



RESEARCH ARTICLE

SIGNIFICANT PRACTICAL FEATURES OF TESLA TRANSFORMERS

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ARTICLE INFO

Article History:

Received 06th August, 2017
Received in revised form
11th September, 2017
Accepted 29th October, 2017
Published online 30th November, 2017

Key words:

Tesla transformers, High-voltage
techniques, Pulse power generators.

ABSTRACT

Although a large number of publications dealing with Tesla transformers have appeared, many of these are confined to providing an analysis of the transformer performance based on a lumped equivalent circuit model. The present paper is concerned with more practical issues and begins by considering the often overlooked significance of the magnetic coupling between the primary and secondary windings for the range of potential applications of these transformers. It continues by discussing the benefits of using a solid-state primary switch and providing an insight into various other additions that may be made to the basic circuit.

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Citation: Richard M Craven, Ivor R Smith and Bucur M Novac, 2017. "Significant practical features of Tesla transformers", *International Journal of Current Research*, 9, (11), 60313-60316.

INTRODUCTION

High-voltage (HV) pulse generators, capable of producing output pulses exceeding 100 kV in amplitude and with a very short rise time form a key requirement of many research activities, particularly in particle and plasma physics. Other applications where such generators are used in either single or multi shot modes include:

- pollution control
- high-power lasers
- X-ray radiography
- high-power microwave generation
- electron beam accelerators
- ultra-wide band electromagnetic radiation generation

In many of these uses, the required high voltage is produced via either a Marx generator or a Tesla transformer, depending on the expertise of the designer and the specific practical needs of the application. The present paper is devoted to the current state of development of the Tesla transformer, one of the many ingenious innovations to emerge from the fertile mind of Nikola Tesla (Lomas, 1999). At the turn of the 20th Century, he was working in his laboratory in Colorado Springs in the USA, with Figure 1 illustrating the typical spectacular evidence of the success of the early experiments that were performed.

Despite many variations on the original concept having appeared, the basic form of the Tesla transformer remains at the heart of many of the pulsed-power generators used in a wide range of current applications (Su et al., 2016; Peng et al., 2011). Numerous detailed and elegant analyses based on a simple linear circuit model have appeared in the literature (Glascoe and Lebacqz, 1948; Sergeant and Dollinger, 1989) that, under certain limited conditions can, with reasonable accuracy, predict and describe the operational characteristics of the transformer. However, few discuss the different constructional forms and other features that a Tesla transformer may require in different practical applications. The present authors have all worked in this area for many years, with the present paper being based on their many combined years of experience and seeking to provide an insight into various practical features that are now widespread. For convenience, the common usage is followed of the term Tesla transformer applying to a transformer in which the primary and secondary circuits have the same natural frequency. It should however be remembered that for maximum energy transfer the coupling coefficient must be one of the well-known series of specific values (1, 0.6, 0.39, 0.23,).

Circuit details

As shown in Figure 2, a Tesla transformer is normally a two-winding air-cored arrangement, in which two resonant circuits, the low-voltage primary and the high-voltage secondary, are

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tuned to the same resonant frequency of several hundred kilohertz when decoupled. Typically, a primary winding will be made from a few turns capable of withstanding peak currents of several hundred amperes while the secondary winding is a multi-turn single-layer solenoid rated to carry a current of a few amperes. The lower end of this winding is normally earthed.

