How I Design my Tesla Coils

My wife and I enjoying Ed Wingate's Cage of Death in Rochester, NY

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By Daniel McCauley

Introduction

When I was in the process of designing my first tesla coil in May of 2002, I was hardpressed to find one source that comprehensibly described the process of designing a tesla coil from scratch. Although there were multitudes of awesome websites devoted to tesla coiling, it was extremely difficult to find one that had a step-by-step process that was easy to follow and to the point. There were very informative websites that contained a plethora of design equations, but with no logical description of how to use them properly when designing a tesla coil. There were also many sites that had beautifully built tesla coils on their site, but with not much background information as to the specifications and design of those coils. In this document, my goal is to present a very easy to use step-by-step process to create a simple tesla coil from scratch. I will provide examples using readily available Tesla Cad software as well as simple equations to create and validate a tesla coil design.

Please note that the purpose of this document is describe my design process for tesla coils. With the goal of keeping the design process as simple as possible, this document does not include any theory regarding how a tesla coil works. This document assumes that the designer already has a basic understanding of how a tesla coil operates.

Where Do I Start?

Good question! The first thing we need to know is that a conventional tesla coil is comprised of five basic fundamental items:

1. High Voltage Transformer
2. Primary Capacitor
3. Primary Coil
4. Secondary Coil
5. Toroid (Secondary Top Load)

Please note that the spark gap is not included in this list solely because its design does not affect either the primary or secondary resonant circuit. The spark gap acts only as a high voltage switch.

A proper tesla coil design will have each of these parameters chosen carefully so they all work together at some fixed resonant frequency. Sound complicated? Not really. Lets simplify the tesla coil and break it down into two separate independent circuits.

The primary circuit is comprised of the high voltage transformer, the primary capacitor, and the primary coil whereas the primary capacitor and the primary coil make up an LC circuit which determines the resonant frequency of the primary circuit.

The secondary circuit is comprised of a secondary coil and a toroid (top load). The toroid basically is modeled as a capacitance so again, we have an LC circuit which determines the resonant frequency of the secondary circuit.

To get a tesla coil to work, we simply need to match the resonant frequency of the primary circuit to the resonant frequency of the secondary circuit. Seems simple, right? Right. So lets get started, and begin our design.

Starting Your Design

Designing a tesla coil is very easy. As there are five basic fundamental components of a tesla coil, there are five basic fundamental design parameters:

1. Output Characteristics of High Voltage Transformer
2. Size and Dimensions of Primary Coil
3. Size of Primary Capacitor
4. Size and Dimensions of Secondary Coil
5. Size and Dimensions of Toroid (Secondary Top Load)

Designing a tesla coil is all about having some of the five parameters above known and then designing the unknown parameters. So the more parameters we have upfront, the less design we need to do. Lets take a walk out to the shed and see what kinds of things I can come up with.

After rooting through the shed for some time, I have found the following materials:

- 4" Diameter PVC Pipe
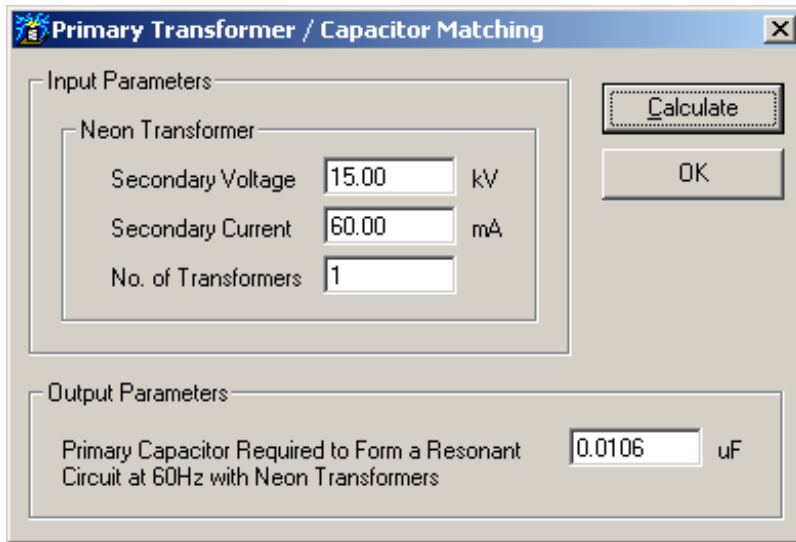- 15kV / 60mA Neon Sign Transformer (NST)
- Spool of 26 AWG Magnet Wire

Hmmm . . . Good start. Lets start the design process.

