

Magnetic Coupling in Tesla transformers

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Abstract

Although many publications dealing with Tesla transformers have appeared, most are confined to detailed investigations of the transformer performance based on a lumped equivalent circuit. The present paper differs widely from these in being concerned with the very practical and important issue of the degree of magnetic coupling between the two transformer windings and considers in detail the importance of the coupling factor for a range of applications of these transformers. The constructional features that may be adopted in various practical implementations are explained.

Keywords: Tesla transformers, high-voltage techniques, pulsed power supplies

1. Introduction

Tesla transformers are high-voltage doubly-resonant air-cored transformers frequently adopted in applications requiring a pulsed voltage exceeding 100 kV with an extremely short rise time. Although used initially for the high-voltage testing of domestic and industrial power insulation and switchgear, in recent years they have become a vital requirement in many research areas, particularly those involving particle and plasma physics, as well as high power systems that involve the generation of microwave and X-ray radiation. Despite the original experiments being performed by Nikola Tesla (Lomas, 2000) well over a hundred years ago, with the typical and very spectacular results evident in Figure 1, important new applications still continue to arise in technically active countries worldwide e.g (Peng, Liu, Song, & Su, 2011; Novac, Wang, Smith, & Senior, 2014; Su et al., 2016).

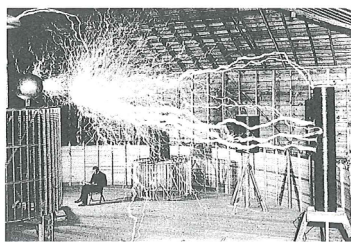


Figure 1. Example of Tesla's experiments at Colorado Springs, USA

Tesla transformers are produced in several different constructional forms and they can be classified in a number of ways depending on the sometimes competing output requirements of extremely high voltage or high average power. It is frequently asserted that the ideal primary/secondary winding coupling factor k is 0.6, despite many practical transformers being deliberately designed with values of k that are far from this figure. In a recent investigation at Loughborough University (Craven, 2014), the distinction was drawn between 'loosely coupled designs' (in which the value of k may be as low as 0.1 to 0.2) and 'tightly coupled designs' (where the value may in fact be around 0.6 or higher), and it is on this distinction that the considerations below are based. Little attempt has previously been made to explain the different constructional forms that a practical implementation of the Tesla transformer may take. Based on the authors' many combined years of experience in this area, the present paper seeks to provide an insight into these important aspects. It is hoped that the paper will be of interest both to those already working in the area and those concerned with the education of prospective engineers in this fascinating field.

2. Equivalent Circuit of the Tesla Transformer

The very familiar equivalent circuit for a Tesla transformer is shown in Figure 2. Typically the primary winding L_1 has few turns, designed to be able to conduct a pulsed current of several hundred amperes, and is coupled to the secondary winding L_2 which is normally a single-layer solenoid able to conduct a few amperes of current. The transformer secondary winding length normally exceeds the diameter, and the shape is generally cylindrical but occasionally conical. Detailed circuit analyses can readily be found elsewhere e.g. (Glasoe & Lebacqz, 1948; Sargeant & Dollinger, 1989).

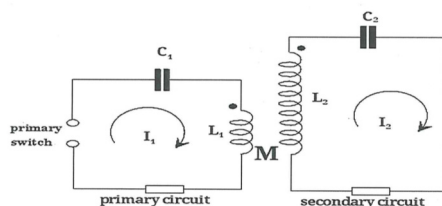


Figure 2. Lumped equivalent circuit for a Tesla transformer

If the primary circuit of Figure 2 is excited in isolation by closure of the primary switch, the current discharge I_1 from the high-voltage capacitor C_1 is at a resonant frequency of typically several hundred kilohertz, as determined by the primary circuit inductance L_1 . The secondary circuit inductance L_2 is tuned to the same frequency in isolation, generally by a distributed capacitor C_2 , comprising the self-capacitance of the secondary winding together with that of a high-voltage terminating electrode and the surroundings. The lower end of the secondary winding is often earthed and the top end feeds the load through a high-voltage terminal (sometimes termed a corona nut, a bung or a corona hat) and possibly a sharpening spark gap. In many typical systems a pulsed forming line (PFL) is fed and thus charged by the secondary winding current I_2 , with the additional capacitance introduced lowering the secondary resonant frequency to well below that associated with the self-capacitance of the secondary winding alone. On this basis, an overall lumped circuit model will frequently enable an adequately accurate prediction of the performance of the transformer to be obtained. In a more detailed and exact physical model, the circuit is described by a transmission line analysis, with the secondary winding capacitance and inductance both comprised of distributed values and taking both skin and proximity effects into account.

