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A proposed optimized equivalent circuit and performance analysis of dielectric barrier discharge ozone generator

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ABSTRACT

Traditionally, low-frequency power supplies are used in dielectric barrier discharge (DBD) ozone generators. These generators require a very high output voltage. This may limit ozone production due to limitations imposed by the dielectric strength of the insulating material. Low-frequency generators also present low efficiency, large volumes, and difficulty in controlling ozone production. On the other hand, the advantages of high frequency DBD ozone generators are the increased power density applied to the chamber electrodes, and the voltage applied to the ozone chamber decreases, allowing for higher ozone production efficiency. From this point of view, in order to enhance and control the DBD ozone generator operating at high frequency, it is necessary to determine all parameter values and optimize the equivalent model for this type of generator. This work presents and proposes the practical methodologies used to extract all parameters of the high voltage high frequency (HVHF) transformer which can be used in these systems. Resonant frequency control techniques are presented in this paper. Elimination of the stray capacitance effect will also be implemented in this paper.

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1. INTRODUCTION

The two main objectives of parameters determination of dielectric barrier discharge dielectric barrier discharge (DBD) ozone generator are to find exactly the resonance frequency and the voltage gain of the entire system [1]–[3]. The design of the DBD ozone generator power supply is basically depending on this frequency [4]–[9]. Establishing of DBD ozone generator equivalent circuit basically depends on a high voltage high frequency (HVHF) transformer and DBD ozone chamber parameters values. A high voltage multiplication stage is required to supply the DBD ozone chamber with the ionization voltage [10]–[13]. If the resonance frequency is higher than the stable frequency range of power electronic switching (metal-oxide-semiconductor field-effect transistors (MOSFETs) or insulated-gate bipolar transistors (IGBTs)), one of the DBD ozone generator stages which are used to determine the resonance frequency has to be designed again or connecting another external controllable variable is mandatory to adjust the resonance frequency. A high voltage multiplication or amplification stage, HVHF transformer or inductance-capacitance (LC) resonant circuit, plays an important role in calculating the transfer function of the entire system [14]–[17]. As a result, extracting the parameters of the DBD ozone chamber is not sufficient to determine ozone generator resonance frequency. Consequently, the determination of HVHF transformer parameters is necessary to establish and complete the DBD ozone generator model.

Extracting of DBD ozone chamber parameters can be estimated by using one of these methods; Lissajous plot, differential evolution (DE), and voltage_current waveforms. Lissajous plot methodology is valid in the frequency range [15-20 KHz] while differential evolution technique is suitable for a higher frequency range. Voltage_current waveforms method can be used at any frequency. Determination of DBD ozone reactor or chamber parameters isn't sufficient to design an ozone generator. It can be considered the first and the easiest step in the design. More accurate design, analysis, and simulation of the ozone generator in-depth have to extract parameters of both the multiplication and DBD ozone chamber stages. This paper indicates the analysis and determination of HVHF transformer parameters.

The general-purpose equivalent circuit of a high voltage (HV) transformer is shown in Figure 1. In this figure the parasitic capacitances had been neglected [18]. In the situation of operating the transformer at high frequency, the parasitic capacitances have a great effect on the transformer transfer function. Consequently, the general-purpose equivalent circuit is invalid. The parasitic capacitances can be generated from three different sources. One of them is the total capacitances between the insulating wires of the transformer primary side while the second one is a result of small capacitances between insulating wires of the transformer secondary side. The other one is due to the mutual inductance between the primary and secondary sides. For simplicity, all of these capacitances will be assumed as one stray capacitance Cs which will be shunted to the primary side. This assumption has been verified by comparing simulation results with practical ones. Figure 2 shows the HVHF transformer equivalent circuit [8], [19], [20]. The transfer function of the entire equivalent system will be formulated and calculated by using Sapwin 4.0 program while the simulation of the entire model has been executed by using Orcad_Allegro_Pspise simulator.

