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Efficient Simulation Method for Dielectric Barrier Discharge Load

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ABSTRACT

The dielectric barrier discharge is recognized as one of the efficient methods of ultraviolet light generation and ozone production. As well, it is widely utilized for gaseous wastes neutralization and other technological processes in industry. This electrochemical reaction is electrically equivalent to a nonlinear capacitive load that represents some difficulties for designing the power supply. Therefore, a conventional power supply is designed for a drastically simplified model of the load and generally is not optimal. This paper presents a fast simulation approach for the nonlinear capacitive model representation of the dielectric barrier discharge load lamp. The main idea of the proposed method is to use analytical solutions of the differential state equations for the load and find the unknown initial conditions for the steady state by an optimization method. The derived expressions for the analytical solutions are rather complicated, however they greatly reduce the calculation time, which make sense when a deeper analysis is performed. This paper introduces the proposed simulation method and gives some examples of its application such as estimation of the load equivalent parameters and load matching conditions.

Keywords: Dielectric barrier discharge, nonlinear capacitive model representation, optimization method, Dielectric barrier discharge applications

1. Introduction

The dielectric barrier discharge (DBD) is a type of electric discharge in gases, which occurs under alternating high voltage in a gas with low pressure. This process takes place in a physical structure as depicted in Fig.1. Usually, the discharge chamber consists of two tubes, one inside another, separated by a dielectric layer. When the voltage applied to the discharge tube exceeds a certain level, the energy of free electrons in the gas becomes enough to ionize gas molecules and numerous microdischarges are produced chaotically in the discharge gap between the electrodes. The dielectric layer placed between the electrodes prevents the formation of an electric arc and secures the conditions for dielectric barrier type discharge. During the discharge, chaotic electrical current streamers are initiated in the discharge gap and low temperature plasma is formed. Depending on the gas components, various electrochemical reactions such as generation of ozone, emission of ultraviolet light and so on are observed in the plasma in the discharge gap [1].

Some other technologies applied for gaseous wastes neutralization and metal surface treatment utilize the similar process and have the same electrical behavior and, therefore, can be considered here as well. These technologies are relatively new in industry and their further practical development is a fairly popular engineering task. Nevertheless, designing of an optimal power supply for a DBD load implies some difficulties due to the nonlinear characteristic of this load. Therefore,

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A drastically simplified and linearized model of the load is usually considered for the power supply design [2-3] and careful parameter adjustments are made experimentally. However, frequency-related specifics of the DBD load are almost omitted in the linearized model and this leads to the generally nonoptimal design and intensive testing of the prototype. In order to evaluate the behavior of the dielectric barrier discharge load carefully, a new simulation method has been developed for the nonlinear load model. By this method, current and voltage waveforms in the load can be calculated much faster than by any numerical solution approach for differential equations. Reduced calculation time makes possible fast simulation for different load parameters and makes sophisticated analysis easier. This paper introduces the proposed simulation method and gives some application

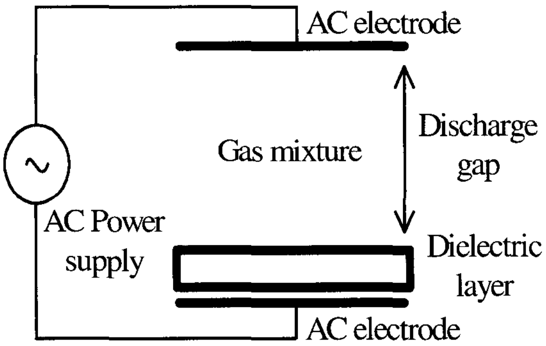

Fig.1 Schematic structure of the DBD load.

examples such as estimation of the load equivalent parameters and load matching conditions.

2. Electrical Circuit Model of Dielectric Barrier Discharge Load

At higher frequencies, low temperature plasma formed in the discharge gap is equivalent to series RC circuit, which is simple for analysis. Often the same model of the DBD load is used for lower frequencies, even if it results in some discrepancy with experiments.