Choosing the High Voltage Transformer

Choosing a high voltage transformer is the first step in any design process. The output characteristics of the high voltage transformer will affect the design of the primary circuit. From my shed, I found a nice 15kV / 60mA NST. This will work nicely and is one of the bigger types of neon sign transformers. So already I have completed 20% of my design! The next step is to choose the primary capacitor. The primary capacitor is chosen so that for each peak cycle of the output waveform of the NST, the primary capacitor is charged up to the rated output voltage of the NST.

Determining Primary Capacitor Size

There are equations to determine the primary capacitor size, however I will use Tesla Coil CAD to solve this for me. Also, please note that we are assuming purely resonant sized capacitor here for this tesla coil for use with static gaps and synchronous rotary spark gaps. Larger than Resonance (LTR) sized capacitors are not dealt with in this document.

Primary Transformer / Capacitor Matching ☒

Input Parameters

Neon Transformer

Secondary Voltage	15.00	kV
Secondary Current	60.00	mA
No. of Transformers	1	

Calculate

OK

Output Parameters

Primary Capacitor Required to Form a Resonant Circuit at 60Hz with Neon Transformers   0.0106   uF

Using Tesla Coil CAD I simply enter the output characteristics of my NST and the program automatically calculates the required capacitor size for me. In this case, the primary capacitor size turns out to be 0.0106uF. Good. With the advent of MMC capacitors, a 0.0106uF rated at 15kV should be simple to build. Alright! 40% of the design is already completed.

Note: Be sure that the CAD program you are using is using the correct line frequency for where you are located.

At this point in our design, we need to determine what the resonant (and operating) frequency of our tesla coil is going to be. Although the primary circuit has a resonant frequency, the primary circuit is an adjustable frequency circuit. The secondary circuit basically has a fixed resonant frequency so this will be the ultimate determiner of what the resonant frequency of the entire system is.

The Secondary Circuit

The secondary circuit is comprised of a secondary coil and a toroid (top load). The toroid has a capacitance associated with it, so the secondary coil (L) and toroid (C) form an LC circuit which has some resonant frequency associated with it. If you change the
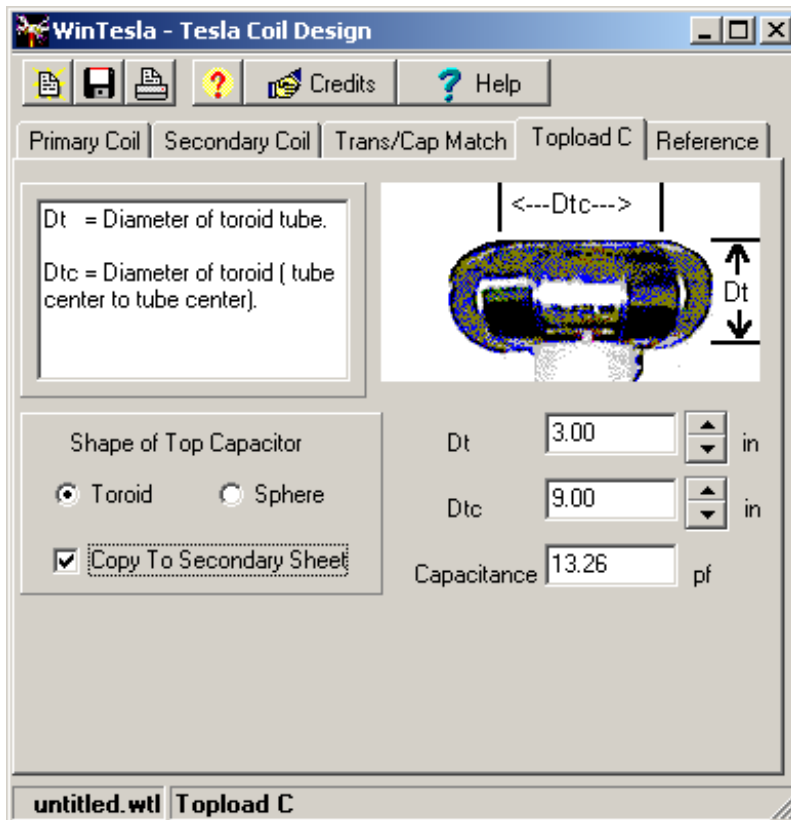
secondary coil you will change the resonant frequency. If you change the toroid size, you will change the resonant frequency.