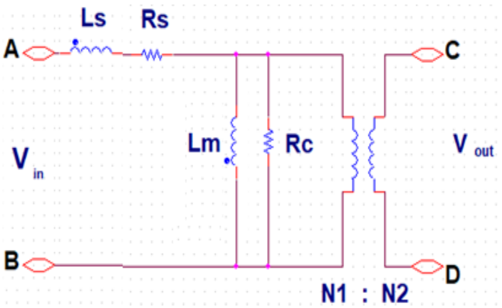

Figure 1. General purpose transformer equivalent circuit

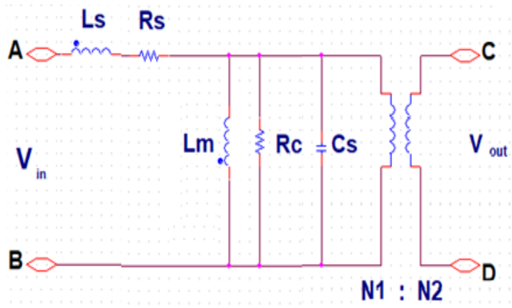

Figure 2. HVHF transformer equivalent circuit

This paper has been arranged as: section 2 discusses and analyzes the extracting of equivalent circuit parameters of HVHF transformer. Section 3 illustrates the effect of a series connection of an external capacitor with a DBD ozone generator on the system transfer function. Section 4 demonstrates the effect of a series connection of an external inductor with a DBD ozone generator on the system transfer function. Section 5 is the conclusion of the entire work.

2. HVHF TRANSFORMER EQUIVALENT CIRCUIT

To investigate all parameters of the HVHF transformer, short and open circuit tests have been selected [21]. All parasitic capacitances are expressed as one stray capacitance C_s. The leakage inductance L_s and the copper resistance R_s will be calculated from the short circuit test. In order to compute the other parameters; core resistance R_c, magnetizing inductance L_m, and stray capacitance C_s, the open circuit test has been executed twice. One of them is without any external electrical component and the other has been experimented with using an external inductor.

2.1. Short circuit test

A short circuit test means that the secondary side of the HVHF transformer will be shorted whilst the input voltage will be applied to the primary side. Figure 3 illustrates the waveform of the input voltage, current, and power dissipated on the primary side. Channel 1 (Ch1) is the applied voltage waveform of the primary side (V_{sc}) and channel 4 (Ch4) is the measured current waveform (I_{sc}) converted to a voltage by using a 3 Ω resistance in series with the primary side. Math waveform is the power dissipated in the primary side multiplied by 3. As a consequence, the copper resistance can be calculated as (1):

$$R_s = \frac{P_{av}}{I_{rms}^2} = \frac{142 * 10^{-3}}{(148*10^{-3})^2} = 6.48\ \Omega \quad (1)$$

The leakage inductance can be expressed as (2).

$$L_s = V_{sc}\frac{\Delta t}{\Delta I_{sc}} = 3.7\ \frac{57*10^{-6}}{0.25} = 843\ \mu H \quad (2)$$

2.2. Open circuit test

Leaving the secondary side of HVHF transformer open and applying voltage at the primary side is known as an open circuit test. Figure 4 demonstrates the voltage and current waveforms at the primary current resonance frequency (18.31 KHz). Channel 3 (Ch3) is the applied input voltage and Ch1 is the current waveform converted to voltage via 3 Ω resistance in series with the primary side. To drive and calculate values of magnetizing inductance, core resistance, and stray capacitance, another resonant frequency is required. This target can be achieved by connecting an external inductance Lex in series with the primary side as shown in Figure 5. Figure 6 illustrates voltage and current waveforms of HVHF transformer open circuit test with an external inductance 5.172 mH at resonance frequency f2=6.92 KHz. Ch1 is the primary voltage V_{oc} and Ch4 is the current waveform converted to voltage via 3 Ω resistance in series with the primary side. Math waveform is the power dissipated in the primary side *Pav_oc* multiplied by three. By neglecting the copper resistance Rs the core resistance can be expressed as (3):

$$R_c = \frac{{V_{oc}}^2}{P_{av\_oc}} = \frac{9.71^2}{138} = 681\ \Omega \quad (3)$$

The voltage gain of Figure 5 can be formulated as (4).

$$A = \frac{V_o}{V_{in}} = \frac{1}{1+\frac{L_{ex}+L_s}{L_m}+\frac{j\omega(L_{ex}+L_s)}{R_c}-\omega^2\, C_s(L_{ex}+L_s)} \quad (4)$$

The resonance frequency can be obtained by $\frac{d|A|}{d\omega} = 0$, thus:

$$\omega_1 = \sqrt{\frac{1}{C_s}\left(\frac{1}{L_s+L_{ex}}+\frac{1}{L_m}\right)-\frac{1}{2}\left(\frac{1}{R_cC_s}\right)^2} \quad (5)$$

