

Development, Design, Applications and Handling of Tesla Coil Transformers: A Review

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Abstract

The aim of this paper is to highlight the development of Tesla transformer throughout the decades since its first patented design and to discuss the designing parameters required in construction and manufacturing of Tesla transformers and to see the applications where different types for the same transformers are used as per different specifications. The paper will also give information on health hazards or how to take personal care while operating a Tesla coil. The paper shall as well try to provide an understanding how the Tesla Coils can be used in various applications in brief. Also the designing of Tesla Transformers in comprehensive stepped flow chart for the clear understanding of readers has been presented in successive sections of this journal article. The article being 'A Review ' paper does not include detailed explanation about the designing of the Tesla Coils and hence a numerous parameters which might be difficult to comprehend for common readers have been excluded and instead easy methodology for explanation has been adopted for better understanding.

Keywords

Tesla coil, disruptive voltage, spark gap, corona, resonating transformer, solid state Tesla coil, magnifier circuit

Indices

H.V. =high voltage

L.V. = low voltage

CRT= cathode ray tube

IF=infrared

RF=radio frequency

W.P.T=wireless power transfer

Parameters

$\lambda/4$ = quarter wavelength in feet

c= propagation speed of wave front or 9.84×10^8 feet/sec or 2.998×10^8 m/s

f_0 = resonant frequency

L/T = Length per turn of wire in inches

D = Diameter of secondary coil form

d = Diameter of wire with insulation and inter-winding distance

N = Required number of turns of wire

L_s = Inductance of secondary coil in μ henries

A = Radius of coil form in inches

C_s = Self-capacitance of secondary coil in farads

H = Required height of winding in inches

$DC\Omega$ = Total DC resistance of the winding in ohms

NS = Number of layers (strands) of wire used

TA= Ambient temperature in Celsius

Ω/ft = DC resistance of one foot of selected wire gauge

AC Ω = Total AC resistance (skin effect only) of the winding in ohms

R_t = Total resistance of secondary winding in ohms

C_t = Terminal capacitance in farads

C_p = Maximum usable primary capacitance for selected step-up transformer

IR = Rated output current of step-up transformer in amps

VR = Rated output voltage of step-up transformer in volts

BPS = Breaks per Second produced by spark gap

C_{pt} = Additional primary tuning capacitance in farads

$W = A / \cos \theta$

θ = angle of incline from horizontal

Introduction

The Tesla coil is basically an electrically resonating transformer circuit which is generally excited by different methods or is tuned singly or doubly or in some cases triply coupled. The Tesla transformer was designed by the scientist Nikola Tesla in 1891. They are used to produce a high voltage A.C. Supply with changeable high frequency and low current which is used in a numerous applications in industries, laboratories, radios and wireless power transfer technologies. This piece of the paper for the most part contains the historical backdrop of the Tesla coil and how it was made for all intents and purposes accessible for genuine use outside the lab. Researcher Nikola Tesla created the Tesla Coil and first showed it in broad daylight in 20th May of 1891 at the AIEE at Columbia College, New York. The primary licensed circuit had all the essential components i.e. H.V. essential, capacitor, start exciter and coreless oscillating transformer ¹. By the examination it was discovered that the transformers utilized as a part of vast power lattice structure which worked diversely at high frequency when contrasted with low frequencies ². The iron core utilized as a part of lower level of power supply suffered from energy losses, and if not insulated properly it could pose dangerous to the person handling it. So another transformer without a solid core was created freely by Nikola Tesla and researcher Elihu Thomson which was known as "oscillating transformer" and the coil circuit to work it to deliver high voltage supply. The Tesla coil was essentially concocted amid endeavor of making a remote lighting network i.e. wireless power supply network ^{3,4}. However Tesla was not the first to build up this circuit rather Henry Rowland built up a start hole thunderous transformer circuit in 1889. Be that as it may, Nikola Tesla was the main visionary who saw the pragmatic uses for it and in this way protected it. Tesla awed gathering of people in his many addresses held at lofty logical traditions by indicating them brush releases and streamer releases, additionally he demonstrated that H.F. streams did not make vibe of stun by applying a few kilovolts his own particular body which made his body to shine up like that of crown in a dull room. The Tesla coil fundamentally made to accomplish the W.P.T however these days the utilization of these is across the board in radios, medication, the stage, training, high voltage creation, spillage discoveries, and ignitron circuits in bend welding applications and so forth^{5,6}. The utilizations and uses of Tesla coil will be clarified in much detail in up-coming segments of the writing.