At lower operating frequencies, the DBD load is represented electrically without inductance by an electric circuit model in Fig.2 [4]. Inductance Ls here represents a leakage inductance of a high-voltage transformer, which is usually introduced for driving the load. Sometimes, a compensating inductance is connected to the load that can be also considered in Ls. For Ca to be the equivalent of the capacitance of the discharge gap depends on gas components, pressure, dimensions of the discharge tube and so forth.

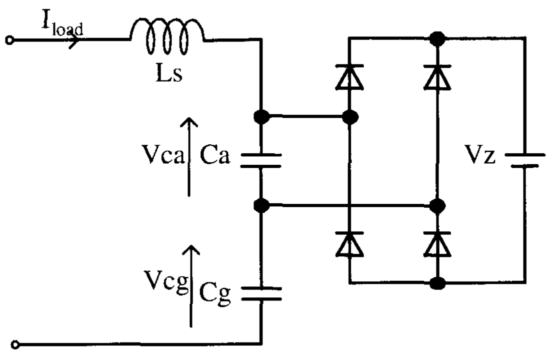

Fig.2 Electrical circuit model of DBD load

Cg is the capacitance of the dielectric layer and it depends on material properties and thickness of the layer. During the discharge time, a voltage drop on the discharge gap remains constant regardless to the changes of the applied voltage that is shown in Fig.2 as a DC voltage source, with voltage Vz defined as the discharge sustaining voltage. Since the same reaction occurs twice, and during the positive and negative half periods if a sinewave signal is applied, the voltage source is connected via a diode rectifier.

3. Simulation Approach for DBD load

The electric circuit shown in Fig.2 can be simulated using its differential state equations solved numerically. Various software packages for the simulation of electric circuits also imply numerical solving of the differential state equations for the nonlinear circuit. However, due to the transient process in the load, a solution for the steady state requires a long simulation time. This might not be a problem, when the waveforms for only one case are needed, but for the frequency response characteristic, calculation time increases tremendously. Also during investigation of the influences of the circuit parameters, the applied voltage and the other factors on the circuit behavior at this time become crucial. The calculation approach proposed here derives the solutions for the steady state directly, without the superfluous calculations of the transient process. It greatly reduces the simulation time and makes simple calculations for a range of parameters, and the other evaluations.

This approach is based on analytical solving of the circuit state equations and determining of the initial conditions by optimization methods. Explanations here are given for the matched load conditions as the simplest case. When the load matches the phase shift between the applied voltage and the current in the load is zero, then that simplifies the conditions for the criterion function. However, this is not the principal for the proposed algorithm. For general cases, the phase shift value can be considered in the equations. If the load in Fig.2 is matched, the phase shift between the input voltage and the current in the load is equal to zero, i.e. the input voltage and the current are crossing the time axis at the same instant. The sinewave e=Em·sin(ωt) with Em=1000V and f=355kHz is applied to the ultraviolet generation tube with parameters: Ca=449pF, Cg=859pF, Vz=970V, Ls=320μH, the voltage and current waveforms as shown in Fig.3-5 are observed. In the proposed method, these waveforms are derived from the analytical solution for the voltage and currents in the load, while the initial state conditions for the general solution formulas are found by using the optimization technique.

If the voltages across Cg at time t_1=0 and at time t_3=T/2, where T is a period of the input voltage, are the same with the opposing sign, the solution is considered as steady state (see Fig.4). In addition, if the current I_{load} at time $t_1$and t_3, is 0