The (5) is valid in the case of the external inductor while, in the case of without an external inductor the resonant frequency can be given by (6). The values of C_s and L_m will be obtained graphically by using the components values from Table 1 and substituting in (5 and 6) as shown in Figure 7. Eventually, all HVHF transformer parameters are postulated in Table 1.

$$\omega_2 = \sqrt{\frac{1}{C_s}\left(\frac{1}{L_s}+\frac{1}{L_m}\right)-\frac{1}{2}\left(\frac{1}{R_cC_s}\right)^2} \quad (6)$$

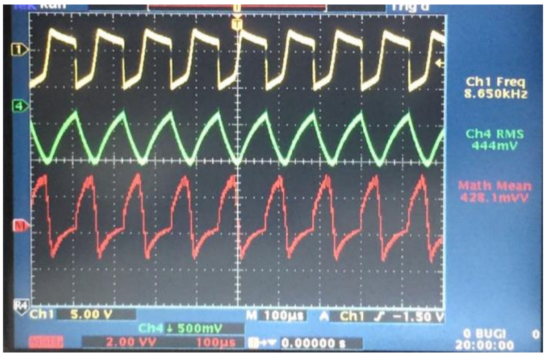

Figure 3. Voltage, current, and power dissipated waveforms of HVHF transformer in the case of short circuit test at frequency 8.65 KHz

Figure 4. Voltage, current, and power dissipated waveforms of HVHF transformer in the case of open circuit test at resonance frequency f1=18.31 KHz

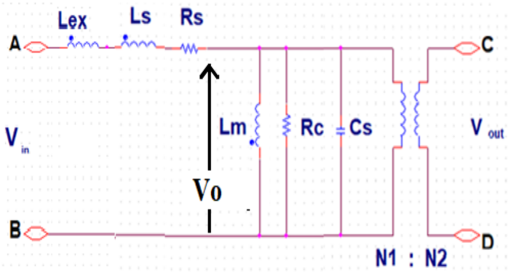

Figure 5. HVHF transformer open circuit test with an external inductance

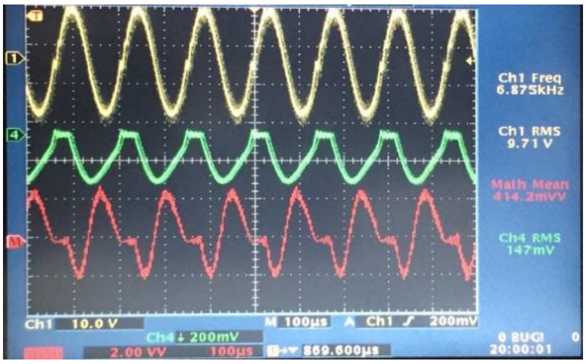

Figure 6. Voltage and current waveforms of HVHF transformer in the case of open circuit test with external inductance 5.172 mH at resonance frequency f2=6.92 KHz

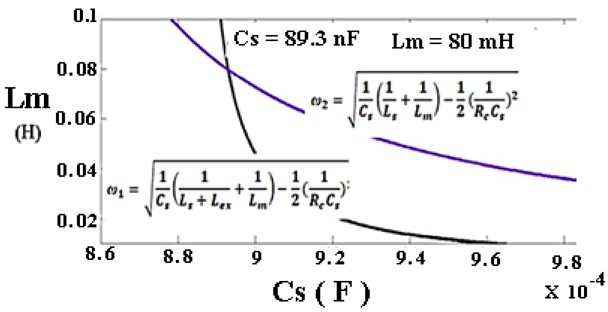

Figure 7. Determination of C_s and L_m values graphically

Table 1. HVHF transformer parameters and open circuit resonant frequencies test

Ls	Lex	Rc	Rs
843 µH	5.172 mH	681 Ω	6.48 Ω
Lm	Cs	ω_1	ω_2
80 mH	89.3 nF	43.2 K(rad/s)	114.98 K(rad/s)

3. EFFECT OF A SERIES CONNECTION OF AN EXTERNAL CAPACITOR WITH DBD OZONE GENERATOR ON SYSTEM TRANSFER FUNCTION

The stray capacitance plays an important role in the DBD ozone generator performance. Neglecting the stray capacitance leads to changing the resonance frequency of the transfer function. Figure 8 illustrates the schematic diagram of the used HVHF transformer which is connected in cascade with the ozone chamber [22]. The gap and dielectric capacitances of the chamber are denoted by *Cg* and *Cd* respectively, while the discharge resistance is represented by *R* [23]–[26]. Neglecting the stray capacitance leads to deviation in the resonance frequency of the entire system as shown in Figure 9. In this figure, the green curve represents the output voltage in the case of the stray capacitance while the red one demonstrates the output voltage without taking the stray capacitance into account.