From our shed we found some long lengths of 4" Diameter PVC pipe. We will use this to design our secondary coil. But first, lets choose a toroid.

Designing the Toroid

Because I like my coils to look as nice as possible, I always try to buy commercially available toroids at least for my smaller coils where the price of toroids is still economical. We will do that here as well. From Science First located in NY, I will purchase a 12" x 3" aluminum toroid for $79.99.

Now that we know the size of this toroid, we need to calculate the capacitance of it. For this calculation, I use WinTesla.

I enter the dimensions of my toroid as shown above and I also check the Copy To Secondary Sheet box so that the result of this calculation is carried over to the other design sheets within WinTesla. As you can see, WinTesla calculated the capacitance of our 12" x 3" toroid to be approximately 13.26pF. Whew! I almost broke a sweat on that one. 60% done – almost there!

The final step for our secondary design it to design the secondary coil itself.
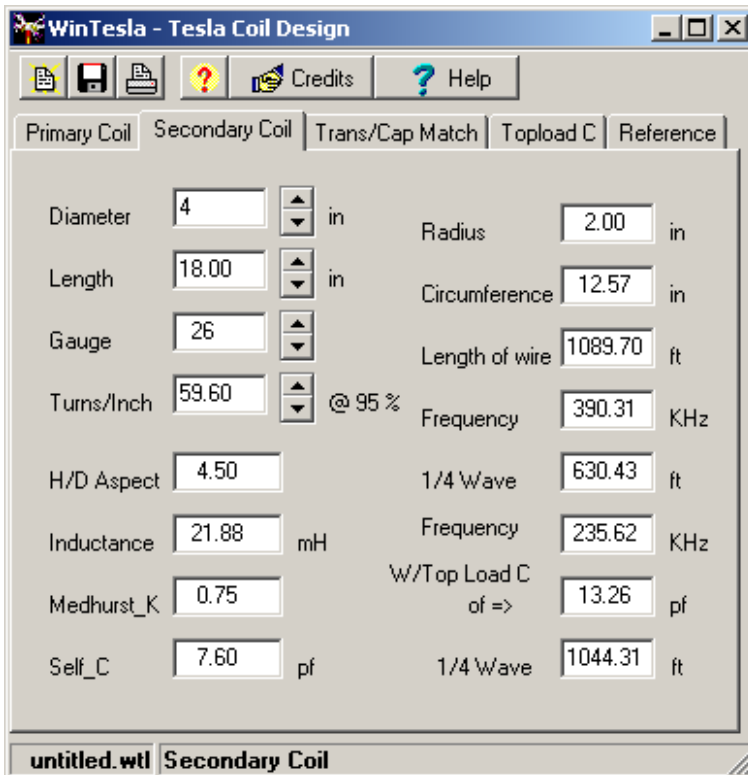
Designing the Secondary Coil

Although I don't want to cover any of the intricate rules and fine details of tesla design in this document, I will include a general guideline to how a secondary coil should be designed.

Aspect ratio is the ratio of coil winding height to its width. For secondary coils of 4" diameter or less, you should go with an aspect ratio of 4.5:1 to 5.0:1. For secondary coils in the 5" to 6" range, aspect ratios of 4.0:1 to 4.5:1 work well. For the largest coils, aspect ratios of 3.0:1 to 4.0:1 should be used. The aspect ratio parameters are designed to allow maximum coupling between the primary and secondary while providing a very high inductance in the secondary coil. This also allows the finished secondary coil to maintain good electrical strength.