3. Coupling between Primary and Secondary Windings

When the objective is for the Tesla transformer to produce an extremely high fast-pulse output voltage the insulation needed, together with the current requirement and the sharpness of the pulse, often preclude the use of ferromagnetic materials, and it is difficult to achieve a high coupling coefficient k . Selection of the type of closing switch, whether a spark gap, a solid state 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 thereby ultimately determines the performance of the transformer, impinging particularly on the overall power efficiency and the total losses. Generally speaking, transformers in which k is low (say $0 < k < 0.3$) will have a low energy transfer efficiency, whilst when k is high, (say $0.6 < k < 1$), the efficiency is correspondingly higher. The time for the energy transfer to the load is inevitably shorter in a closely-coupled (high k) transformer and the power output is comparatively high. Effective design of the primary switch governs the ultimate secondary voltage that is delivered, since during the time the secondary is free to deliver an output, the primary is effectively an open circuit. If this fails to happen, out-of-phase currents are induced in the secondary winding, whose vector sum with the in-phase components results in lower amplitude current which leads to a reduction of the secondary voltage. Nevertheless, in extremely loosely-coupled transformers ($0 < k < 0.2$) (Scott, O'Loughlin, & Copeland, 1989; Skeldon, 2000) the degree of damping that the secondary winding experiences due to the presence of the primary winding is extremely low, and since the Q-factor of the secondary winding is likely to be greater than if the windings were tightly-coupled, a higher secondary output voltage may be achieved. In summary, a tightly-coupled Tesla transformer will achieve a high average power output but at a lower ultimate voltage, whereas a loosely-coupled transformer will provide 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 obtained only after a certain number of resonant half cycles have been completed.

3.1 Construction with Tightly-Coupled Windings

The winding geometries of tightly-coupled Tesla transformers often differ significantly from those of loosely-coupled transformers and usually take one of three forms: cylindrical, heliconical and (less often) flat spiral.

3.1.1 Cylindrical Design

This is the simplest form, with the secondary wound on a cylindrical former as a single-layer solenoid and surrounded by the primary winding as a coarse helix. Inter-winding insulation is provided either by layers of high dielectric strength material or by a fluid with similar properties such as transformer oil. Coupling coefficients $k \geq 0.7$ can be achieved when using ferrite loading of the solenoidal core or even $k \geq 0.9$ by either a very experienced designer or by the use of a metallic core, although voltage gradient and insulation strength issues then sometimes arise. Figure 3(a) illustrates the outline of a Tesla transformer (Martin, 1971) having this cylindrical format.

3.1.2 Heliconical Design

This form provides considerable scope for the ingenious designer. In the basic arrangement the secondary is again in the form of a single-layer solenoid, but the surrounding primary has a conical cross-section tapering upwards and outwards. Although easing the voltage gradient and insulation problems of the cylindrical design, the maximum coupling coefficient is inevitably reduced. In an alternative approach (Abramyan, 1971) the primary winding, constructed from copper sheet, couples into the lower end of the internal secondary, which has a base diameter slightly smaller than that of the primary winding and an apex diameter about 10% smaller than the base diameter. The distributed capacitance of such a winding is lower than that of a conventional single-layer winding. In a further alternative (Buttram & Rohwein, 1979) a heliconical primary winding is surrounded by a single-layer solenoidal winding with several hundred turns. An unusual feature of this design is that hydrogen thyratron switches running with a PRF of several hundred per second replaced the traditional spark gap in the primary circuit. With a k of approximately 0.6 and a resonant frequency of tens of kHz, the extremely high efficiency claimed was 95%. Another design (Sarkar et al., 2006) employs a conical secondary winding and is shown in Figure 3(b). To ensure both adequate insulation for the 0.5 MV secondary winding and optimisation of the coupling where $k = 0.54$, the secondary was wound on a conical polyethylene mandrel, immersed in transformer oil and contained in a cylindrical housing.

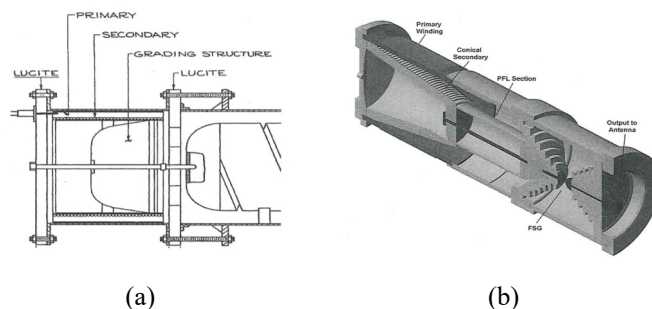


Figure 3. Tightly-coupled design (a) cylindrical (b) heliconical

Spiral design. In this design the primary and secondary windings are both constructed in the form of flat Archimedean spirals, with the primary and secondary stacked upon one another. Although high coupling coefficients can be obtained without the need for any core material, this is at the expense of high electrical stresses at the copper edges. In practice the insulation coordination that is required to hold off the high secondary voltage proves difficult to implement successfully.