Different Types of Tesla transformers

The Tesla coil circuits can be classified by the methods of excitation employed in that particular circuit, what circuit is used to apply the current to primary of the resonant transformer.

1) Spark-gap Tesla coil

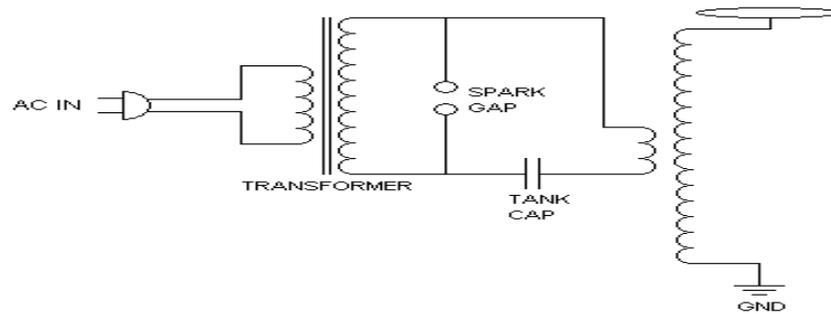


Figure 1: Tesla coil with spark - gap

This kind of coil circuit utilizes a start hole/spark gap to turn on the essential twisting of the circuit. This flagged beat drive makes a H.V. wave at the yield. The detriment of start hole is the treatment of high essential streams, boisterous operation, ozone gas, and high temperature. That is the reason they require cooling framework regularly. Likewise the Q-factor and yield voltage lessens in this kind of development ⁷.

1-A) Stationary excited spark gap

In this sort of development, circuits regularly utilize D.C. voltage source to charge the capacitor and H.V. pulses are produced to trigger the start hole which allows the control of start rate and energizing voltage. The economically accessible start holes are encased in protecting gas environment like SF₆ which promote more help in decreasing the length and accordingly the loss of energy.

1-B) Rotating Spark gap

This development comprises of a start hole having cathodes (electrodes) around the surface of a wheel which is pivoted at rapid by an engine that makes releases or circular segments when they go by a relentless terminal. The quick division speed of the cathodes douses the sparks/arcs rapidly which helps in getting higher voltages at the yield. In this type the wheel

is rotated by a synchronous machine (motor) with the goal that the anodes are turned at a uniform speed and an unadulterated sine wave is gotten.

2) Solid State Tesla Coil (SSTC)

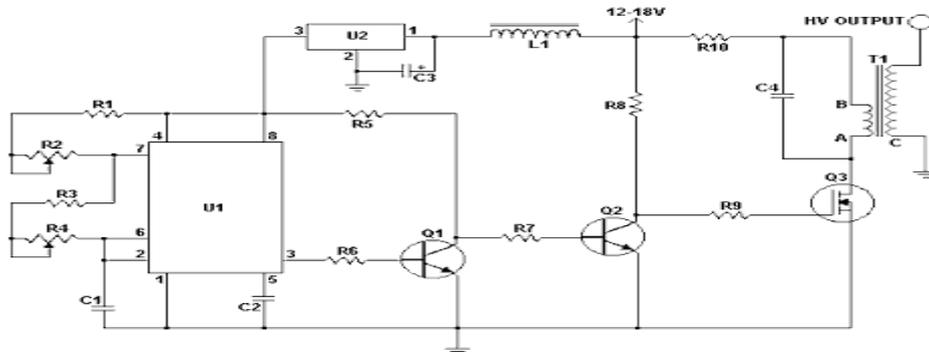


Figure 2: Solid state Tesla coil

They utilize semiconductor gadgets like thyristors (S.C.R), transistors (IGBT or MOSFET) to give switching beats/pulses of current from a DC source to primary of the Tesla Transformer. They give pulsed starting without the detriment of a spark gap i.e. uproarious operation, high temperature, and low proficiency (efficiency). The points of interest being calibrating or control of voltage, current and excitation waveforms ^{8,9}.

