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I am submitting herewith a thesis written by Zhiyu Chen entitled “Impedance Matching and PSpice[®] Simulation of One Atmosphere Uniform Glow Discharge Plasma (OAUGDP[™]) Reactor/Actuator Systems”. I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

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**Impedance Matching and PSpice[®]
Simulation of One Atmosphere Uniform
Glow Discharge Plasma (OAUGDP[™])
Reactor/Actuator Systems**

A Thesis Presented for
The Master of Science
Degree
The University of Tennessee, Knoxville

Zhiyu Chen
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DEDICATION

I would like to dedicate this thesis to my parents, who were research nuclear engineers and devoted most of their professional life to the thermal plasma nuclear fusion research program of China. I would like to thank my parents for giving me the gifted talent in science and technology and their influences on me in those fields, and their unconditional support for my own decision on choosing my life path.

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ABSTRACT

This thesis addresses two important issues relevant to One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) reactors and actuators — impedance matching and PSpice® simulation.

An OAUGDP™ reactor/actuator with the plasma energized can be modeled as a capacitor in parallel with a resistor. In addition, the non-ideality of the transformer between the RF power supply and the plasma reactor/actuator introduces an imaginary component in its impedance. Thus, the load of the RF power supply, as seen by its output terminals, is highly reactive. An impedance mismatch resulting from the absence of a matching network will cause a large reflected power from the plasma reactor back to the power supply that does not contribute to plasma formation, but requires an expensive, over-rated power supply. All the impedance matching networks in the existing literature are for much higher RF or microwave plasma applications at low pressures, and they cannot readily be adapted to OAUGDP™ applications, which are normally operated at lower frequencies and higher voltages. In this thesis, the design, theory, and experimental performance of two types of low RF impedance matching circuits are presented, that match OAUGDP™ reactors/actuators to their power supplies.

This thesis also considers PSpice® simulation of the electrical characteristics of OAUGDP™ reactor/actuator systems. An OAUGDP™ reactor/actuator system normally includes a power supply, a transformer, an impedance matching network, and the plasma reactor/actuator. The principal task in simulation is to develop a comprehensive PSpice® model for the plasma discharge in an OAUGDP™ reactor/actuator. In an OAUGDP™, at least one electrode is covered with a dielectric, which can be modeled as a capacitor, as can the gap containing the plasma. The plasma discharge itself is modeled as a voltage-controlled current source that is switched on when the voltage across the gap exceeds the plasma initiation voltage. The output current follows a power law of the applied voltage,

an observed phenomenological characteristic of the voltage-current behavior of normal glow discharges. Simulation results agree qualitatively and quantitatively with experimental data from actual reactors/actuators. In addition to simulation of the plasma discharge in OAUGDP™ reactors/actuators, the modeling of the whole OAUGDP™ reactor/actuator system including a non-ideal transformer and impedance matching network can help engineers to improve the design of actual OAUGDP™ reactor/actuator systems.

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Chapter 1 Introduction

1.1 Motivation

The One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) investigated at the Plasma Sciences Laboratory of the University of Tennessee (UT) [1], [2] can be operated in a wide range of geometrical configurations, ranging from a slab plasma between parallel plates [1], to a surface layer of plasma on flat panels [3], all of which are capacitively-coupled. The OAUGDP™ is capable of operating at one atmosphere in air and other gases, and its active species can be used, among other things, to sterilize and decontaminate surfaces, or to modify surface characteristics. The OAUGDP™ generated by a plasma actuator is also capable of accelerating aerodynamic flows [4] and/or improving aerodynamic flow control [5], [6]. An OAUGDP™ reactor/actuator characteristically requires a power supply capable of delivering a few kilowatts at a frequency of 1 – 10 kilohertz, and an RMS voltage of up to 20 kilovolts. Fig. 1.1 shows a schematic of the MOD IV OAUGDP™ parallel plate reactor and Fig. 1.2 shows a photograph of it in operation. Fig. 1.3 shows a schematic of a symmetric plasma panel used to generate a flat layer of OAUGDP™ plasma. All were developed at the UT Plasma Sciences Laboratory [6] – [9].

An OAUGDP™ reactor/actuator is mainly a capacitive load seen by the power supply and the secondary side of the transformer. The OAUGDP™ reactor with plasma energized can be modeled as a capacitor in parallel with a resistor. The transformer converts the low voltage output of the power supply to a high voltage for plasma formation. The capacitive plasma reactor can reflect a large part of input power back to the power supply, and in this circumstance, only a small part of the power supply output power is delivered to the plasma, i.e. the plasma reactor is not impedance matched to the

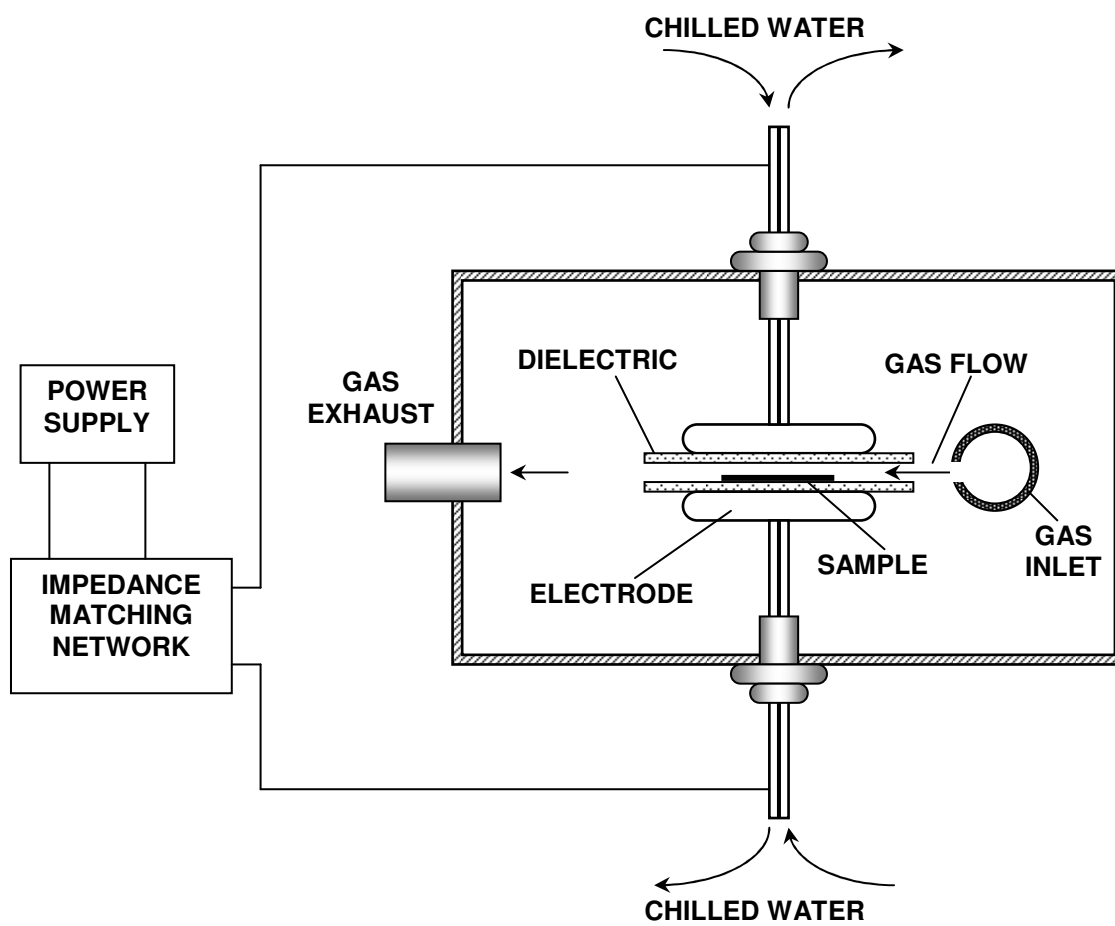


Figure 1.1. Schematic of the MOD IV OAUGDP™ parallel plate reactor system

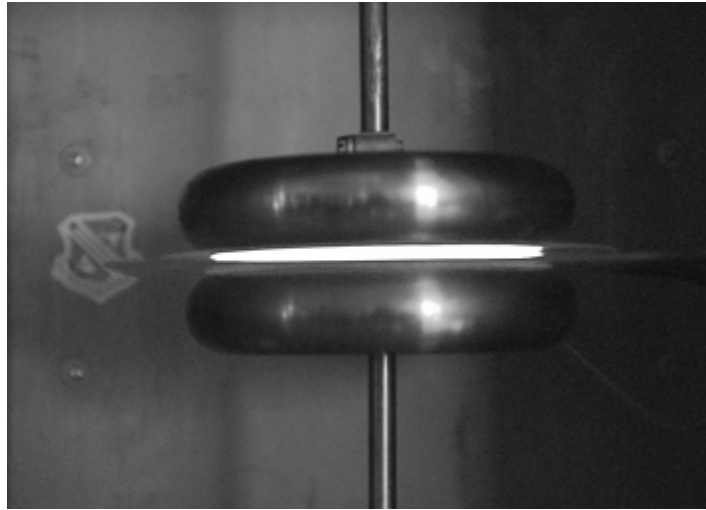


Figure 1.2. Photograph of the MOD IV OAUDGP™ parallel plate reactor in operation

power supply. The reflected power does not contribute to plasma formation, but requires an expensive over-rated power supply. In addition, the non-ideality of the transformer between the RF power supply and the plasma reactor also contributes an imaginary part to its impedance. Thus, the whole load for the power supply, seen by its output terminals, is highly reactive. The impedance of the load seen by the power supply should be optimized in order that the maximum power is delivered to the plasma. However, the equivalent impedance of the plasma is strongly dependent on the power dissipated in it. By changing the parameters of the matching network, the impedance match to the load can be optimized. For optimum performance, an impedance matching circuit must be inserted between the power supply and the plasma reactor in order to efficiently generate a high power OAUDGP™.

The characteristics of many electrical systems can be simulated with proprietary computational tools such as PSpice®. Devices employing plasmas are embedded in electrical systems and in many situations, it is advantageous to simulate the complete system, including the plasma, with such commercial software. The One Atmosphere

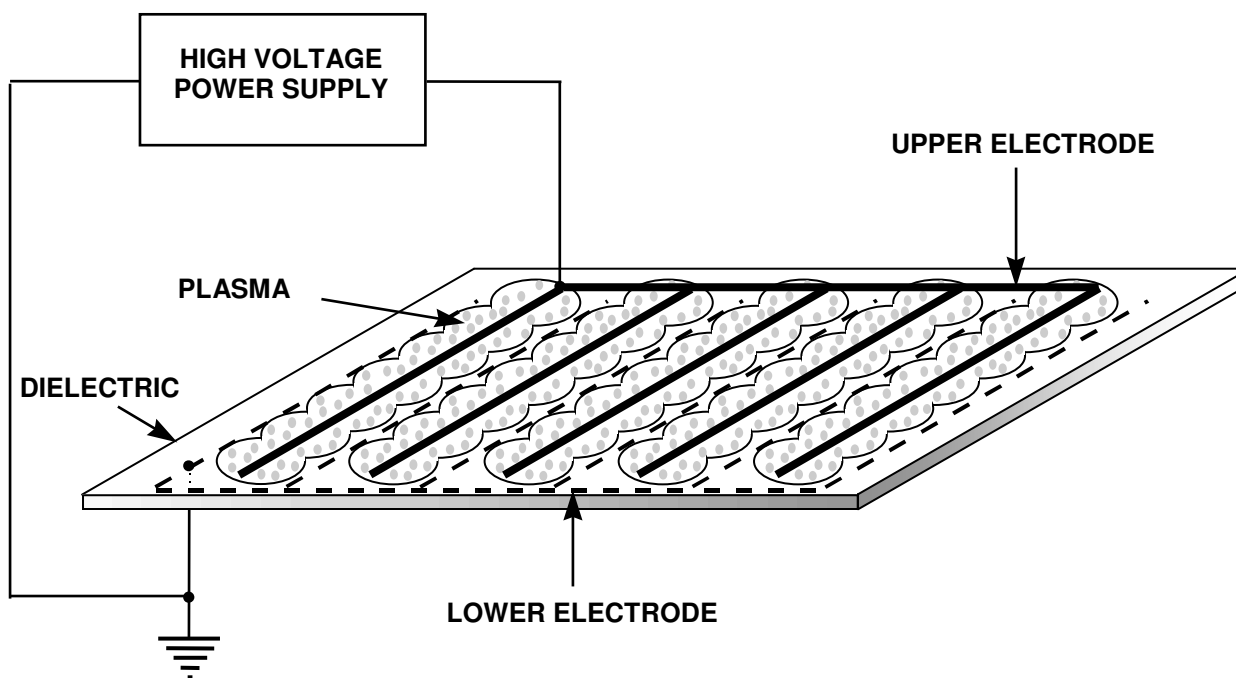


Figure 1.3. Schematic of a symmetric plasma panel to generate a flat layer of OAUGDP™ plasma

Uniform Glow Discharge Plasma (OAUGDP™) [1], [2] reactor/actuator system consists of a power supply, a transformer, an impedance matching network, and the plasma reactor/actuator. This system is a candidate for simulation with such computational tools. Simulation of the plasma discharge in OAUGDP™ reactors/actuators, and modeling of the whole OAUGDP™ reactor/actuator system, including the non-ideal transformer and impedance matching network, can help engineers to improve the design of actual OAUGDP™ reactor/actuator systems.

1.2 Contributions

In this thesis work, two types of impedance matching circuits have been developed to match OAUGDP™ reactors/actuators to their power supplies. The two types of matching circuits are referred to as a secondary-side impedance matching circuit, and a primary-side impedance matching circuit, respectively, according to the matching network's location relative to the transformer. The two impedance matching circuits are designed to satisfy the unique operation requirements of OAUGDP™ systems — low RF frequency, high voltage, and high current.

Besides impedance matching, in this thesis work, specific circuit models of One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) parallel-plate reactor and co-planar actuator systems have been formulated. In addition, simulations of the electrical characteristics of these OAUGDP™ reactor systems have been obtained with the proprietary circuit simulation software, PSpice®. Simulation results agree qualitatively and quantitatively with the experimental data.

1.3 Organization of Text

Chapter 2 is a literature review of impedance matching and computational circuitry simulation of plasmas. Chapter 3 covers the design, theory, and experimental results of two impedance matching circuits for OAUGDP™ reactor/actuator systems. Chapter 4 covers PSpice® models of OAUGDP™ reactor/actuator, simulation results, and comparison with actual discharge current data. Chapter 5 summarizes this thesis work and contributions.

Chapter 2 Literature Review

2.1 Impedance Matching

Impedance matching is a well-studied subject in the fields of RF and microwave applications, and there are numerous books specifically devoted to this subject [10] – [12]. There are also numerous articles pertaining to the issue of matching a plasma reactor to a power supply in the literature [13] – [17]. The classical Π -type, T -type and L -type matching networks [11], [13], [15] – [17] should not be applied to the OAUGDP™ system, since their circuit leg in series with the OAUGDP™ reactor will share a significant part of the output voltage of the transformer, and the generation of the OAUGDP™ needs a higher voltage (4 kV rms – 20 kV rms) than low-pressure glow discharge plasmas. Therefore, if a Π -type, T -type or L -type matching network is used, the available maximum voltage across the OAUGDP™ reactor will be significantly decreased and a more expensive transformer capable of generating higher voltages is necessary in order to generate a high power OAUGDP™.

To the knowledge of the author, however, the impedance matching techniques and matching networks in the existing literature are for megahertz or microwave plasma applications at low pressures. They cannot readily be adapted to applications of the OAUGDP™, which is operated at much lower frequencies (from 1 kHz to 10 kHz), and much higher voltages (from 4 kV rms to 20 kV rms). Therefore, new impedance matching techniques are needed for OAUGDP™ applications. The characteristics of OAUGD plasmas can be found in [2].

2.2 Computational Simulation of Plasma Reactors

Previous work regarding the computational simulation of plasma reactors has been published [18] – [23]. In these papers, simulation of low-pressure plasmas in gaseous discharge lamps, pulsed, RF and/or inductively coupled electrical discharges were investigated.

In Wu, et al.'s [18] and Ben-Yaakov, et al.'s [20] papers, they developed two similar comprehensive SPICE models for low-pressure gaseous discharges in fluorescent lamps. The model is basically a voltage-controlled current source. In Shvartsas and Ben-Yaakov's paper [21], they used a behavioral dependent current source to model the high density discharge in gaseous discharge lamps. In Hopwood's paper [23], an inductively-coupled plasma is modeled as a single current loop with an inductance and a resistance.

Other papers provide plasma circuit models capable of incorporation into circuit simulations, although simulation was not reported [24] – [26].

In Ben Gadri's paper [27], the physical processes in such a plasma were simulated by one-dimensional numerical methods. However, his simulation was not a complete OAUGDP™ reactor/actuator system, and simulation of such a system has not been reported by other researchers. In an OAUGDP™ system, the inductor and capacitors in the impedance matching network [28], the power supply, and the transformer are ordinary electrical components and have well-developed PSpice® models. However, there is no available electrical model in PSpice® for the plasma discharge in an OAUGDP™ reactor/actuator, so a principal task in developing such a simulation is to develop such a model.

Chapter 3 Impedance Matching of OAUGDP™ Reactor/Actuator Systems

3.1 Introduction

An OAUGDP™ reactor/actuator is mainly a capacitive load seen by the power supply and the secondary side of the transformer. The OAUGDP™ reactor with plasma energized can be modeled as a capacitor in parallel with a resistor. The transformer converts the low voltage output of the power supply to a high voltage for plasma formation. The capacitive plasma reactor can reflect a large part of input power back to the power supply, and in this circumstance, only a small part of the power supply output power is delivered to the plasma, i.e. the plasma reactor is not matched to the power supply. The reflected power does not contribute to plasma formation, but requires an expensive over-rated power supply. In addition, the non-ideality of the transformer between the RF power supply and the plasma reactor also contributes an imaginary part to its impedance. Thus, the whole load for the power supply, as seen by its output terminals, is highly reactive. The impedance of the load seen by the power supply should be optimized in order that the maximum power is delivered to the plasma. However, the equivalent impedance of the plasma is strongly dependent on the power dissipated in it. By changing the parameters of the matching network, the impedance match to the load can be optimized. For optimum performance, an impedance matching circuit must be inserted between the power supply and the plasma reactor in order to generate a high power OAUGDP™ efficiently.

This chapter presents two types of impedance matching circuits that match OAUGDP™ reactors to their power supplies. The two types of matching circuits are designated the secondary-side impedance matching circuit and the primary-side impedance matching circuit, respectively, according to the matching network's location

relative to the transformer. The two impedance matching circuits are designed for OAUGDP™ systems, and can satisfy the unique operation requirements of OAUGDP™ systems — low RF frequency, high voltage and high current.

3.2 Secondary-Side Impedance Matching Circuit

3.2.1 Definition of Impedance Matching

Impedance matching is the connection of additional impedance to an existing circuit in order to accomplish a specific effect, such as to balance a circuit or to reduce reflection in a transmission line [29]. Impedance matching is required in order to optimize the power delivered to the load from the source. It is accomplished by inserting matching networks into a circuit between the source and the load.

At the UT Plasma Sciences Laboratory, the task of impedance matching is to add a circuit composed of passive electrical parts (inductors, capacitors and/or resistors) between the RF power supply (or its output transformer) and the reactive load in such a way as to make the impedance of the whole load resistive, as seen by the output terminals of the power supply or its output transformer. By eliminating the reactive power, one can increase the power factor of the whole load to nearly unity. By adjusting the impedance of the whole load to a proper resistive value, the maximum power can be delivered from the power supply to the load.

3.2.2 Electrical Circuit Model of OAUGDP™ Reactor with Plasma Initiated

An OAUGDP™ reactor/actuator — both the parallel plate reactor and the plasma panel — is essentially a capacitor. When the plasma is energized, a resistive component responsible for the power dissipation in the plasma is added to the basic capacitor.

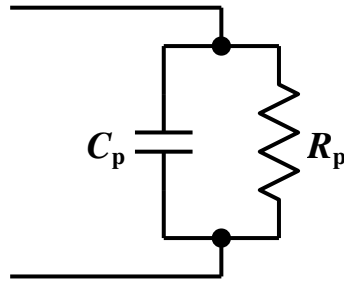


Figure 3.1. Electrical Model of OAUGDP™ Reactor with Plasma Initiated

Therefore, the OAUGDP™ reactor with plasma initiated can be represented by a capacitor in parallel with a resistor, as shown in Fig. 3.1, in which R_p is the equivalent resistance of the plasma, and C_p is the capacitance of the plasma reactor. Although this simple and crude model does not describe the physics of the OAUGD plasma, it is sufficient to serve the task of making possible an impedance match to the capacitive impedance of the plasma reactor. Some more complicated plasma circuit models presented in the literature [24] – [26], [30] can actually be transformed into the form of the simple circuit in Fig. 3.1 by circuit analysis techniques. Therefore, for the task of impedance matching, the simple plasma model in Fig. 3.1 not only makes the job easier, but also is no different from the more complicated models from the point of view of circuit analysis; although the more sophisticated models may represent the real plasma more accurately.

3.2.3 Basic Impedance Matching Theory

The classical II -type, T -type and L -type matching networks [11], [13], [15] – [17] should not be applied to the OAUGDP™ system, since their circuit leg in series with the OAUGDP™ reactor will share a significant part of the output voltage of the transformer, and the generation of the OAUGDP™ needs a higher voltage (4 kV rms – 20 kV rms) than low-pressure glow discharge plasmas. Therefore, if a II -type, T -type or L -type

matching network is used, the available maximum voltage across the OAUGDP™ reactor will be significantly decreased and a more expensive transformer capable of generating higher voltages is necessary in order to generate an OAUGDP™. Thus, all the circuit legs of an OAUGDP™ impedance matching network should be in parallel to the OAUGDP™ reactor.

The schematic electrical system of an OAUGDP™ reactor is shown in Fig. 3.2. The secondary-side impedance matching network is the circuitry within the dashed-line. It is so-called because it is connected to the secondary side of the transformer.

The matching network is composed of an inductor and a capacitor in parallel. R_L is the resistance of the inductor winding. The matching network is in parallel with the plasma reactor and close to the transformer output, so the stray capacitance of the long cables between the transformer and the plasma reactor can be included in the reactor capacitance and matched by the matching network. Seen by the transformer output terminals, the impedance of the whole load — the matching network plus the plasma reactor — is

$$Z = (R_L + j\omega L) // \frac{1}{j\omega(C + C_p)} // R_p \quad (3.1)$$

$$= \frac{R_L + j\omega[\delta L - R_L^2(C + C_p)]}{\delta^2 + \omega^2 R_L^2(C + C_p)^2} // R_p$$

where $\delta = 1 - \omega^2 L(C + C_p)$. The symbol “//” indicates that the two electrical components are in parallel to each other.