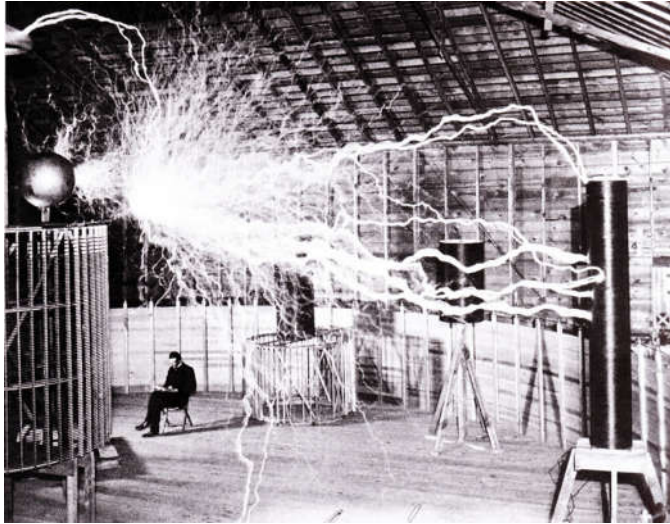


Figure 1. An example of Tesla's experiments at Colorado Springs

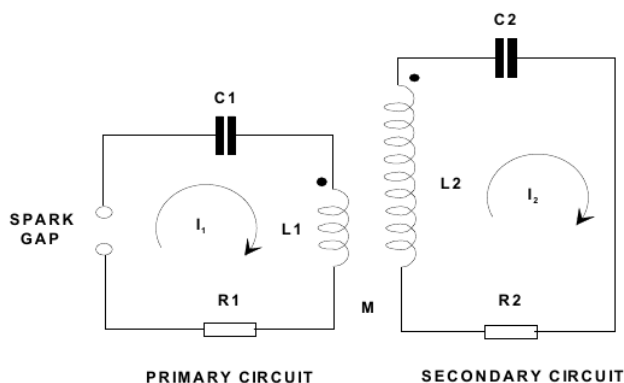


Figure 2. Equivalent lumped circuit of a Tesla transformer

The winding inductances L_1 and L_2 are tuned to resonance respectively by the lumped capacitance C_1 and the distributed capacitance C_2 , comprising the self-capacitance of the secondary winding plus its surroundings and a high-voltage termination electrode, often feeding a pulse-forming line (PFL) possibly via a sharpening gap. In some systems, the load capacitance may be sufficiently high to reduce the resonant frequency to well below that of the isolated circuit alone. Under these conditions, a lumped element assumption based on the equivalent circuit of Figure 2 is adequate for predicting the transformer performance, and detailed analyses can be found elsewhere (Glascoe and Lebacqz, 1948; Sergeant and Dollinger, 1989). In single-shot operation, the capacitor C_1 is typically charged to about 20 kV and then discharged into the transformer circuit by closure of a primary switch, often in the form of a spark gap.

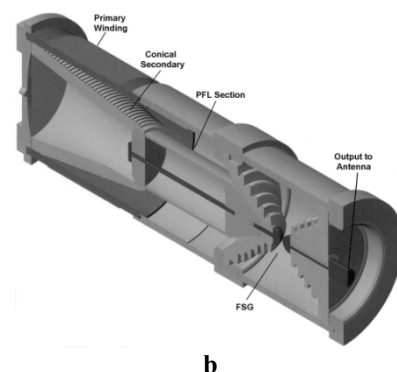
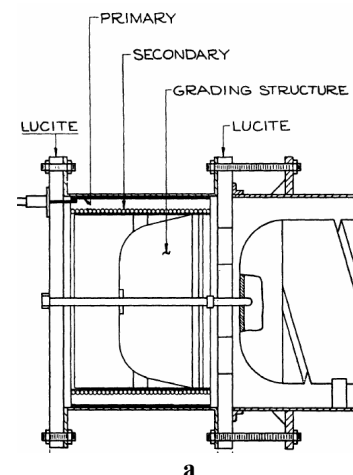
Coupling in Tesla transformers

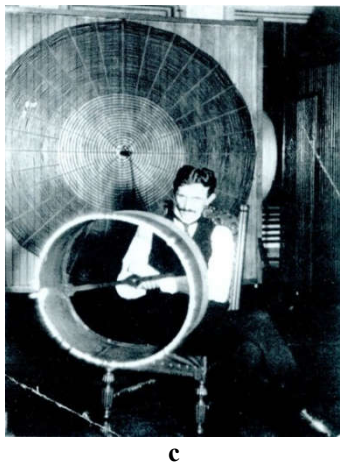
Different designs of transformer are required for different applications, and during an extensive investigation at

Loughborough University (Craven, 2014) a number of important aspects emerged. When the aim of the transformer is to generate an extremely high secondary voltage, the insulation requirements, together with the high primary current and the sharpness of the output pulse required, often preclude the use of a ferromagnetic core, and it is difficult to achieve a high magnetic coupling coefficient k between the two windings. Alternatively, when k is low (typically < 0.3), the energy transfer efficiency is also low, which impinges on the total power efficiency and the overall losses. Arising from the different values of k , there are inevitable differences between the winding and geometric arrangements of Tesla transformers for different applications. These have led to a convenient classification being adopted based on the magnetic coupling between the two windings either being 'tight' ($k > 0.6$) or 'loose' ($k < 0.3$). Considerations of this and various other significant features of practical transformers are given below. Although the value of k has a major impact on the transformer characteristics, it has received little treatment in the literature, other than to explain why a value of 0.6 may often be beneficial.