2-A) Solo resonant solid state Tesla Coil (SRSSTC)

In this development the essential does not comprise a condenser as isn't a tuned circuit yet the auxiliary is just the tuned one. The pulses acquired by the power semiconductor gadgets connected to essential energize the auxiliary winding's tuned circuit. SRSSTC are more straightforward to plan yet the hindrance is the low Q-factor and can't create voltage level as high as a DRSSTC.

2-B) Double Resonating Solid State Tesla Coil (DRSSTC)

The circuit is like the double tuned start-hole development, with the exception of that set up of a start excitation a power semiconductor exchanging gadgets are utilized. The capacity of this kind of circuit is like double tuned start energized circuit, which yields higher Q-factor and create high voltage from the given input control.

2-C) Musical or Singing Tesla Coil



Figure 3: Musical Tesla coil

This is the coil which can be played like a musical instrument with its H.V. output discharges reproduce or creating the very basic musical tones. The current signal in form of the pulses applied to the primary are tuned or modulated at an audio rate by a power semiconductor interrupter circuit which causes the arc from the H.V. terminal to emit sounds of different musical notes. So far only basic chords have been produced so the coil itself cannot function as a loud speaker. Therefore complex music or vocal sound is possible with this circuit. So a keyboard with MIDI interface is needed to control the sound output. Such types of Tesla coils are built for entertainment purpose only^{10,11}.

3) Continuous Wave

In these kind of development the transformer is driven by a closed loop (feed-back) oscillator which gives a sine wave current to primary winding of the transformer. The primary here acts a tank circuit of the oscillator and the circuit carries on like a radio transmitter. This circuit gives an unadulterated, ceaseless sine wave at the yield. Here the vacuum tubes are for the most part utilized rather than control transistors due to their much hearty development.

4) Two coil or Double-tuned/ resonant circuits

These days all the business Tesla loops/coils utilize doubly tuned transformer. The L.V. winding is furnished with current heartbeats, auxiliary winding that gives high yield voltage. The expression "Tesla Coil" is for the most part alluded to these sort of circuits¹².

5) Three coil or triple-tuned/ resonant circuits or Magnifier circuits

In this construction is based on Nikola Tesla's magnifying transmitter circuit developed during 1898-1900 in Colorado Springs Lab. This consists of a two coil air core transformer with the secondary connected to a third coil not magnetically coupled to other two. This third

coil is also called extra coil or the resonator coil and is series fed and resonates with its own capacitance. This type of construction has limited use in a few practical applications¹³.

Type	Sub-type			Designing complexity
Spark Excited	Spark-excited gap	Rotary Spark gap	-	Easiest and most basic type
Switched or Solid State Tesla Coil	Single resonant solid state	Double Resonant Solid State	Musical or Singing	Quite difficult (as the components used need perfect coordination to function properly)
Continuous Wave	-	-	-	Moderately difficult
Two coil or Double-tuned / resonant circuits	-	-	-	Somewhat complex (as proper insulation has to be provided to windings as there two different primaries and their dimensions may also vary)
Three coil or triple-tuned / resonant circuits or Magnifier circuits	-	-	-	More complex than double tuned circuit

Table1: Comparison Table from Designer's P.O.V for manufacturing of Tesla Coil

Development of Tesla Coils over the years

The Tesla coils have themselves experienced various adjustments since its initially patented model. From the extremely fundamental spark energized Tesla transformers with subdivisions like static and rotating switches which had issues of low quality factor and low

yield voltage, the following change to circuits was the use of power-semiconductor devices with microcontrollers to give the quick exchanging of these components, so the operation is noiseless and the fine control and tuning of output voltage is achievable. Next the continuous wave Tesla coils helped in accomplishing the unadulterated/pure sinusoidal output voltage. The double tuned and triple tuned Tesla coils have discovered their applications in current circumstances. One of the most recent advancement of Tesla transformer is the D.C. Tesla coil which evacuates the massive transformer part which is supplanted by a battery, spark gap is supplanted by a solid state devices, and is fit for auto-tuning itself¹⁴.