From Eq. (3.1), the impedance characteristic of the whole load is determined by the sign of the function [Chen, 2002]

$$f(\omega) = \delta L - R_L^2(C + C_p) = L - \omega^2 L^2(C + C_p) - R_L^2(C + C_p) \quad (3.2)$$

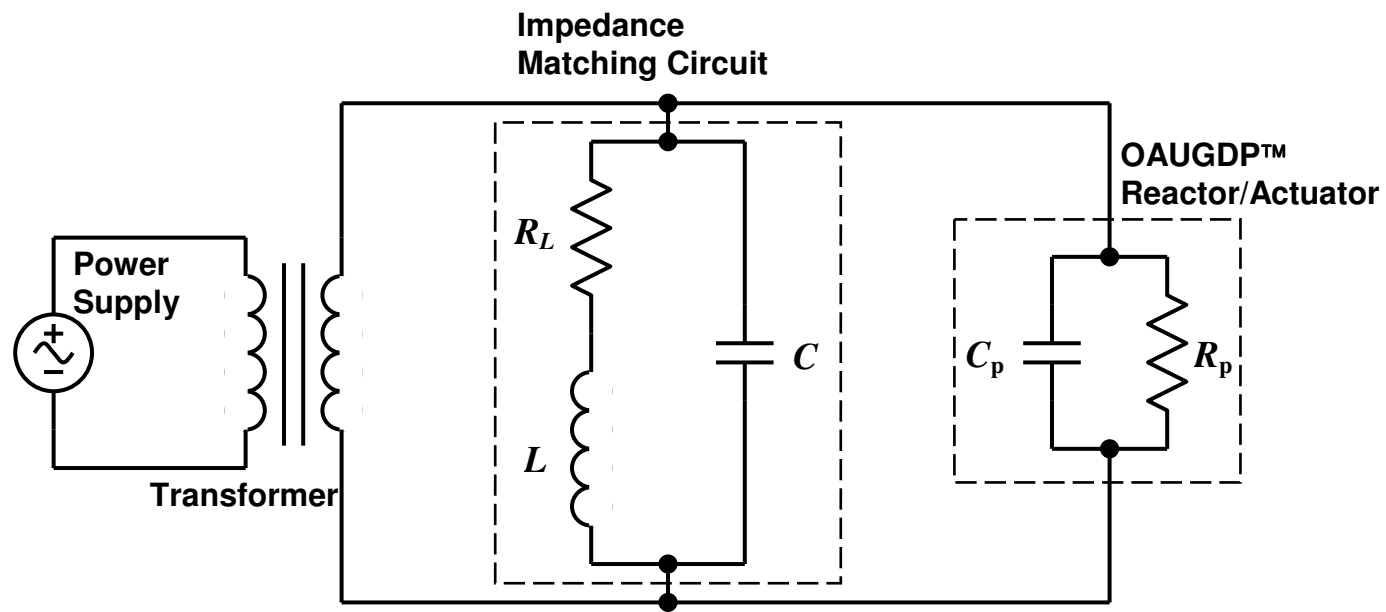


Figure 3.2. An OAUGDP™ system with secondary-side impedance matching circuit

By adjusting the operating frequency ω , the sign of $f(\omega)$ can be changed. For $f(\omega) < 0$, the whole load is capacitive; for $f(\omega) > 0$, the whole load is inductive; for $f(\omega) = 0$, the whole load is purely resistive, and impedance matching is achieved. The matching frequency ω_r can be derived from $f(\omega) = 0$,

$$\omega_r = \sqrt{\frac{1}{L(C + C_p)} - \frac{R_L^2}{L^2}} \quad (3.3)$$

If the transformer is ideal, i.e., the imaginary part of its impedance is small, and it transmits almost all input power from the primary side to the secondary side, then the above matching theory is sufficient. The plasma reactor is matched when the system is operated at the matching frequency ω_r . However, the high primary/secondary turns ratio (characteristically 20:1) and range of operating frequency encountered in OAUGDP™ applications make it difficult to avoid non-ideal transformer characteristics. If the transformer is not ideal, i.e., it has a large reactive component in its impedance, the transformer will reflect a large fraction of the input power back to the power supply, instead of transmitting it to the secondary side. Therefore, the system is still not impedance-matched as seen by the power supply, although the plasma reactor is matched as seen by the transformer output when operated at the matching frequency ω_r .

The ultimate impedance matching should be the match seen by the power supply, since it is the source of the power. In a well-matched electrical system, the power reflected back to the power supply should be an absolute minimum. A better impedance matching theory should consider the load seen by the power supply output terminals instead of the transformer output terminals. Therefore, consideration of a non-ideal transformer is worthwhile. In the next section, a more refined impedance matching theory is investigated.

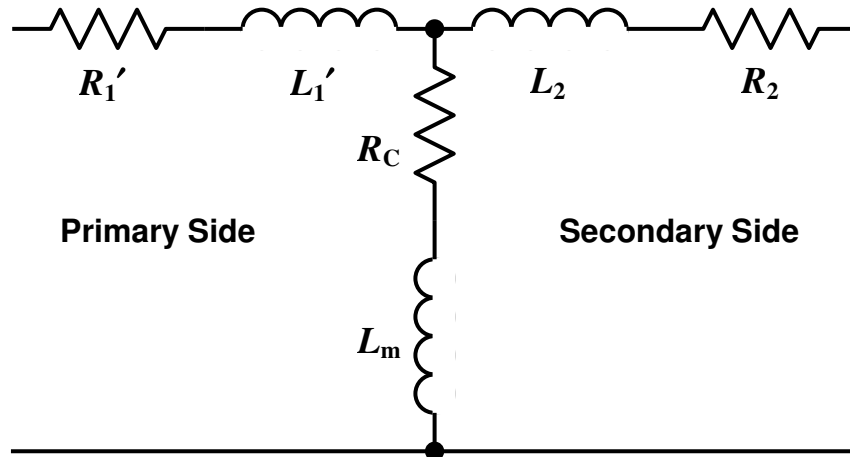


Figure 3.3. Equivalent Circuit of a Non-ideal Transformer

3.2.4 Refined Impedance Matching Theory

a) Equivalent Circuit of a Non-ideal Transformer

The equivalent circuit of a non-ideal transformer referred to the secondary side is shown in Fig. 3.3. R_1' is the resistance of the primary winding referred to the secondary side, L_1' is the leakage inductance of the primary winding referred to the secondary side, R_2 is the resistance of the secondary winding, L_2 is the leakage inductance of the secondary winding, L_m is the magnetizing inductance of the transformer, and R_C is the equivalent resistance of the core losses.

The impedance of the magnetizing inductance L_m is much greater than that of the other components in the OAUGDP™ system. Therefore, the branch containing L_m is neglected in the following circuit analysis to simplify the task. Fig. 3.4 shows the schematic of the electrical system of the OAUGDP™ reactor with the non-ideal transformer replaced by its simplified equivalent circuit.

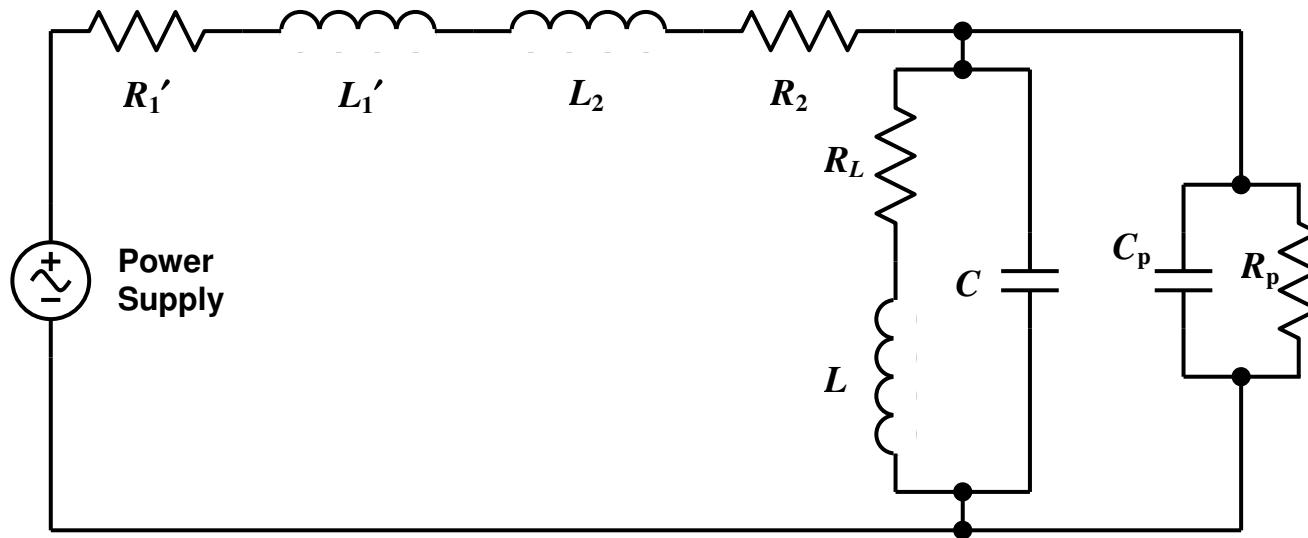


Figure 3.4. Equivalent circuit of the OAUGDPTTM system with secondary-side impedance matching circuit

b) *Circuit Analysis*

As seen by the power supply output, the impedance of the whole load including the transformer, the matching network, and the plasma reactor is

$$\begin{aligned}
 Z &= R_1' + j\omega L_1' + j\omega L_2 + R_2 + (R_L + j\omega L) // \frac{1}{j\omega(C + C_p)} // R_p \\
 &= (R_1' + R_2) + j\omega(L_1' + L_2) + \frac{R_L + j\omega[\delta L - R_L^2(C + C_p)]}{\delta^2 + \omega^2 R_L^2(C + C_p)^2} // R_p \\
 Z &= (R_1' + R_2) + j\omega(L_1' + L_2) + \\
 &\quad \frac{R_L R_p \{R_L + R_p [\delta^2 + \omega^2 R_L^2(C + C_p)^2]\} + R_p \omega^2 [\delta L - R_L^2(C + C_p)]^2}{\{R_L + R_p [\delta^2 + \omega^2 R_L^2(C + C_p)^2]\}^2 + \omega^2 [\delta L - R_L^2(C + C_p)]^2} + \\
 &\quad \frac{j\omega [\delta L - R_L^2(C + C_p)] [\delta^2 + \omega^2 R_L^2(C + C_p)^2] R_p^2}{\{R_L + R_p [\delta^2 + \omega^2 R_L^2(C + C_p)^2]\}^2 + \omega^2 [\delta L - R_L^2(C + C_p)]^2}
 \end{aligned} \tag{3.4}$$

where $\delta = 1 - \omega^2 L(C + C_p)$. The impedance characteristic of the fourth term in the above expression is still determined by the sign of the function $f(\omega)$ defined in Eq. (3.2),

$$f(\omega) = \delta L - R_L^2(C + C_p) = L - \omega^2 L^2(C + C_p) - R_L^2(C + C_p) \tag{3.2}$$

By adjusting the operating frequency ω and making $f(\omega) = 0$, the impedance of the combination of the matching network and the plasma reactor can be made purely resistive. However, the impedance of the whole load seen by the power supply still has a reactive component — the second term in Eq. (3.4), which is caused by the leakage inductance of the transformer. If the transformer is not ideal, this reactive component can be fairly large and can reflect a large fraction of power back to the

power supply. In this situation, impedance matching is not achieved at the resonant frequency ω_r defined by Eq. (3.3).

However, an adequate impedance match can still be achieved with the non-ideal transformer and the same matching network. By adjusting the operating frequency ω and making $f(\omega) < 0$, the impedance of the combination of the matching network and the plasma reactor has a capacitive component, which can partly cancel the effect of the transformer leakage inductance. At the condition described by Eq. (3.5) below, the effect of the leakage inductance is cancelled, and impedance matching will be achieved:

$$\frac{[\delta L - R_L^2(C + C_p)] [\delta^2 + \omega^2 R_L^2(C + C_p)^2] R_p^2}{\{R_L + R_p [\delta^2 + \omega^2 R_L^2(C + C_p)^2]\}^2 + \omega^2 [\delta L - R_L^2(C + C_p)]^2} + (L_1' + L_2) = 0 \quad (3.5)$$

The realization of the above condition is not difficult to achieve experimentally, although its expression is very complex.

We next derive the matching frequency ω_r' for a simple case — plasma is off. When plasma is off, $R_p = \infty$. Thus Eq.(3.5) can be simplified as

$$\frac{\delta L - R_L^2(C + C_p)}{\delta^2 + \omega^2 R_L^2(C + C_p)^2} + (L_1' + L_2) = 0 \quad (3.6)$$

Moreover, since normally $\delta L \gg R_L^2(C + C_p)$ and $\delta^2 \gg \omega^2 R_L^2(C + C_p)^2$ for the experimental parameters used in the OAUGDP™, Eq. (3.6) can be further simplified to

$$L/\delta + (L_1' + L_2) = 0 \quad (3.7)$$

It is now possible to derive the matching frequency ω_r' from Eq. (3.7) with the help of $\delta = 1 - \omega^2 L(C + C_p)$,

$$\omega_r' = \sqrt{\frac{1}{C + C_p} \cdot \left(\frac{1}{L} + \frac{1}{L_1' + L_2} \right)}. \quad (3.8)$$

3.3 Requirement on the Magnitude of the Matching Network Impedance

Making the whole load impedance resistive is not sufficient to transmit maximum power to the plasma. Since the leakage inductance of the transformer is in series with the combination of the matching network and the plasma reactor/actuator, they form a voltage divider. For a non-ideal transformer, the value of $L_1' + L_2$ is quite large. If the impedance of the combination of the matching network and the plasma reactor/actuator is not high enough, then the leakage inductance will share a larger part of the total output voltage, and there will be insufficient voltage across the plasma load to generate a dense plasma. In the worst case, the voltage may not be high enough to break down the gas.

We now examine Eq. (3.4) again to find a way to increase the combinatorial impedance of the matching network and the plasma reactor/actuator. It can be seen that the real part of the combinatorial impedance, the third term in Eq. (3.4), needs to be increased. Let us still consider the simple case — the plasma is off, or the equivalent plasma resistance is so large that it can be taken as infinity. Therefore, the third term in Eq.(3.4) can be simplified to

$$Z_{real} \approx \frac{R_L}{\delta^2 + \omega^2 R_L^2 (C + C_p)^2} \quad (3.9)$$

Eq.(3.9) indicates that the load capacitance $C + C_p$ must be decreased in order to increase the load impedance Z_{real} , if the operating frequency ω is kept the same. When the plasma is on, and especially when it's dense, its equivalent resistance R_p is quite small

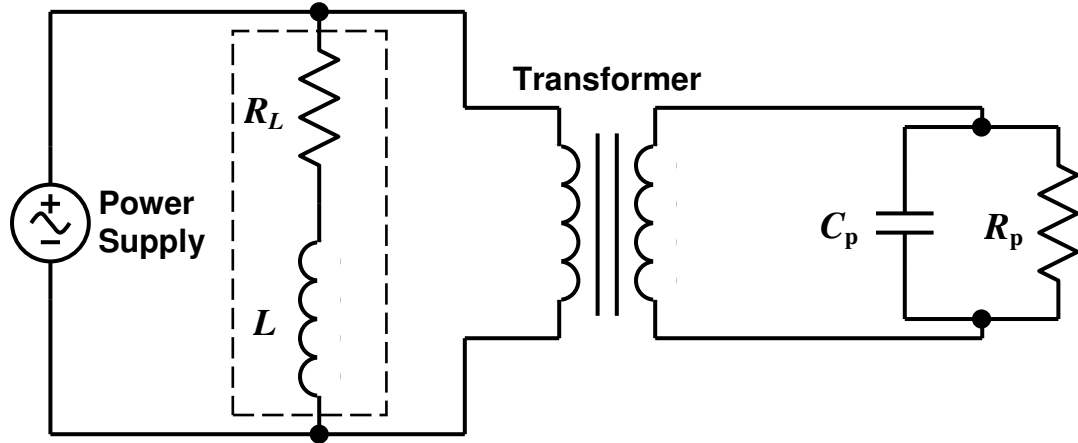


Figure 3.5. An OAUGDP™ system with primary-side impedance matching circuit

(on the order of $10\text{ k}\Omega$), and the capacitance of the plasma reactor, C_p , is approximately constant. As a result, the only way to make Z_{real} as large as possible is to increase the impedance of the matching network at the matching frequency, Z_r' . This makes it necessary to decrease C and increase L in the matching network. Z_r' can be calculated by Eq. (3.10), and is given by

$$Z_r' = \frac{R_L}{\delta^2 + \omega^2 R_L^2 C^2} = \frac{R_L}{[1 - \omega^2 L(C + C_p)]^2 + \omega^2 R_L^2 C^2}. \quad (3.10)$$

3.4 Primary-Side Impedance Matching Circuit

The performance of the secondary-side impedance matching circuit is satisfactory; however, it has a couple of drawbacks. Since they are connected to the secondary side of the transformer, the inductor coil and the capacitor bank in the secondary-side impedance matching circuit must be designed to be capable of handling high voltage (at least 10 kV).

In addition, the inductance required in the secondary-side impedance matching circuit is generally quite large (~ 100 mH), and the inductor winding must be capable of handling large currents (~ 10 A) because of the large resonant current in the impedance matching tank circuit. Therefore, the consequent inductor coil is bulky, heavy, and expensive; and the consequent high voltage, large current capacitor bank is also expensive.

In order to avoid the drawbacks of the secondary-side impedance matching circuit, another type of impedance matching circuit was also developed, called the primary-side impedance matching circuit, shown in Fig. 3.5 within the dashed-line frame. It consists of an inductor connected in parallel with the primary side of the transformer. L is the inductance of the coil and R_L is the resistance of its winding.

Fig. 3.6 shows the equivalent circuit of Fig. 3.5. R_1 , L_{l1} , L_{l2}' , R_2' , L_m' , r_c are parameters of the equivalent circuit of the transformer. R_1 is the resistance of the primary winding, and L_{l1} is its leakage inductance. R_2' is the resistance of the secondary winding (R_2) referred to the primary winding, and $R_2' = R_2 / N^2$, where N is the turns ratio of the transformer. L_{l2}' is the leakage inductance of the secondary winding (L_{l2}) referred to the primary winding, and $L_{l2}' = L_{l2} / N^2$. L_m' is the magnetizing inductance of the transformer (L_m) referred to the primary winding, and $L_m' = L_m / N^2$. r_c is the equivalent resistance of the transformer core loss. C_p' is the capacitance of the plasma reactor (C_p) referred to the primary winding, and $C_p' = N^2 C_p$. R_p' is the equivalent resistance of the plasma (R_p) referred to the primary winding, and $R_p' = R_p / N^2$.

In order to simplify the circuit analysis, we assume that the transformer is ideal and can be ignored in the circuitry, and we obtain the simplified circuit shown in Fig. 3.7. It is easy to recognize that Fig. 3.7 is similar to Fig. 3.2, so the same circuit analysis procedures were performed and the matching frequency for the primary-side impedance matching circuit is found to be

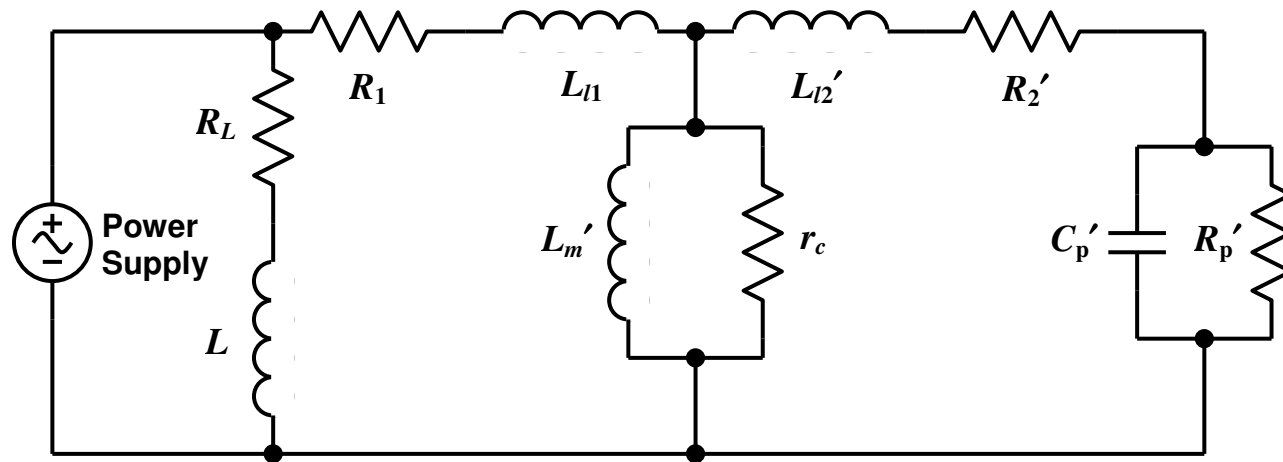


Figure 3.6. Equivalent circuit of an OAUGDP™ system with primary-side impedance matching circuit

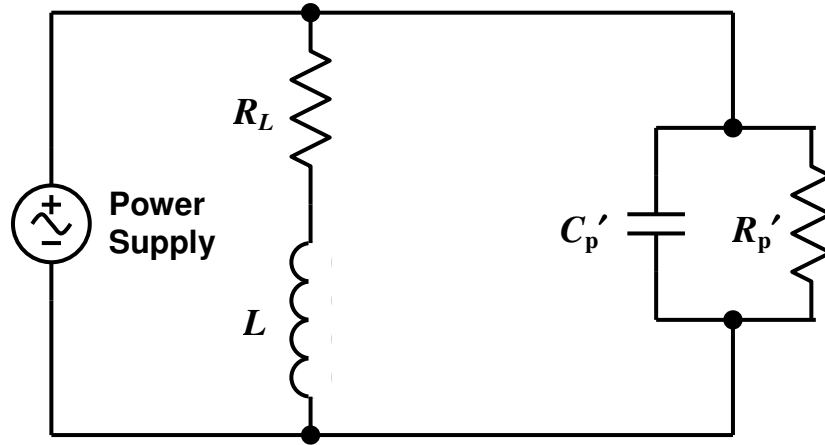


Figure 3.7. Simplified equivalent circuit of OAUGDP™ system with primary-side impedance matching circuit

$$\omega_r = \sqrt{\frac{1}{LC_p'} - \frac{R_L^2}{L^2}} \quad (3.11)$$

This result is similar to Eq. (3.3), but the capacitance in Eq. (3.11) is the *equivalent* capacitance of the plasma reactor, which is much larger (N^2) than the actual capacitance. Therefore, the matching inductance L in the primary-side matching circuit is much smaller than that in the secondary-side matching circuit for the same matching frequency.