In all tightly-coupled transformers, the primary switch may operate at several hundreds of Hz or more, and careful design is necessary to ensure that quenching of the primary current occurs at the instant at which complete energy transfer from the primary to the secondary winding has taken place. The time required for this is termed the filling time, and since this reduces as the coupling becomes tighter the need for quenching becomes ever more stringent. Several techniques to achieve this are available, based on two-terminal self-breakdown gaps, trigatron switches and field distortion and rail gaps. Other more complex techniques include air blast cooling, which minimises thermal electron emission and sweeps out uncombined electron pairs to increase the channel length and so force the conducting arc to extinguish and return the gas to the off state. Operation in a pressurised

gas medium (H_2 , N_2 or SF_6) may also either be used to increase the electron mobility so enabling rapid recombination, or to decrease mobility so that the conducting channel self-extinguishes rapidly.

3.2 Construction with Loosely-Coupled Windings

The windings of loosely-coupled transformers can take either a cylindrical or a spiral form, but with the proportions and geometries of the two windings changed to suit the value of coupling coefficient required. In the most typical geometry shown in Figure 4 the primary winding is in the form of a flat Archimedean spiral that begins with an inner radius r_1 and ends with an outer radius r_2 , and is orientated horizontally with the secondary winding standing vertically at the centre of the spiral. The base of the secondary winding can be in the same plane as the primary winding, or raised above or depressed below it as a method of tuning, and with the radius less than r_1 for this to be possible. In practice the plane of the primary winding is often positioned within the lower 25% of the secondary winding height.

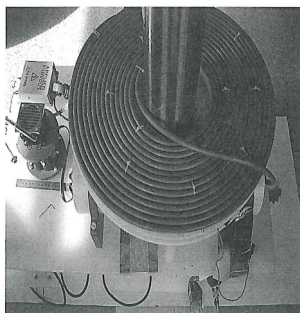


Figure 4. Typical loosely-coupled design

The aspect ratio (height/diameter) of the secondary winding lies typically between 4 and 6, as a compromise between the Q factor, wire 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 ratio is 0.4, the winding will have maximum inductance (Grover, 1947), thus minimising both the amount of copper wire required and the corresponding copper losses. The height is again prohibitively short and surface breakdown a hazard, although this can be overcome by the use of pressurised gas. An alternative configuration uses a heliconical primary coil similar to that of the tightly-coupled design, in which the circular diameter tapers both outwards and upwards. The secondary is again a single-layer solenoid. Voltage grading and insulation problems are reduced by the increased winding separation at the high-voltage end, but although higher coupling coefficients can be obtained mechanical design considerations make the construction more difficult. In practice the insulation requirement is often realised by housing both windings in a container filled with transformer oil or a gas such as SF_6 at high pressure. If the walls of the container are metallic, a high degree of shielding is provided for surrounding equipment (Hoffmann, 1975; Andreev et al., 1997). The values of the transformer parameters are also affected, with both the resonant frequency and the coupling factor being reduced.

In a design optimised for maximum spark length, a ‘topload’ in the form of a conducting toroid is connected to the high-voltage end of the secondary winding. This provides both an electric field grading structure that controls the field in the vicinity of the winding, and forms a charge storage area that allows conduction of the accumulated charges into the spark channel as it is forming. The transformer design has to take the ‘topload’ capacitance into account when implementing the secondary winding, such that the secondary resonance is at the desired frequency. Since the coupling coefficient may be as low as 0.2, or sometimes even 0.1, the degree of damping is lower and the secondary Q higher so that a greater voltage is achieved than if the coupling was tighter.

In practice, loosely-coupled transformers are often of an ‘open’ construction, using simple geometry and 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 pressurised insulating gas atmosphere.

4. Conclusions

The magnetic coupling between the windings of Tesla transformers varies considerably between zero and one, despite the frequent assertion that the ideal value is 0.6. The actual value selected depends on the requirements of the application and in turn has a very significant effect on the constructional form adopted in any practical implementation and the different reliability issues that are brought about. The details illustrated in the paper are thus an essential addition to the many readily available theoretical studies, and provide a valuable background awareness to both those already working in the area and to anyone in the early stages of designing or using a Tesla transformer for the first time.

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