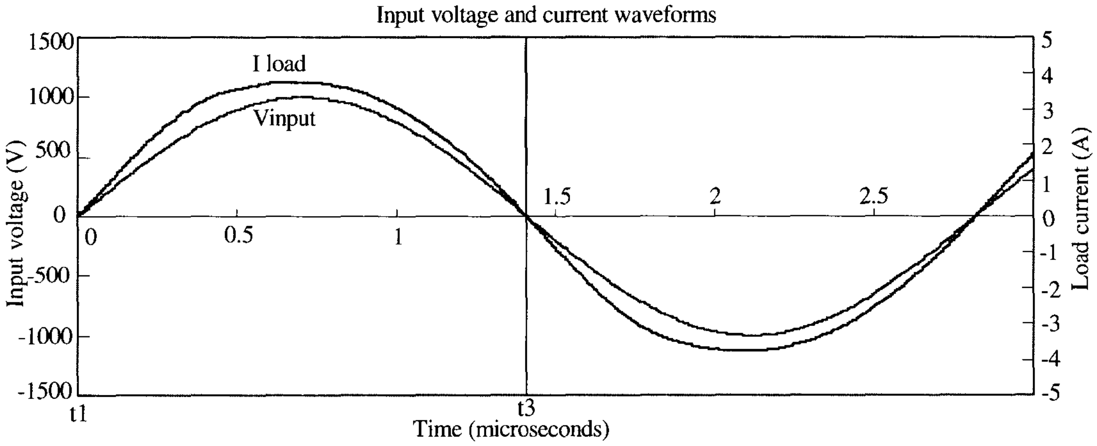

Fig.3 Input voltage and currents

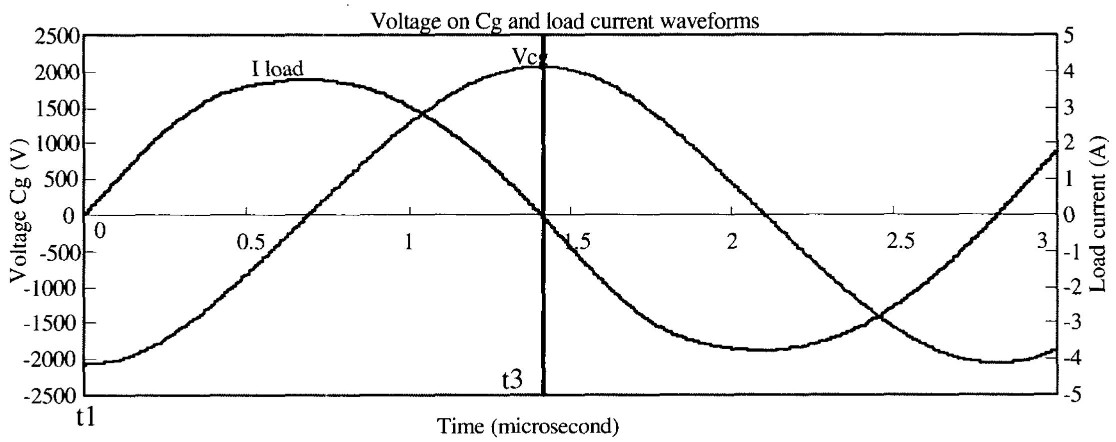

Fig.4 Voltage and current in the capacitor Cg

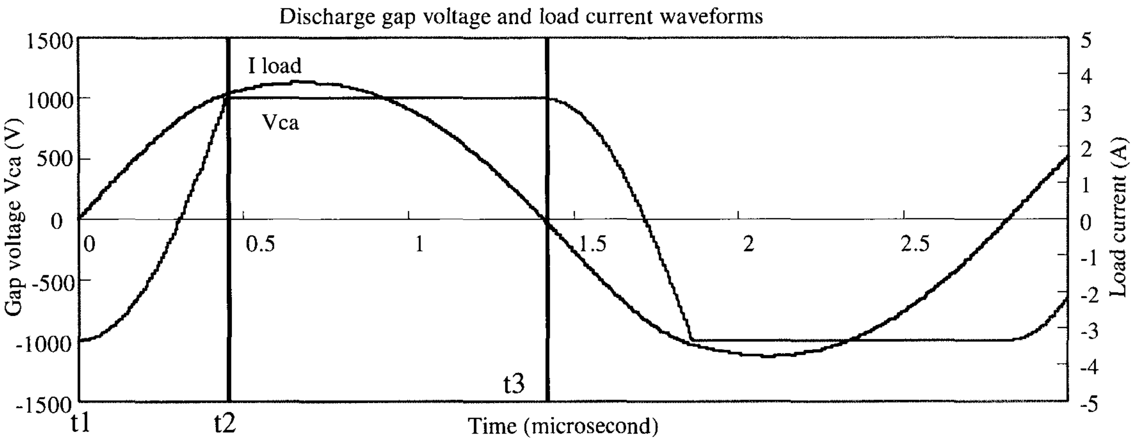

Fig.5 Voltage and current in the capacitor Ca

(see Fig.3), the load is considered as a match. The initial circuit conditions at time t_1 and the solution for steady state and matched load case are explained below.