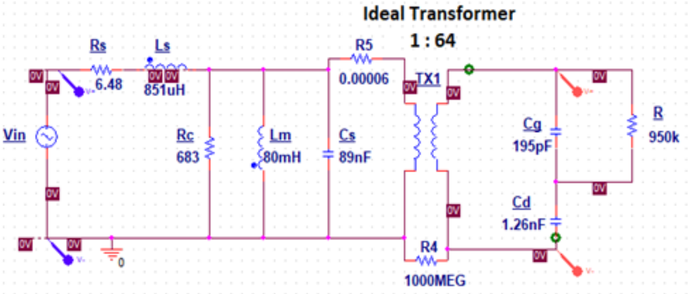

Figure 8. The entire equivalent circuit of DBD ozone generator of chamber construction I

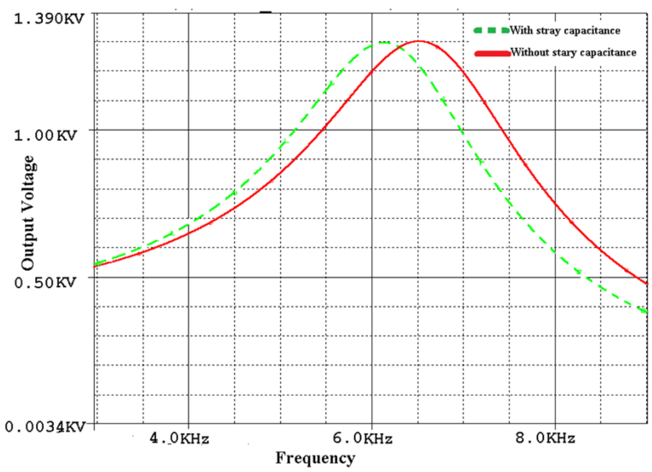

Figure 9. Frequency response of DBD ozone generator models

The effect of neglecting the stray capacitance clearly appears by increasing the operating resonance frequency of the DBD ozone generators. In order to operate the generator at a higher resonance frequency, another DBD chamber has been connected in cascade with the used HVHF transformer as shown in Figure 10. Figure 11 depicts the effect of neglecting the stray capacitance in the case of operating the generator at a higher resonance frequency. As shown in this figure, the red curve represents the output voltage in the case of the stray capacitance while the purple one demonstrates the output voltage without taking the stray capacitance into account.

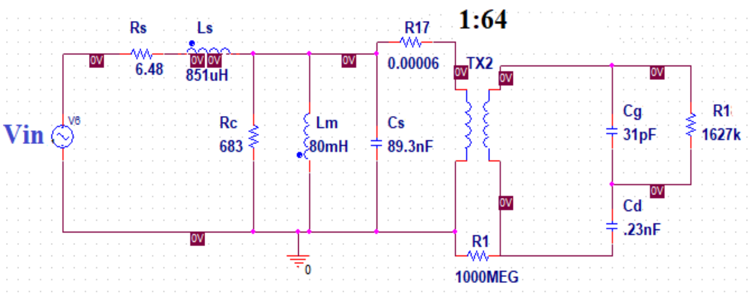

Figure 10. The entire equivalent circuit of DBD ozone generator of chamber construction II

Figure 12 shows the circuit diagram of the entire DBD ozone generator of Figure 8 which is connected in cascade with an external capacitor C. Figure 13 illustrates the effect of this capacitor on the output voltage of the DBD ozone generator. In this figure, the green curve shows the output voltage of Figure 8. As shown in Figure 13, the resonance frequency is inversely proportional to the external capacitor value. On the other hand, the output voltage amplitude is proportional to the external capacitor value. Increasing the DBD ozone generator transfer function resonance frequency can be implemented using a suitable capacitor value that achieves the desired resonance frequency. As is well known, the effect of the stray capacitance dramatically appears at higher operating frequencies. Fortunately, employing connecting an external capacitor technique eliminates the stray capacitance effect on the output voltage of the DBD ozone generator as shown in Figure 14. Consequently, in the case of connecting an external capacitor, the stray capacitance effect on the transfer function can be neglected.