Primary-side impedance matching has several advantages over secondary-side matching. The primary-side matching circuit is connected to the primary side of the transformer, so the matching circuit components do not need to handle high voltage. The inductor coil for primary-side matching is smaller than that for secondary-side matching, so the cost of primary-side matching is lower.

However, primary-side impedance matching also has several disadvantages. The primary-side matching circuit cannot be used in all situations. If the capacitance of the plasma reactor is fairly large, the required matching inductance will be too small and this

will cause unacceptably large currents through the matching inductor and the transformer primary winding. In addition, unlike the secondary-side matching, the plasma reactor is not part of an actual tank circuit in primary-side matching. Thus, it is more difficult to achieve a high power input to the plasma because energy stored in the tank circuit cannot be used to increase plasma power.

3.5 Experimental Results and Discussion

Both kinds of impedance matching circuits were built and tested at the UT Plasma Sciences Laboratory.

Since the OAUGDP™ is operated at a frequency much lower than radio or microwave frequency, and at high voltages on the order of 10 kV, the inductor coil in the matching network must have a larger inductance (~ 100 mH for the secondary-side matching circuit and several mH for the primary-side matching circuit) than that for RF or microwave plasmas. In addition, the inductor coil must also be able to handle high voltage (~ 10 kV, for secondary-side matching) and large currents (~ 10 A). The selection of such inductor coils available commercially is very limited, so we built the required coils at the UT Plasma Sciences Laboratory. The formula for designing and building practical air-core inductors is shown in Eq. (3.12) [31],

$$L(\mu\text{H}) = \frac{d^2 n^2}{18d + 40l} \quad (3.12)$$

where L is the inductance in μH , d is the coil diameter in inches (from wire center to wire center), l is the coil length in inches, and n is the number of turns. Eq. (3.12) can be changed into S. I. units as shown in Eq. (3.13),

$$L(\mu\text{H}) = \frac{d^2 n^2}{45.7d + 102l} \quad (3.13)$$

where d is the coil diameter in cm, and l is the coil length in cm.

Although it is said in the reference that the above formulae are restricted to calculating the inductance of single-layer long air-core coils, we found by experiment that they are also adequate for multi-layer air-core coils, as long as the aspect ratio of the coils (the ratio of length to diameter) is no less than 3:1, and d in the formula should be the average coil diameter (of the middle layer). Our inductor coils were built by winding insulated wire around a standard 4-inch-diameter (10.2 cm) PVC pipe. The coil for the secondary-side matching circuit is 40 cm long, wound with AWG-14 wire. Its average diameter is 15 cm. The coil has 12 layers, and each layer has a tap, so a range of inductances is available to achieve different matching frequencies. The maximum inductance of this coil is 80 mH, and its maximum winding resistance is $6\ \Omega$. The coil for the primary-side matching circuit is 35 cm long, wound with AWG-10 wire. It has three taps, and its maximum inductance is 2 mH.

The capacitor bank for the secondary-side matching circuit was built by connecting tens of $1\ \mu\text{F}$ electrolytic capacitors in series to provide the desired variable capacitance while withstanding high voltage.

The capacitance of OAUGDP™ reactors was measured by a capacitance meter. The capacitance of the MOD V OAUGDP™ remote exposure reactor (with 11 plasma panels in parallel) at the UT Plasma Sciences Laboratory is about 3 nF, and the capacitance of the MOD IV OAUGDP™ parallel plate reactor is about 100 pF.

The capacitance of a parallel plate reactor can also be calculated by the formula, $C = \epsilon A/d$. The axi-symmetric MOD IV parallel plate reactor at the UT Plasma Sciences Laboratory has a radius of 9 cm, the dielectric plates on each electrode are 1.5mm-thick quartz, and the gap between the two quartz plates is 2 mm. The relative permittivity of quartz is 4. Therefore, the capacitance of the MOD IV reactor is calculated to be 82 pF.

The measured capacitance is larger than this theoretical value because of the parasitic capacitance of connecting cables.

The procedure to predict the value of L and C used in the matching network to match the OAUGDP™ reactors at the desired frequency is illustrated by the following example.

Fig. 3.8 shows the voltage and current waveforms of a set of OAUGDP™ plasma actuator panels energized without impedance matching. The waveform with many filaments is the current through the plasma panels. The large sinusoidal component in the current waveform is the large reactive current, which is not in phase with the voltage waveform.

We tried to match the MOD V OAUGDP™ remote exposure reactor at 1.5 kHz, which consists of the same set of plasma panels used in Figure 3.8. In this case, the maximum inductance of the coil was used. One reason for this was discussed in Section 3.3 of this chapter. The second reason was that, because the desired frequency was relatively low, a larger inductance would be advantageous in decreasing the resonant current in the matching circuit tank, which in turn minimizes the Ohmic losses in the coil. Substituting the following numbers into Eq. (3.3),

$$f_r = 1500 \text{ Hz}, C_p = 3 \times 10^{-9} \text{ F}, L = 0.080 \text{ H}, R_L = 6 \Omega,$$

we obtain $C = 1.377 \times 10^{-7} \text{ F}$. Since each capacitor in the capacitor bank is $1 \mu\text{F}$, we need 8 capacitors connected in series to achieve this C . Since the capacitance of 8 capacitors in series is actually $0.125 \mu\text{F}$, the actual matching frequency that would be achieved in experiment can be calculated by substituting into Eq. (3.3) the following numbers,

$$C = 1.25 \times 10^{-7} \text{ F}, C_p = 3 \times 10^{-9} \text{ F}, L = 0.080 \text{ H}, R_L = 6 \Omega,$$

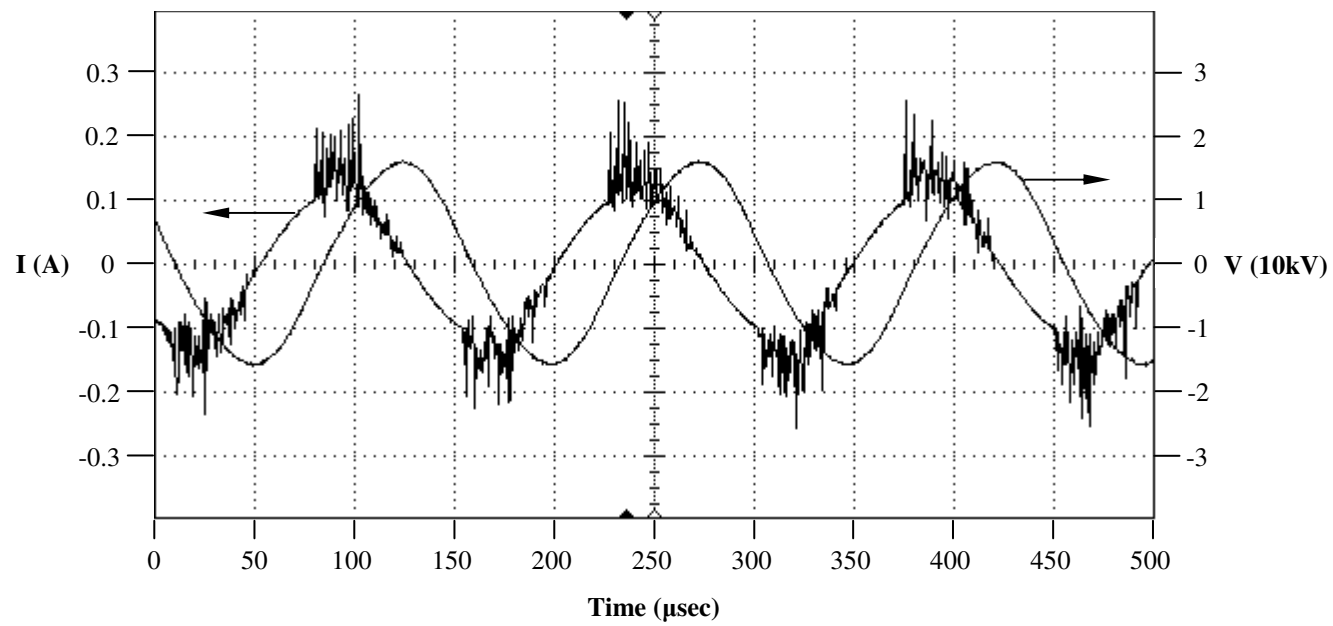


Figure 3.8. Experimentally-obtained voltage (sinusoidal waveform) and current waveforms without impedance matching

from which we get $f_r = 1.57 \text{ kHz}$, exactly the resonant matching frequency observed. Fig. 3.9 shows the voltage and current waveforms of the plasma discharge for this experimental set-up.

Fig. 3.9 shows the voltage and current waveforms that result when operating the same set of plasma panels used in Figure 3.8, but with secondary-side impedance matching. It can be seen that the voltage and current waveforms of the transformer secondary output are in phase, indicating that the impedance matching circuit in addition to the OAUGDP™ reactor/actuator are purely resistive seen by the transformer and impedance matching has been achieved.

Fig. 3.10 shows similar voltage and current waveforms that result when operating the MOD V OAUGDP™ remote exposure reactor with secondary-side impedance matching, but these waveforms were obtained digitally from a digital oscilloscope. The sinusoidal waveform is the voltage across the plasma panels. With impedance matching, the plasma discharge current has been dramatically increased and the reactive current has been minimized.

Since the voltage and current waveforms of the transformer secondary output are in phase when impedance matching is achieved, the equivalent resistance of the plasma, R_p , can be estimated by Ohm's Law. In this case, $R_p \approx 5.7kV/0.3A = 19k\Omega$. By using Eq. (3.10), we can also calculate the impedance of the matching network at this matching frequency and get $Z_r' = 109k\Omega$.

Fig. 3.11 shows the waveforms of the power supply output voltage and current prior to the primary-side matching circuit and the transformer, and the waveform of the discharge current of the primary-side impedance matched MOD IV OAUGDP™ parallel plate reactor. The power supply output voltage and current waveforms are in phase with

Voltage V_{rms} across the load (10 kV/div)

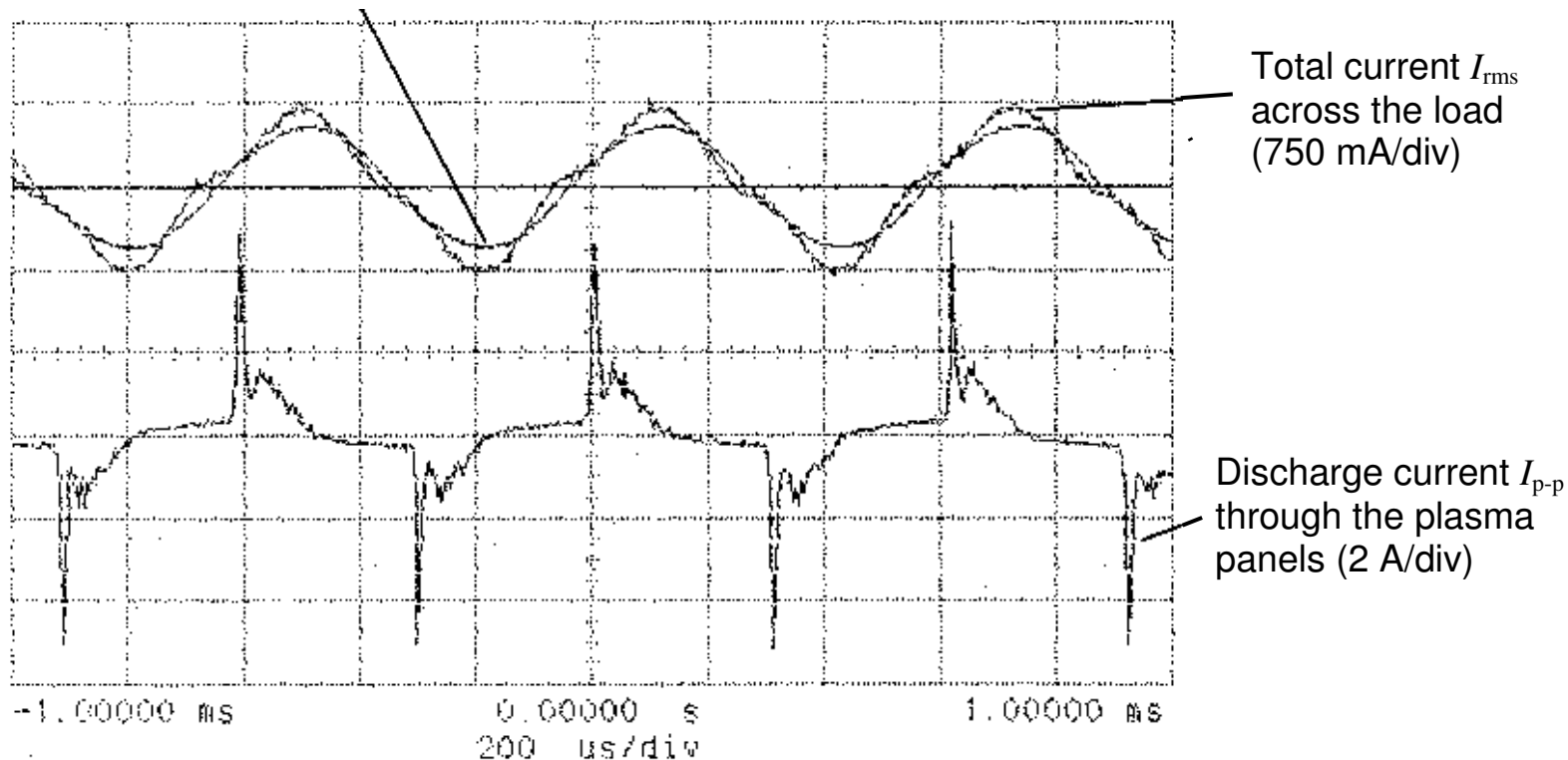


Figure 3.9. Time variation over 3 cycles of half the applied voltage (sinusoidal waveform) and the discharge current in the impedance matched MOD V Remote Exposure Reactor with 11 panels energized (The waveforms were experimentally-obtained)

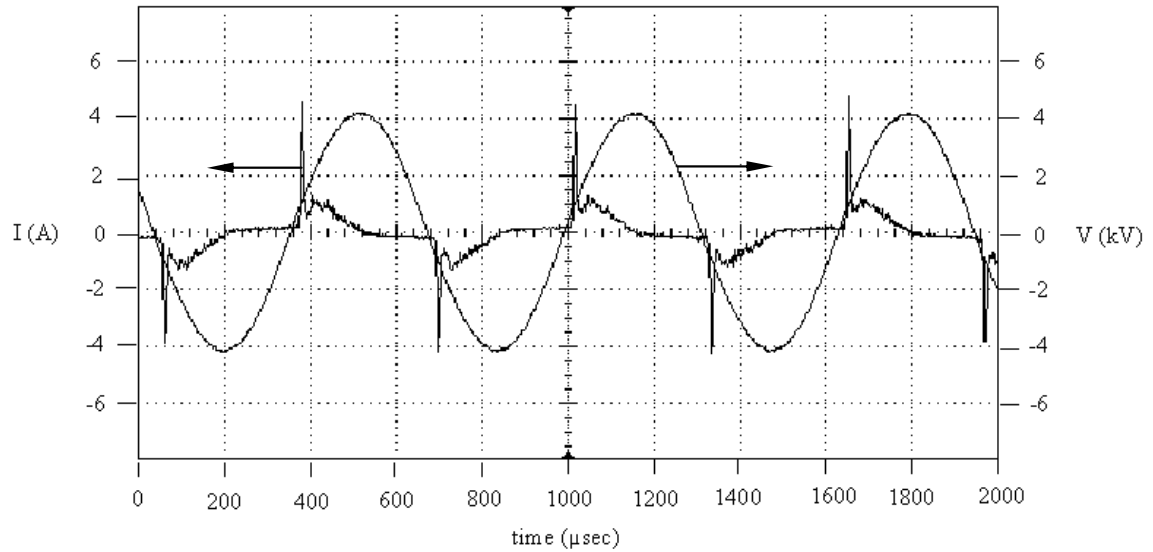


Figure 3.10. Time variation over 3 cycles of half the applied voltage (sinusoidal waveform) and the discharge current in the impedance matched MOD V Remote Exposure Reactor with 11 panels energized (The waveforms were experimentally-obtained)

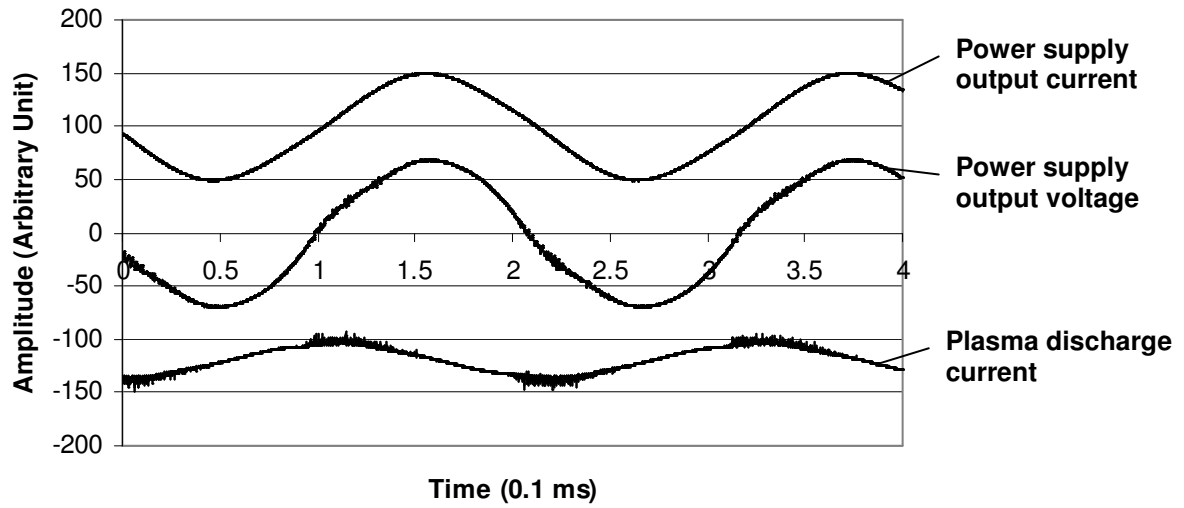


Figure 3.11. Experimentally-obtained waveforms of the measured power supply output voltage and current before the primary-side matching circuit and the transformer, and the measured discharge current of the primary-side impedance matched MOD IV OAUGDP™ parallel plate reactor

each other. This clearly shows that the system is matched at the primary side of the transformer.

In order to investigate the effect of the impedance of the matching network, Z_r' , on plasma power, different combinations of inductance and capacitance in the secondary-side matching circuit were applied to a parallel plate OAUGDP™ reactor at an affiliated company. The operating frequency was adjusted to maximize the plasma power. Experimental results are shown in Table 3.1. The results clearly show that the maximum plasma power increases with increasing inductance and decreasing capacitance.

However, the inductance in the matching network should not be too large, and the capacitance not too small. The reason for this is that the inductor and the capacitor in the matching network form a tank circuit, which can store energy. The stored energy can enhance the formation stage of the plasma discharge. If the inductance in the secondary-side matching network is increased and the capacitance is decreased, the energy stored in the tank circuit will be decreased. This might have an adverse effect on plasma formation and plasma power. A change in the shape of plasma discharge current waveform was observed in experiments when the matching capacitance was changed.

Table 3.1. Maximum plasma power with different combinations of inductance and capacitance in the secondary-side matching circuit

Input Signal (mVrms)	Inductance (mH)	Capacitance (nF)	Plasma Power (Watts)
400	90	20	587
400	90	10	887
400	213	3	1039
500	90	20	867
500	90	10	1359
500	213	2	1509
700	213	2	2287
700	300	1	2446
750	213	2	2600
750	300	1	2804

Chapter 4 PSpice[®] Simulation of OAUGDP[™] Reactor/Actuator Systems

4.1 Introduction

The characteristics of many electrical systems can be simulated with proprietary computational tools such as PSpice[®]. Devices employing plasmas are embedded in electrical systems. In many situations, it is advantageous to simulate the complete system, including the plasma, with such commercial software. Previous work regarding the computational circuitry simulation of plasmas has been published [18] – [23]. In these papers, simulation of low-pressure plasmas in gaseous discharge lamps, as well as pulsed, RF, and/or inductively coupled electrical discharges were investigated. Other papers provide plasma circuit models capable of incorporation into circuit simulations, although simulation of complete reactors was not reported in those papers [24] – [26]. The One Atmosphere Uniform Glow Discharge Plasma (OAUGDP[™]) [1, 2] reactor/actuator system consists of a power supply, a transformer, an impedance matching network, and the plasma reactor. This electrical system is a candidate for simulation with such computational tools.

The plasma parameters of the OAUGDP[™] vary as a function of distance between the instantaneous anode and cathode. Unlike DC glow discharges operated at low pressure, the plasma parameters of the OAUGDP[™] vary with time, and follow the RF cycle. Characteristic values of the plasma parameters of a parallel-plate OAUGDP[™] reactor are listed in Table 4.1.

In Ben Gadri's paper [27], the physical processes in such a plasma were simulated by one-dimensional numerical methods. However, his simulation was not a complete

Table 4.1. Characteristic values of the plasma parameters of a parallel-plate OAUGDP™ reactor

Plasma Parameters of the MOD IV Parallel-Plate OAUGDP™ Reactor	
Gas	atmospheric air or other gases, relative humidity below 14%
Neutral pressure	760 ± 25 Torr (1 atmosphere)
Electron number density	$5 \times 10^{16} - 5 \times 10^{17} / \text{m}^3$ (time averaged)
Electron collision frequency	$0.5 - 2.0 \times 10^{12}$ collisions/sec
Electron kinetic temperature	not well known
Volumetric power dissipation	$0.01 - 1.0$ watts/cm ³
Gap distance	2 – 5 mm
RF voltage	8 – 16 kV RMS
Frequency of operation	3 kHz – 10 kHz

OAUGDP™ reactor system, and simulation of such a system has not been reported by other researchers. In an OAUGDP™ system, the inductor and capacitors in the impedance matching network [28], the power supply, and the transformer are ordinary electrical components and have well-developed PSpice® models. However, there is no available electrical model in PSpice® for the plasma discharge in an OAUGDP™ reactor, so a principal simulation task is the development of such a model. In this paper, specific circuit models of One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) parallel-plate and co-planar plasma actuator systems have been formulated. In addition, simulations with the electrical characteristics of these OAUGDP™ reactor/actuator systems have been obtained with the proprietary circuit simulation software, PSpice®, and compared with experimental data.