Operation of a basic spark-excited Tesla coil with necessary equations

For the testing of electrical instruments for switching waves (surges), high frequency, H.V. damped oscillations are necessary which need high voltage Tesla transformer circuit. The benefits of using these Tesla coil circuits are:

- A) The transformers are devoid of a solid core and hence saving in parameters like bulkiness and expense,
- B) Pure sinusoidal power voltage signal at the output,
- C) Gradual production of voltage over initial cycles and hence no damage due to sudden surges, and
- D) Equal voltage distribution over the coils due to subdivision of coil stack into a number of parts.

The common arrangement of a circuit is given in the figure shown below. The primary is fed from a direct or alternating power source through the capacitor C_1 . A spark-gap G connected across the primary is excited at the desired voltage V which induce a high disruptive voltage in the secondary.

The L.V. and the H.V. windings (L_1 and L_2) are wound on an insulated bobbin with no core (air-cored) and are oil immersed. The windings are tuned to a frequency of ten to hundreds of kilo Hertz by the help of the capacitors C and C_1 .

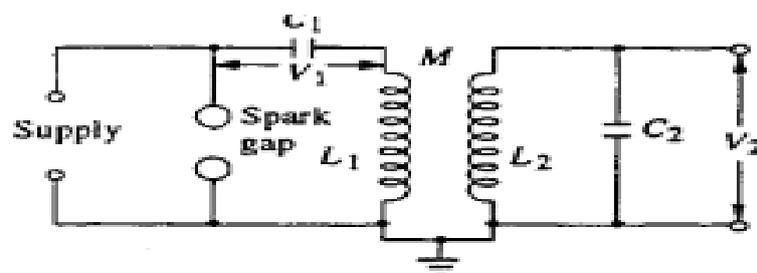


Figure 4: Tesla coil equivalent circuit

The output voltage V_2 is a function of individual inductances and capacitances and mutual inductance M . If i_1 and i_2 are the circuit currents and V_1 and V_2 are the input and output voltages respectively then we get the following equations^{14,15}

$$V_1 = \frac{1}{C_1} \int_0^t i_1 dt + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \quad (1)$$

$$0 = \frac{1}{C_2} \int_0^t i_2 dt + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} \quad (2)$$

From the Laplace transformation of the equations (1) and (2) we get:

$$\frac{V_1}{s} = \left[L_1 s + \frac{1}{C_1 s} \right] I_1 + M s I_2 \quad (3)$$

$$0 = [M s] I_1 + \left[L_2 s + \frac{1}{C_2 s} \right] I_2 \quad (4)$$

The output voltage V_2 and its Laplace transformation is given by;

$$V_2 = \frac{1}{C_2} \int_0^t i_2 dt \quad V_2(s) = \frac{I_2}{C_2 s} \quad (5)$$

The solution for equation (5) yields;

$$V_2 = \frac{M V_1}{\sigma L_1 L_2 C_1} \cdot \frac{1}{(\gamma_2)^2 - (\gamma_1)^2} [\cos \gamma_1 t - \cos \gamma_2 t] \quad (6)$$

Where;

$$\sigma^2 = 1 - \frac{M^2}{L_1 L_2} = 1 - K^2 \quad (7)$$

The roots are given by;

$$\gamma^{1,2} = \frac{\omega_1^2 + \omega_2^2}{2} \pm \sqrt{\frac{\omega_1^2 + \omega_2^2}{2} - [\omega_1^2 \omega_2^2 (1 - K^2)]} \quad (8)$$

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \quad \text{and} \quad \omega_2 = \frac{1}{\sqrt{L_2 C_2}} \quad (9)$$

Also;

$$W_1 = 0.5 \eta C_1 V_1^2 = (0.5 * C_2 V_2^2) \quad (10)$$

Therefore;

$$V_2 = V_1 \sqrt{\eta \frac{C_1}{C_2}} \quad (11)$$

Designing of Tesla Transformers

In this section the designing of a spark excited Tesla Coil will be discussed with all the basic parameters which are actually needed to design an actual Tesla transformer .