Practical tightly-coupled designs

The winding geometries of tightly-coupled transformers are usually cylindrical, helical or less frequently flat spiral in form, with Figure 3(a) showing a typical cylindrical transformer wound on a cylindrical former. The single-layer solenoidal secondary winding is surrounded by a coarsely wound helical primary, with layers of high electrical strength plastic material or a fluid with similar properties providing the necessary inter-winding insulation. Coupling coefficients $k > 0.7$ can be achieved by using ferrite loading of the solenoidal core or even $k > 0.9$ by an experienced designer using a metallic core. In this case however, voltage grading and insulation strength problems sometimes then arise.





c

Figure 3. Tightly coupled transformers (a) cylindrical (b) helical (c) spiral

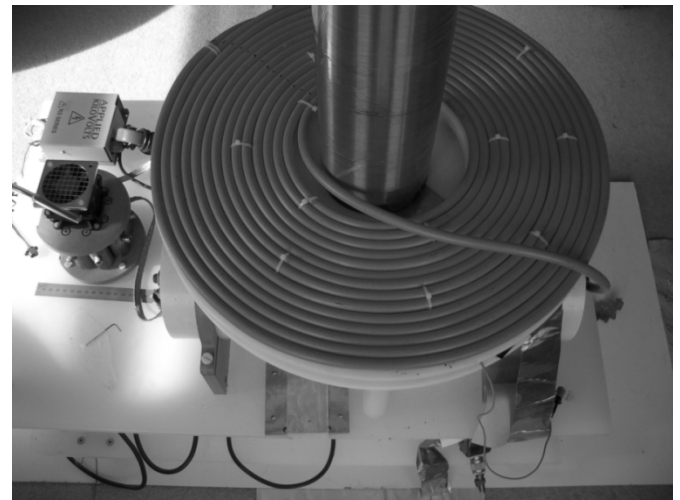


Figure 4. Typical loosely coupled design

In the typical helical design of Figure 3(b) (Sarkar *et al.*, 2006), the secondary winding is again a single-layer solenoid. However, the surrounding primary winding is of conical cross section, with the radius broadening towards the high-voltage end. Although easing the voltage gradient and insulation difficulties of the cylindrical design, this is at the expense of the maximum coupling coefficient that is achievable. In an alternative design (Abramyan, 1971), the primary winding has a few turns of copper sheet that couple into the lower end of the internal secondary. This again is in the form of a circular cross-section cone, with a base diameter similar to that of the primary winding and the final diameter some 10% of the starting diameter. The distributed capacitance of such a winding is lower than that of a conventional single-layer winding. In yet a further design (Buttram and Rohwein, 1979) a helical primary winding of several turns of copper strip is surrounded by a single-layer solenoidal winding having several hundred turns. In a common spiral design shown behind the seated figure of Tesla in Figure 3(c), the primary and secondary windings are both flat Archimedean spirals of copper strip or wire stacked on a common axis. Although a high coupling coefficient can be obtained without the use of a core material, high electrical stresses are present at the copper edges and the insulation coordination required to sustain the high secondary voltage provides a serious engineering challenge.

Practical loosely-coupled designs

The windings of loosely-coupled designs can again be helical, cylindrical or spiral in form, but with the proportions and geometries of the windings changed to enable the lower value of k to be achieved. However, in the very common form shown in Figure 4, the horizontal primary winding is constructed as a flat Archimedean spiral with the secondary winding solenoid standing vertically at the centre of the spiral. The base of the secondary winding may be in the plane of the primary winding, but it can be either raised or lowered from this position as a means of tuning the value of k . In practice, it is often positioned within the lower 25% of the secondary winding height. An alternative configuration is to use a helical primary of circular cross section, with the diameter tapering outwards and upwards, and the secondary again in the form of a single-layer solenoid. Although this minimises both voltage grading and insulation difficulties, and achieves higher values of k than the flat spiral approach, the mechanical construction is significantly more difficult.

Loosely-coupled transformers are often of an 'open' construction, using simple geometry and relying on unpressurised air insulation. This is in sharp contrast to tightly-coupled transformers, which frequently employ an 'enclosed' design, utilising metal pressure vessels within which both windings are housed in a fluid insulator such as transformer oil or a pressurised insulating gas atmosphere of H_2 , N_2 or SF_6 .

Important design features

- (i) The aspect ratio (length-to-diameter) of a typical secondary winding lies between 4 and 6, as a compromise between the quality factor (Q), conductor diameter for a given design inductance, self-capacitance and voltage grading. A short, large diameter coil with an aspect ratio of 0.5 may give the highest Q for a given inductance, but the high-voltage end of the winding may not be separated sufficiently far from the earthed end, and surface breakdown along the winding surface is a risk. If the aspect ratio is 0.4, the winding has minimum inductance (Grover, 2004), thus minimising the amount of copper required and the corresponding copper losses. However, the height is again prohibitively short and surface breakdown a hazard, although this can be overcome by immersion in an insulating fluid or pressurised gas. An alternative approach is to use a helical primary of circular cross section, with the diameter tapering outwards and upwards, and the secondary again a single-layer solenoid. The increased winding spacing minimises both voltage grading and insulation difficulties, but despite higher coupling coefficients being obtained than with the flat spiral approach the mechanical construction is significantly more difficult.
- (ii) If the design objective is for the Tesla transformer to produce at the output a spark of maximum length, a 'topload' in the form of a conducting toroid is connected to the high-voltage end of the secondary winding. In addition to controlling corona formation on the secondary winding, by controlling the electric field, the increased charge storage area allows rapid conversion of the accumulated charge into the spark as it forms. The transformer design clearly has to account for the effect of the toroid on the self-capacitance of the secondary winding, to ensure that the secondary resonance is still achieved at the desired frequency. The toroid is often made by spinning a metal sheet on a lathe and forming against a mandrel to shape the sheet into a half toroid. Two of these are precision welded together, with the welded seam ground flush and the combined unit, of "anchor ring" or "donut" form,

is polished to provide a very uniform surface as shown in Figure 5.