A parallel-plate OAUGDP™ reactor consists of two parallel metal electrode plates with a gap between them. At least one electrode is covered with a dielectric plate, as shown in Fig. 4.1. The dielectric plate can be modeled as a capacitor, as can the gap containing the plasma. Based on the phenomenology of glow discharges, the plasma discharge itself can be modeled as a voltage-controlled current source that is switched on as long as the voltage across the gap exceeds the plasma initiation voltage. The current source and its output current follow a power law of the applied voltage [1], an observed phenomenological characteristic of the voltage-current behavior of normal glow discharges. Fig. 4.2 shows the universal voltage-current characteristic of a DC electrical discharge tube [1, Fig. 10.1]. The normal glow discharge regime is between F' and G on the diagram. Roth reported that the current-voltage relationship of the glow discharge in the Electric Field Bumpy Torus experiment, a high power glow discharge, was $I \propto V^2$, and $I \propto V^3$, depending on operating regime [1]. Ben Gadri's paper shows that an atmospheric pressure RF glow discharge in helium exhibits the same luminous and dark structures as low-pressure DC glow discharges [27]. In the next section, we will present a PSpice® model for OAUGDP™ plasma reactors, which simulates the current waveforms experimentally observed in OAUGDP™ reactors [30].

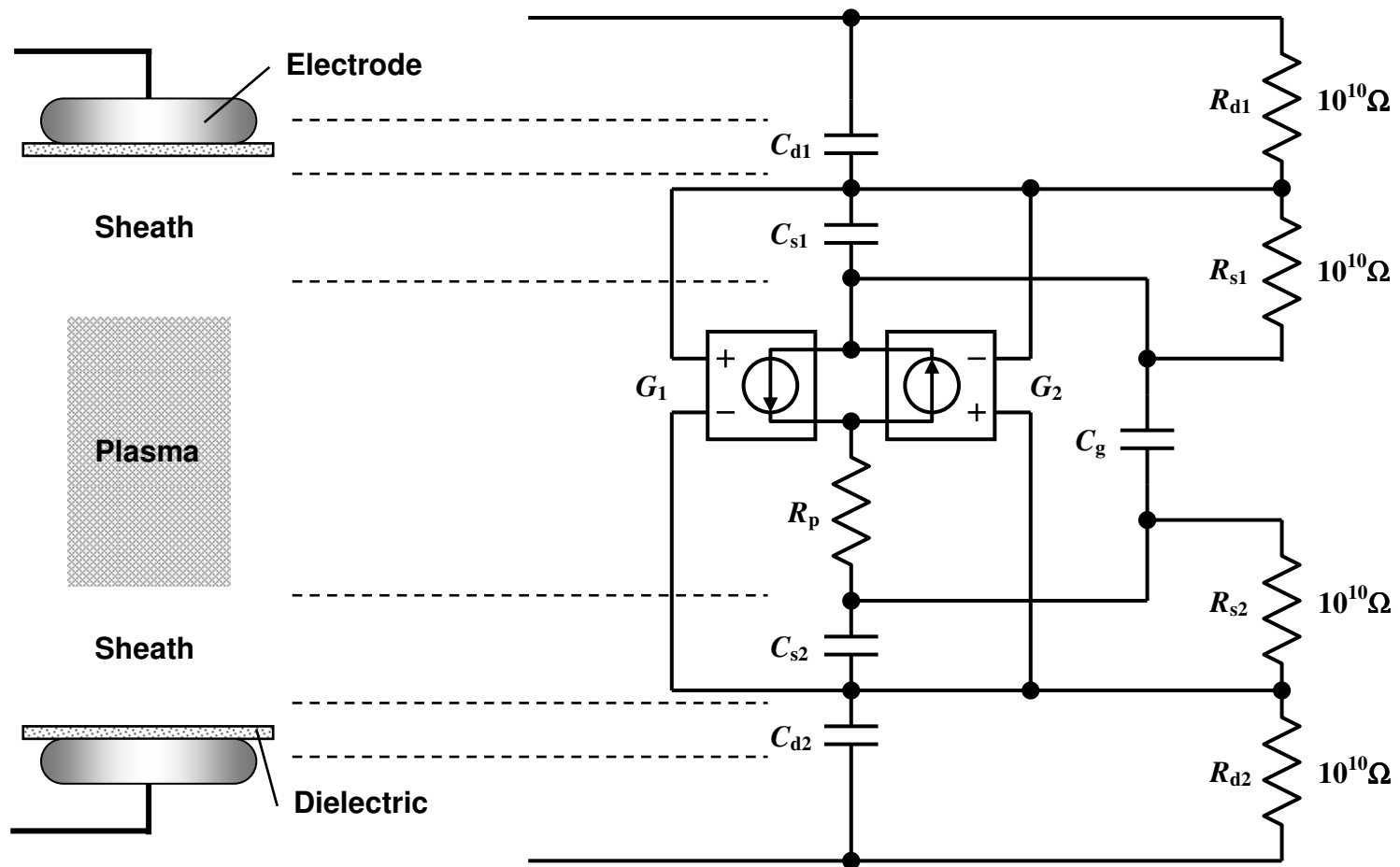


Figure 4.1. A PSpice® Model for parallel-plate OAUGDP™ reactors

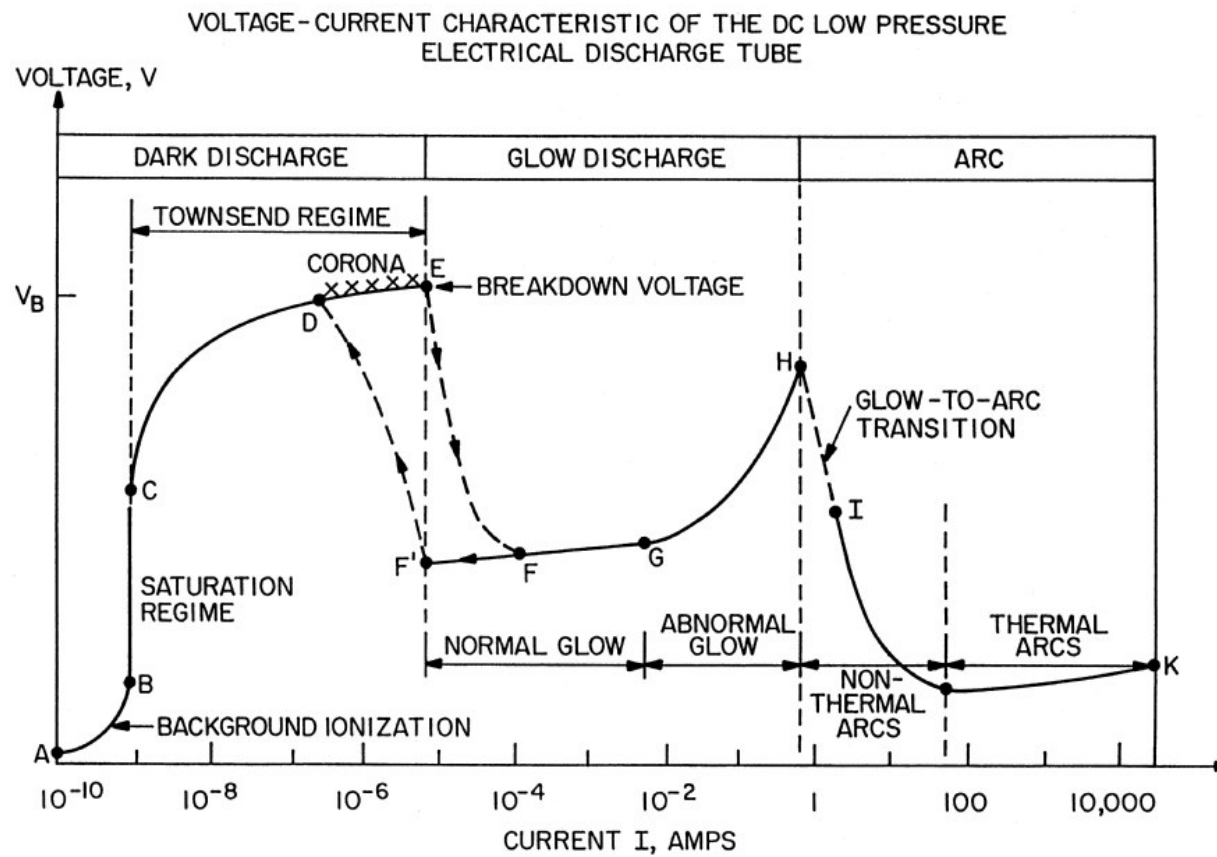


Figure 4.2. Universal voltage-current characteristic of the DC electrical discharge tube [1, Fig. 10.1]. The normal glow discharge regime is between F' and G on the diagram

4.2 A PSpice® Model for Parallel-Plate OAUGDP™ Reactors

A parallel-plate OAUGDP™ reactor consists of two parallel metal electrode plates with a small gap between them. At least one electrode is covered with a dielectric plate or coating, as shown in Fig. 4.1. The PSpice® model for the dielectric plate or coating can be represented by a capacitor, as can the gap containing the plasma. The sheath between the plasma and the dielectric plate can also be modeled as a capacitor, which may have a larger capacitance than the dielectric plate if the thickness of the sheath is smaller than that of the dielectric. The plasma discharge within the gap is the only complex component to be modeled. Thus, it is necessary to consider the physical processes in an OAUGD plasma in order to construct a useful PSpice® model for it.

A parallel-plate OAUGDP™ reactor characteristically operates at an RF voltage of about 10 kV rms and 7 kHz applied across the two parallel electrode plates. During the first half of an RF cycle, when the voltage across the gap exceeds the plasma initiation voltage, the air in the gap is ionized and a plasma is formed. A discharge (displacement) current flows through the plasma in response to the high voltage across the gap. The time-averaged value of this current is a power law function of the voltage across the gap, an observed phenomenological characteristic of the voltage-current behavior of normal glow discharges. As the discharge continues, electrons reach the dielectric plate on the instantaneous anode and accumulate on it. This electron density decreases the rate of voltage increase, and later the voltage across the gap itself [27]. This build-up of negative charge on the dielectric plate prevents dramatic discharge current increases or decreases. As soon as the voltage across the gap is decreased below the plasma initiation voltage, the discharge current ceases and the plasma extinguishes. In the second half of the RF cycle, the plasma discharge restarts, and the current flows in the opposite direction due to the change of RF voltage polarity [27].

Based on the physical processes in an OAUGDP™, the discharge can be simulated by a voltage-controlled current source in PSpice®. As long as the voltage across the gap exceeds the plasma initiation voltage, this current source is switched on and its output current increases with the voltage across the gap according to the power law discussed by Roth [1, Eq. 9.169],

$$J = J_0 V^k \quad (4.1)$$

where k has been observed to range over the values $1 < k < 12$.

A resistor should be added in series with the current source in the PSpice® model to account for power dissipation in the plasma. The schematic of a PSpice® model for parallel-plate OAUGDP™ reactors is shown in Fig.4.1. In this model, both electrodes are covered with dielectric plates, so there are two dielectric capacitors, C_{d1} and C_{d2} , in the schematic. C_g is the gas capacitance of the gap. The capacitance of the plasma sheaths is represented by C_{s1} and C_{s2} , which may be much larger than C_{d1} , C_{d2} and C_g if the plasma sheath is thinner than the dielectric. R_p is an equivalent plasma resistance to account for power dissipation in the plasma. There are two voltage-controlled current sources G_1 and G_2 . Each of them generates the discharge current in one half of the RF cycle, so a full RF cycle can be represented. The output current of G_1 and G_2 is defined in Eq. (4.2) by a power law function of the difference between the gap voltage, V_g and the plasma initiation voltage, V_{pi} in order to simulate the voltage-current behavior of a normal glow discharge plasma. If one of the two electrodes is not covered with a dielectric plate, the model must be modified by shorting the corresponding dielectric capacitor.

$$I \begin{cases} = 0, & \text{for } V_g < V_{pi} \\ \propto (V_g - V_{pi})^\alpha, & \text{for } V_g \geq V_{pi} \end{cases} \quad (4.2)$$

In Eq. (4.2), α is an integer that ranges from 1 to 12 in different glow discharge plasma devices. Resistor R_{d1} , R_{d2} , R_{s1} and R_{s2} are required by the PSpice[®] software to keep the capacitor terminals from floating. Since their values are very large, these resistors have no effect on simulation results. The schematic of a complete parallel-plate OAUGDP[™] reactor system for PSpice[®] simulation is shown in Fig. 4.3. The circuitry will be described in Section 4.4.

4.3 A PSpice[®] Model for Co-Planar OAUGDP[™] Actuators

A co-planar OAUGDP[™] actuator panel for aerodynamic flow control consists of a flat panel with multiple co-planar plasma electrode strips alternating in RF polarity, and with each polarity connected in parallel on either the top or the bottom of the panel. Fig. 4.4 shows a schematic of such a panel, and Fig. 4.5 shows an image of such a plasma actuator panel as was used in subsonic plasma aerodynamic experiments [4] – [6]. This actuator panel consists of a thin dielectric plate either with electrode strips on one or both sides, or with electrode strips on one side and a metallic electrode sheet on the other. When an RF voltage of about 4 kV rms and 1–7 kHz is applied to a flat panel plasma actuator, a planar plasma layer is generated either on both sides of the dielectric or only on the side having the electrode strips, depending on the electrode configuration.

Fig. 4.6 illustrates a cross section of a flat panel with plasma energized on both sides. Since the plasmas generated on each side of the dielectric plate resemble the plasma in a parallel-plate reactor, we can construct a PSpice[®] model for co-planar actuators based on the model for parallel-plate reactors. Fig. 4.6 also illustrates an approximate circuit model for the co-planar plasma actuator. A PSpice[®] model for co-planar OAUGDP[™] actuators is shown in Fig. 4.7, which is a merging of two copies of the circuit model for parallel-plate reactors.

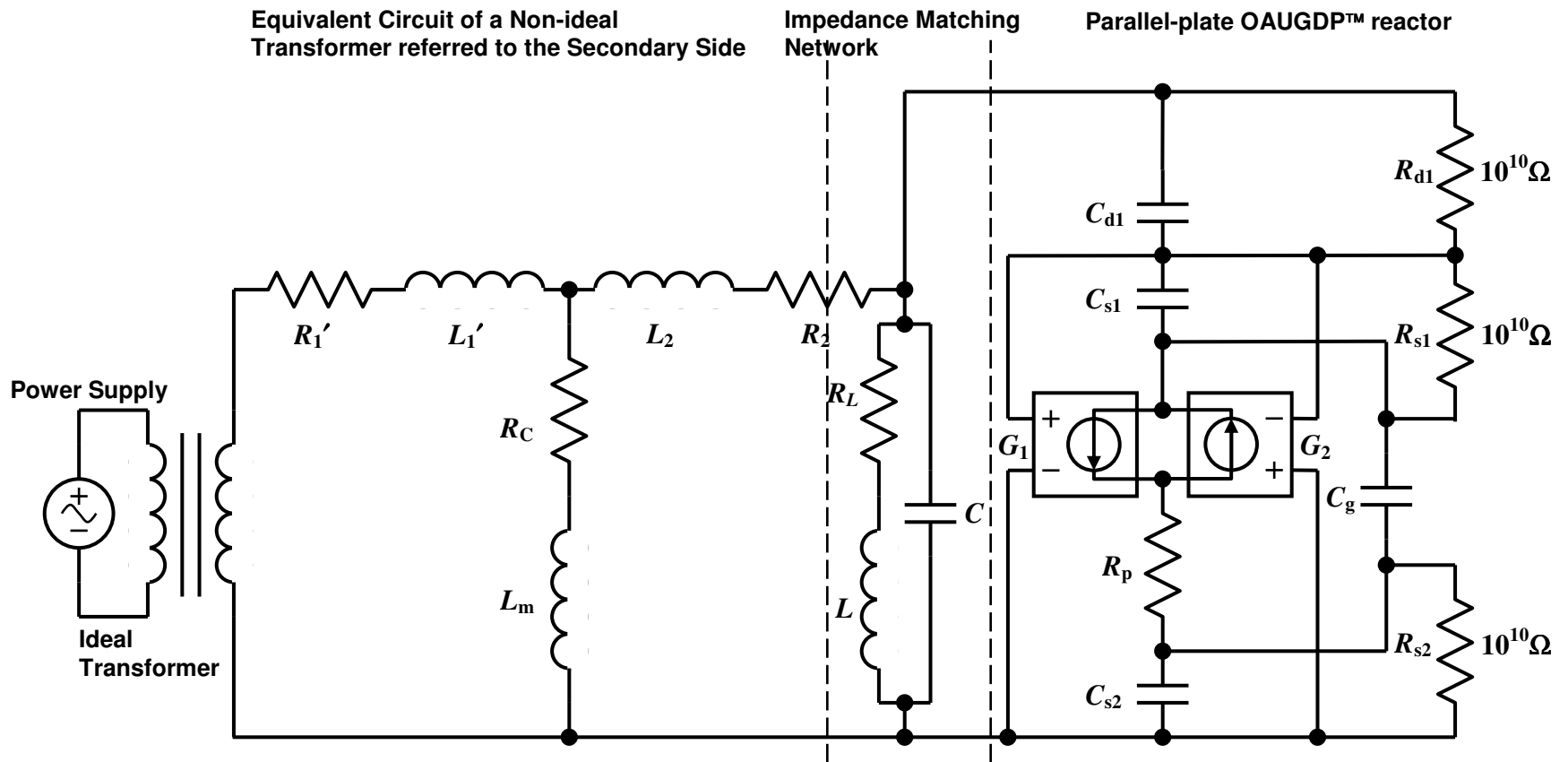


Figure 4.3. Schematic of a parallel-plate OAUGDP™ reactor system for PSpice® simulation

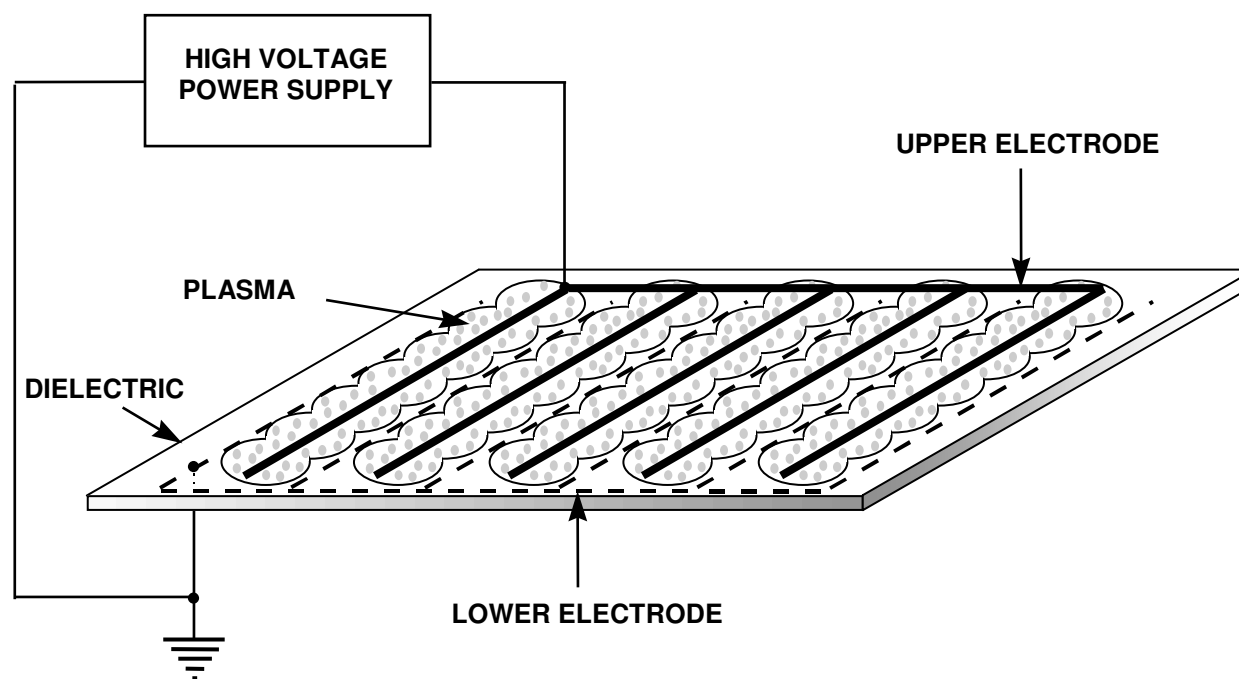


Figure 4.4. Schematic of a flat layer of OAUGDP™ plasma on a plasma actuator panel

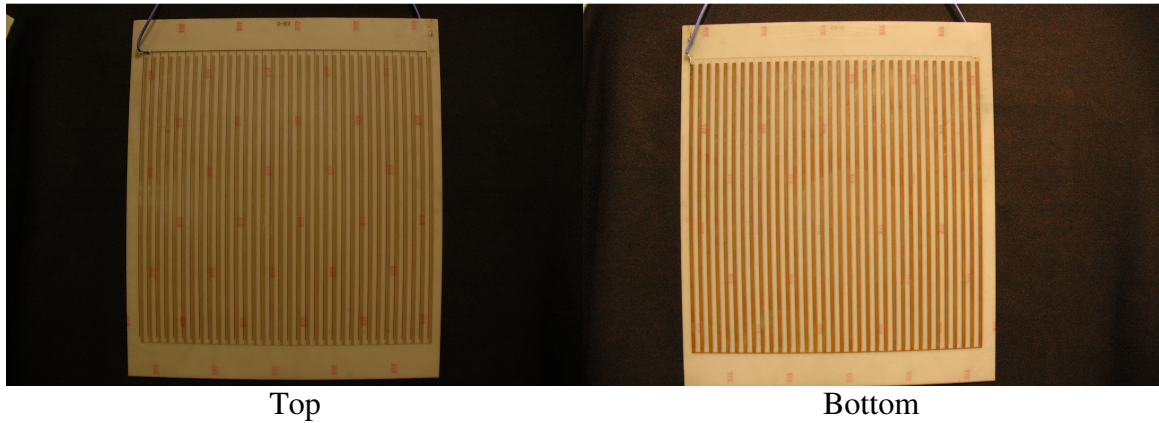


Figure 4.5. Photographs of an OAUGDP™ actuator panel

4.4 Computer Simulation and Comparison with Experimental Results

Fig. 4.3 shows the schematic of a complete parallel-plate OAUGDP™ reactor system for PSpice® simulation. In the schematic, the real (non-ideal) transformer is modeled as an ideal transformer with an equivalent circuit of a non-ideal transformer referred to its secondary side. An impedance matching network between the transformer and the OAUGDP™ reactor matches the capacitive OAUGDP™ reactor to the power supply. The impedance matching network reduces reflected power and increases power supply efficiency [28].