a) Length of secondary winding

$$\frac{\lambda}{4} = \frac{c}{f_0} \quad (12)$$

b) Per turn length

$$L/T = Dp + d \quad (13)$$

c) Number of turns

$$N = \frac{\lambda/4}{L/T} \quad (14)$$

d) Winding height

$$H = N * L / T \quad (15)$$

e) Inductance of winding

$$L_s (\text{[h]}) = \frac{A^2 N^2}{9A + 10H} \quad (16)$$

f) Capacitance

$$C_s = \frac{1}{4\pi^2 * f_0^2 L_s} \quad (17)$$

g) DC resistance

$$DC \Omega = \frac{\frac{(\lambda/4) * \Omega / ft}{NS}}{1 + [TA - 20^\circ C] * 0.00393} \quad (18)$$

h) AC resistance

$$AC \Omega = \frac{9.96 * 10^{-7} * \sqrt{f_0}}{d} \quad (19)$$

i) Quality of Secondary Winding

$$Q_s = \frac{\omega_0 L_s}{R_t} \quad (20)$$

j) Resonant frequency of secondary winding

$$f_{so} = \frac{1}{2\pi \sqrt{L_s (C_t + C_s)}} \quad (21)$$

k) Total impedance of the secondary winding

$$Z_s = \sqrt{R_t^2 + \left(\omega_{so} L_s - \frac{1}{\omega_{so} (C_s + C_t)} \right)^2} \quad (22)$$

l) Primary Capacitance

$$C_p = \left(\frac{IR}{V_R} * \frac{1}{BPS} \right) - C_{pt} \quad (23)$$

m) Inductance of the primary winding for helically and spirally wound structure and Top Load

$$L_s (\text{[h]}) = \frac{A^2 N^2}{9A + 10H} \quad (24)$$

$$L_s (\text{[h]}) = \frac{A^2 N^2}{8A + 11W} \quad (25)$$

n) Resonant frequency of primary winding

$$f_p = \frac{1}{2\pi \sqrt{(L_p + L_{pt})(C_p + C_{pt})}} \quad (26)$$

o) Resistance and Impedance of the Primary Winding and Spark gap

$$R_{ge} = \frac{8(193.04S+34)}{\pi l p} \tag{27}$$

$$Z_{pss} = \sqrt{(R_p + R_g)^2 + (\omega p L_p - \frac{1}{\omega p C_p})^2} \tag{28}$$

$$Z_{ps} = \frac{(\omega p M)^2}{Z_s} + Z_{pss} \tag{29}$$

p) Quality factor of primary winding

$$Q_p = \frac{\omega p * L_p}{Z_{pss}} \tag{30}$$

All the above formulae for the designing of Tesla transformers hold true, but from manufacturer to manufacturer and applications to environmental conditions the formula for different parameters change as per the necessity, cost, and of course the consumer's requirements. The formulas have been taken from an authentic source of information and many research articles ^{16-21, 24-25}.