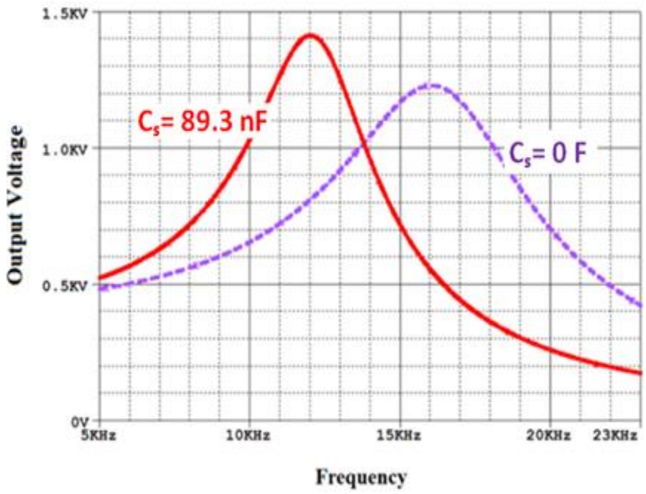

Figure 11. Frequency response of DBD ozone generator of chamber construction II

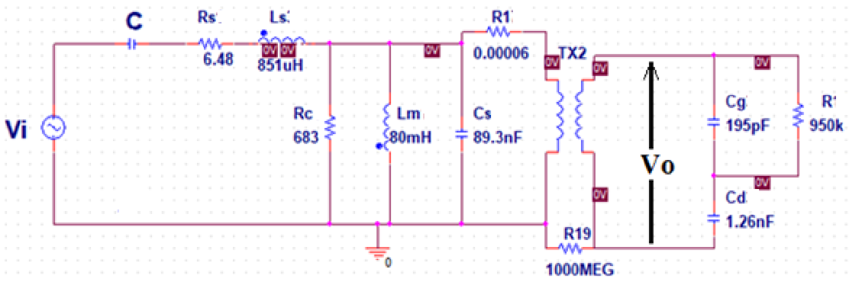

Figure 12. The equivalent circuit with connecting of an external capacitor C in series with DBD ozone generator

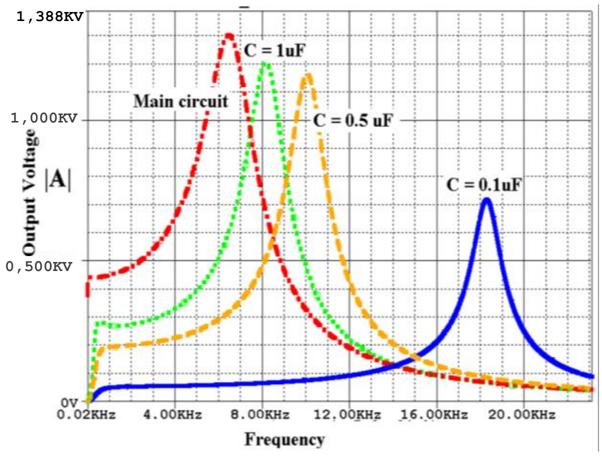

Figure 13. Effect of connection of an external capacitor on the output voltage of DBD ozone generator

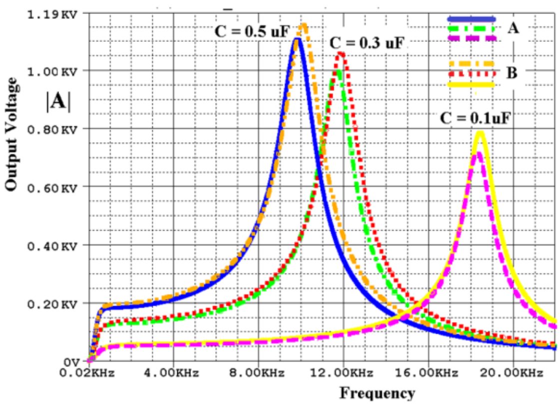

Figure 14. Elimination of stray capacitance effect on the output voltage of DBD ozone generator using an external capacitor (group A without neglecting stray capacitance while group B with neglecting stray capacitance)