The parameters used in this simulation are of a parallel-plate OAUGDP™ reactor system operated at an affiliated company. Since only one electrode of the reactor is covered with a dielectric coating, there is only one dielectric capacitor in the PSpice® model for this OAUGDP™ reactor; the other is shorted out. A list of component parameters used in the PSpice® simulations of the parallel-plate reactor is shown in Table 4.2.

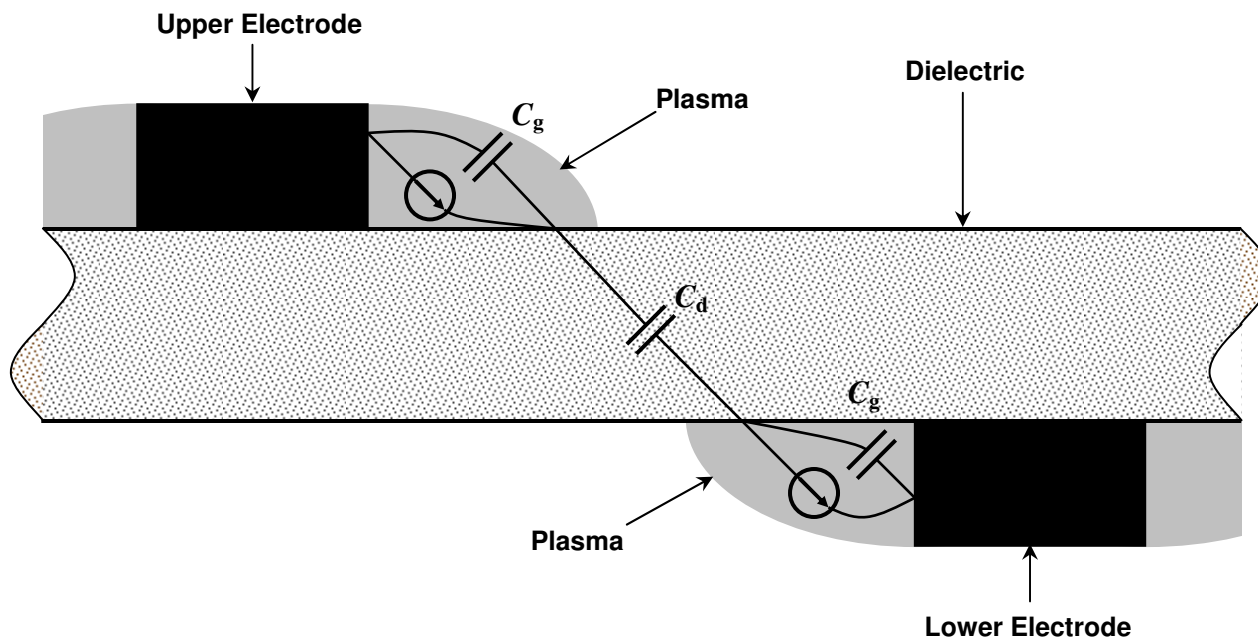


Figure 4.6. Cross section of a flat panel plasma actuator with plasma energized on both sides

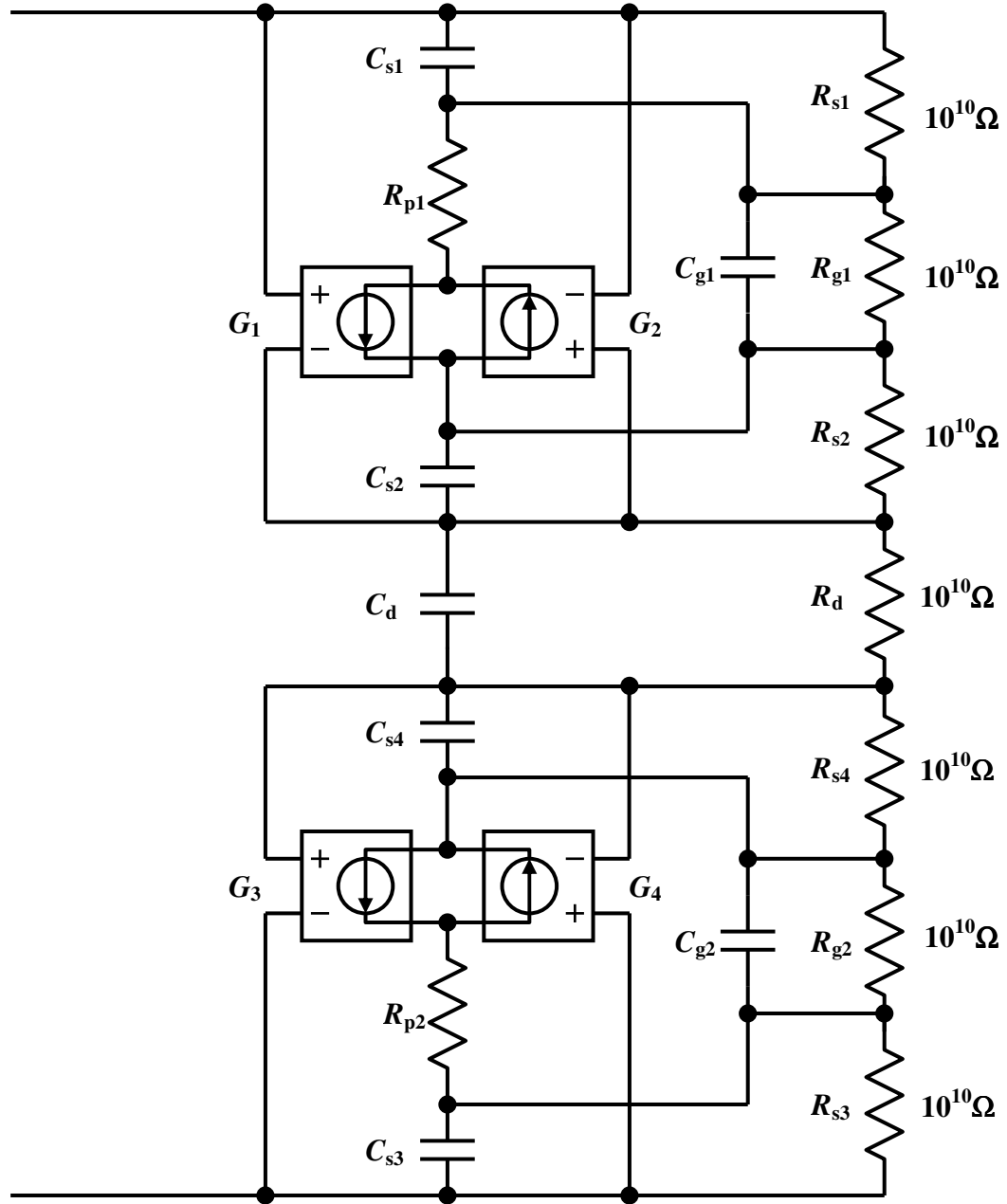


Figure 4.7. A comprehensive PSpice® model for a co-planar OAUGDP™ actuator panel

Table 4.2. PSpice® Simulation Parameters of a Parallel-Plate OAUGDP™ Reactor

PSpice® Simulation Parameters of a Parallel-Plate OAUGDP™ Reactor	
Ideal transformer (Based on measured characteristics)	$R_{xtrm} = 0.1 \, \Omega$, $L_{primary} = 1 \, \text{H}$, $L_{secondary} = 800 \, \text{H}$, $K_{xtrm} = 1$
Equivalent circuit of the non-ideal transformer referred to its secondary side (The numbers were measured)	$R_1' = 503.1 \, \Omega$, $L_1' = 233.6 \, \text{mH}$, $L_2 = 0.292 \, \text{mH}$, $R_2 = 431.9 \, \Omega$, $L_m = 180.8 \, \text{H}$
Impedance matching network (The numbers were measured)	$R_L = 8.9 \, \Omega$, $L = 213 \, \text{mH}$, $C = 2 \, \text{nF}$
Parallel-plate OAUGDP™ reactor (The numbers were calculated, based on experimental data)	$C_{d1} = 3.094 \, \text{nF}$, $C_{s1} = C_{s2} = 0.6 \, \mu\text{F}$, $R_p = 8 \, \text{k}\Omega$, $V_{pi} = 7.6 \, \text{kV}$

Figs. 4.8 – 4.10 show the actual discharge current waveforms observed in experiments and their PSpice® simulations. Key simulation parameters are also listed below the figures. The shape and amplitude of the discharge currents simulated by PSpice® agree well with those of actual discharge currents. This indicates that our model is a good simulation of the plasma in this parallel-plate OAUGDP™ reactor. Since both of the actual and simulated voltage waveforms in the experiments are purely sinusoidal, it is not necessary to display them in these figures.

The gas capacitance C_g used in simulation is calculated by the formula for calculating the capacitance of a parallel-plate capacitor $C = \epsilon A/d$. For the parallel-plate OAUGDP™ reactor being simulated here, its electrode is 0.70 m long and 0.15 m wide, and the gap distance d is about 4 mm. Therefore, the calculated gas capacitance is 0.23 nF, the value used in Figs. 4.9 and 4.10. When the plasma operating conditions change, the capacitance C_g might change slightly. Although the plate-capacitor model for the plasma capacitance C_g is crude, it is satisfactory for simulation purposes. Based on the simulation results, the value of C_g could be adjusted by a small amount to match the simulated reactive current (the sinusoidal baseline in the discharge current waveform) to the actual reactive current obtained experimentally. This iteration procedure leads to a better simulation, and the final C_g is a more accurate value of the plasma capacitance.

The values of C_{s1} and C_{s2} listed above are an estimate of plasma sheath capacitance by the formula $C = \epsilon A/d$, with sheath thickness $d = 1.5 \mu\text{m}$, an estimate based on the electron Debye shielding distance. Actually, the value of the plasma sheath capacitance is not crucial and has no effect on simulation results, since the sheath capacitances are in series with the gas capacitance and dielectric capacitance in the PSpice® model, and the sheath capacitance is much larger than both of these together. The value of the plasma initiation voltage V_{pi} listed is obtained from experimental data. When the OAUGDP™ is barely energized, the voltage across the reactor is measured.

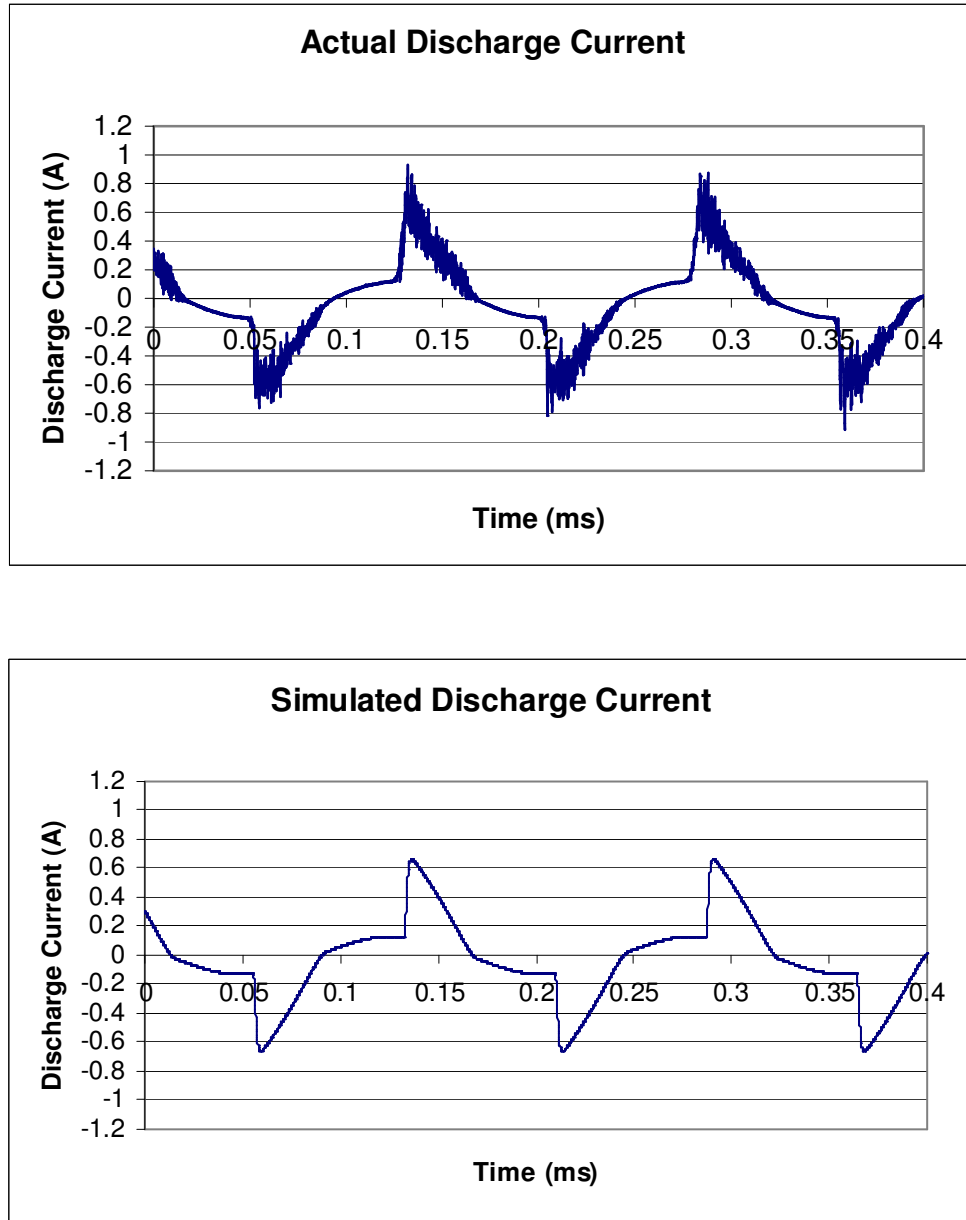


Figure 4.8. Comparison of the actual discharge current with the simulated discharge current for a parallel-plate OAUGDP™ reactor (Frequency $f = 6480$ Hz , Amplitude of input voltage at the transformer primary side $V_i = 420$ V , Plasma capacitance $C_g = 0.25$ nF , Power law of the discharge current: $I = [(V_g - V_{pi})/1000]^3$, Power-law exponent $\alpha = 3$)

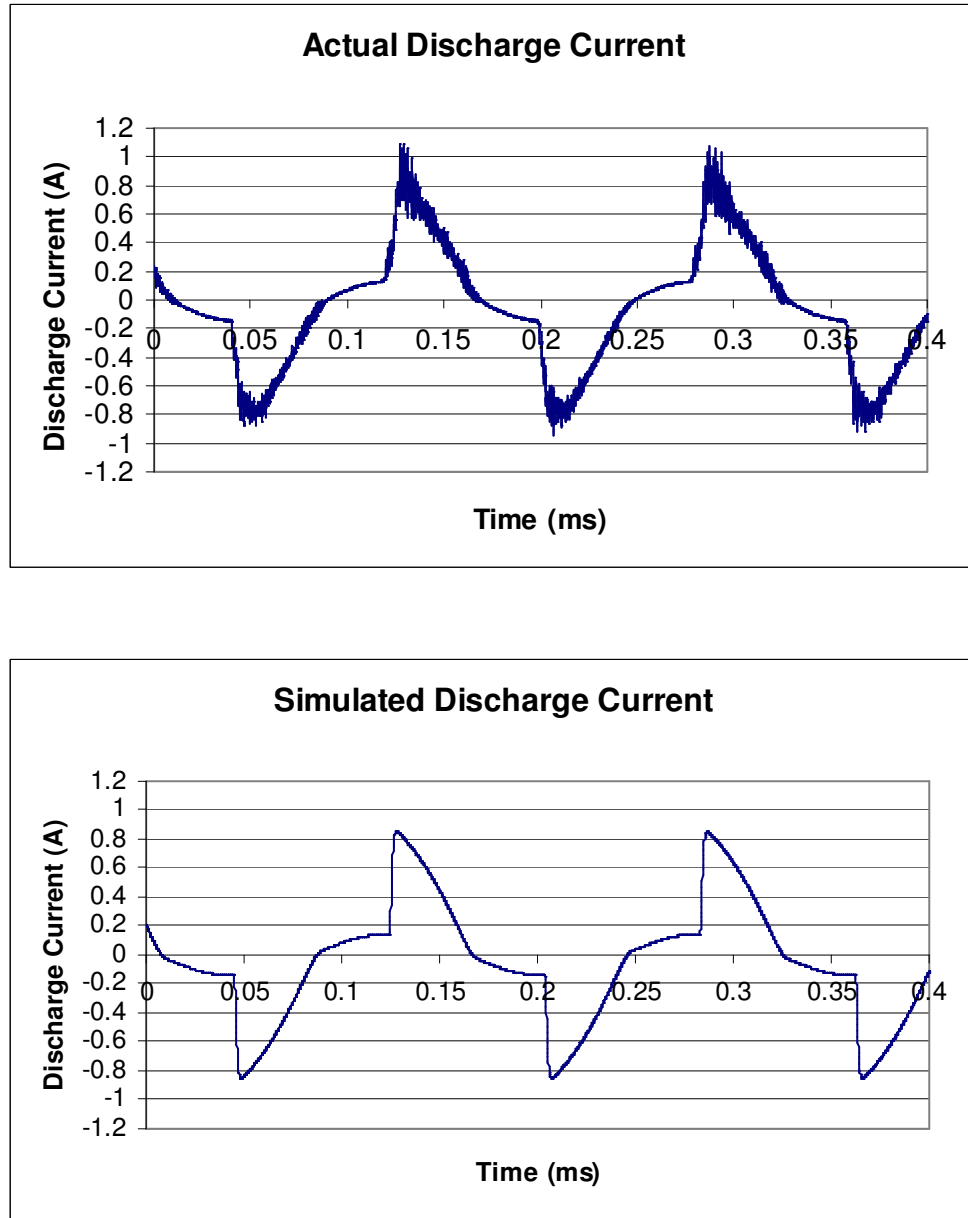


Figure 4.9. Comparison of the actual discharge current with the simulated discharge current for a parallel-plate OAUGDP™ reactor (Frequency $f = 6300$ Hz , Amplitude of input voltage at the transformer primary side $V_i = 465$ V , Plasma capacitance $C_g = 0.23$ nF, Power law of the discharge current: $I = [(V_g - V_{pi})/1000]^3$, Power-law exponent $\alpha = 3$)

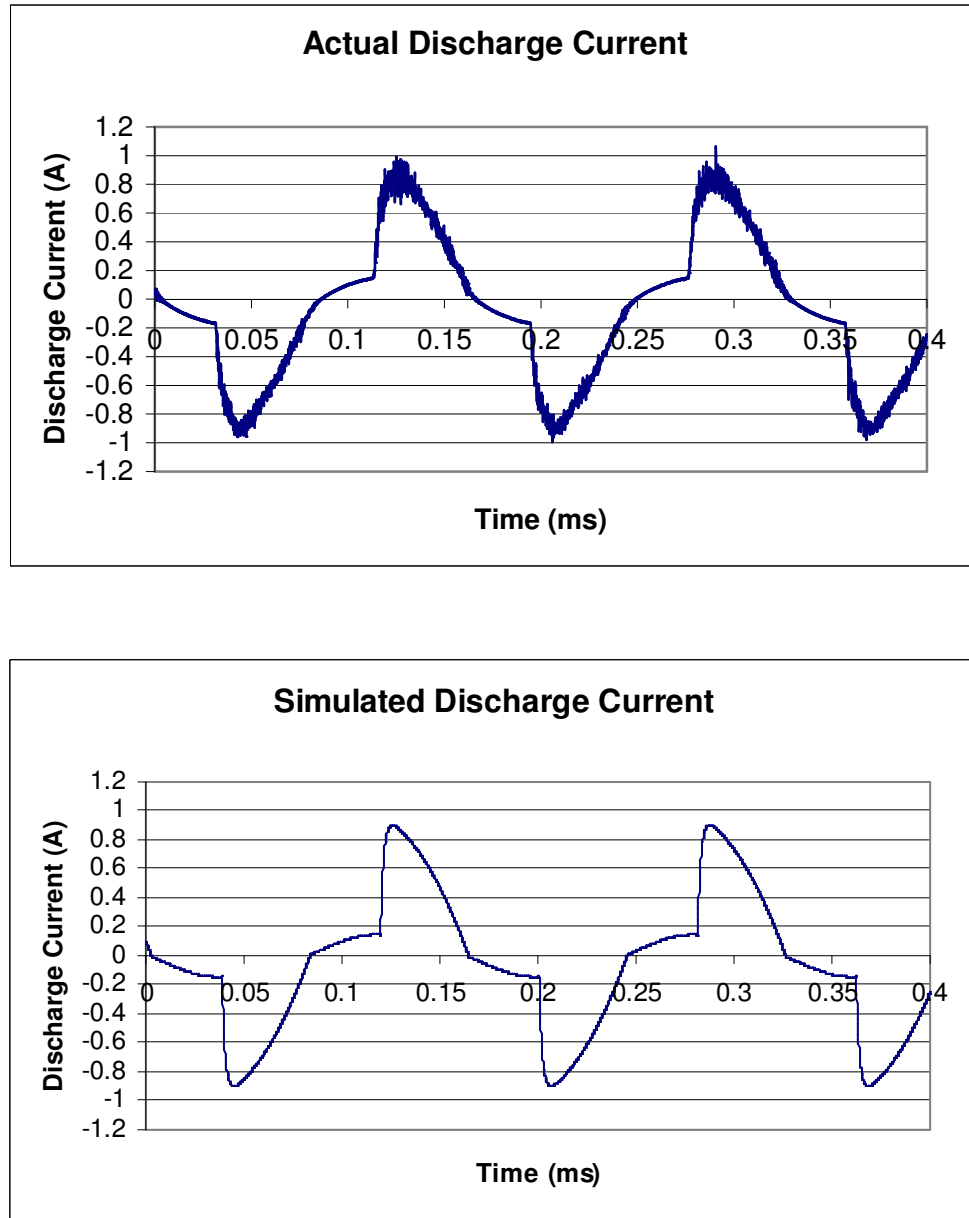


Figure 4.10. Comparison of the actual discharge current with the simulated discharge current for a parallel-plate OAUGDP™ reactor (Frequency $f = 6180$ Hz , Amplitude of input voltage at the transformer primary side $V_i = 480$ V , Plasma capacitance $C_g = 0.23$ nF , Power law of the discharge current: $I = (V_g - V_{pi})/1000$, Power-law exponent $\alpha = 1$)

Given that the values of the dielectric capacitance and gas capacitance of the reactor are known, the plasma initiation voltage can be derived from the measured applied voltage.