Flowchart Representation for the Representation of Designing Procedure

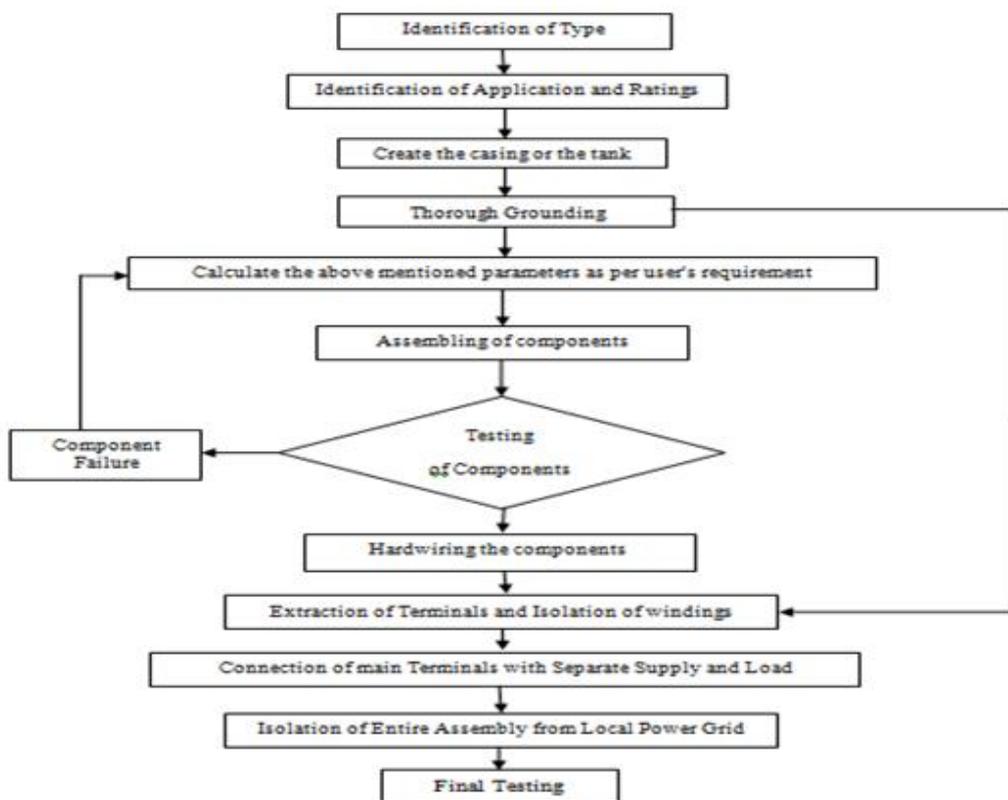


Figure 5: Flowchart describing comprehensive steps for designing and manufacturing of Tesla Transformer

The above flow chart describes how manufacturers design the Tesla Coils according to different applications and user specifications. The complex steps and testing have not been mentioned and a simplified diagram has been presented for better understanding.