The state differential equation set for the load can be simply composed considering the input voltage as e =Em·sin(ωt) and current I_{load} as equal to zero at t_1. This system can be resolved by common rules for the differential equations for the charge on the capacitive element and current through the inductive element as state variables. At that point, the waveforms in Fig.3-5 can be simply derived from the formulas for the charge and current.

For the period t_1-t_2 when discharge is not observed, the functions q_{12} for the charge on C_{ag}, and current in the load i_{12} can be derived from the differential state equations system for this circuit as:

$$q_{12} = e^{(-a_{12}t)}\{A_{12}\cos(\gamma_{12}t) + B_{12}\sin(\gamma_{12}t)\} - \frac{E_m\cos(\omega t + \theta_{12} - f_{12})}{\omega Z_{12}}$$

$$i_{12} = e^{(-a_{12}t)}\begin{Bmatrix}[-a_{12}A_{12} + B_{12}\gamma_{12}]\cos(\gamma_{12}t) \\ -[a_{12}B_{12} + A_{12}\gamma_{12}]\sin(\gamma_{12}t)\end{Bmatrix} + \frac{E_m\sin(\omega t + \theta_{12} - f_{12})}{Z_{12}} \quad (1)$$

where,

$$A_{12} = -(V_z + V_{cg0})C_{ag} + \frac{E_m\cos(\theta_{12} - f_{12})}{\omega Z_{12}},$$

$$B_{12} = \frac{a_{12}A_{12} - \frac{E_m\sin(\theta_{12} - f_{12})}{Z_{12}}}{\gamma_{12}},$$

$$\gamma_{12} = \frac{\sqrt{4\frac{L}{C_{ag}} - R^2}}{2L},$$

$$Z_{12} = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C_{ag}}\right)^2},$$

$$f_{12} = \tan^{-1}\left(\frac{L\omega - \frac{1}{\omega C_{ag}}}{R}\right),$$

$$a_{12} = \frac{R}{2L},$$

$\theta_{12} = 0$, initial phase shift

$$C_{ag} = \frac{C_a C_g}{C_a + C_g},$$

$\omega = 2\pi f$,

V_z: discharge sustaining voltage,

V_{cg0}: voltage on Cg at time t_1.

For the period t_2-t_3 when discharge is taking place, the functions q_{23} for the charge on Cg, and the current in the load i_{23} as:

$$q_{23} = e^{(-a_{12}t)}\{A_{23}\cos(\gamma_{12}t) + B_{23}\sin(\gamma_{12}t)\} - \frac{E_m\cos(\omega t + \theta_{23} - f_{12})}{\omega Z_{12}} - V_Z C_g$$

$$i_{23} = e^{(-a_{12}t)}\left\{\begin{matrix}[-a_{12}A_{23} + B_{23}\gamma_{12}]\cos(\gamma_{12}t) \\ -[a_{12}B_{23} + A_{23}\gamma_{12}]\sin(\gamma_{12}t)\end{matrix}\right\} + \frac{E_m\sin(\omega t + \theta_{23} - f_{12})}{Z_{12}} \quad (2)$$

Where:

$$A_{23} = V_z C_g + \frac{E_m\cos(\theta_{23} - f_{12})}{\omega Z_{12}} + q_{2initial},$$

$$B_{23} = \frac{a_{12}A_{23}\dfrac{-E_m\sin(\theta_{23} - f_{12})}{Z_{12}} + i_{2initial}}{\gamma_{12}},$$