The value of the equivalent plasma resistance R_p is calculated from the plasma power measured experimentally, and the measured voltage across the reactor. Since the OAUGDP™ system is impedance-matched at the secondary side of the transformer, the transformer output voltage and current are in phase with each other [26]. The plasma power is then calculated by multiplying the RMS values of the transformer output voltage and current, and subtracting the Ohmic loss in the inductor coil from the product. Simulations show that the value of the equivalent plasma resistance has no effect on the amplitude and shape of the simulated discharge current waveform. This result is counter-intuitive but understandable. Since the discharge current is generated by the voltage-controlled current source in the PSpice® model of OAUGDP™, the current source is controlled by the voltage across the capacitors C_{s1} , C_g and C_{s2} , and this voltage is in turn controlled by the charges delivered by the current source to the capacitor terminals, and the equivalent plasma resistance has no part in this process. The reason for incorporating a plasma resistance into the PSpice® model is to account for power dissipation in the plasma. There is also a physical reason backing up the above result — the plasma resistance is the result of the gas breakdown and glow discharge, but not the cause. The discharge current is determined by the gas breakdown mechanism, which, in the case of our PSpice® simulation, is the circuitry consisting of the voltage-controlled current source and the various capacitors in the model.

When an OAUGDP™ is operated under improper conditions, such as a wrong gap distance, a high humidity level, a dirty dielectric surface, a weak airflow, a wrong operating frequency, etc, the experimental discharge current waveform is very noisy due to coarse transient filaments in the plasma. These filaments are clearly visible and are streamer-like phenomena. They may cause noise on the discharge current waveform. When many localized filaments are present, the plasma is a mixture of the OAUGDP™

and a dielectric barrier discharge. However, when an OAUGDP™ system is adjusted to proper operating conditions, the dielectric barrier discharge is suppressed — the visible streamers and localized filaments disappear and the OAUGDP™ becomes homogeneous. The discharge current waveform of an OAUGDP™ can remain somewhat noisy, as the result of instabilities caused by asperities at the edges of the electrode, imperfections of the dielectric plate, water vapor, and attaching oxygen species in the plasma, etc. The noise on the experimental discharge current waveforms shown in Figs. 4.8 – 4.10 are due to such instabilities.

Based on the simulation results, it has been found that the exponent α in the power law has a minor effect on the rising edge and the sharpness of the peak in the modeled discharge current waveform. When the exponent α in Eq. (4.2) is larger, the rising edge is steeper and the current peak is sharper, and vice versa. Therefore, the profile of the simulated discharge current waveform can be adjusted to match the experimental current waveform by changing the value of α . It has been found that, for the discharge current in Figs. 4.8 and 4.9, $\alpha = 3$ yields the best simulation results; for the discharge current in Fig. 4.10, $\alpha = 1$ yields the best simulation results. This indicates that the current-voltage relationship of the OAUGDP™ is described by power laws with different exponents at different operating conditions [1]. Fig. 4.11 shows four simulations which illustrate the effect of the power-law exponent α on the shape of the discharge current waveform. It can be seen that when α is changed from 1 to 12, the shape of the discharge current peak becomes sharper.

Fig. 4.12 shows a bimodal discharge current waveform observed experimentally and its PSpice® simulation. The discharge current starts with a small transient spike, followed by a much larger secondary peak. The mono-modal to bimodal transition of the shape of the discharge current waveform was observed experimentally when the capacitance in the impedance matching network was reduced. The physical process responsible for the observed bimodal discharge current waveform is the following: the

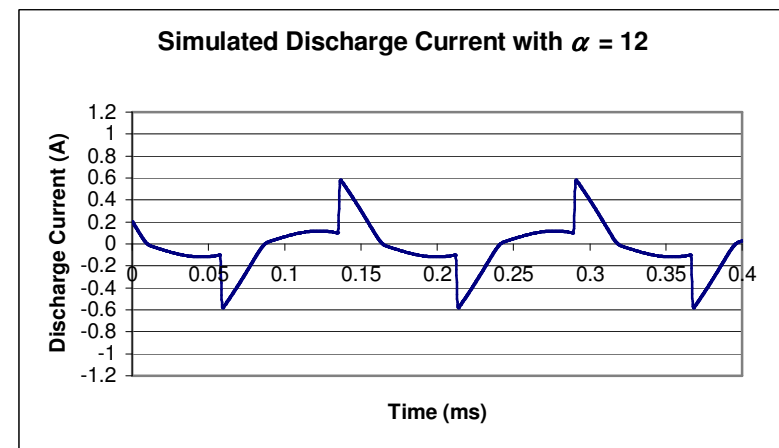
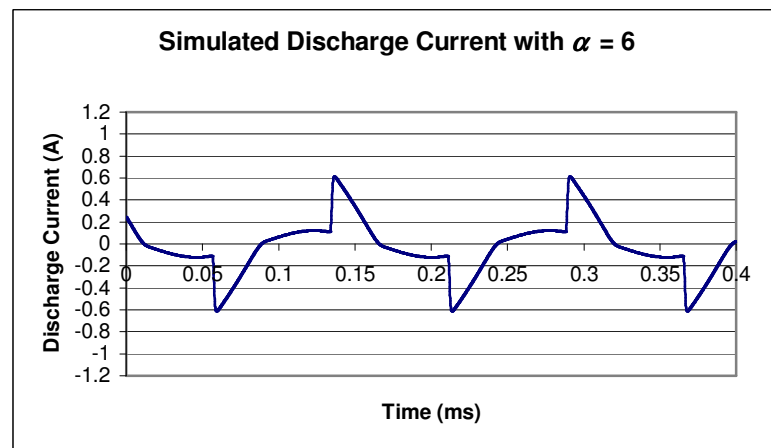
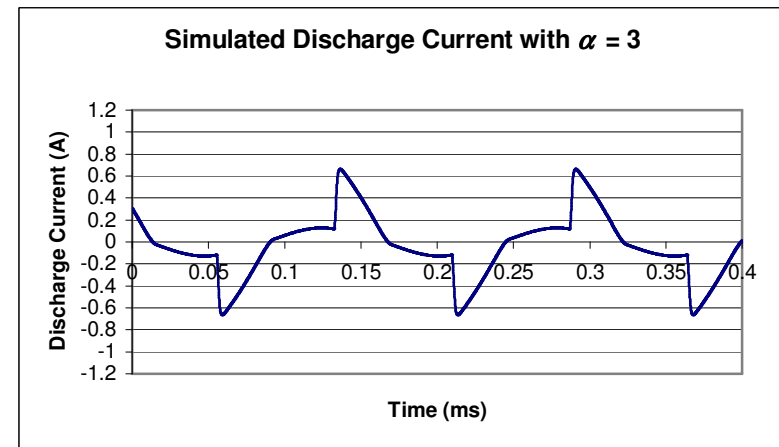
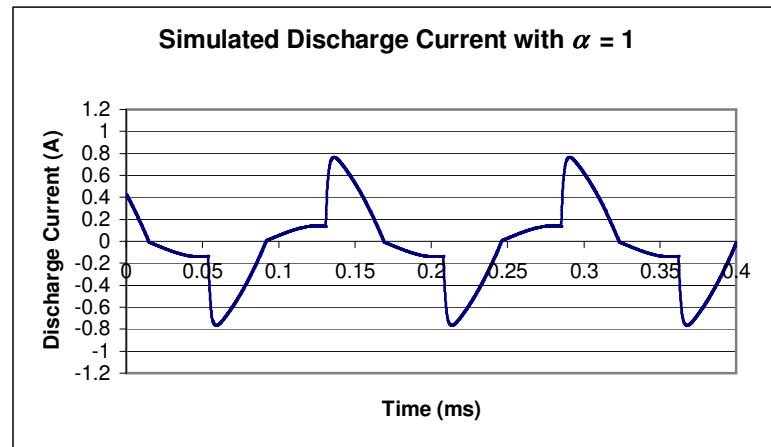


Figure 4.11. Effect of the power-law exponent α on the shape of discharge current waveforms (All the simulation parameters except α are the same as those in Fig. 4.8)

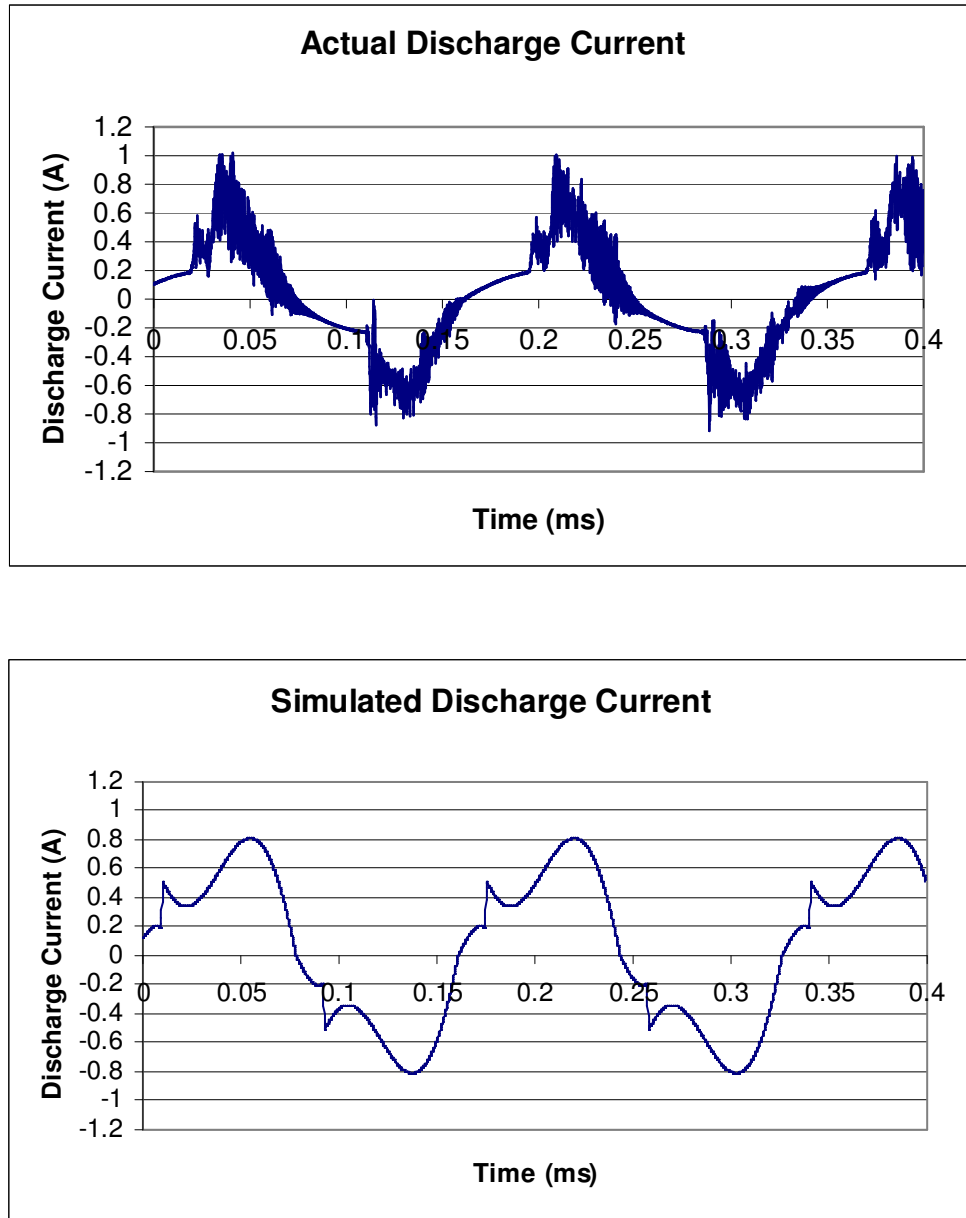


Figure 4.12. Comparison of the actual discharge current with the simulated discharge current for a parallel-plate OAUGDP™ reactor (Matching inductor $L = 190 \text{ mH}$, Matching capacitor $C = 0$, Frequency $f = 6050 \text{ Hz}$, Amplitude of input voltage at the transformer primary side $V_i = 840 \text{ V}$, Plasma capacitance $C_g = 0.13 \text{ nF}$, Power law of the discharge current: $I = (V_g - V_{pi})/1000$, Power-law exponent $\alpha = 1$)

energy stored in the tank circuit of the impedance matching network is lower when the capacitor is smaller. In this situation, there is not enough energy to support the discharge current after it starts, causing the current drop and the small transient spike. However, continuing increase of the voltage across the gap due to its RF phase overcomes the current drop, and causes the discharge current to increase again until the voltage starts to decrease. This forms the secondary peak in the discharge current waveform.

Fig. 4.13 shows four simulations which illustrate the effect of varying the capacitor in the impedance matching network on the shape of the discharge current waveforms. It can be seen that, when the capacitor is larger, the dip between the transient spike and the secondary peak is shallower, and it eventually disappears as the discharge current becomes a single large peak. The energy stored in the matching network provides the current to fill the dip between the transient spike and the secondary peak.

Since the capacitor in the impedance matching network affects the shape of the discharge current waveform, it is also interesting to investigate the effect of the inductor and resistor in the matching network on the discharge current waveform: Fig. 4.14 shows four simulations which illustrate the effect of the inductor in the impedance matching network, and Fig. 4.15 shows four simulations which illustrate the effect of the resistor on the shape of the discharge current waveform. They also exhibit a bimodal to mono-modal transition of the shape of the discharge current waveform when the inductance or resistance is increased. However, these transitions are different from the one related to the capacitor in Fig. 4.13. For the latter two transitions, the disappearance of the dip is due to the increase of the secondary peak when the inductance or resistance is increased. The result is a mono-modal current peak, different from that in Fig. 4.13. The reason for the larger secondary current peak is that, when the inductance or resistance in the matching network is increased, the impedance of the whole load (the matching network and the plasma reactor) seen by the non-ideal transformer is increased. As a result, the actual applied voltage across the reactor is also increased. Thus, the effect of the inductor

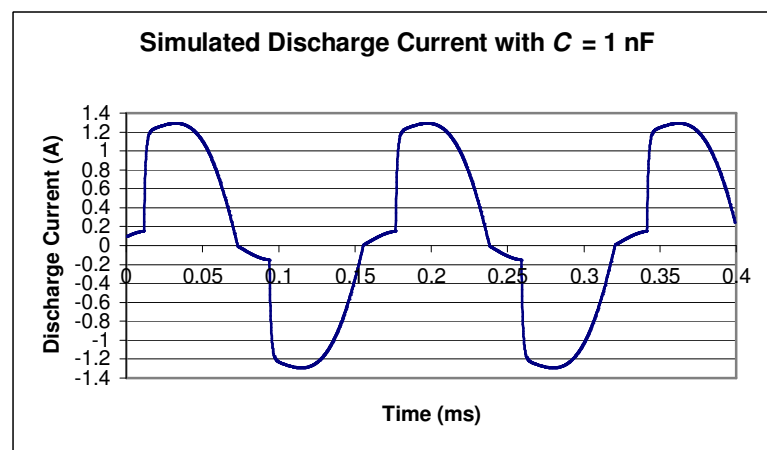
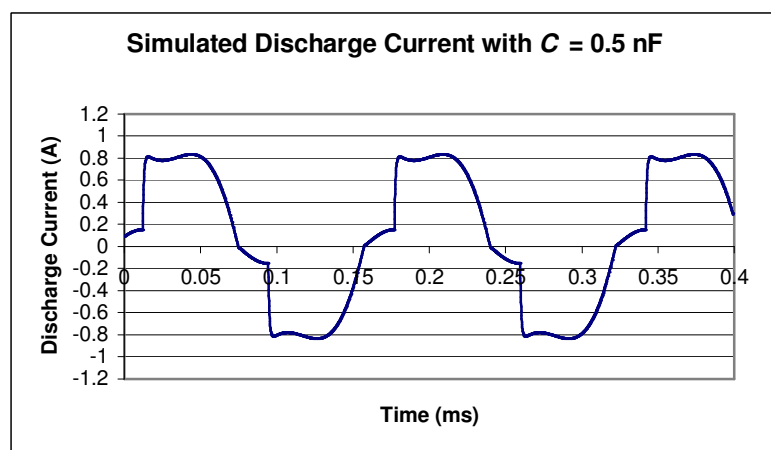
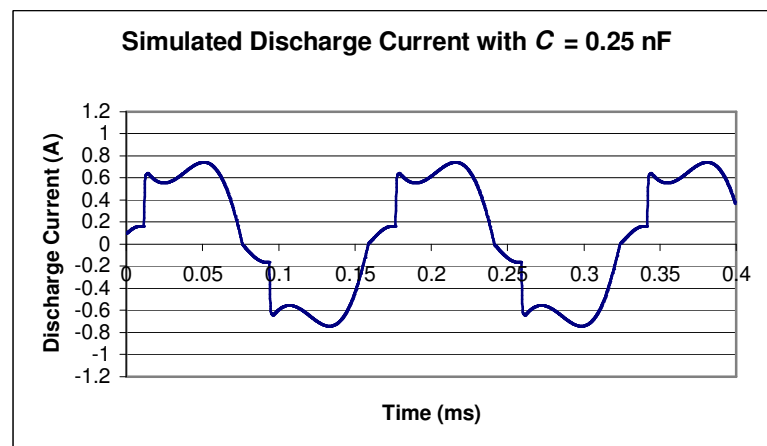
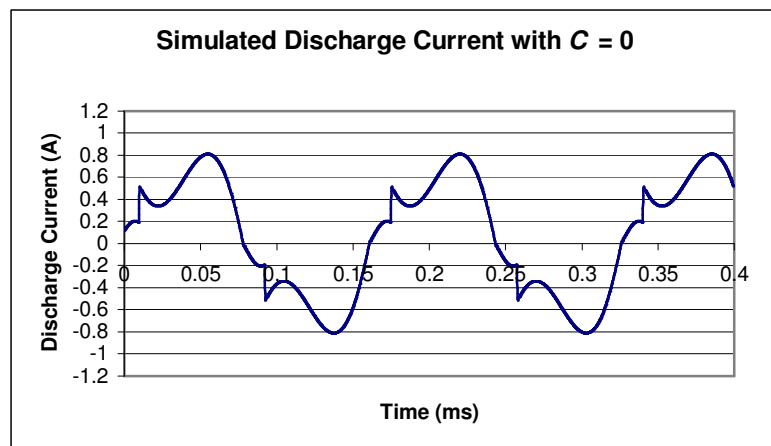


Figure 4.13. Effect of the capacitor in the impedance matching network [28] on the shape of discharge current waveforms of a parallel-plate OAUGDP™ reactor (All the simulation parameters except C are the same as those in Fig. 4.12)

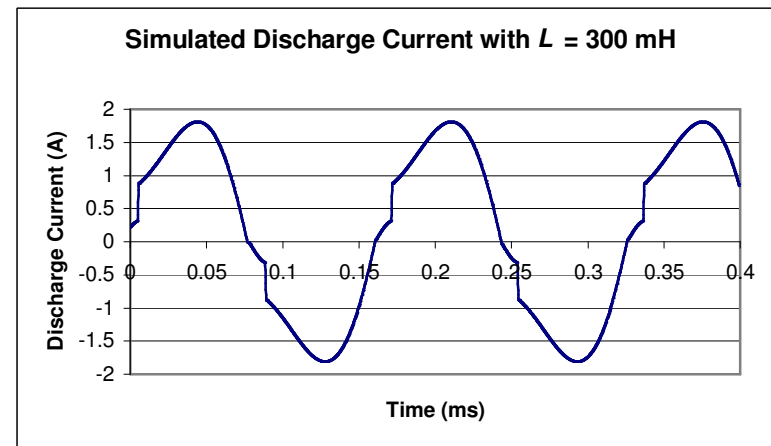
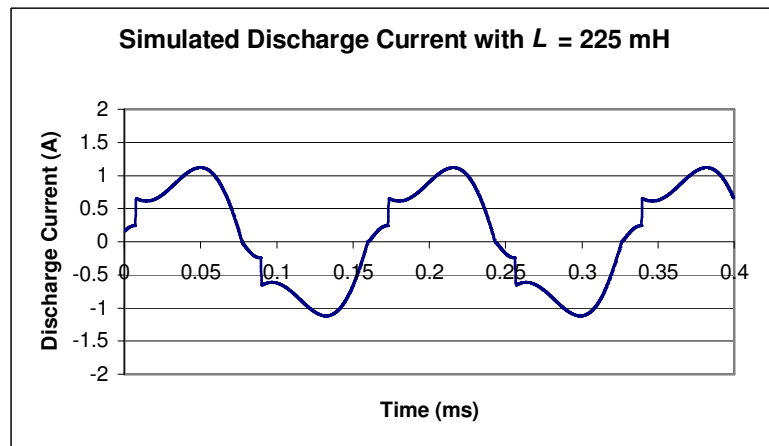
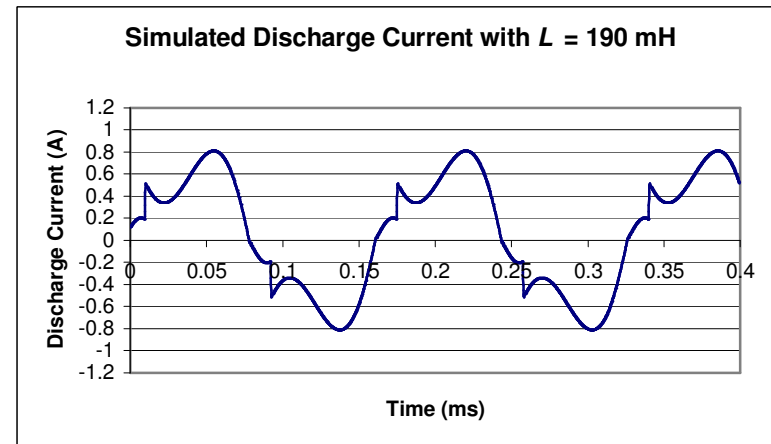
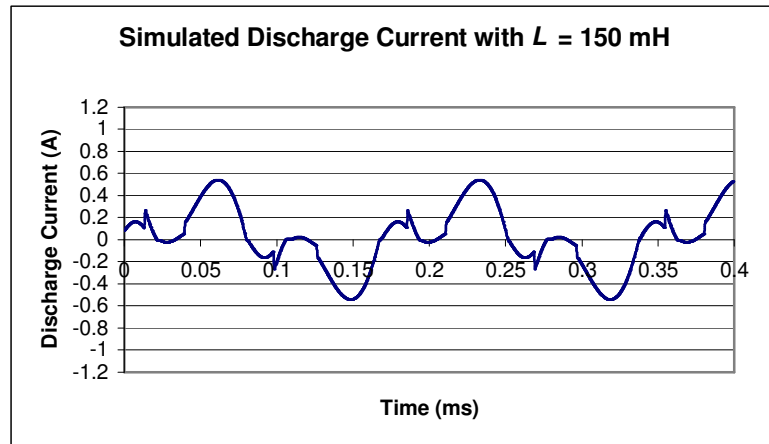