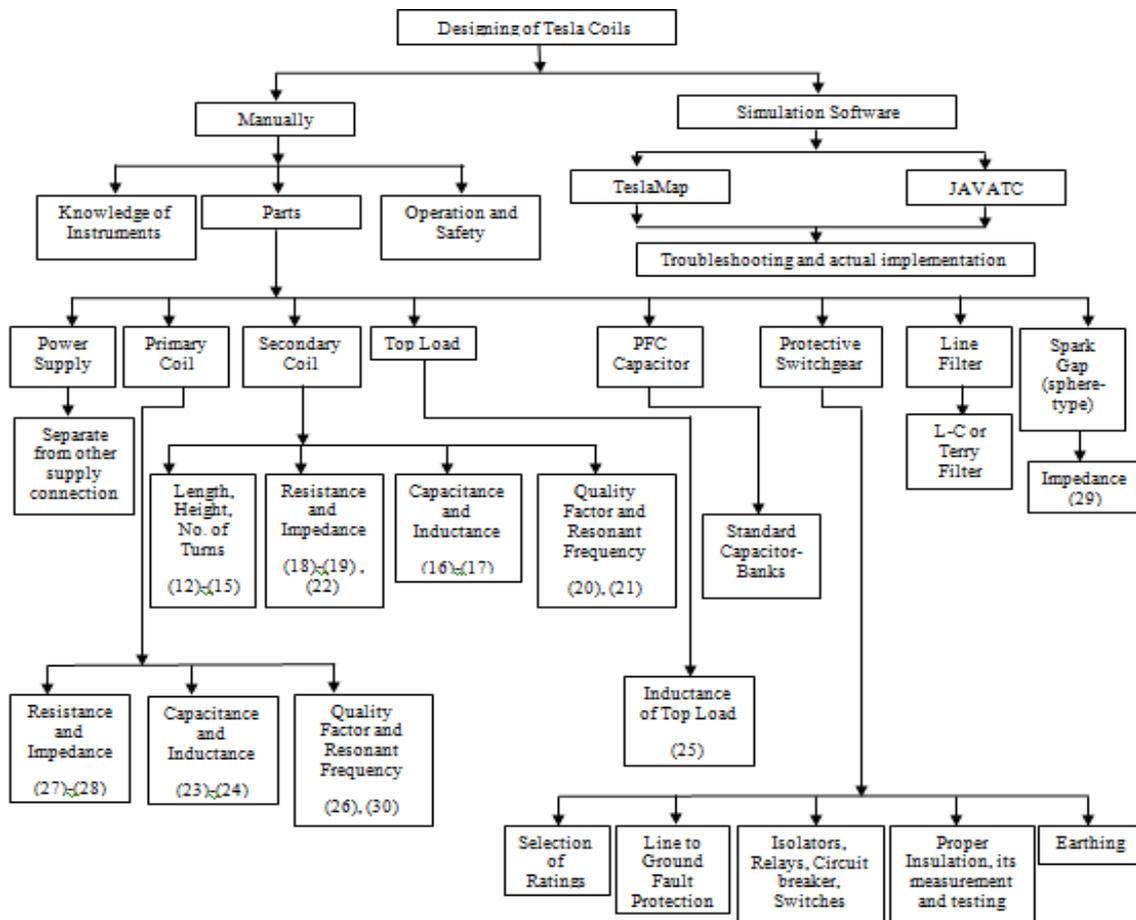


Figure 6: Flowchart Describing comprehensive steps for designing of Tesla Transformer both manually and computerized software

In the above flowchart it can be seen that designing the Tesla Coil manually is a complex procedure requiring a thorough knowledge and a numerous tedious calculations, which in case if one makes errors, may lead to faulty parts and risky operation. Therefore nowadays entire assembly of Tesla Coil is simulated first using softwares mentioned in the flowchart, then troubleshooting in the software itself is done and only after the desired results; the actual Tesla Coil is manufactured according to customer's satisfaction. This shows that using software, valuable time and assets are saved which is not possible in case of a manually produced assembly for the same.

The succeeding sections of the paper shall describe the applications, handling and health hazards associated with Tesla Coils.

Applications of the Tesla coil

1) Wireless power transfer

The remote power exchange was first endeavored to accomplish by Nikola Tesla inside 1891-1900. Transmitting radio power waves restricted to short distances by making suitable magnetic coupling between the turns of primary and secondary. These days this idea is broadly utilized as a part of IF transformers and short range remote power networks. In spite of the fact that the work in WPT is as yet a work in advance however the idea and utilization of the Tesla transformer is the foundation of the research and application of WPT²².

2) Radio Transmission

The idea of spark energized Tesla coils was first utilized as a part of Radio in 1890's. Many different groups of researchers and scientists prompted an alternate constructional advancement in Tesla coil which was the four-circuit/ quadrupled excited circuit. Be that as it may, they ended up noticeably out of date as the principle part with the coming of vacuum tubes and with its mix with Tesla transformer it is one of the fundamental segments of Radio to this date³.

3) Medical Applications

As we probably am aware at this point Nikola Tesla investigated himself utilizing a huge amount of voltage produced by Tesla coil's secondary , a perception can be made that high recurrence streams over 10 to 15 kHz did not cause the sentiment an electrical stun/shock. These streams could undoubtedly be gone through a human body without causing hurt. By a few human investigations it was discovered that power signals made by Tesla coil if connected day by day could help mitigating gloom. The warming impacts of these streams were additionally utilized as the base for Diathermy for different joints like elbow and knees. The Paul Marie Oudin influenced adjustments to existing Tesla coil which was later known as Oudin's Coil for the treatment of diabetes, treatment of malignancy, diathermy and so on³.

4) Show business

The high recurrence safe ebbs and flows and eye getting streamer releases and starts drove the utilization of Tesla coils in the realm of diversion business. Voyaging jamborees and carnival's monstrosity appears, side shows and so on utilized the Tesla coil to catch the concentration of the watchers and indicated how current flashes escaped their body parts. Additionally the sci-fi films likewise began to utilize this which additionally added to prevalence of the Tesla coils and motion pictures too³.