For wire sizing, for most coils you should be using anywhere from 22 AWG to 28 AWG. Anything greater than 28 AWG is considered lossy and is good only for the smallest secondary coils (typically 1" to 2.5" in diameter) If you have a 4"-6" secondary and using only modest (<3kW) power, 22 AWG to 26 AWG should work well.

So lets stop wasting time with rules and get on with our design. As stated before, we did manage to find a nice roll of 26 AWG magnet wire in our shed. Again, I am using the WinTesla software to perform my design calculations.

The only values I entered on the worksheet above are the diameter (4") and the gauge (26 AWG). In the bottom right corner you can see that the Top Load C (toroid capacitance) was automatically copied over from the toroid calculator worksheet.

Now the only design rule here is that we want to maintain an aspect ratio of 4.5:1. So to accomplish this, simply change the winding length of the coil until the aspect ratio is 4.50. I have already done this and it is shown in the worksheet above. So, the final specifications of our secondary coil are as follows:

Diameter: 4"
Length: 18.00"
Gauge: 26 AWG
Aspect Ratio: 4.50
Frequency: 390.31kHz
Frequency: 236.62kHz (w/ Top Load C of 13.26pF)

The first frequency listed, 390.31kHz, is the 1/4wave resonant frequency of the secondary coil by itself. This is the resonant frequency of the secondary coil if there was no toroid attached to the top. But since we have a toroid attached, we will use the 236.62kHz resonant frequency. This is the frequency we are concerned about.

Secondary Coil Resonant Frequency = 236.62kHz

Okay, 80% done. The only thing left to do is to design our primary coil which should be easy enough.

Designing the Primary Coil

Unfortunately, we didn't find anything in our shed to use for our primary coil, so we will go shopping to Home Depot and see what we can come up with. When we get to Home Depot, we find that they have 100ft rolls of 0.25" flexible copper tubing. This is perfect.

There are basically only a few rules I follow which I will list below:
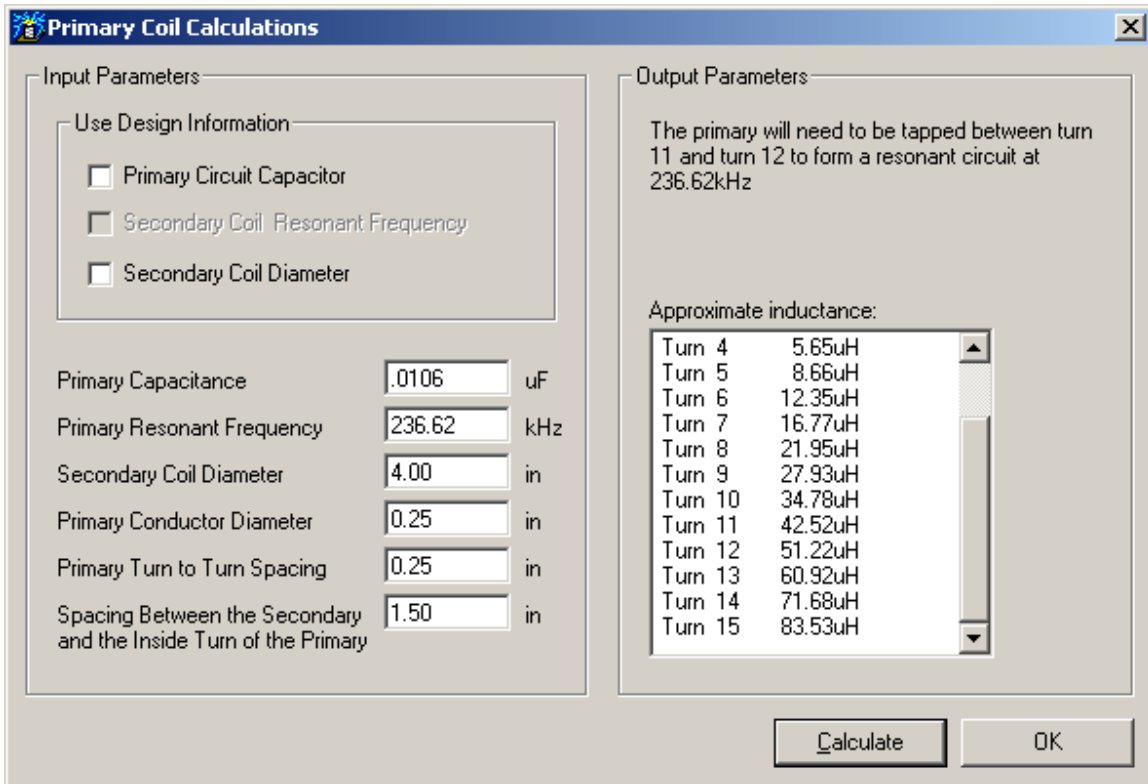
1. Primary coil should have at least 3-5 turns on either side of calculated tap location to accommodate final tuning. This is important as your actual built secondary coil, capacitor, toroid, etc… will have a slightly different value than what any CAD program or equation will tell you. You want to be able to tune out any discrepancies or variances.