Figure 4.14. Effect of the inductor in the impedance matching network on the shape of discharge current waveforms of a parallel-plate OAUGDP™ reactor (All the simulation parameters except L are the same as those in Fig. 4.12)

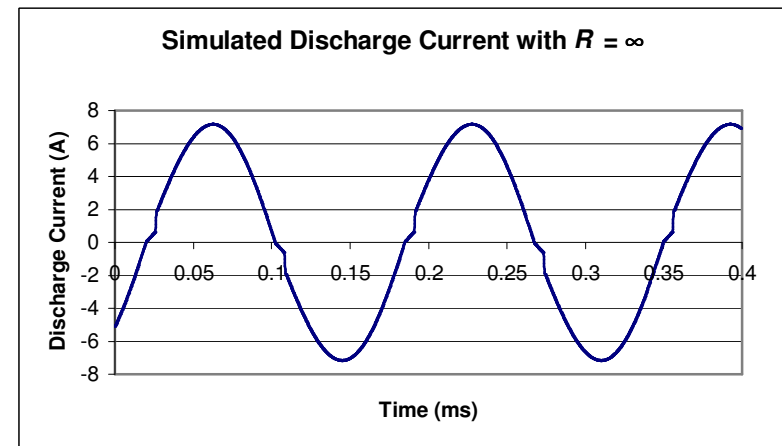
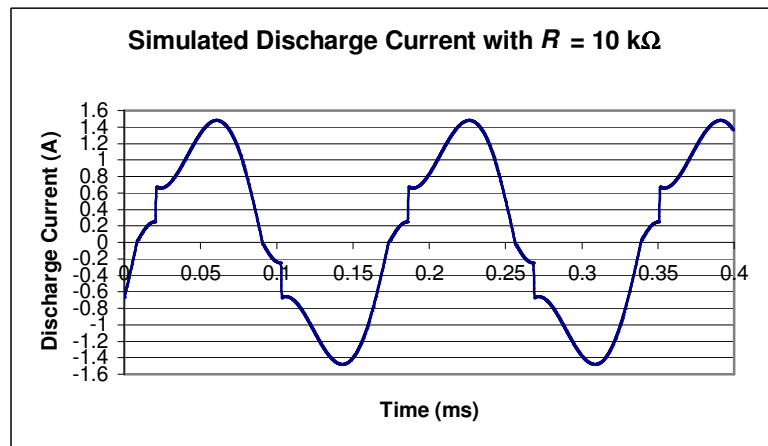
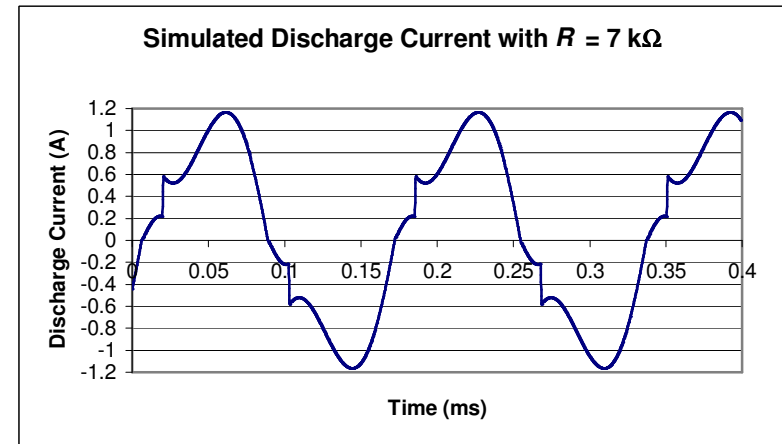
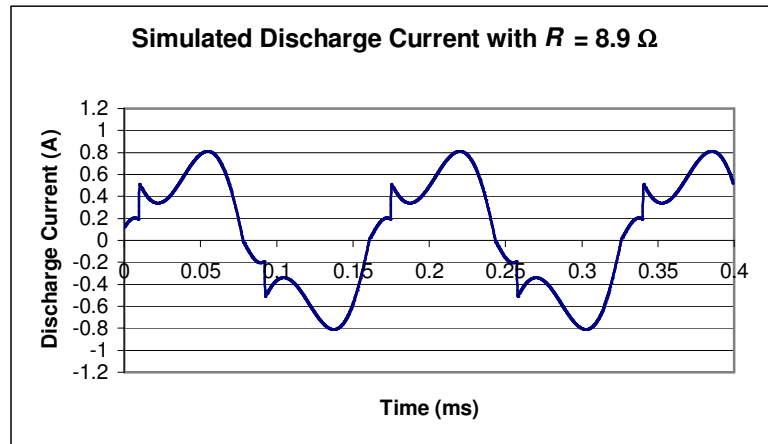


Figure 4.15. Effect of the resistor in the impedance matching network on the shape of discharge current waveforms of a parallel-plate OAUGDP™ reactor (All the simulation parameters except R are the same as those in Fig. 4.12)

or resistor in the matching network on the shape of the discharge current waveforms is different from that of the capacitor.

The simulation of a parallel-plate OAUGDP™ reactor driven by a pulsed power supply has also been investigated. In the PSpice® code, a pulsed high-voltage power supply is directly connected to the OAUGDP™ reactor. The code for the matching network and the transformer are deleted. The simulated discharge current is shown in Fig. 4.16. The shape of the discharge current has changed to pulses, which indicates that pulsed power supplies are not suitable for generating the OAUGDP™, as the plasma is of very brief duration.

Active flow control is a topic in full expansion due to associated industrial applications of huge importance, particularly for aeronautics. Among all flow control methods, such as the use of mechanical flaps, wall synthetic jets or MEMS, plasma-based devices are very promising. The main advantages of such systems are their robustness, simplicity, low power consumption and ability for real-time control at high frequency. Moreau recently conducted a review of the worldwide works on airflow control by non-thermal plasma actuators, from its origin to the present [32].

Figs. 4.17 – 4.19 shows the discharge current waveform observed in subsonic plasma aerodynamics experiments [4] – [6] and its PSpice® simulation. The plasma layer was generated by co-planar electrodes on a co-planar plasma actuator panel as shown in Figs. 4.4 – 4.6. Corke et al. used a similar electrode configuration in a similar plasma aerodynamics experiment [33]. In spite of the very different reactor geometry, the simulated current waveforms still exhibit a single broad current peak during each half RF cycle, and agree well with the actual discharge current waveforms. A list of some component parameters used in this PSpice® simulation is shown in Table 4.3.

The importance of an impedance matching circuit in an OAUGDP™ reactor/actuator system can be illustrated by the matching circuit's impact on discharge

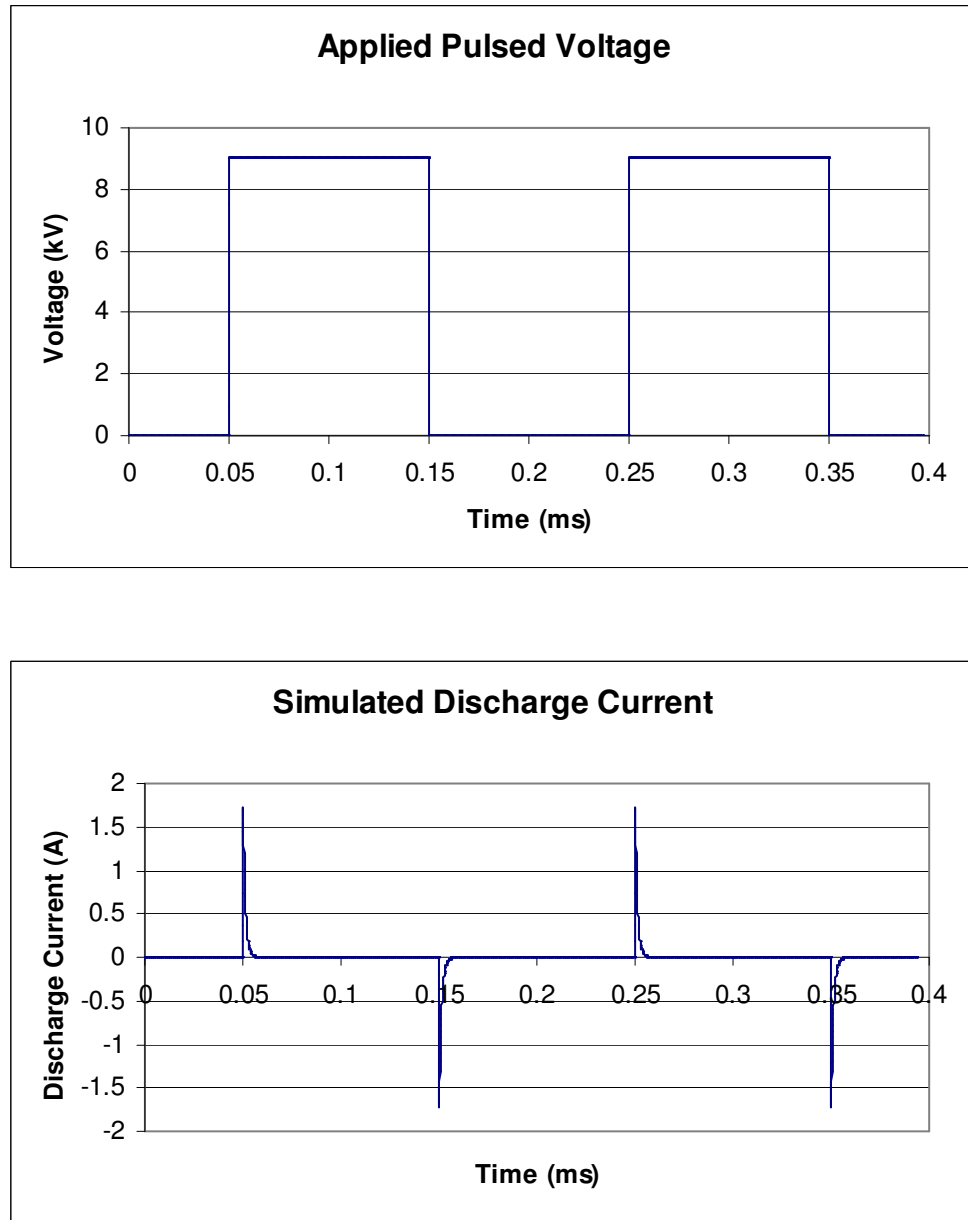


Figure 4.16. The simulated discharge current in a parallel-plate OAUGDPTTM reactor driven by a pulsed power supply (Internal resistance of the pulsed power supply $R_s = 5 \text{ k}\Omega$, Plasma capacitance $C_g = 0.25 \text{ nF}$, Power law of the discharge current: $I = [(V_g - V_{pi})/1000]^3$, Power-law exponent $\alpha = 3$)

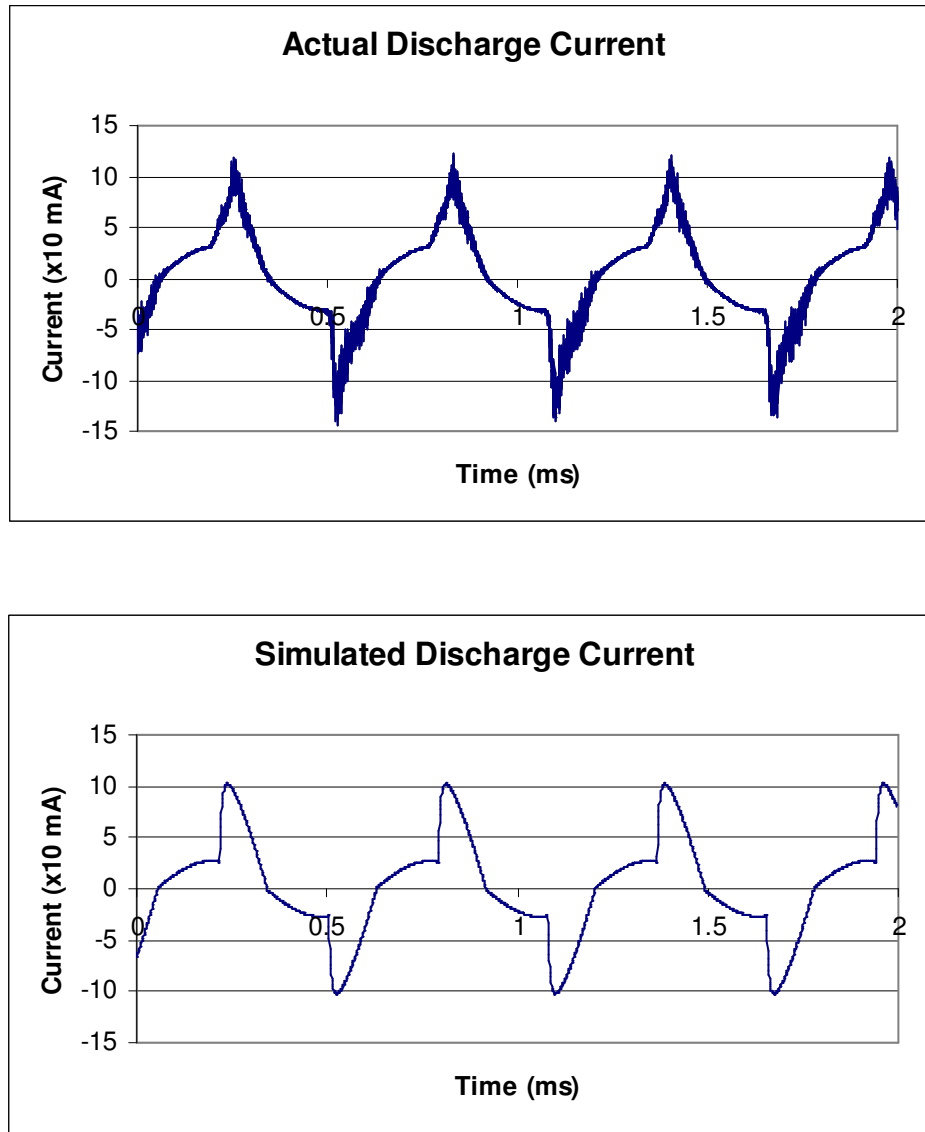


Figure 4.17. Comparison of the actual discharge current with the simulated discharge current for a co-planar plasma actuator panel (Frequency $f = 1741 \text{ Hz}$, Amplitude of input voltage at the transformer secondary side $V_o = 4600 \text{ V}$, Plasma capacitance $C_g = 1.4 \text{ nF}$, dielectric capacitance $C_d = 2.3 \text{ nF}$, Power law of the discharge current: $I = (V_g - V_{pi})/1000$, Power-law exponent $\alpha = 1$)

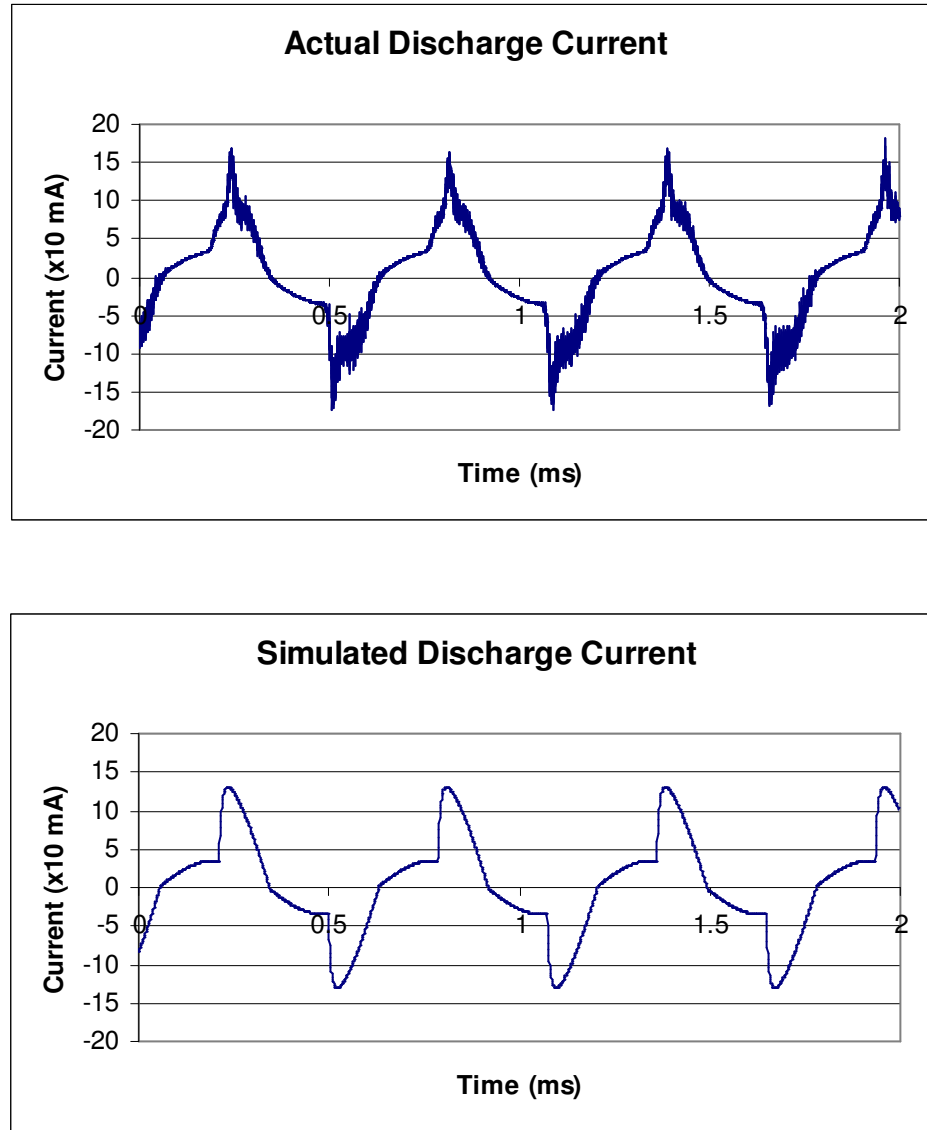


Figure 4.18. Comparison of the actual discharge current with the simulated discharge current for a co-planar plasma actuator panel (Frequency $f = 1741 \text{ Hz}$, Amplitude of input voltage at the transformer secondary side $V_o = 4920 \text{ V}$, Plasma capacitance $C_g = 1.7 \text{ nF}$, dielectric capacitance $C_d = 2.7 \text{ nF}$, Power law of the discharge current: $I = (V_g - V_{pi})/1000$, Power-law exponent $\alpha = 1$)

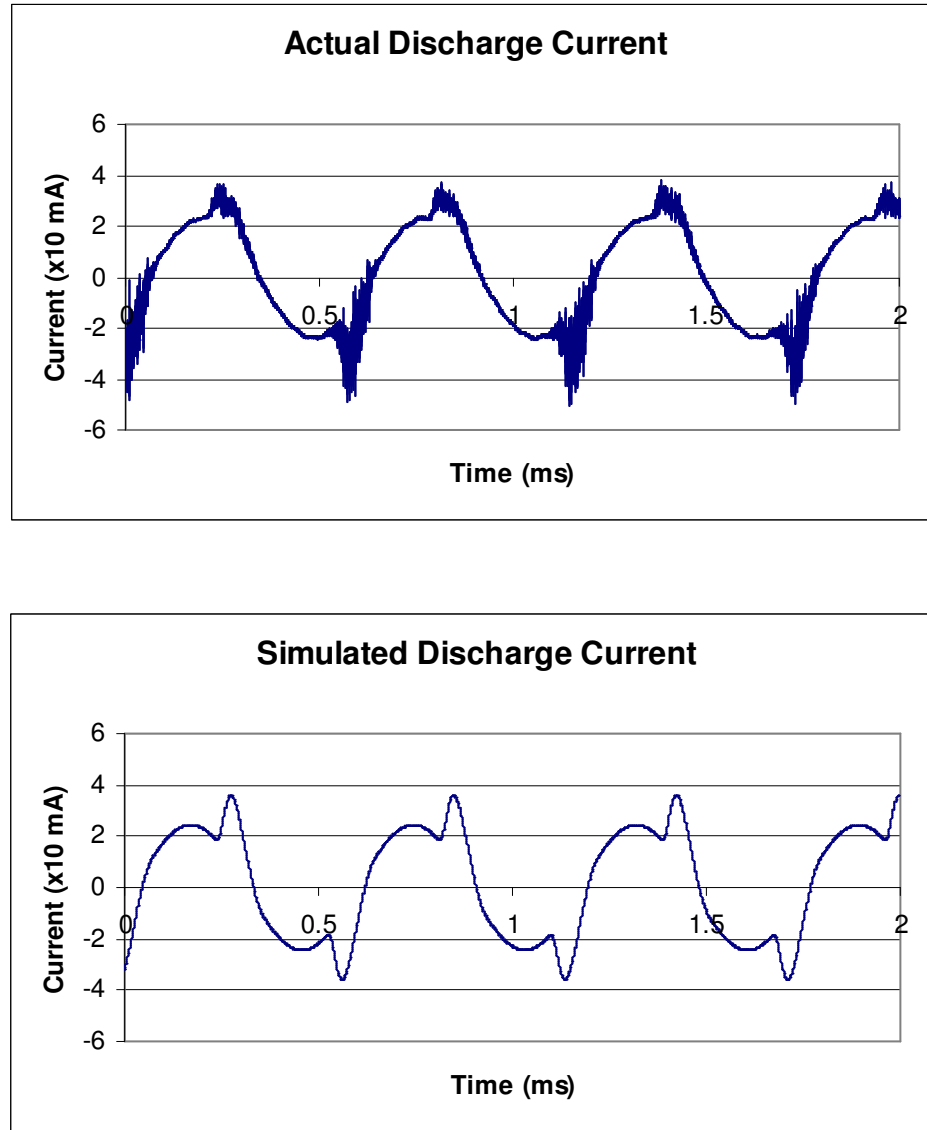


Figure 4.19. Comparison of the actual discharge current with the simulated discharge current for a co-planar plasma actuator panel (Frequency $f = 1741 \text{ Hz}$, Amplitude of input voltage at the transformer secondary side $V_o = 4000 \text{ V}$, Plasma capacitance $C_g = 1.5 \text{ nF}$, dielectric capacitance $C_d = 2.2 \text{ nF}$, Power law of the discharge current: $I = [(V_g - V_{pi})/1000]^3$, Power-law exponent $\alpha = 3$)

Table 4.3. PSpice® Simulation Parameters of a Co-planar Plasma Actuator Panel

PSpice® Simulation Parameters of a Co-planar Plasma Actuator Panel	
Impedance matching network (The numbers were measured)	$R_L = 6 \Omega$, $L = 80 \text{ mH}$, $C = 125 \mu\text{F}$
Co-planar Plasma Actuator Panel (The numbers were calculated, based on experimental data)	$C_{s1} = C_{s2} = C_{s3} = C_{s4} = 1 \mu\text{F}$, $R_{p1} = R_{p2} = 30 \text{ k}\Omega$, $V_{pi} = 1.1 \text{ kV}$, $C_d = 2.3 \text{ nF}$

voltage and current waveforms. Figs. 4.20 and 4.21 show the waveforms of the transformer output voltage and plasma actuator discharge current observed when the impedance matching circuit was disconnected from the OAUGDP™ actuator system. It can be seen that, without impedance matching, the power supply was overdriven, not only the amplitude of the output voltage is constrained, the voltage waveform is also distorted; For current waveforms, without impedance matching, not only the amplitude of reactive current is significantly increased, the profile of actual discharge current is also significantly altered, losing the single-peak-feature observed when the impedance matching circuit was connected. The altered discharge current profile may indicate different discharge processes, different plasma characteristics and/or different plasma chemistry, which are subject to further investigation.