When beginning the discharge time, t_2 is known, the initial charge $q_{2initial}$ across C_g and the initial phaseθ_{23} at t_2 are found from (1) as:

$$q_{2initial} = C_g\left(\frac{q_2}{C_{ag}} - V_z\right)$$
$$\theta_{23} = \omega t_2 \quad (3)$$

For an arbitrary set of the applied voltage, frequency and initial voltage across C_{cg}, the discharge might not take place. To verify the evidence of the discharge, it should be checked whether the voltage V_{ca} on C_a exceeds V_z or not on the interval t_1-t_3. V_{ca} is derived as a function of q_{12} and V_{cg0}:

$$V_{ca} = \frac{[q_{12} + (V_z + V_{cg0})C_{ag}] - V_z C_a}{C_a} \quad (4)$$

Where q_{12} is defined from function (1).
Hence, the maximum level of V_{ca} can be calculated by using any maximum-searching algorithm. If the maximum value of the V_{ca} exceeds V_z on the time interval t_1-t_3 then a discharge is taking place for the given parameters. Otherwise, other initial values must be chosen. The time t_2 when a discharge starts can be found from (4) by using any procedure of zero finding for the difference V_{ca}-V_z. Such procedures are usually embedded in software such as Matlab and t_2 can be easily determined.
When t_2 is found, the voltage V_{cg3} on C_g and current i_3=$i_{23}(t_3)$ in the load at time t_3 can be derived from (2). If i_3 is zero (see Fig.4) and voltage V_{cg3} is equal to V_{cg0} with the opposite sign (see Fig.4) the steady state conditions are observed and the load can be considered.

$$i_3 = 0$$
$$V_{cg3} = -V_{cg0} \quad (5)$$

These conditions can be determined by a criterion function F_c, defined below, which reaches zero, when the equations (5) are valid. Function F_c is defined here as:

$$F_c = A(i_3)^2 + (V_{cg3} + V_{cg0})^2 \quad (6)$$

Where, A is a coefficient for unit matching.

To find the Em, f and V_{cg0}, when F_c reaches zero, the following algorithm is used. At first, for some sets of constant Em and f, minimum of F_c can be found considering V_{cg0} as an independent value. This minimum can be found by using any optimization algorithm for nonlinear equations applied for (6). The value of V_{cg0}, which provides the minimum of F_c is defined as $V_{cg0steady}$:

$$V_{cg0steady} = V_{cg0}, \text{ at } F_C(F_C = F_{cmin}) \text{ is minimum} \quad (7)$$

Then minimum of F_c is derived as a function of $V_{cg0steady}$ as:

$$F_{cmin} = F_C V_{cg0steady} \quad (8)$$

Next, the applied frequency f is considered as a constant, applied voltage Em as a variable in (8) and the zero point of the function F_{cmin} is found. This procedure implies a subroutine for the finding of $V_{cg0steady}$ inside. Zero-finding algorithms are well known and included in Matlab and other software. The value of E_m, which provides F_{cmin}=0 is defined as:

$$E_{mopt} = E_m, \quad \text{at } F_{cmin} = 0 \tag{9}$$

As a result, the initial voltage across Cg and the amplitude of the applied voltage Em, which provides the solution for the steady state and the matched load can be found for the operating frequency f. The whole algorithm implies a zero point finding procedure executed in (9), which contains the minimum-searching operation implemented in (7). This complex algorithm can be calculated easily in Matlab using its embedded procedures for zero finding and minimum searching. This proposed algorithm is adapted for finding the steady state and matched load conditions. Therefore, the phase shift between the applied voltage and current in the load is considered zero. To apply this algorithm for the general problem of finding the voltage and current waveforms in the load for some operating frequency and amplitude of the applied voltage, several parts should be changed. Thus, initial current should be considered as well and the equality of the load current at t_1 and t_3 with the opposite sign should be considered as one of the indicators of the steady state solution.

