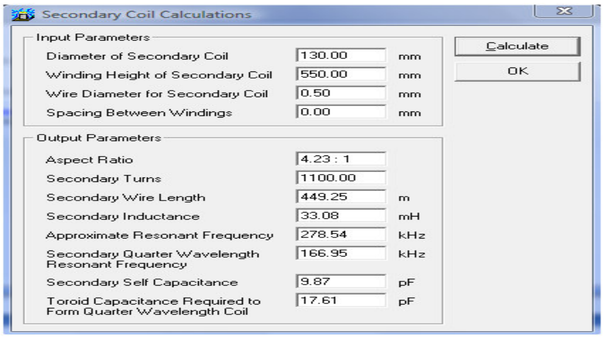

Fig. 9. Secondary coil calculations using Tesla Coil CAD.

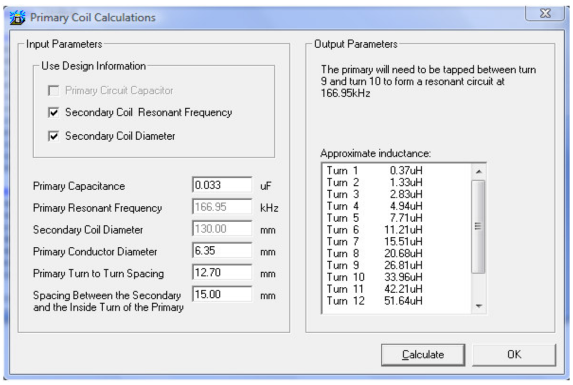

Fig. 10. Primary coil calculations using Tesla Coil CAD.

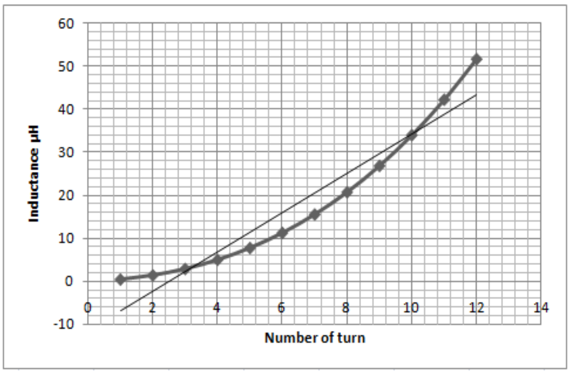

Fig. 11. Primary inductance versus number of turns.

4. TEST RESULTS

4.1. Air break down mechanism

Once the multi-mini capacitor C_p (Fig. 12) has been charged fully the air in the spark gap is unable to hold-off the high electric field and breakdown occurs. The capacitor C_p is now connected across the primary winding through the spark gap. This forms a parallel resonant circuit [8], [9] and the capacitor discharges its energy into the primary winding in the form of damped oscillations. The close proximity of the primary and secondary windings causes magnetic coupling between them. The high amplitude oscillating current flowing in the primary causes a similar oscillating current to be induced in the secondary coil. Energy is gradually transferred from the primary resonant circuit to the secondary resonant circuit [10]. Over several cycles the amplitude of the priamry oscillation decreases and that of secondary oscillation increases. When the secondary voltage becomes high enough, the Toroid is unable to prevent breakout and sparks are formed as the surrounding air breaksdown.It should be noted that this repeating process is an important mechanism for the generation of long sparks. This is because successive sparks build on the hot ionised channels formed by previous sparks. This allows sparks to grow in length over several firings of the system. In practice the whole process described above may take place several hundred times per second.

The terrific voltage of the tesla coil comes from the fact that the energy in the lage primarymulti-mini capacitor is transferred to the comparatively small stray capacitance of the secondary circuit. The energy stored in the primary capacitor is measured in Joules and is given in equation (8).

$$E_p = 0.5C_pV_p^2 \tag{8}$$

Since, the primary capacitance is 33.3nF and it is charged to 12kV then th stored energy ca be calculated as 2.4 Joules.If we assume there are no losses in the transfer of energy to the secondary winding, the theory of coservation of energy states that this energy will be transferred to the secondary capacitance C_s. C_s is typically around 22.1 pF. If it contains 2.4 Joules of energy when the energy transfer is complete. And the the secondary voltage can be calculated as around 466kV.

4.2. Some useful test

Firstly, glowing a fluorescent light wirelessly: Since the air surrounding the toroid forms ionised channel due to high voltage, the gas even inside the tube light would be ionised if it brings into the proximity of toroid and hence the tube light get illuminated (Fig. 13).Secondly, observation of Partial discharge (corona): The localized partial discharge has been observed at the sharp edge of the conductor (Fig. 14). 'Corona' a type of partial discharge is the premature breakdown consists of audible and luminous effect. Despite of its minuses it has some pluses viz., applicable for high-speed printing devices, electrostatic precipitator, paint sprayer, Geiger counter, production of ozone etc.

Fig. 13. Glowing a flurescent light wirelessly.

Fig. 14 Corona at sharp edge

5.CONCLUSIONS

A medium-sized (1-3kW) tesla coil has been designed using a mix of approximated and empirical design equations. The finished apparatus measures 4 feet in height, with a base support measuring four square feet. After the assembly completion, the value of each component has been directly measured or calculated. The empirical equations provided a satisfactory degree of precisions: the secondary resonance frequency was achieved with an error of about 5%, while the secondary coil capacitance was measured to be within 9% from the expected. The theory describing the functionality of the tesla coil has been reported, including the classical treatment. The simulation of MOT power supply has been done by using MicroSim Schematics. Moreover, other components viz. MMC, spark gap, toroid, primary coil have been chosen accordingly to the requisite of the design. Due to unavailability of most commonly used Neon Sign Transformer (NST) two Microwave Oven Transformers (MOT) have been used. Unfortunately, the secondary MOT voltage is not sufficient to conduct the main spark gap thus the voltage doublers circuit has been used. The output of voltage doublers circuit was 12 KVDC. The multi-mini capacitor (MMC) has been designed according to supply voltage having three strings in parallel each containing 9 capacitors in series to get 14.4 KV and 33.33 nF. The proper tuning has been done by tapping primary coil in between turns 9 and 10. The primary resonance frequency has been calculated same as the secondary resonance frequency, 166.95 kHz. The top terminal load (toroid) has been designed by much chipper and easier process by applying the theory of minimum Skin depth at high frequency. Conclusively, the outcome gives the fundamental ideas about behaviour of high frequency, high voltage, corona effect, and partial discharge.

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