Fig. 4.22 shows comparison of the actual discharge current with the simulated discharge current for a single plasma actuator strip. In spite of the very different electrical parameter values, the simulated current waveforms still exhibit a single broad current peak during each half RF cycle, and agree well with the actual discharge current waveforms. A list of some component parameters used in this PSpice® simulation is shown in Table 4.4. Fig. 4.23 shows the actual discharge current of this single plasma actuator strip operating in the filamentary mode. It can be seen that there are much more filaments in the discharge current than when the plasma actuator operates in the glow discharge mode.

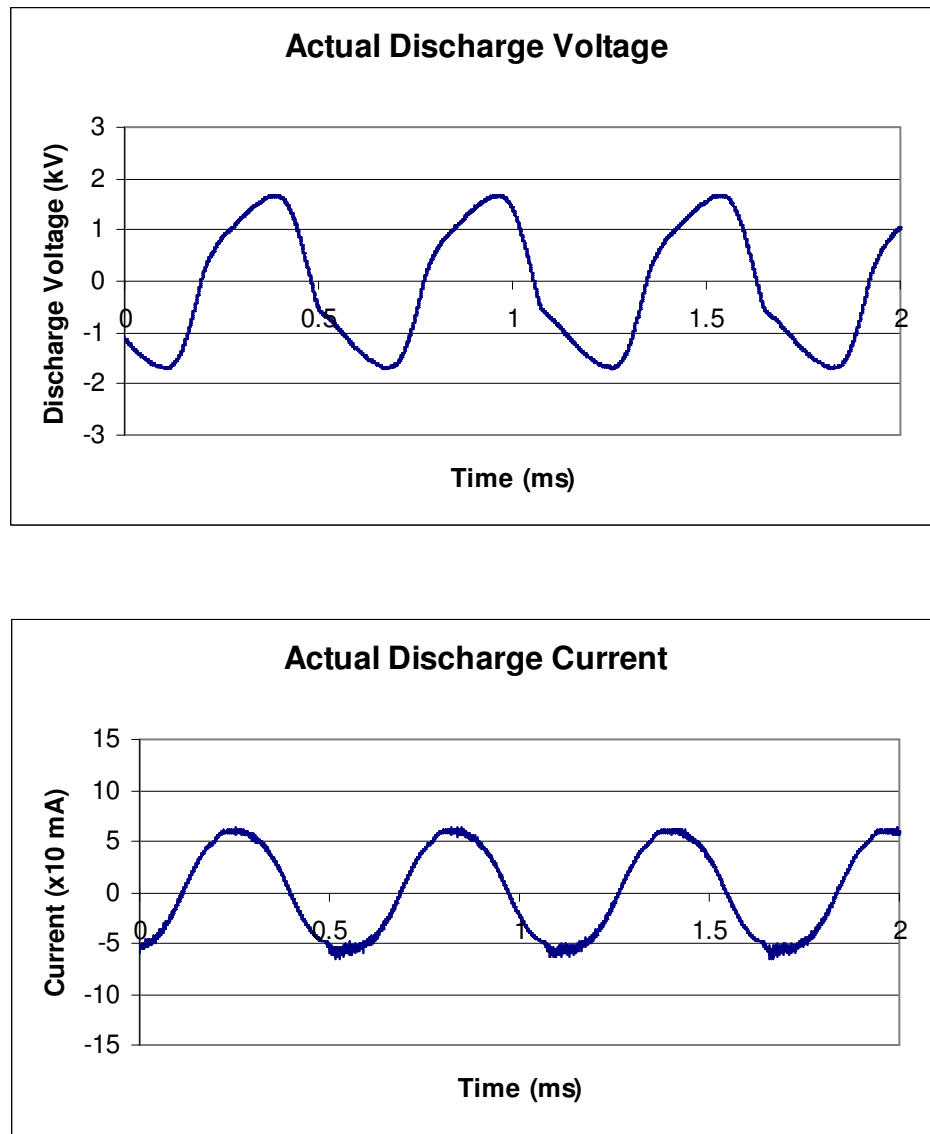


Figure 4.20. Transformer output voltage and plasma actuator panel discharge current observed when the impedance matching circuit was disconnected from the OAUGDP™ plasma actuator system.

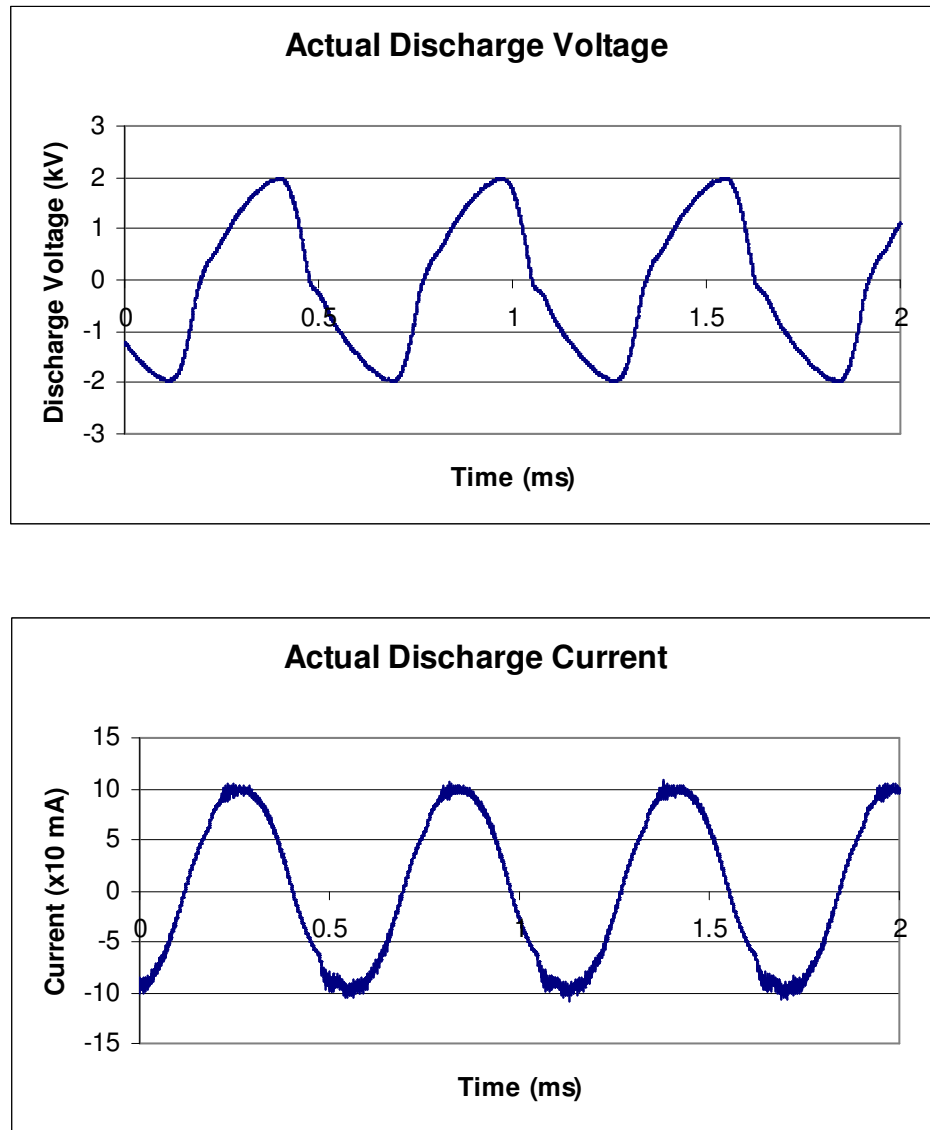


Figure 4.21. Transformer output voltage and plasma actuator panel discharge current observed when the impedance matching circuit was disconnected from the OAUGDP™ plasma actuator system.

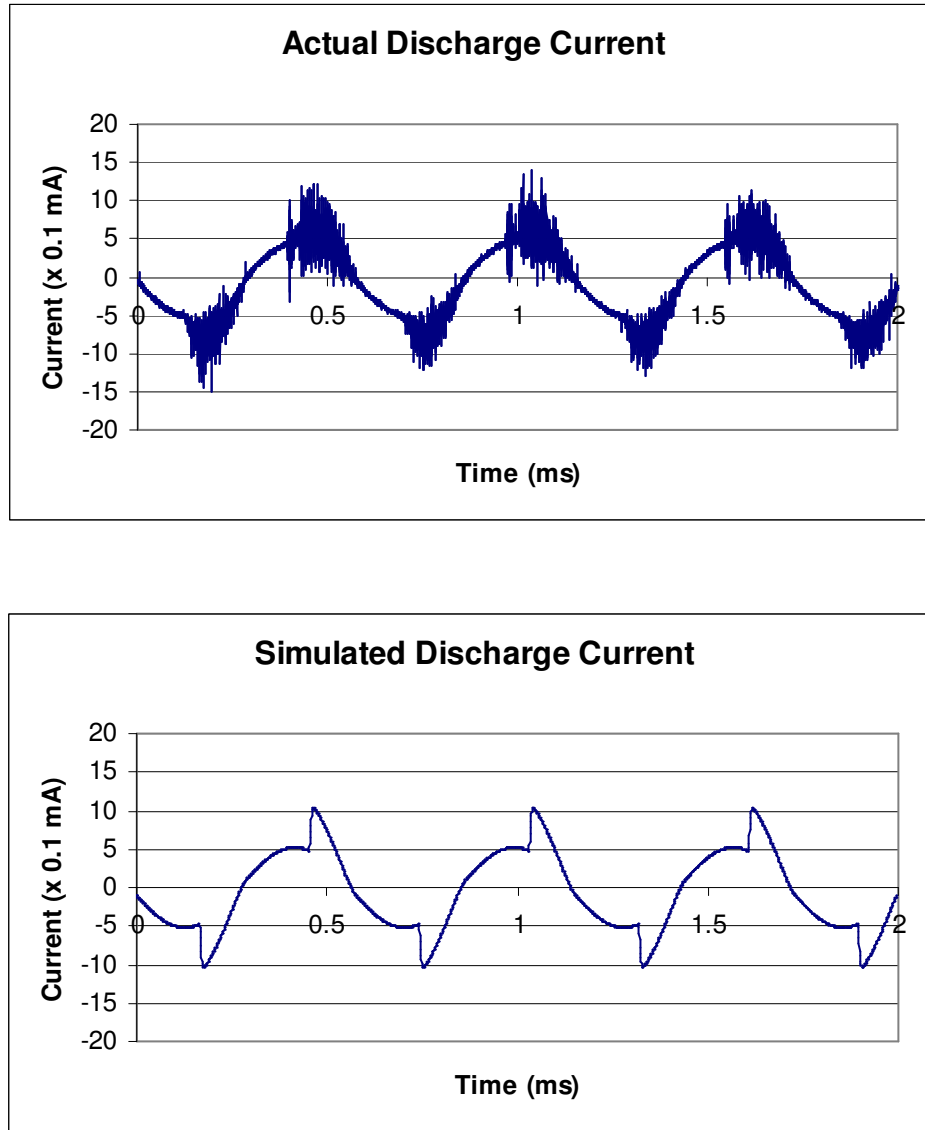


Figure 4.22. Comparison of the actual discharge current with the simulated discharge current for a single plasma actuator strip (Frequency $f = 1735$ Hz , Amplitude of input voltage at the transformer secondary side $V_o = 5600$ V , Plasma capacitance $C_g = 0.03$ nF , dielectric capacitance $C_d = 0.02$ nF , Power law of the discharge current:

$$I = \left[(V_g - V_{pi}) / 1000 \right]^3, \text{ Power-law exponent } \alpha = 3$$

Table 4.4. PSpice® Simulation Parameters of a Single Plasma Actuator Strip

PSpice® Simulation Parameters of a Single Plasma Actuator	
Impedance matching network (The numbers were measured)	$R_L = 6 \, \Omega$, $L = 80 \, \text{mH}$, $C = 125 \, \mu\text{F}$
Co-planar Plasma Actuator Panel (The numbers were calculated, based on experimental data)	$C_{s1} = C_{s2} = C_{s3} = C_{s4} = 0.01 \, \mu\text{F}$, $R_{p1} = R_{p2} = 3 \, \text{M}\Omega$, $V_{pi} = 1.1 \, \text{kV}$, $C_d = 0.02 \, \text{nF}$, $C_g = 0.03 \, \text{nF}$

4.5 Discussion and Conclusions

The voltage values and waveforms resulting from simulations such as those of Figs. 4.17 – 4.19 match those of experiments. Simulations verify that the amplitude of the simulated discharge current is determined by three independent variables — plasma initiation voltage, dielectric capacitance and the applied voltage across the electrodes. Simulations also verify that the plasma capacitance C_g and the applied voltage determine the amplitude of the reactive current — the sinusoidal baseline in the discharge current waveform. This reactive current is intrinsic to capacitatively-coupled OAUGDP™ reactors. It has been found that the power-law exponent α has a minor effect on the rising edge and the sharpness of the peak in the modeled discharge current waveform. The profile of the simulated discharge current waveform can be adjusted to match the experimental current waveform by changing the value of α . This might indicate that the current-voltage relationship of the OAUGDP™ is described by power laws with different exponents at different operating conditions. Simulations verify that the capacitance of the impedance matching network affects the shape of the discharge current waveform. The mono-modal-to-bimodal transition of the shape of the discharge current waveform was observed both in experiment and simulation. Simulations also indicate that the

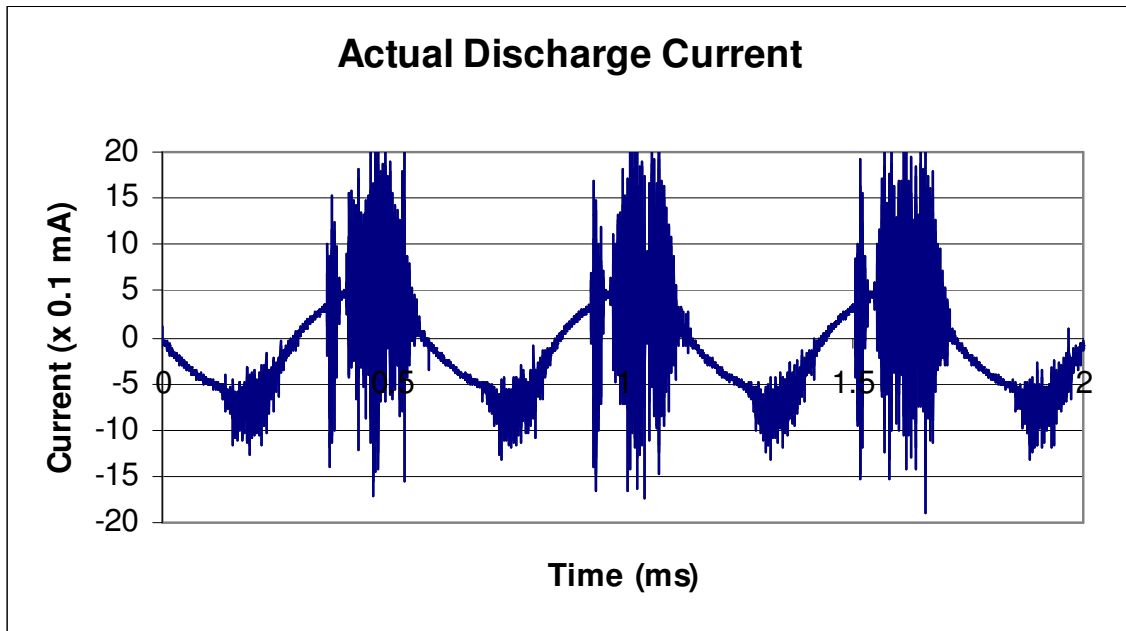


Figure 4.23. Actual discharge current of a single plasma actuator strip operating in the filamentary mode

inductance and resistance of the impedance matching network also affect the shape of the discharge current waveform.

We have developed a satisfactory PSpice® model for the plasma discharges in a parallel-plate OAUGDP™ reactor and on a co-planar OAUGDP™ actuator panel. Simulation results agree qualitatively and quantitatively with the experimental data if the current-voltage power-law exponent α is chosen to fit the particular OAUGDP™ geometry simulated and the plasma operating conditions. In addition to simulation of the plasma discharge in OAUGDP™ reactors, the modeling of the whole OAUGDP™ reactor/actuator system including the non-ideal transformer and impedance matching network can help engineers to improve the design of actual OAUGDP™ reactor/actuator systems.

Chapter 5 Summary and Discussions

This thesis has addressed two important issues around One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) reactor/actuator systems — impedance matching and PSpice® simulation.

A characteristic One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) reactor/actuator requires a power supply capable of delivering a few kilowatts at a frequency of 1 – 10 kilohertz, and an RMS voltage up to 20 kilovolts. The OAUGDP™ reactor/actuator with the plasma energized can be modeled as a capacitor in parallel with a resistor. In addition, the non-ideality of the transformer between the RF power supply and the plasma reactor/actuator introduces an imaginary component in its impedance. Thus, the load of the RF power supply, as seen by its output terminals, is highly reactive. An impedance mismatch resulting from the absence of a matching network will cause a large reflected power from the plasma reactor back to the power supply that does not contribute to plasma formation, but requires an expensive over-rated power supply. All the impedance matching networks in the existing literature are for the radio-frequency or microwave plasma applications under low pressures, and they cannot be adapted to the applications of the OAUGDP™, which is operated at much lower frequencies and much higher voltages. In this work, two types of low RF impedance matching circuits were designed specifically for matching OAUGDP™ reactors/actuators to their power supplies and non-ideal transformers, and the experimental results show that their performance is satisfactory.

This thesis also presents PSpice® simulation of the electrical characteristics of OAUGDP™ reactor/actuator systems. An OAUGDP™ reactor/actuator system normally includes a power supply, a transformer, an impedance matching network, and the plasma reactor/actuator. The principal task in simulation is to develop a comprehensive PSpice®

model for the plasma discharge in an OAUGDP™ reactor/actuator, which may consist either of two parallel electrode plates with a small gap between them, or a planar plasma layer generated by co-planar parallel electrode strips on a flat panel plasma actuator. In an OAUGDP™, at least one electrode is covered with a dielectric, which can be modeled as a capacitor, as can the gap containing the plasma. The plasma discharge itself is modeled as a voltage-controlled current source that is switched on when the voltage across the gap exceeds the plasma initiation voltage. The current source and its output current follow a power law of the applied voltage, an observed phenomenological characteristic of the voltage-current behavior of normal glow discharges. Simulation results agree qualitatively and quantitatively with experimental data from actual reactors/actuators. It has been found that in different operating regimes, the discharge current of the OAUGDP™ is described by voltage power laws with different exponents, and that the capacitance of the impedance matching network affects the shape of the modeled discharge current waveform in a manner consistent with experiment. In addition to simulation of the plasma discharge in OAUGDP™ reactors/actuators, the modeling of the whole OAUGDP™ reactor/actuator system including the non-ideal transformer and impedance matching network can help engineers to improve the design of actual OAUGDP™ reactor/actuator systems.

This thesis work has generated two journal articles [28], [30] that both appeared in *IEEE Transactions on Plasma Science*, and have been widely cited.

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List of References

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Vita

Zhiyu Chen was born in Leshan, Sichuan Province, China. His parents were research engineers of the Southwestern Physics Research Institute of China, which was located in Leshan. The research institute mainly conducts the Chinese thermal plasma nuclear fusion research program. Growing up in such an environment, he became very interested in and enthusiastic about science and technology at a very early age. When he was in high school, he moved to Tianjin in North China with his family. After graduating from Tianjin Experimental High School, he attended Tsinghua University in Beijing. As an undergraduate student, he studied nuclear electronics at the Engineering Physics Department, a field that is specialized in developing electronic instrumentation and computer software for nuclear science research and nuclear industry. After graduating as a top student with a Bachelor of Engineering degree from Tsinghua University, he was awarded with admission to the Graduate School of Tsinghua University without admission exams, where he studied plasma physics and nuclear fusion at the Engineering Physics Department. After graduating with a Master of Science degree from Tsinghua University, he attended the University of Tennessee, Knoxville, in the United States of America, and studied industrial plasma engineering at the Electrical and Computer Engineering Department. He was a student member of the IEEE Nuclear and Plasma Sciences Society and a recipient of the IEEE NPSS (Nuclear and Plasma Science Society) Graduate Student Award (2002). He graduated with a Master of Science degree in Electrical Engineering from the University of Tennessee in December, 2007.