4. Advantages of Proposed Method and DBD Load Analysis

The proposed simulation method derives the solution for the steady state by using the analytical formulas for the current and voltage waveforms in the load. The formerly unknown initial state conditions in the circuit are found by procedures of optimization in a few steps. Since this approach derives the solution directly, without the calculations of the transient process, the simulation time is greatly reduced. Compared to the numerical solution of the state equations, it has been found that the calculation time is reduced up to 20 times. This time saving is crucial for the calculations in a range of circuit parameters for a frequency band.

Using the proposed algorithm, the amplitude of the applied voltage necessary to provide load matching in the frequency range from 250kHz to 700kHz has been found for the ultraviolet light generation tube with parameters: Ls=320μH, Ca=449pF, Cg=859pF and Vz=970V. The relationship between the applied voltage and the frequency, providing a match in the load, is shown in Fig.6. The lower trace in Fig.6 shows the minimal voltage, at which discharge occurs. The equivalent electric circuit model of the DBD load has two specific frequencies, f_1 and f_2, which are the resonant frequencies determined by L_s-C_g and L_s-C_a-C_g series resonant circuits (see Fig.2). For the ultraviolet tube here, $f_1 \cong 303$kHz and $f_2 \cong 515$kHz. As was found here, the load cannot be matched outside the frequency band f_1-f_2.

Unlike an ordinary linear LCR circuit, at some frequency power factor in the DBD, load can be increased not only by adjusting the series compensating inductor value, but also by changing the applied voltage. This makes it possible to keep a high power factor by adjusting the applying voltage when the frequency is changed due to an output power control system. If the load is driven at a maximum power factor, the output power depends on an operating frequency as shown in Fig.7. This characteristic is based on the proposed calculation method, by integrating the waveforms of the voltage and current in the load for the range of the operating frequencies. If the power factor in the load is kept maximal, the output power rises drastically while approaching f_1. From a practical point of view, the output power of the ultraviolet generation tube is restricted by about 300W. Therefore, it can driven in matched conditions in a very narrow range from about 450kHz to f_2. For the design of the power supply, equivalent impedance of the load is also one of the important characteristics to consider. When DBD load is matched, the current is nearly sinusoidal and load impedance can be considered as only resistive. This resistance is calculated from the waveforms obtained previously and shown in Fig.8. Since the power factor is unity, equivalent capacitance of the DBD load is compensated by the inductance and changes as shown in the same figure. As seen from Fig.8 even in a narrow frequency range 450kHz-510kHz, the equivalent resistance of the load is changing from 0 to 250 Ohms and that makes effective driving of the load difficult. To provide stable load parameters and control output power effectively, the pulse density modulation (PDM) control method can be considered as the best for DBD load driving[5]. In PDM pulses with constant width, amplitude and frequency are applied to the load and changing the number of the applied pulses regulates the output power. Since the amplitude and frequency of the driving signal are constant, they can be adjusted so as to provide maximal power factor in the load.

By applying the proposed simulation method, all discussed evaluations can be done at a very short time. With a conventional simulation technique based on a numerical solution of the differential state equations for this circuit, such an analysis of the influence of the loads parameters on the frequency response could hardly be done in a reasonable time.