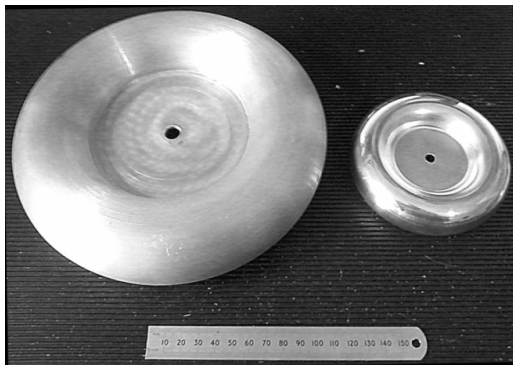


Figure 5. Examples of conducting toroid toploads

Primary switching

The type of primary switch, whether a spark gap, a solid-state device or a thermionic device is governed primarily by the degree of coupling that is sought and the peak and average powers to be switched, and ultimately decides the performance of the transformer. In tightly-coupled transformers ($k > 0.6$), the time for the energy transfer to occur is inevitably shorter than that of a loosely-coupled device and the power fed to the load is comparatively high. Effective design of the primary switch then governs the ultimate secondary voltage that is developed, since during the time that the secondary is free to deliver an output (ringing down) the primary is effectively an open circuit, as the primary switch ceases conduction immediately the primary current has fallen to zero and all the energy has been transferred to the secondary circuit. If this fails to happen, the out-of-phase currents that are generated in the secondary winding prevent the intended output voltage from being achieved. In extremely loosely-coupled transformers, ($k < 0.2$) the degree of damping that the secondary suffers due to the presence of the primary winding is extremely low. Nevertheless, since the effective Q of the secondary winding is likely to be higher than if the windings were tightly coupled, it is unlikely to suffer from this problem and may achieve a higher voltage. In summary, a tightly-coupled Tesla transformer produces a higher average power output, but at a lower ultimate voltage, whereas a loosely-coupled transformer provides a higher output voltage at the expense of a lower power transfer efficiency. The efficiency can however be restored by operating the transformer in the pulsed resonant mode, when the maximum energy transfer is achieved after a certain number of resonant half-cycles of the primary oscillations have been completed.

Solid-state switching

Solid-state Tesla transformers use semiconductor devices as the primary switch, configured as “half” or “full” H-bridge circuits formed from commercially available MOSFET or IGBT packages. Each of the devices needs to be able to withstand the full voltage applied to the bridge. Their performance approaches that of an ideal device, with an on-state resistance usually below a few hundreds of milliohms and an off-state resistance that is extremely high. Their ability to switch rapidly between the two states enables them to be used in tightly-coupled circuits, although a relatively high cost compared with that of a simple spark gap, the complexity of their associated electronics, the susceptibility to damage from

electromagnetic interference and their limited power handling and dV/dt limitations are less desirable features. Solid-state switching can be used “off-line”, with domestic electrical mains power providing the supply to the primary winding via an H-bridge converter, which is driven at the resonant frequency of the secondary circuit and capacitive tuning becomes unnecessary. It can also be run in a continuous-wave mode, when there is little difference between the peak power delivered to the primary winding and the r.m.s. power at the same point. The primary circuit is again untuned and, since the mode delivers a medium average power, the stresses experienced by the switch are relatively low. In pulsed operation, the supply to the primary winding during a proportion of the number of the supply cycles is significantly higher than that during the remainder of the cycles. Although a slightly lower average power is delivered the peak power is higher, and a higher peak voltage is delivered by the transformer.

Conclusion

The practical details presented in this paper constitute an essential addition to the many readily available theoretical analyses of the Tesla transformer, and provide an important background to anyone contemplating designing or using such a transformer for the first time. It is hoped that the paper will interest and benefit those concerned with the education of prospective engineers in this fascinating field of technology. Additional contributions regarding further refinements to the solid-state switch topology and control of the electric field are planned for a future paper.

Acknowledgement

The authors wish to thank Matthew Woodyard for his diligent work, in helping to prepare and format the figures and for checking the written work of this paper, which has contributed directly to the quality of the finished article.

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