4. EFFECT OF A SERIES CONNECTION OF AN EXTERNAL INDUCTOR WITH DBD OZONE GENERATOR ON SYSTEM TRANSFER FUNCTION

Figure 15 shows the circuit diagram of the DBD ozone generator which is connected in series with an external inductor L. Figure 16 illustrates the effect of this inductor on the output voltage of the DBD ozone generator. In this figure, the green curve shows the output voltage amplitude of Figure 8 without an inductor. As shown in Figure 16, the resonance frequency is inversely proportional to the external inductor value. On the other hand, the output voltage amplitude is also inversely proportional to the external inductor value. Decreasing the resonance frequency of DBD ozone generator can be implemented by using a suitable inductor value that achieves the desired resonance frequency. Employing connecting an external inductor technique will also eliminate the stray capacitance effect on the output voltage of the DBD ozone generator as shown in Figure 17.

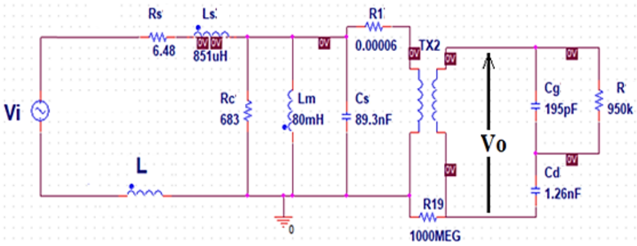

Figure 15. Connecting of an external inductor L in series with DBD ozone generator

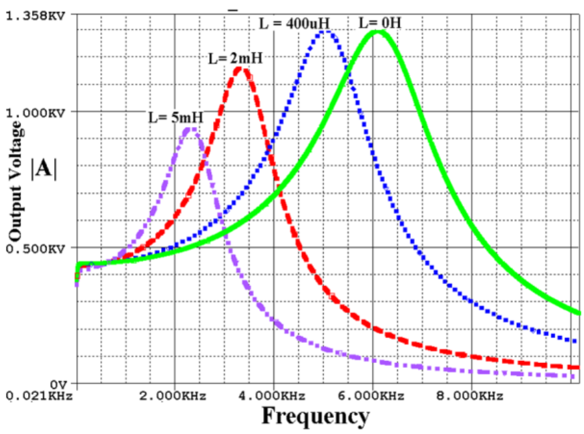

Figure 16. Effect of connection of an external inductor on the output voltage of DBD ozone generator

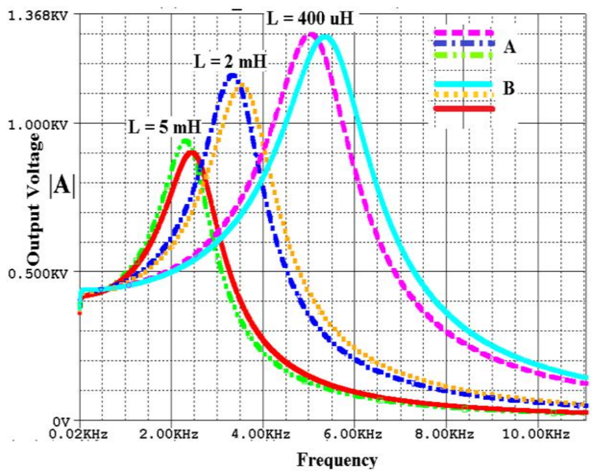

Figure 17. Elimination of stray capacitance effect on the output voltage of DBD ozone generator using an external inductor (group A without neglecting stray capacitance while group B with neglecting stray capacitance)

5. CONCLUSION

The determination methodology of HVHF transformer parameters is presented. The amplitude and resonance frequency of the system transfer function mainly depends on parasitic capacitance values. Controlling the resonance frequency of the transfer function can be implemented by either an external inductor or capacitor. In the case of connecting an external capacitor in series with the HVHF transformer primary side, the resonance frequency of the entire system will be increased. On the other hand, connecting an external inductor in series with the HVHF transformer primary side leads to decreasing the resonance frequency of the entire system. Elimination of parasitic capacitances effect can also be achieved by connecting an external inductor or capacitor in series with the HVHF transformer primary side.

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