5) Education

As part of studies from basic middle school to colleges and research stations the Tesla Transformer have always been a part of interest. At school level students prepare this as a part of their mini projects, in which the whole structure is placed in a globe of glass and whenever the glass is touched one can see the lightning streams touching their own finger tips at glass and their hair stands up. So at school level it one of the hot favorite topics of project and a part of fun, while at research stations and college levels it is an extremely important part of High Voltage Engineering field which deals with power system networks, switchgear and their testing, WPT etc.

6) Evacuated system's leak detectors

Tesla transformer's releases are utilized to distinguish the openings in high vacuum frameworks and mechanical assembly. At the point when the framework is cleared the high voltage cathode is moved over the outside surface of device to be checked. On the off-chance that there is a minute gap the power goes through it and crown lights up the opening and henceforth the detection of leakage is hence achievable ²³.

7) CRT

Every CRT tube has a small Tesla Transformer called Fly-back Transformer which is used to provide the necessary high voltage to excite and accelerate the electrons emitted from electron gun section toward the picture tube to phosphor screen of the television ²³.

8) Vehicles

Oil filled Tesla coil popularly called as the ignition coil IC engine type vehicles which are used to give required high voltage to the spark plug to start the vehicles ³.

Personal Care and Health hazards while Handling Tesla coils

It should never be forgotten that the low voltage primary of the Tesla transformer carries a power supply of 50Hz or 60Hz and thus the currents are lethally dangerous for the operator if carelessness is observed. Also now it is also found that high frequency discharges can also cause the nerve damage and as no pain is felt the experimenters assume that these currents are harmless. If the arcs or discharges touch the bare skin they do cause skin-burns. Even a nominally rated Tesla transformer has the energy to stop the heart of a person or electrocution is also possible ²⁷.

Following are the guidelines one needs to take a note for personal care while operating a Tesla Transformer:

1. Check the main power supply and the switchgear. Never leave the assembly of system unattended while power cable is connected with an electrical outlet.
2. Whenever the Tesla coil circuit is turned on, one should never come in contact with any part, or try to assemble or dismantle it. Even if it is turned off, do not attempt to touch it, as it takes some time to completely discharge the coil.
3. As Tesla coil emits large amount long electrical arcs (streams of lightening) , the nearby vicinity of Tesla Transformer has to be kept clear (20 feet or 6 meters) for avoiding unintentional shocks.
4. A separate power supply which is isolated from other main supplies has to be provided because if any other electrical equipment connected to the same supply that of Tesla coil can be damaged.
5. If there is no separate supply then unplug all electrical equipments and then operate Tesla coil.
6. The entire system should be provided with proper electrical earthing.
7. Tesla coils can damage or destroy hearing aids, pacemakers in its proximity. It means that Tesla coils can kill patients with pacemaker/ heart patients. So a person with cardiac diseases must stay away from it.
8. The facilities where Tesla coils are operated, must be properly ventilated and have fire safety equipment as the system produces large amount of heat if overloaded.
9. The arcs from the coil may produce suffocating gases, therefore ventilation must be according to standards.
10. Do not look or observe the internal arcs produced in the assembly itself for long time duration because they are many times brighter than the arcs produced at the outlets. This can damage the vision of any person if not taken care off.
11. Verify that nobody ever comes in contact with low voltage winding of transformer because it is carries high magnitude currents capable killing a person.
12. The facilities employing Tesla Transformer should be moisture, dust free.

Conclusion

The presented review of Tesla coil gives in detail the information regarding various different aspects of its history, development, operation, designing. The paper also discusses important parameters which are taken into consideration for designing any kind of Tesla coil in its basic form. Also the applications and in-depth knowledge of operation, handling, personal care

while operation for the same is also provided. The different works by various authors on this concept has also been presented for the sake of verification and for the readers who are willing to know about Tesla Coils in much more detail. In a nutshell we can say that Tesla transformers themselves have gone through different modifications over considerable time span and hence have found their way through variety of useful concepts, one of most important being the concept of wireless power transfer whose backbone is itself the Tesla coil which is the future of power supply and distribution grids. The current trend is of transmitting D.C. power supply because of its low loss content and higher system efficiency and then back to A.C. supply. The latest and the future scope is of D.C. Tesla Coil which can aid the power grid to generate a wireless, harmonic free, almost loss-less power supply.

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