2. Use about 1.5" to 3.0" spacing between inside turn of primary and secondary to prevent arcing between primary and secondary coil.

3. I make my turn-to-turn spacing equal to the diameter of my primary conductor. For example, if I am using 0.25" copper tubing, my turn-to-turn spacing is 0.25".

4. Utilize a Flat Pancake primary coil design.

So from the rules above, I get the following parameters:

Conductor Diameter:	0.25"
Turn-to-turn Spacing:	0.25"
Pri-Sec Spacing:	1.50"

For this calculation, I turn to Tesla Coil CAD since I like the primary coil worksheet better than using WinTesla as this ones shows you where exactly the turns needed to be tapped for tuning.

From this worksheet, we can see that we will need to tap our primary coil between turn 11 and turn 12 to get the circuit to be resonant at 236.62kHz. Of course, in practice this will could quite a bit off which is the reason to use extra turns for our primary coil.

For my design, I will use a 15 turn primary coil. This gives me up to 3.5 turns extra tuning capability should I need it. There is nothing worse than trying to tune your tesla coil for the first time and realizing you don't have enough primary turns to tune your circuit.

Finalized Design

So there you have a complete tesla coil design. The following table lists the specifications for this particular tesla coil:

Requirement	Specification
High Voltage Transformer	15kV / 60mA NST
Primary Capacitor	0.0106uF, 15kV MMC
Primary Coil Type	Flat Pancake
Primary Coil Conductor Diameter	0.25"
Primary Coil Turn-to-turn Spacing	0.25"
Distance between Primary Inner Turn and Secondary	1.50"
Total Number of Primary Turns	15 Turns
Calculated Primary Tap Point for Resonant Frequency	11-12 Turns
Secondary Coil Diameter	4.00"
Secondary Coil Wire Gauge	26 AWG
Secondary Coil Winding Length	18.00"
Secondary Coil Aspect Ratio (H/D)	4:5 to 1
Toroid Dimensions	12" x 3"
Toroid Capacitance	13.26pF
Resonant Frequency of Secondary w/ Toroid	236.62kHz

Final Notes

So that was easy enough, right? Just remember that things may not go as smoothly as anticipated while you are designing your tesla coil. You may find that for the size secondary / toroid you are using that you may need 22 turns on the primary to get the correct resonant frequency. Since we ideally want to limit the primary to about 15 turns, we need to go back to our secondary / toroid design and tweak it until we get the proper number of turns. This may mean modifying toroid size, changing winding length (and aspect ratio) of the secondary, changing wire size of the secondary, etc… to get the exact specifications you need. It's a back and forth compromising process, but relatively a simple one. Good luck!

Tesla Coil CAD Software Resources

WinTesla
Written by R. Scott Coppersmith
http://www.hot-streamer.com/rscopper/index.htm

Tesla Coil CAD
Written by Richard Chapman
http://www.richardsplace.net/tesladownload.htm

The links for these software programs are also available on my website at www.SpaceCatLighting.com