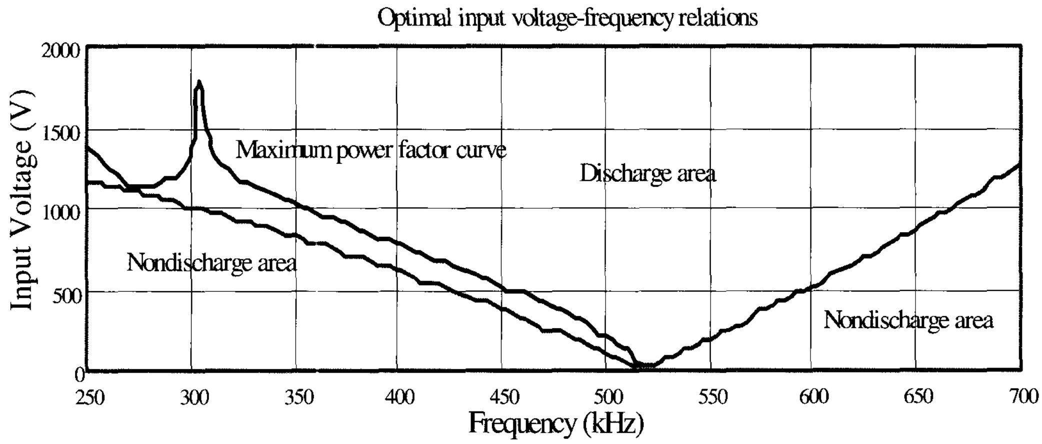

Fig.6 Area of discharge and optimal voltage-frequency graph

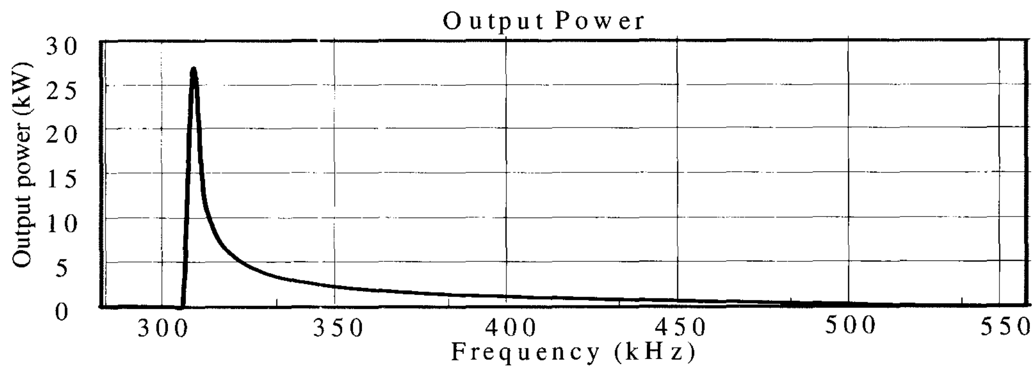

Fig.7 Frequency response for driving in load matched conditions.

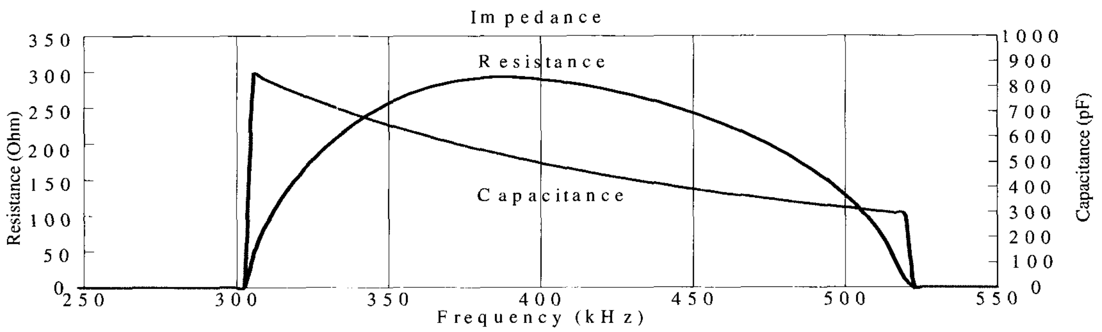

Fig.8 DBD load's equivalent impedance for driving in load matched conditions.

7. Conclusions

In this paper, a fast simulation method for DBD load has been proposed. Though this method implies rather complicated mathematical transformations for the algorithm, the calculations are many times faster than when using the numerical solution of circuit state differential equations. Due to the drastically reduced calculation time, the characteristics of the accurate electric circuit model of the DBD load can be evaluated easily. Based on this proposed method, the frequency dependence of various circuit characteristics, influence of the loads parameters and other analysis important for designing the power supply can be accomplished at a rapid pace. As an application example, optimal driving parameters for the ultraviolet generation tube have been derived and such load characteristics as consumed power and equivalent impedance have been calculated. These evaluations for an accurate model of the DBD load have been done for the first time and are very helpful for understanding the electrical behavior of this load.

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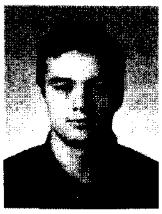

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